# Uranium as an energy source: medium to long term prospects

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Uranium is the only metal used as energy source.[1] The extraction of uranium from the Earth's crust involves a complex chain of physical and chemical separation processes and the consumption of large quantities of energy, and of different chemicals.
The energy and chemicals consumed during extraction increase exponentially with decreasing ore grade, accompanied by an exponentially increasing emission of $CO_2$. The grades of the available uranium resources decrease with time, because the mining companies mine the richest resources first, and because these offer the highest return of investment. Above phenomena cause the existence of the "energy cliff" and the "$CO_2$ trap". They thus call into question, for the century to come, the viability of a nuclear based solely on $^{235}U$ extracted from natural uranium whose geological occurence couldn't suffice to make it self-evidently an energy resource.
One way to overcome this $^{235}U$ limitation would be to exploit $^{238}U$ resources. Nevertheless, this requires the industrial development and worldwide deployment of reactors operating in fast neutron mode (e.g. FNR). However a significant share of the energy produced by such reactors is difficult to envisage at a world level before the end of this century, as we shall see in this article.

## Introduction – Purpose of the article

When we talk about the civil use of uranium, we are of course thinking of energy production, and particularly electricity production, which is the almost exclusive application of uranium in this sector. Currently, the fleet of reactors in operation worldwide is based on the fission of $^{235}U$. This isotope of uranium represents 0.7% of natural uranium, while the remaining 99.3% is composed of $^{238}U$, which is envisaged for energy use in the context of the deployment of future generation IV reactors, known as "fast neutron reactors" (or FNR), as opposed to current reactors which operate in a thermal neutron regime. The main advantage of FNR lies in the energy potential they would allow by exploiting $^{238}U$, thus multiplying by a factor of about 100 the amount of energy produced, compared to the exploitation of $^{235}U$ alone.

[1] It should be noted, however, that some metals (e.g. alkali metals) are likely to react with air or water by releasing heat. However, they cannot be considered as a source of energy in the same way as uranium insofar as, in their case, we are in the field of chemical reactions, whereas in the case of uranium, it's nuclear reactions which are involved. The latter are, as we know, far more energetic than the former, where the energy spent on extracting and refining metals must be compensated for by the energy released by the heat-producing chemical reactions, which is hardly the case. Nevertheless, we have to notice that numbers of metals (e.g. copper, cobalt, boron, beryllium, etc.) play a crucial role in energy systems, whether they are renewable or nuclear in nature.

In France, the lessons learned from the work carried out in the field of fast reactors are largely due to the feedback from the operation of the Phénix reactor, an industrial demonstrator with an electrical power of 250 MWe, connected to the grid between 1973 and 2010, and whose material balances made it possible to establish a rate of $^{239}Pu$ overgeneration of 1.16. The practical implementation of fast reactors has thus been demonstrated in France on a pre-industrial scale. More recently, a French programme called ASTRID (FNR-Na reactor) was launched in 2010, one of the objectives of which was to resolve a problem of core instability in case of coolant loss. It was initially intended to lead to a pilot, but the decision was taken in the summer of 2019 to terminate the project.

Outside France, several prototypes or industrial pilots of the FNR type have been built in recent decades. Of particular note are the Russian BN600 and BN800 demonstrators, commissioned in April 1980 and June 2014 respectively, and still in operation. In addition, new generation IV reactors are currently under study in several countries, notably in China and Russia.

However, what has to be noticed is that after decades of research in seven countries (USA, UK, France among others), along with investments of some 100 billion dollars, the breeder concept didn't go beyond the pre-industrial level. Therefore, the global deployment of FNR technology is still not in sight and will most likely not be effective at large scale before the end of this century, as explained below. During this transition period, nuclear electricity production will thus again rely mainly on $^{235}U$, and the question of the availability of natural uranium by 2100 is therefore raised.

So, after recalling some available figures on the world's uranium resources, and providing some details on the main techniques for exploiting uranium deposits, this article will analyse the geological factors likely to limit the associated energy yield rates, as well as the expected consequences, for this century, in terms of limiting greenhouse gas emissions. Finally, some considerations on the prospects for the deployment of FNR technology in France, and on a global scale will also be presented.

It should also be noted that this article only deals with physical limits on a global scale, without taking into account the geostrategic stakes of the main countries for access to mineral resources.

## About recoverable uranium resources

In terms of natural uranium resources, while the baseline data used in this article is not the most recent, having been established by the IAEA, OECD and NEA in 2008 [22], this has relatively little impact here as the objective of the article is not to establish precisely the current state of uranium resources, but, as said in the introduction, it is more on the limiting factors of its production in the foreseable future.

Nevertheless, the total amount of uranium represented by this diagram, wich is 5.469 Tg (1 teragram = 1 million metric tonnes), corresponding with the total resources (RAR + Inferred cost category up to 130 USD/kg U), is quite similar to the 2022 Red Book [23] figures which states 6.078 Tg, partly due to the fact that during the past decades no large new recoverable uranium deposits have been discovered as illustrated below (Figure 1).

