URANIUM
What is to be done?

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The global sustainability of Uranium supplies for nuclear power depends upon the energy requirements, the amount of mineable Uranium on the planet, and the nuclear technologies used to exploit it. We aim to give the simplest possible outline of the problems and solutions.

Global Energy Requirements

Let us first simplify the discussion by basing our energy units on the kilowatt-hour, the unit in which our electricity bills are paid – currently 14p/kWh in the UK. This is far too small a unit for national and global considerations where power stations can generate a million kilowatts of electricity, called a Gigawatt, every hour. Even that is too small so we will use Gigawatt-days (GW-d) and Gigawatt-years (GW-y). Because only about 1/3rd of the total energy produced is in the useful forms of electricity, domestic or industrial heating, or transportation as the laws of thermodynamics condemn 2/3rd. of it to be lost as waste heat, we distinguish between thermal energy, GWth, and electrical energy, GWe.

The total world energy production from all fuels in 2005 is about 16,500 GWth-y, of which about 14,000 GWth-y comes from billions of tons of the fossil fuels, coal, oil, and gas. About 2000 GWe-y is delivered as electricity. Unfortunately, the use of fossil fuels is unsustainable and dangerous to all life on the planet.

The effect of greenhouse gases on global warming was first recognised in 1827 by the great French scientist, Fourier. The concentration of Carbon Dioxide in the atmosphere is a tiny 0.037 %, which the workings of the biosphere over aeons have adjusted to this level. In the 1980s it was realised that the world was burning enough fossil fuels to triple the CO_2 concentration by 2100. The Kyoto agreement is a small step towards evading this fate, breached by its strongest proponents, and vigorously fought by global business interests.

A more immediate and financially devastating problem is that the total supply of cheap oil and gas will peak around 2010 to decline at a steady 3% per annum to the end of the century. Expensive oil from tar sands and other sources will only ease supply for North America after about 2040. By 2100 the world will have permanently lost this 10,600 GWth-y energy source. A world agreement on rationing the declining supplies will be necessary. Current forms of renewable energy and biofuels are unable to meet this level of demand.

By the end of this century the world needs alternative annual sources for at least 14,000 GWth-y of energy, from sources which are carbon-free and sustainable for many centuries or millennia.

Nuclear Energies

Thanks to Einstein's famous equation, $E = mc^2$, we know that most of the energy in the universe is locked away in matter. The heaviest naturally occurring element is number 92, Uranium, which has 18 isotopes, from ^{222}U to ^{242}U, containing different numbers of neutrons. Only two of them, ^{235}U and ^{238}U, have half lives of hundreds of millions of years and can still be found in mineral deposits. The odd numbered isotope fissions easily on absorbing a stray thermal neutron, producing an average of 2.5 further fast neutrons, depending on how it shatters, and allowing for a chain reaction with other ^{235}U nuclei. The total mass of the fragments – fission decay products – is slightly less than the original mass and the difference appears as a huge kinetic energy of the fragments.

The other isotope, ^{238}U, can absorb a thermal neutron to then transmute into element 93, Neptunium, which later transmutes into to the fissile isotope ^{239}Pu of element 94, Plutonium. In other words, ^{238}U is **fertile** and breeds fresh **fissile** fuel. Further neutron absorptions create families of fissile Heavy Metal isotopes, the Actinides. Only a few of these higher elements and isotopes have half lives of even thousands of years but they are the source of the long lived (250,000 years) very radioactive waste at the heart of the Nuclear Waste Disposal dilemmas.

The glorious result is that the fission of a single tonne of any of these Heavy Metals yields about 1000 GWth-days of energy. At 14p/kWh of electricity, their retail value is £1.68Bn per tonne.

Uranium Resources.

