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a look at ...

Nuclear fuel resources

The abundance of projects to build nuclear power plants, the desire of new countries to acquire civil atomic power, contracts sometimes deemed fantastically high for the operation of uranium mines, etc. All of these signals indicate a return to nuclear power in a context dominated by the fight against global warming. But can nuclear power make a durable contribution to the effort to meet the ever-increasing demand for energy?

Today, nuclear energy mostly serves to produce electricity, although its earliest applications were of a military nature. It is also used in various fields, ranging from the medical sector to agri-business to the aerospace industry. According to the International Energy Agency (IEA), nuclear energy now covers 6% of world requirements for primary energy while hydrocarbons (oil and gas) account for 60%, coal 27% and renewable energies 13%. Nuclear energy satisfies 14% of world electricity demand, but this statistic fails to convey the existence of large disparities. In France, for instance, the nuclear sector covers nearly 80% of national energy demand. Generating far less CO_2 than fossil-fuel-based energies (on the order of 500 times less), nuclear energy is currently returning to center stage. By 2030, demand for uranium is expected to rise by between 40 and 80%.

Nuclear fuels

The production of nuclear electricity aims to recover the energy produced by the controlled fission of nuclei in the heavy atoms contained in “fuel assemblies”.

Most existing nuclear reactors are fueled by uranium, a natural element mainly composed of two isotopes: ^{238}U and ^{235}U. In today’s light water reactors (LWRs) as well as the EPR (European/Evolutionary Power Reactor) under construction in Flamanville (France), Finland and China, for instance, the ^{235}U isotope, which is fissile, contributes the bulk of the energy produced. The only reactors to draw significantly on the ^{238}U isotope are fast neutron reactors (FRS). The FRs technology exists, but is not yet applied at industrial level. However, FRs present a big advantage for the optimized or sustainable use of natural resources, considering that natural uranium is composed of 99.27% ^{238}U and only 0.72% ^{235}U.

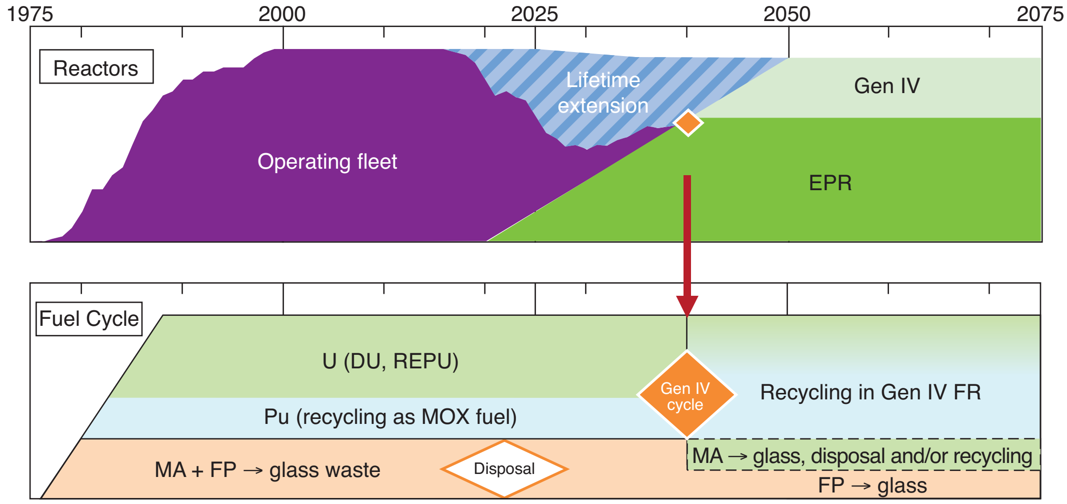
In the case of existing LWRs or the EPR, natural uranium must be enriched with the U-235 isotope (to about 4 or 5%) to produce a uranium oxide fuel known as UOX. The enrichment operation also yields what is called “depleted” uranium (DU), which only contains about 0.2% of ^{235}U. This type of uranium is currently being stockpiled with a view to subsequent use in the fast neutron reactors of tomorrow.

After four years in a light-water reactor, the spent UOX fuel is withdrawn. Its composition has changed: although 96% of the original “nuclear” material is still present, it also contains plutonium (Pu, a fissile element derived from ^{238}U) and waste consisting of fission products (FP) and minor actinides (MA).