Practically, the nuclear industry distinguishes sometimes two categories of uranium resources, based on economic considerations: conventional and unconventional resources. Conventional resources are deposits of the kind now being mined, and, when uranium can be extracted in an economic way, the rock containing this uranium is called "ore" which is then an economic notion. As far as unconventional resources are concerned, they are resources from which uranium is only recoverable as a minor by-product, such as uranium associated with phosphate rocks, non-ferrous ores, carbonatite, black shale and lignite.

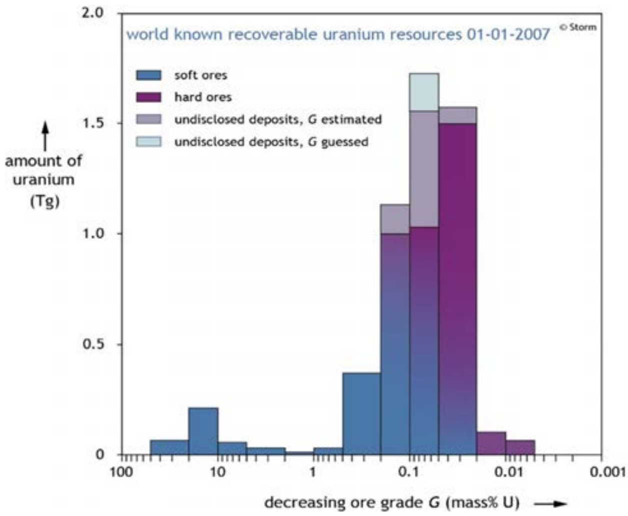


Figure 2. World known recoverable uranium resouces in 2007 (Source: Red Book 2008).

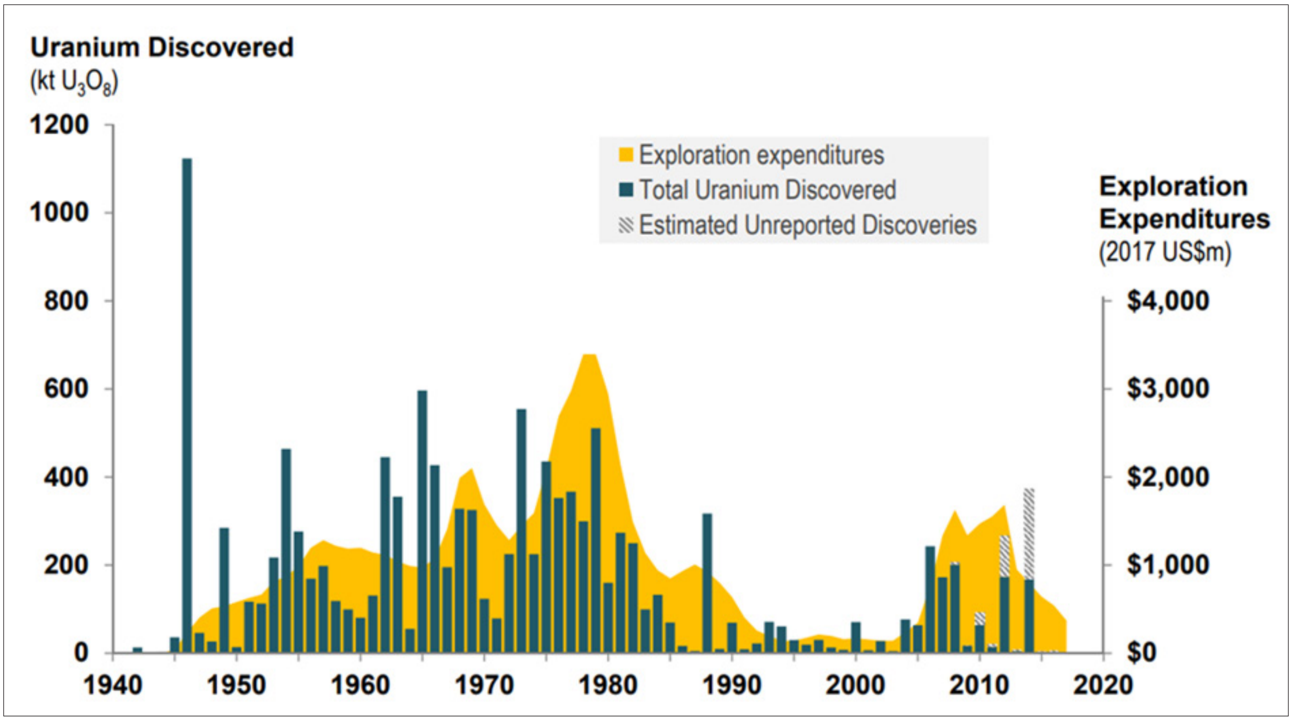


Figure 1. World exploration expenditures, versus uranium discovered (1940-2016).

In addition, uranium occurs in many kinds of minerals in the earth's crust. In this article the conventional ores are divided into two groups (Figure 2):

- soft ores, easily mineable and millable, e.g. sandstones and calcretes, with typical grades ranging from more than 10% down to about 0.02% $U_3O_8$;
- hard ores, hard to mine and mill, e.g. quartz pebble conglomerates, with grades varying typically from about 0.1% down to the mineralisation limit (see box here-after). Some high-grade vein-type ores are also hard to mill.

## Main processing methods currently used

It should be noted that, in addition to the declared resources, the Red Book generally also mentions the processing method envisaged for their uranium extraction. These types of exploitation, of which there are three, are briefly as follows.