The definitive database of mineable Uranium is maintained by the IAEA, the Uranium Red Book. Existing mining areas, not all of which are working, hold about 3.2 million tonnes. Similar geological formations which have not been explored are estimated to hold about 5.1 Mt. Speculation about unexplored regions suggests there may be a further 12.1 Mt to be found. Because the global nuclear industry stalled in the 1980s there has been no exploration since. However, politically acceptable claims that there is a lot more to be found are not based on new information but on trivial resource vs. price models, such as are used to deny the peaking of oil, and must be dismissed.

Unfortunately, Uranium oxides are very soluble in water and so most of this watery planet's endowment of 4 billion tonnes is at sea at a concentration of 3 parts per billion.

The bad news is that only 0.7% of the ore is the fissile component, ^{235}U, a mere 140,000 tonnes in total. A mere 800 reactors like the Westinghouse AP1000 or the EPR would use all this in one century.

Current Nuclear Reactor Technologies.

The existing and proposed fleets of thermal nuclear reactors, with an overall efficiency of about 33%, use a Once-Through-Then-Out, or OTTO, fuel cycle. The natural Uranium is enriched by centrifuge to produce fuel with 4.5% of ^{235}U, leaving a large stock of 'depleted' Uranium containing 0.3% of ^{235}U. The fuel is burned in a PWR or other reactor and extracted as spent fuel after 18 months to two years in the reactor. The spent fuel contains 1.1% ^{235}U, 1.3% of newly bred ^{239}Pu, and 0.12% of Actinides, which is to say 2.52% of fissile fuels, and 5.15% of fission products – the ash which still produces heat after fission has ceased. All this is stored in cooling ponds and could eventually be buried in nuclear waste disposal facilities.

Exclusive use of this system would lead to the 'Easter Island Collapse' scenario by 2100, with the oil, gas, and Uranium depleted or buried, and irreversible global warming. Power would come from tens of millions of windmills, coal, and billions of acres of biofuel agriculture.

High Temperature Reactor Technologies

New, high temperature, gas cooled reactors can drive gas turbines to give an overall efficiency around 50%. New fuel packaging in tiny ceramic coated spheres also allows for much Deep Burn of all their contents. These reactors can run just on the Plutonium and Actinide components of spent fuel, which produces 95% of all the radioactivity in spent fuel. About 90 such reactors could burn up all the legacy waste by 2075 – the smart alternative. Self cleaning versions could be deployed instead of more of the traditional thermal reactors to increase the reactor fleets.

A thousand High Temperature reactors could eliminate the most dangerous parts of the legacy nuclear waste, and all that they themselves produce - this century. They would use up the fissile Uranium supply in about 150 years, but would only leave wastes which would be safe in 500 years.

Reprocessing Nuclear Fuel.

The OTTO fuel cycle must be abandoned in favour of a reprocessing system which separates Uranium, Fission Products, and the fissile Plutonium and Actinides in spent fuel. The fission products will be buried and the rest used as fuel. This will be more expensive than the throwaway economics of OTTO, but so what, since UK electricity prices have moved from 5p/kWh to 14p/kWh in the last 3 years.

Nuclear fuel reprocessing and manufacture will be an enormous part of the 21st. century energy market. It will require international regulation to ensure fissile materials are only used for energy.

Breeder Reactors

Clearly, most of the nuclear energy resource is in the fertile isotope, ^{238}U. The primary goal of the nuclear industry has been to develop reactors which convert ^{238}U into ^{239}Pu, usually in a blanket of natural Uranium surrounding a reactor core which provides a high fast neutron flux into the blanket. These reactor designs push the limits of materials, heat transfer, and nuclear engineering and have proved difficult to make safe, serviceable, and economic. The fast neutrons can also fission all Actinide products and eliminate any highly radioactive products. The current international research programmes are focussed on these reactor concepts - but the funding is weak.

The French Super-Phenix breeder achieved a breeding ratio of 1.16, sufficient to generate Plutonium fuel for 10,000 reactors in 65 years, starting from the 300 tonnes of civilian Plutonium plus 200 tonnes of military Plutonium in stock. Japan is vigorously pursuing this path. At this level the global production of reactor grade Plutonium would be about 16,000 t/year.