If spent fuel is sent to a final storage site without reprocessing, the fuel cycle is referred to as “open”. France has made a different choice, i.e. to recycle material from spent fuel. Today, various reprocessing operations can be used to recover the uranium and the plutonium remaining in spent fuel and incorporate them into new LWR fuels. These include uranium oxide (UOX) fuels – containing reprocessed uranium (REPU), then enriched to obtain enriched reprocessed uranium fuels (UREs) – or mixed-oxide (MOX) fuels, which are a blend of uranium oxide and plutonium oxide. At existing LWRs, however, the number of recycles is limited by the accumulation of unwanted isotopes. At present, fuel undergoes one recycle. This once-through fuel cycle is referred to as “closed”.

Today, one of the reprocessing operations in the recycle is the vitrification of minor actinides and fission products. The latter are put into temporary storage pending their final disposal at a geological storage site. The plutonium recycle yields initial gains in terms of the radiotoxicity of the waste. In future, when new-generation (Generation IV

Fig. 1 - Scenario for the replacement of the French electronuclear fleet



Sources: EDF, ENC 2002

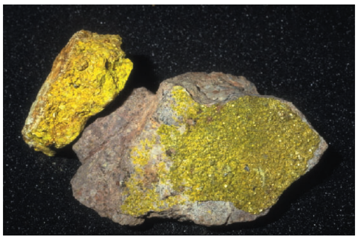
or Gen IV) fast neutron reactors have come onstream, depleted uranium, reprocessed uranium and plutonium will be used for fuel, which will substantially reduce the requirements for natural uranium. Moreover, it will be possible to further decrease the toxicity of the radioactive waste package by transmuting minor actinides in the reactor. Regarding the use of nuclear fission in a more distant future, the key issue will be to determine when FRs should be deployed at industrial level.

In France, the plan for existing French fleet of nuclear power plants is to replace end-of-life reactors, whose original service life (i.e. 30 years) will have been extended in some instances. They will first be replaced with EPR reactors and then, from 2040 onwards, with Gen IV fast neutron reactors (Figure 1).

Uranium resources

Uranium has no other important application besides the production of nuclear energy. Relatively abundant in the earth's crust (average content: 3 g/t), it is a thousand times more plentiful than gold. The uranium content will range from 0.3 to 200 kg/t, depending on the deposit. It is present in the form of veins of ore (Figure 2). Uranium can also be a by-product of the extraction of phosphates, coal, copper or gold. It is even present in sea water (3 mg/m^3). Since raw materials only represent 5% of the cost per kilowatt-hour (kWh), the nuclear industry is much less dependent on the cost of resources than other industries and can withstand potentially high variations in uranium mining costs.

Fig. 2 - Uranium ore



Source: Areva

Fig. 3 - The McLean Lake/Jeb open pit mines, Canada

Source: Areva

In 2007, the world reserves of uranium recoverable at less than US$130/kg stood at an estimated 3.3 million t[1] (Mt), to which one should add 2.1 Mt of presumed resources. Nearly two-thirds of these reserves are located in five countries: Australia, Kazakhstan, the Russian Federation, South Africa and Canada (Figure 4). The mines fall into two categories: open-pit and underground. Most of the open-pit mines are located in Canada (Figure 3) and Australia while the bulk of the underground mines are found in Kazakhstan and the United States. The largest

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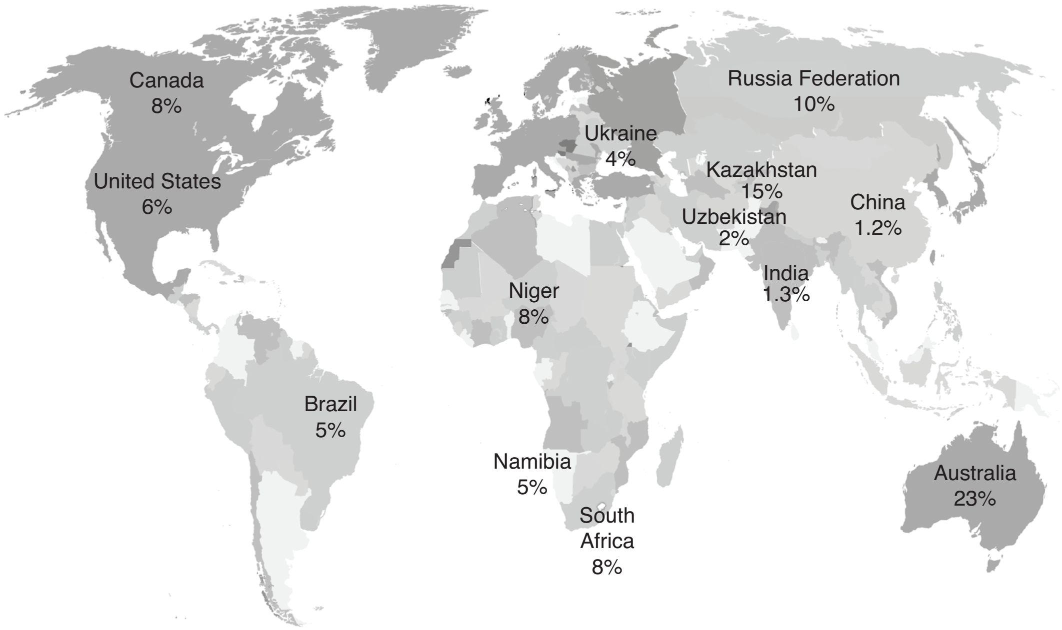
(1) Source: "Uranium 2007: Resources, production and demand," IAEA/OECD 2008 (cf. world breakdown of these resources)