### Open pit mining

This processing method involves extracting rock or minerals from an open pit. In this respect, it is important to take into account the thickness of the upper layers of waste rock in order to estimate the mining costs, and the economics of the project.

### Underground mining

This is a processing method used when any ore body lies a considerable distance below the surface, and especially when the amount of waste that has to be removed in order to uncover the ore through surface mining becomes economically prohibitive.

### In Situ Leaching (ISL)

This processing method, also known as in situ recovery (ISR) in North America, involves leaving the ore where it is in the ground, and recovering the minerals from it by dissolving them and pumping the pregnant solution to the surface where the minerals can be recovered.

In general, the extraction of any metal from its ore involves a number of physical transformations and chemical equilibria (Figure 4), all governed by basic physical and chemical laws, which cannot be circumvented by technology. In particular, from the Second Law of thermodynamics, it follows that separation never can be complete, and there always will be losses in the processes.

For this article, the reference uranium mine is the Ranger mine, an open pit mine that may be taken as a world-averaged mine.[2] Underground mining is generallly more energy intensive than open pit mining. Differences in specific energy consumption and $CO_2$ emissions between individual uranium mines are substantial, due to widely varying conditions.

It should also be noted that mines applying the In Situ Leaching (ISL) method have, in some respects, a different flowsheet. Nevertheless, the specific energy consumption and accompanying $CO_2$ emission of ISL mines may be considered similar to those of open-pit mines, as large numbers of injection and production wells are to be drilled due to clogging, and as large volumes of leaching liquids are consumed. In addition, apart from energy consideration, the harmful impact of ISL on the environment can be high [40] and irreversible.

## Extraction yield, as a function of the ore grade

Basically, the industrial processes to extract metal from the Earth's crust consume chemicals and energy, and emit $CO_2$ and other greenhouse gases. For energy, two factors contribute to the specific extraction energy: 1) the dilution factor, 1/G, where G is the grade of the ore, and 2) the extraction yield Y, also called the recovery factor, or recovery yield, wich represents the ratio of the mass of metal actually extracted, over the mass of metal present in the treated amount of rock.

In case of an open pit mining, as it is of course for all the other technologies, losses occur at all stages of the extraction process, as illustrated in Figure 3. More specifically, as far as the leaching and subsequent solvent extraction phase, the lower the concentration of uranium in the liquor, the higher the entropy of the uranium and the less complete its separation from the liquor, which means the greater is the fraction lost in the waste streams. However, a low yield may always be improved by application, if any, of more selective separation processes, but at the expense of much higher specific energy requirements.

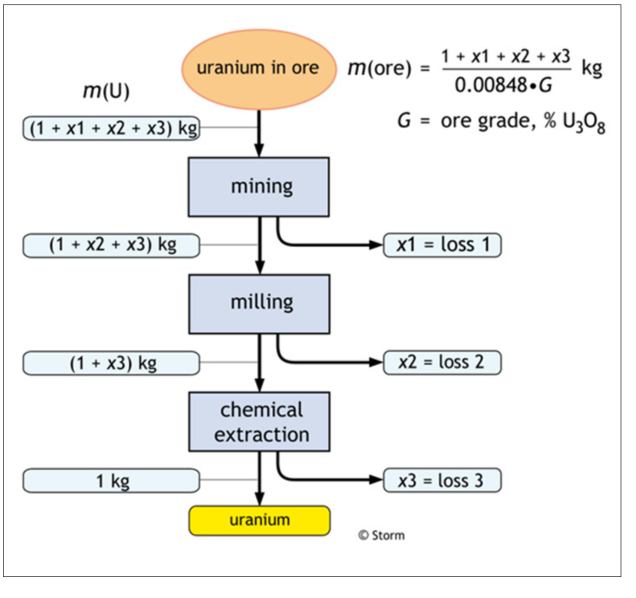


Figure 3. Losses in mining and milling processes in case of an open pit mine.

[2] The Ranger's mine in Australia, is one of the cheapest operating mines in the world, due to its favourable conditions. The flowsheet presented in Figure 4, representative of Ranger mine's one, is used as reference in this study. Many open-pit and underground uranium mines in the world operate according a similar flowsheet.