If only half of the IAEA Red Book Uranium resource can be converted to fissile fuel there will be enough to run 10,000 reactors for about 1200 years. This is one solution to the energy needs of the human race which should be brought to fruition this century.

Thorium

The 90th. element, Thorium, is found only as the isotope ^{232}Th, and is 3 times as abundant as Uranium. The oxides are not soluble in water and it has not been dispersed in the oceans. This Thorium can absorb a thermal neutron and transmute to the fissile ^{233}U. The Molten Salt Thorium Breeder Reactor was designed and a Uranium version tested at the US Oak Ridge National Laboratories in the 1960s. It should be self cleaning and produce only tiny amounts of Plutonium. Development was soon stopped in favour of the Plutonium breeder. New design studies are under way in France.

The MSTBR could provide thousands more years of nuclear power.

Fusion

Fusion is the ultimate, cleanest, large scale source of nuclear energy, fusing Hydrogen isotopes to produce harmless Helium, and is capable of powering our civilisation for tens of thousands of years. Fusion does not require the production of any fissile, weapons useable materials. The first tests of a 500MWth reactor will be made in Cadarache, France as the International Tokamak Experimental Reactor (ITER) some time in the 2030s. This could obviate the need for Breeder reactors after 2050. The nuclear power programme could be reduced to smaller, more specialised applications.

Fusion is the ultimate power source for our civilisation. Its development should be strongly accelerated in the face of global warming and the decline of oil and gas.

What is to be Done?

1. The Nuclear Industry should be vigorously expanded, around the developed world, with a target of 10,000 reactors by 2100.
2. Uranium and Thorium exploration should be completed.
3. The programme must begin soon with the new, fail-safe reactors like the Westinghouse AP100 and the European EPR.
4. Development of the more efficient, high temperature reactor systems must be completed rapidly to be deployed from 2025.
5. Recycling facilities must be built to match the growing reactor fleets and to process the highly radioactive components of spent fuel as new fuel for the Deep Burn reactors for smart waste disposal.
6. The development of fast reactors must be accelerated to identify and solve remaining problems in a timely fashion. Only they can expand the reactor fleet above the 1000 level.
7. The alternative Thorium systems should be revived as a possibly simpler, safer, and more economic alternative to the fast reactors.
8. Fusion engineering and materials development must be funded vigorously so complete fusion systems could be deployed from 2050.

The United Kingdom has special problems: All Nuclear Engineering university departments have been closed, along with research laboratories supporting nuclear power. This must be reversed and the UKAEA Fusion Laboratory should be expanded back to its former size and renown.

All UK nuclear power infrastructure is in the process of being sold into foreign ownership at prices far below their value, including the Nuclear Decommissioning Agency (NDA).

In order to meet its energy needs the UK will need about 50 nuclear reactors by 2050, including a few Deep Burn reactors as part of the smart Waste Disposal programme.

Other UK governments may consider rebuilding British expertise in nuclear energy, but this will take a couple of decades. In the meantime, the only areas where government will have any influence are in the bureaucratic realms of regulation, planning, licensing, and a more open dialogue with the public. In the near absence of indigenous expertise, it will have to rely on the IAEA, the European Commission, and the US Nuclear Regulatory Commission for technical guidance. It is vital that, having sold off the infrastructure, that our governments do not then emerge as the major obstacle to progress and to the security and affordability of our energy supply. The NDA operations could cost completely arbitrary sums if regulation is weak or ill informed, or if the smart approach is not taken to radioactive waste disposal. These points are being strongly made by the nuclear industry.

The UK could find itself abandoned by the nuclear energy industry if barriers of planning approval, inappropriate regulation beyond international practice, or perceived threats of punitive taxation or seizure of profits, are not removed, leading to energy poverty for all in the UK.

Nuclear power will be the primary source of energy on the planet by 2100 and one of man's greatest technical and political achievements.

Author

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