Nuclear fuel resources

Fig. 4 - Breakdown of the world's known uranium resources (recoverable at <130 $/kg of uranium)



Source: IAEA/OECD 2008

deposit of uranium oxide ever found is the Cigar Lake Mine in the province of Saskatchewan, Canada. According to estimates, it contains 154,600 t of uranium with an average grade of 7.9%.

At the 2007 level of consumption (69,000 t), world reserves could keep existing reactors running for nearly 80 years. But the Nuclear Energy Agency (NEA) estimates that undiscovered uranium reserves stand at 10 Mt and that phosphate mining could yield another 22 Mt of uranium as a by-product. In addition, the recycle of materials (U or Pu) and the future implementation of FR technology (fast neutron reactors) are expected to optimize resources. The switchover to FRs will add value to existing stocks of depleted uranium (e.g. about 250,000 tons in France), which are available at very low cost, and reprocessed uranium. In a scenario like this, nuclear energy would generate electricity for humankind for centuries without having to mine any uranium. Fifty to 80 times more efficient in their utilization of energy resources, FRs can be fueled with depleted uranium (large stocks of which already exist) or reprocessed uranium.

Supply and demand

Demand

In 2008, the 438 commercial electronuclear reactors in service worldwide represented installed capacity of 370 GWe (gigawatts of electricity). According to the NEA scenarios, this figure will rise to between 509 and 663 GWe by 2030, with demand for uranium situated between 94,000 and 122,000 t/yr (+40 to 80%).

Today, 35 countries consume uranium to produce electricity. Western Europe accounts for one-third of world installed capacity, followed by North America and Asia. The United States is the world's top producer of electronuclear energy, used to generate 20% of its electricity. France is the second largest producer of electronuclear energy, which accounts for 80% of domestic electricity production. Then come Japan, the Russian Federation, South Korea and the United Kingdom for the number of nuclear reactors in operation. In future, this breakdown is expected to change, especially now that Asia is developing capacity on a massive scale (Figures 5 and 6).

Forecasts of uranium requirements are subject to variations in reactor consumption per quantity of energy produced. There are several ways to improve the energy efficiency of existing reactors like the LWRs, which reduces demand for uranium: richer or more refined nuclear fuels can be used, spent fuels can be reprocessed, and uranium and/or plutonium can be recycled. In a more distant future, when existing reactor technologies are deployed, the quantities of energy produced from the same initial quantity of natural uranium will vary in a ratio of 1 to 80 (between the least efficient fission reactors and the fast neutron reactors, which produce more fuel than they consume[2]). Finally, there is