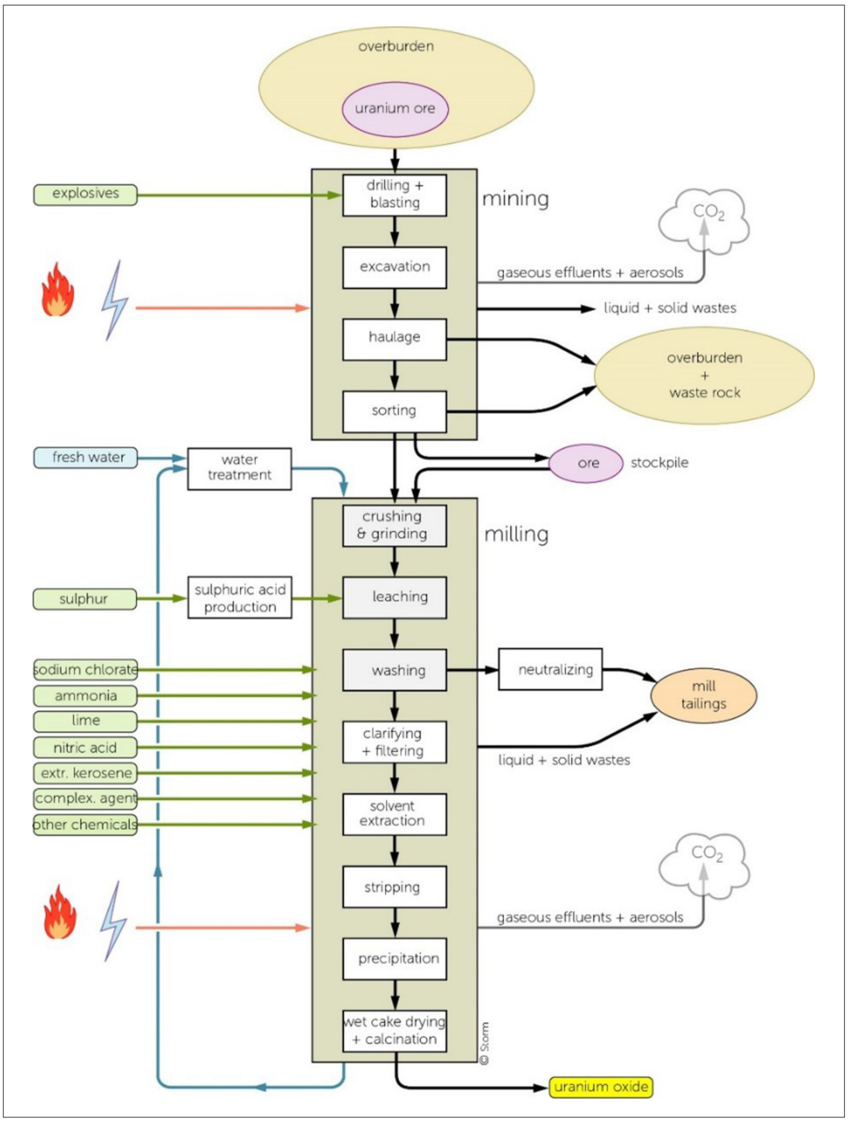


Figure 4. Process of mining and milling in case of an open pit mine.

## About the mineralization limit

Mineralization limit is an important notion, quite unknown and very rarely mentioned. This is a notion that is not included, for instance, in the Red Book, even if the indications on the reserves of certain deposits sometimes mention a consideration of extraction yields, but with little consideration on energy expenditures.

For all natural elements, the mineralization limit corresponds to a content below which they cannot exist in mineral form, but are present in the form of separate grains of minerals, and dispersed at atomic scale among the other constituents of the rock. Concerning uranium, this limit corresponds roughly at grades below 0.01% $U_3O_8$. Hence, to extract uranium from rock types below the mineralisation limit, the whole rock has to be brought into solution. Conversely, if uranium is present as separate minerals, the lixiviation process starts with selectively dissolving the uranium minerals, and subsequently discarding the other minerals from the processed rocks.

To put it another way, in his book: “Extracted. How the Quest for Mineral Wealth is Plundering the Planet” [42], Ugo Bardy defines the mineralization barrier as the threshold below which the only way to extract an element is to work from the undifferentiated crust, what means a very important extra energetical cost, compared with an extraction from ore.

From the above considerations, it follows that it must exist a relationship between the uranium content of an ore and its recovery rate. In order to approach this relationship, a large number of data from current and past operations have been mobilised for this. This has led to the graph shown Figure 5.

The data used for this graph may seem perhaps outdated, but during the past 4-5 decades the extraction techniques applied in the uranium industry have not changed significantly. The study in [Mudd 2011] shows that the blue curve in Figure 5 can be considered as the upper limit of achievable extraction efficiencies with current extraction technologies.

The grey squares in this figure are also taken from the empirical data in [1], while the red points and bars, which are those used in this study, have been taken from references [2] to [15].[3]

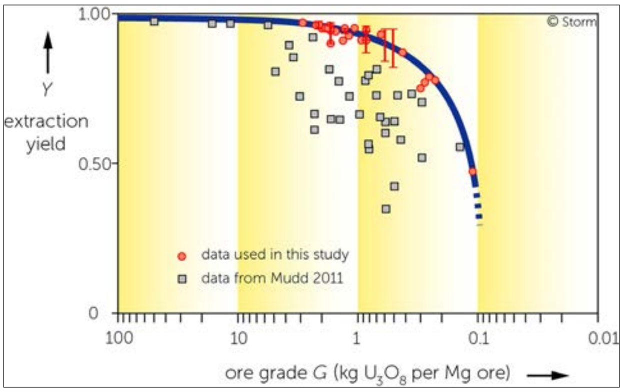


Figure 5. The extraction yield of uranium from ore as a function of the ore grade.