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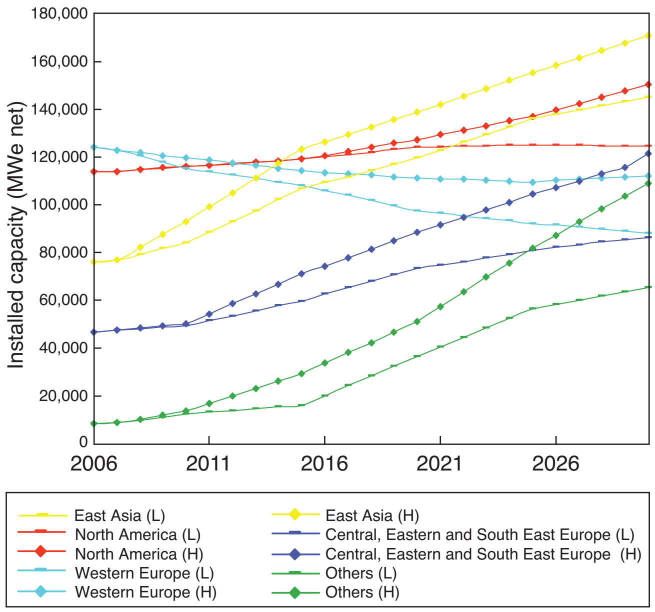
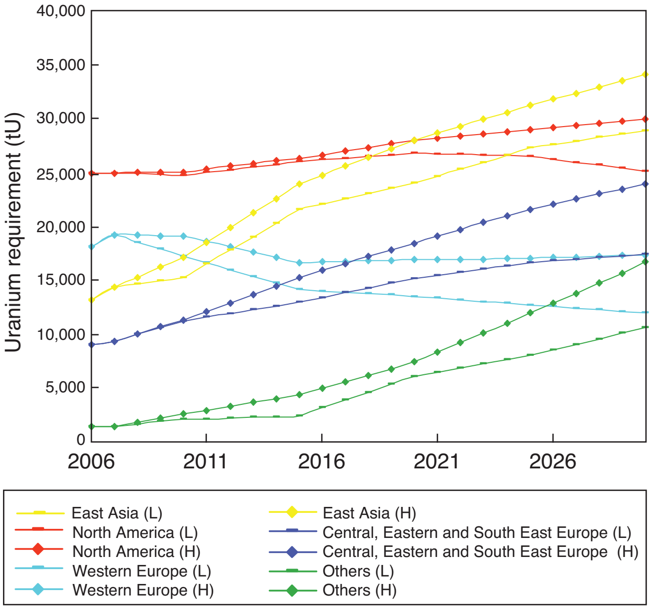
(2) Breeder reactors

Fig. 5 - Projections (high and low) of nuclear installed capacity through 2030



Source: IAEA/OECD 2008

Fig. 6 - Annual uranium demand through 2030



Source: IAEA/OECD 2008

the possibility of using thorium as a raw material as well. Thorium is more abundant than uranium in the earth's crust on average, but contains no fissile isotopes.

A few statistics

- 438 civilian reactors in service in 35 countries and 46 units under construction,
- 370 GWe of installed capacity today; between 509 and 663 GWe by 2030,
- Uranium represents 5% of the price per kilowatt-hour.

Supply

Uranium mining production

In 2006, world uranium production stood at nearly 40,000 t. Only eight countries accounted for 93% of the total: Australia (19%), Canada (25%), Kazakhstan (13%), Namibia (8%), Niger (9%), the Russian Federation (8%), United States (5%) and the Uzbekistan (6%). Europe, the second largest consuming region, does not produce uranium. All in all, 35 countries currently consume uranium in commercial nuclear power plants. In other words, there is a lack of correspondence between producing and consuming countries. Moreover, fewer than ten mines produce more than 1,000 t/year of uranium. The other mines yield less than 1,000 t/yr.

Table 1

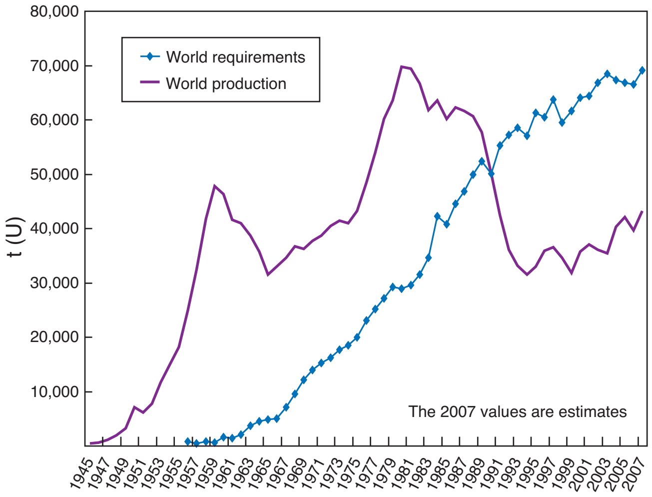
Key mining companies and uranium production (t) for 2006

Mining companies	Production (t)	%
Cameco	8,249	20.9
Rio Tinto	7,094	18.0
Areva	5,272	13.4
Kazatomprom	3,699	9.4
TVEL (Atomenergoprom)	3,262	8.3
BHP Billinton	2,868	7.3
Navoi	2,260	5.7
Uranium one	1,000	2.5
Key producers (subtotal)	33,704	85.5
Other producers	5,726	14.5
Total	39,430	100.0

Source: World Nuclear Association

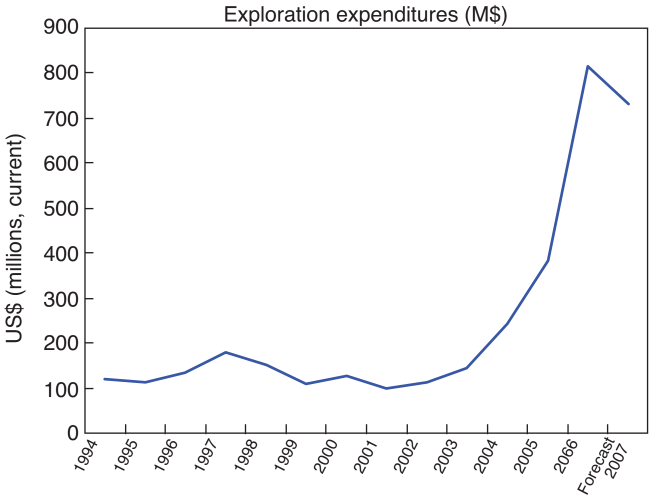
Like the producing countries, uranium mining companies are few in number (Table 1). Among the largest are the integrated nuclear specialists with upstream and downstream capability such as Areva, or, to a lesser extent, Cameco, which produces electricity, as well as "generalist" mining companies (e.g. Rio Tinto and BHP Billiton) that produce many other industrial minerals. These companies have a great deal of power over the uranium market, but it is blunted by the existence of secondary sources on the market. For one thing, the quantities accumulated in civilian and military stockpiles since the 1950s are being reduced. For another, the uranium and

Fig. 7 - Annual uranium production and demand (1945-2007)



Source: IAEA/OECD 2008

Fig. 8 - Investment in exploration and development



Source: IAEA/OECD 2008

plutonium in spent fuel have been recycled since the 1990s. Today, secondary sources are bridging the gap between uranium mining production (about 40,000 t/yr) and consumption (69,000 t), as shown in Figure 7.

The level of the stocks that were compensating for the production deficit fell while prices rose between 2004 and 2008. This prompted the industry to start investing in uranium exploration again (Figures 8 and 9). According to current projections, uranium mining production capacity could theoretically exceed 95,000 t/year by 2015, compared to 54,000 t in 2007.

World exploration activities were concentrated in the regions thought most likely to contain undiscovered deposits, among them Australia, Canada, China, India, the Russian Federation, South Africa and the United States.

Economizing resources

One way to economize resources is to recycle spent fuel. For about twenty years, Areva's reprocessing facility (La Hague, France) has been recovering uranium and plutonium from spent fuels and incorporating them into fresh UOX or MOX fuels.

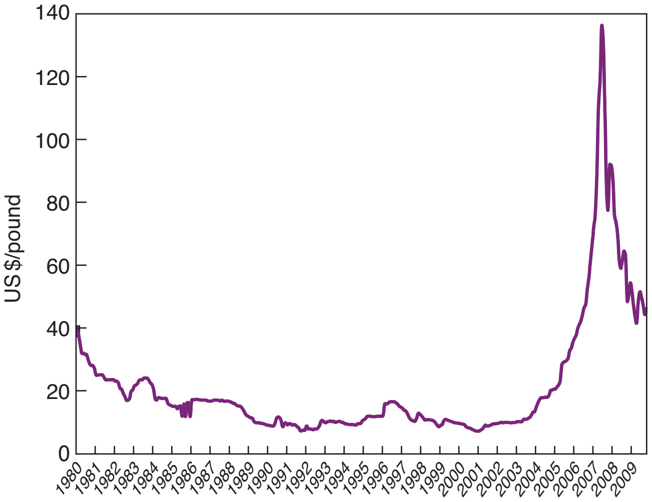
In January 2007, more than 33 reactors (about 8% of the world fleet of reactors in service) were authorized to use MOX fuel. These reactors were located in Belgium, Germany, France, India and Switzerland. There are spent fuel reprocessing facilities and MOX fuel production units in operation or under construction in China, France, India, Japan, the Russian Federation and the United Kingdom. According to the Euratom Supply Agency, the use of MOX fuel reduced natural uranium requirements in the Europe of Fifteen (prior to EU enlargement in 2004) by a quantity estimated to be more than 1,200 t in 2006. All in all, complete recycling of uranium-235 and plutonium in LWRs would economize about 20% of uranium resources.