## Energy consumption and $CO_2$ emission of the recovery of uranium

Along with the above definitions, it follows that the specific energy consumption increases exponentially with decreasing ore grade G, and with extraction yield Y. More precisely, the thermal energy requirements of the recovery of one kilogram of uranium leaving the mill, Jm+m(U), as function of the ore grade G, counted in kg uranium per Mg ore, and the recovery yield Y, can be calculated via the following equation:

$$J_{m+m}(U) = \frac{J_{m+m}(ore)}{Y \cdot G}$$

$J_{m+m}(U)$ = specific energy consumption, GJ/kg uranium
$J_{m+m}(ore)$ = specific energy consumption, GJ/Mg ore
$Y$ = extraction yield = fraction of recovered U
$G$ = ore grade, kg U/Mg ore

However, it should be noted here that the specific energy consumption calculated in with this equation excludes the embodied energy of the used chemicals, namely the energy needed to fabricate the chemicals.

As far as the $CO_2$ emission attached with the mining and milling of the ore, it can be simply derived from the energy Jm+m(ore) in considering that the electricity consumed at uranium mines is generally generated by oil-fuelled generators.[4] This way, all energy inputs of mining and milling may be considered to be provided by fossil fuels.

Moreover, it will be here assumed a thermal-to-electric conversion efficiency of 40% to calculate the all-thermal energy input of mining and milling. Hence, assuming the specific $CO_2$ emission of the used fossil fuels (diesel oil and fuel oil) is 75 $gCO_2$/MJ, the specific $CO_2$ emission can be calculated by the following equation:

$$\gamma_{m+m}(U) = 75 \cdot \frac{J_{m+m}(\Sigma th, ore)}{Y \cdot G}$$

$\gamma_{m+m}(U)$ = specific $CO_2$ emission, kg $CO_2$ /kg uranium
$J_{m+m}(\Sigma th, ore)$ = specific all-thermal energy consumption, GJ/Mg ore
$Y$ = extraction yield = fraction of recovered U
$G$ = ore grade, kg U/Mg ore

Considering the great diversity of uranium mining conditions around the world (type of deposit, type of operation, logistical chains, access to water and energy, overburden ratios, hauling distances, etc.), the choice made for this article was limited to taking into account an "average" operation, as illustrated by the choice of the Ranger mine taken as a reference. The only distinction made here is that between "soft" and "hard" ores. This has led to the following figures (Table 1) being used for our purpose.

| quantity | unit | soft ores | hard ores |
|---|---|---|---|
| total thermal energy investment mining | GJ/Mg ore | 1.237 | 1.843 |
| total thermal energy investment milling | GJ/Mg ore | 1.508 | 8.67 |
| total thermal energy investment mining + milling | GJ/Mg ore | 2.745 | 10.51 |
| $CO_2$ emission mining + milling | kg $CO_2$/Mg ore | 206 | 788 |

Table 1. Summary of specific energy investment and $CO_2$ emission of uranium mining + milling at mines with average overburden ratio and hauling distance.

[3] For further details see: https://www.stormsmith.nl/index.html

[4] In recent years, however, we have seen the gradual introduction of battery-powered construction vehicles. However, there is still a lot to be done in this area, especially as for many mining sites, especially those far from electrical infrastructure, the question of electricity production is difficult to resolve without recourse to fossil resources.

Finally, taking into account all these hypotheses and data, two graphs can be derived which illustrate: 1) the energy consumption related to the recovery of uranium (mining and milling), as function of the ore grade (Figure 6); and 2) the $CO_2$ emissions related to the recovery of uranium (mining and milling), again as function of the ore grade (Figure 7).

Concerning energy, Figure 6 shows a blue band representing the grades of deposits currently in production around the world. Obviously, because the richest ores are mined first, for these offer the highest return of investments for the mining companies, the remaining resources will contain deposits with lower uranium grades, and the average uranium content of available uranium resources will then decrease with time.

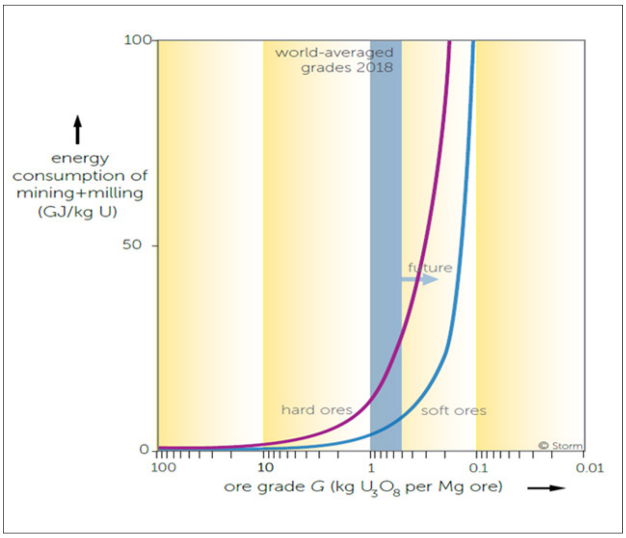


Figure 6. Energy consumption of the recovery of uranium from the earth's crust (mining + milling) as function of the ore grade.

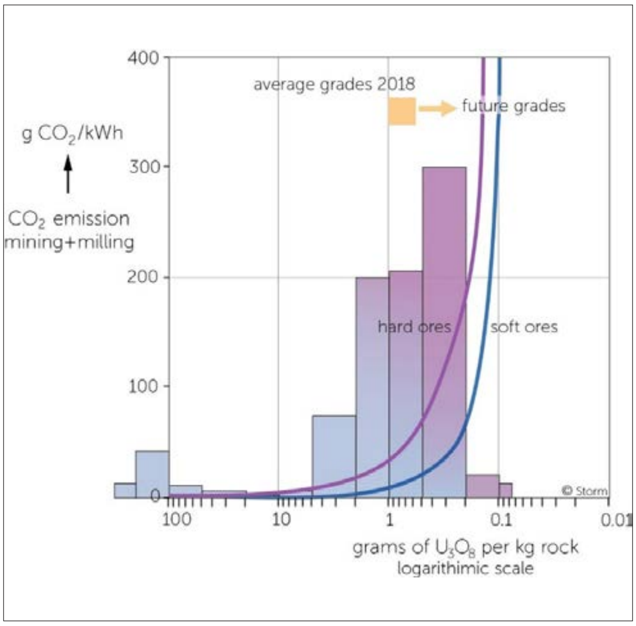


Figure 7. $CO_2$ emissions of the recovery of uranium from the earth's crust (mining + milling) as function of the ore grade.

## Toward the Energy cliff…

With regard to the energy balance of uranium extracted from ore, there is a threshold below which no net energy production from an uranium deposit is possible. In other words, by falling below this threshold, an uranium ore could no longer be considered as an energy source, because the extraction of, say, one kg of natural uranium would consume more energy (noted "Einvested" hereafter, and which is limited here to the energy expended in the extraction processes alone than the energy (noted "Ereturned" hereafter) than that can be generated from one kg of natural uranium.

This can be illustrated by what is called the Energy Returned Over energy Invested[5] (or EROI, see article from J. Treiner and G. Bonhomme for details). In its basic expression, it is defined as follows:

$$EROI = E_{returned} / E_{invested}$$

from which we can easily derive the net energy produced in the extraction process, namely:

$$E_{net} = E_{invested} *(EROI - 1)$$

So, as to have a net energy positive, EROI must be superior to one, this critical value corresponding to the threshold mentioned above. This conducts to the notion called the "energy cliff", as represented Figure 8, based on $^{235}U$ technologies, and where the net energy production of nuclear power will fall to zero.

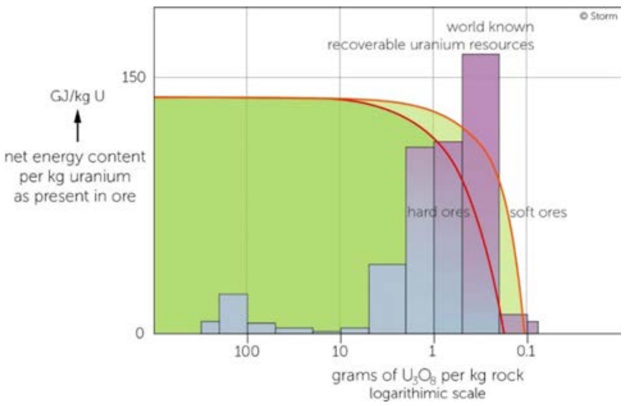


Figure 8. Energy cliff: Net energy content of natural uranium obtained from $^{235}U$, and as function of the ore grade.

It can therefore be seen that, for $U_3O_8$ contents below 100 ppm, and considering the most favourable case of soft ores, the net energy derived from uranium ore mining takes on negative values. It should also be noted that the variation in net energy, described as a function of the content in grams of $U_3O_8$ per kilo obtained from the uranium deposit, is simply the result of a comparison between the data presented in Figure 6, and the energical potential of one kilo of uranium, based solely on the exploitation of $^{235}U$.

[5] As pointed out above, it should be borne in mind that the energy ratios presented here do not include the energy consumption further down the energy production cycle.

Moreover, given the presence of a mineralogical barrier below the 100 ppm limit (see box above), the energy used in the uranium extraction process is bound to increase sharply, leading to a sharp deterioration in the energy balance. This is illustrated Figure 9 below where this energy expenditure is then multiplied by a factor of around 100.

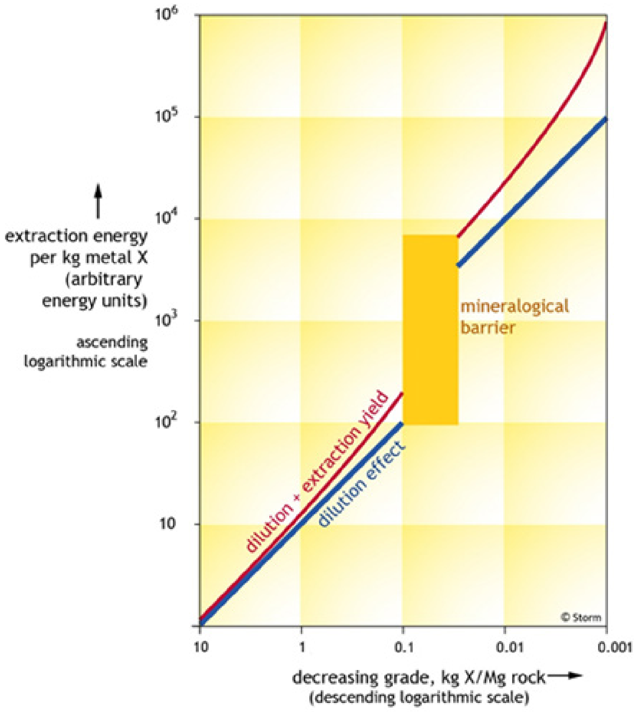


Figure 9. Mineralogical barrier and specific extraction energy of a scarce metal X from the earth's crust.