In a more distant future, the development of FR technology would increase uranium energy reserves by a factor of between 1 and 80.

It's all very well to talk about optimizing resources and economizing uranium in the FRs of the future, but this begs the question of plutonium availability: Will there be enough to "launch" the fleet of FR reactors? The latter will have to use fuels containing plutonium, which will thus be critical to any massive deployment of FR technology. However, the initial source of plutonium will be the spent fuel of LWR reactors. Subsequently, FRs will produce enough plutonium to cover their own requirements.

According to the French atomic energy agency (CEA), it is perfectly plausible to think that 20% of commissioned reactors will be FRs. On the other hand, a nuclear energy scenario postulating significant growth (more than 2 TWe installed by 2100) as well as exclusive reliance on FR technology is incompatible with the quantities of plutonium produced by the reactors in service today. The coexistence of the LWR and FR technologies appears to be a reasonable and desirable eventuality for both technical and geopolitical reasons. In France, for instance, the second replacement of the nuclear fleet is

Fig. 9 - The uranium price set in long-term contracts



Source: IMF

planned for 2100, that's why the full impact of breeder technology, which produces more fissile material than it consumes, will not be felt before the 22nd century.

Neither our grandchildren, nor our descendants will have to extract uranium from mines, which will not be necessary for centuries. In the meantime, recycling materials from spent LWR fuels is as efficient as installing 20% of FRs.

The ups and downs of uranium prices

Many factors influence the price of uranium: supply and demand trends, the mining output deficit, the resurgence of interest in nuclear power in step with world population growth, the development of emerging countries and environmental concerns.

There are two types of price for uranium ore. Spot prices are negotiated for quick deliveries (within 2 to 12 months) and low unit volumes (not exceeding one hundred tons). There are also the prices set under long-term contracts. In 2007, 30% of the 69,000 t of uranium consumed came from secondary sources (commercial and military stockpile surpluses), 15% from the spot market, and 55% from long-term transactions.

The price of uranium reached its all-time high in real value in the 1980s, driven up by the demand generated by military applications and the development of civilian electronuclear energy. After an initial steep decline, it entered into a slow, twenty-year downswing due to several factors: nuclear power developed more slowly than anticipated, accidents occurred at Three Mile Island (United States, 1979) and Chernobyl (Ukraine, 1986) and a substantial amount of uranium in military stockpiles was released to the market. The price bottomed out in 2000, then began an uptrend – fueled by the market realization that a shortage of supply in the short or medium term was possible and by speculation – that lasted until 2008. The onset of the financial crisis at the end of 2008 brought the price of uranium, like that of most raw materials, crashing down (Figure 9).

Conclusions and outlook

In the 22nd century, resource availability should not be an obstacle to the development of nuclear energy, judging by the technologies that already exist or are under development. By then, reactors should be deployed and producing more fuel than they consume. At most, availability problems may constrain growth, because it will take time to produce enough plutonium to launch the FR reactors. Between now and then, new techniques may emerge to help bridge the gap until the FRs come onstream. In the meantime, it will be necessary to keep prospecting for uranium and recycling nuclear fuels so that nuclear energy can make its contribution to the energy mix.

Glossary

Actinide
Chemical element whose nucleus contains more than 88 protons. In order, the actinides include actinium, thorium, protactinium, uranium and the transuranium elements. Neptunium, americium and curium are known as the "minor actinides".

Breeding
A nuclear reactor technology that produces more fissile material than it consumes.

Fertile
Said of a nucleus of an atom that can be converted into a fissile nucleus by means of neutron capture. In LWRs, a portion of the ^{238}U is transformed into plutonium-239, a fissile element.

Fissile
Said of a nucleus of an atom whose probability of being split by a neutron is greater than that of other possible reactions. The nuclear fission reaction liberates energy and several neutrons that sustain the chain reaction.

Fission products
Fragments produced by the fission of heavy nuclei (e.g. uranium or plutonium) or the subsequent radioactive decay of nuclides formed during fission. All fission fragments and their descendants are called "fission products".

Installed capacity
The capacity of reactors to produce energy, measured in GWe (million kilowatts of electricity).

MOX fuel
A blend of uranium oxide and plutonium oxide.

UOX fuel
Uranium oxide enriched with ^{235}U.

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