## …and toward the $CO_2$ trap

As highlighted above, the world average available ore grade of uranium decreases with time. As a result, the specific $CO_2$ emission of uranium recovery, and consequently of nuclear generated electricity, rises with time, and steeply at low grades. To put it more precisely, Figure 7 shows that at a grade of 130-100 gU/Mg ore, and based on $^{235}$U technologies, the specific $CO_2$ emission of nuclear recovery surpasses that of gas-fired electricity generation, which is of the order of 400 $gCO_2$/kWh: this is called the $CO_2$ trap.

To put these figures into perspective, and assuming that the world nuclear capacity remains at the current level, at about 370 GWe,[6] the specific $CO_2$ emission of nuclear recovery will grow to values of gas fired power plant within the lifetime of new nuclear build. This is what is illustrated as scenario 1 in Figure 10 below.

If, instead of scenario 1, we consider a scenario 2 assuming a constant growth of 2% in the share of nuclear power in world electricity consumption, $CO_2$ emissions of nuclear recovery will surpass those of gas fired plants about twenty years sooner than in scenario 1, as shown in Figure 10.

## About the transition of the French nuclear fleet: from PWR to FNR

As mentioned above, the deployment of reactors based on fast neutron technologies will hardly be possible before the end of this century, as illustrated in Figure 11 for the French nuclear fleet. This roadmap shows one of the scenarios for the deployment of these reactors which

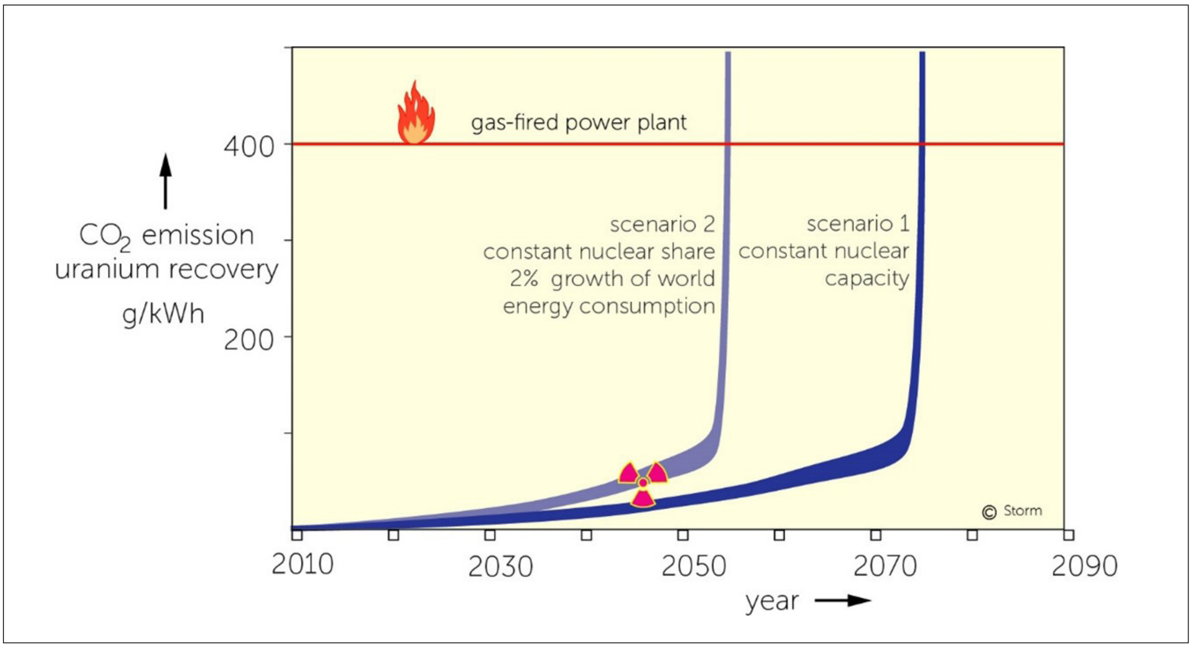


Figure 10. $CO_2$ emissions in a constant share scenario, and in a constant capacity scenario, both based on $^{235}$U technologies.

[6] World nuclear capacity in 2021 (Source: WNA, "*World nuclear performance, 2022*" [28]).

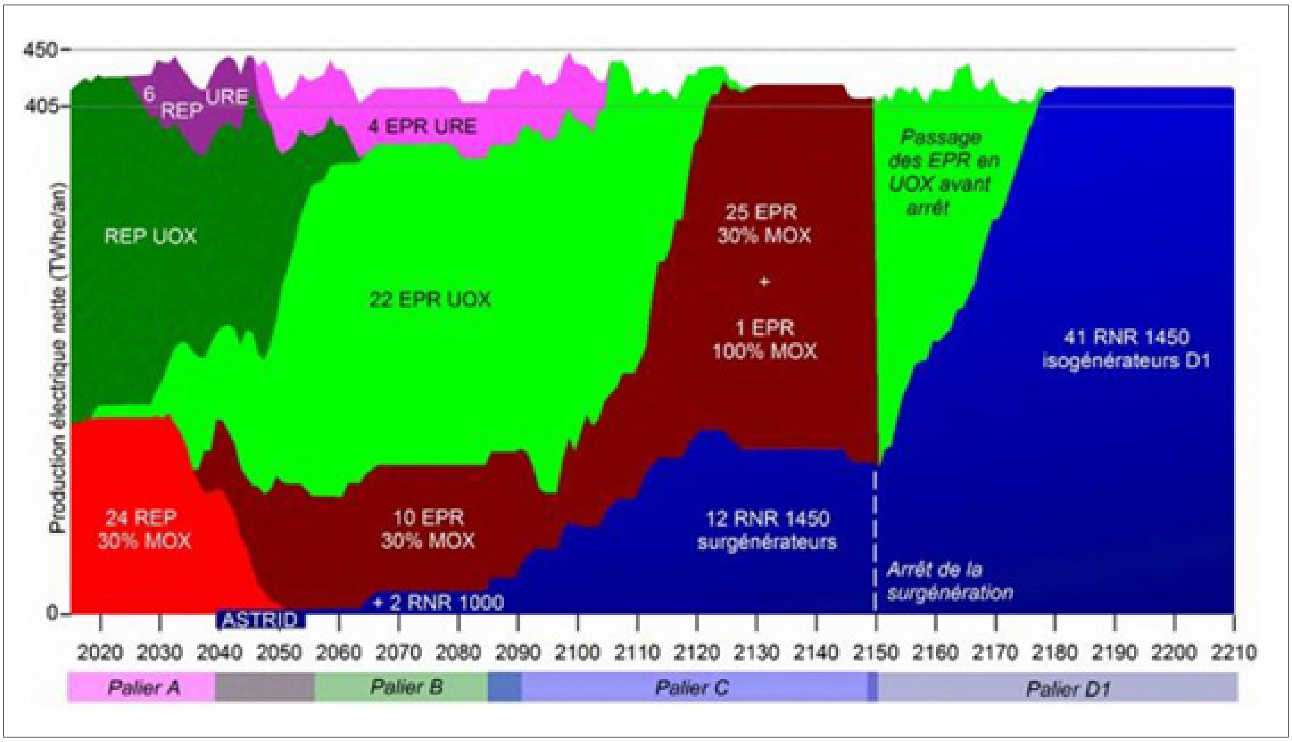


Figure 11. Scenario for the development of the French nuclear fleet leading to a 100% FNR fleet (Source: CEA/DEN/DISN/ACF, 25/10/2018).

was envisaged for the French fleet in the framework of the ASTRID project. It has been defined just before the abandonment of this project, what has thus postponed the date of deployment of such a reactor fleet.

In any case, it can be seen that, although France has the necessary tools for the reprocessing of fuels, as well as for the manufacture of MOX fuels, the deployment of FNR-type reactors is anything but immediate. This is even more true on a global scale, especially since a rapid deployment of FNRs would require a sufficient quantity of $^{239}$Pu, of the order of 18 tonnes of Pu per initialized GW, which represents the Pu inventory over the entire cycle.[7] As an example, France currently has around 360 tonnes of mobilizable Pu, i.e. potentially the possibility of initializing around twenty GW of FNRs.

## Conclusions

The main lesson of this article concerns the occurrence, by 2100, of a degradation of the energy ratios (EROI) attached to the exploitation and use of $^{235}$U. If, as pointed out in the article, the data used in this article certainly need updating, this does not detract from the facts that:

- uranium is a metal that has to be extracted from the Earths crust, whose geological occurence couldn't suffice to make it self-evidently an energy resource;
- the amount of extraction energy per kg of uranium increases exponentially with decreasing ore grade, so as to lead toward a negative net energy, what has been labelled "energy cliff";
- the same holds true for the coupled $CO_2$ emission which will finally reach and go through values of natural gas fuelled power plant, what has been labelled "$CO_2$ trap".

One solution to this problem would be to turn to the use of $^{238}$U by the fateful deadline of 2100, but, as mentioned above, this requires taking FNR technology beyond a pre-industrial stage, and thus into the commercial phase, which is still not in sight. However, it is only when FNR technology is deployed that it would be possible to solve both the nuclear energy constraint and the one attached to $CO_2$ emissions. As we have seen, these constraints are largely attributable to the mining and milling of natural uranium. Thus with the use of $^{238}$U, which is already available in the form of hundreds of thousands of tonnes of depleted uranium, these constraints would disappear, with the prospect of energy autonomy over several thousand years and, as the icing on the cake, virtually zero $CO_2$ emissions per kWh.

[7] Instead of using $^{239}$Pu for initialize a FNR, it is also possible to use $^{235}$U enriched to about 30%, but this would require sufficient enrichment capacity, and would put further pressure on $^{235}$U availaibility.

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More details on the subjects addressed in this article can be found in the following reports on: www.stormsmith.nl [reports]:

m01 Uranium-Plutonium breeder systems

m20 Reprocessing of spent fuel

m24 Thorium for fission power

m26 Uranium mining + milling

m27 Unconventional uranium resources

m28 Uranium from seawater

m29 Uranium for energy resources

m35 Energy cliff and $CO_2$ trap

m44 Process analysis of the Ranger mine