Is nuclear energy a possible solution to global warming?

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Since 2000 the nuclear industry has mounted a massive international media and lobbying campaign to promote nuclear energy as a solution to the enhanced greenhouse effect. Nuclear energy, the industry claims, emits no or negligible amounts of CO_2 and can be rapidly deployed to substitute for coal-fired power stations.

In reality, only reactor operation is CO_2-free. All other stages of the nuclear fuel chain – mining, milling, fuel fabrication, enrichment, reactor construction, decommissioning and waste management – use fossil fuels and hence emit CO_2. The fossil energy used in the nuclear fuel chain is called the *energy input* to nuclear power. The *energy output* is simply the electricity generated by a nuclear power station. The *energy payback* period of nuclear power is defined to be the time required by the nuclear power station to generate a quantity of electricity that is equivalent to the energy input to the nuclear fuel chain.

Quantifying the CO_2 emissions

The CO_2 emissions arising from the energy input have been quantified by researchers who are independent of the nuclear industry. Early work was published by Nigel Mortimer[1], until recently Head of the Resources Research Unit at Sheffield Hallam University, UK. In the 2000s a very detailed study was done by Jan Willem Storm Van Leeuwen, a senior consultant in energy systems, together with Philip Smith, a nuclear physicist, both of whom were based in Holland[2].

These studies find that the total CO_2 emissions depend sensitively on the grade of uranium ore used. Following Van Leeuwen and Smith, we define *high-grade uranium ores* to be those with at least 0.1% uranium oxide (yellowcake, U_3O). In simpler terms, for each tonne of high-grade ore mined, at least 1 kg of uranium can be extracted. For high-grade ores, such as most of those being mined in Australia, the energy inputs from uranium mining and milling are small. However, there are significant emissions from the construction and decommissioning of the nuclear power station, with the result that the station must operate for several years to generate its energy inputs.

Low-grade uranium ores contain less than 0.01% yellowcake, that is, they are at least 10 times less concentrated than the high-grade ores. To obtain 1 kg of yellowcake, at least 10 tonnes of low-grade ore has to be mined. This entails a huge increase in the fossil energy required for mining and milling. Van Leeuwen and Smith find that the fossil energy consumption for these steps in the nuclear fuel chain becomes so large that nuclear energy production emits total quantities of CO_2 that are comparable with those from an equivalent combined cycle gas-fired power station.

Furthermore, the quantity of known uranium reserves with ore grades richer than the critical level of 0.01% is very limited. The vast majority of the world's known uranium resources are low-grade. With the current contribution by nuclear energy of 16% of the world's electricity production, the high-grade reserves would only last several decades. If nuclear energy were to be expanded to contribute (say) half of the world's electricity, high-grade reserves would last only a decade or two. No doubt more reserves of high-grade uranium ore will be discovered, perhaps even doubling current reserves, but this would be insufficient for a sustainable substitute for coal.

Recently a physicist, Martin Sevior, has produced a critique of Van Leeuwen and Smith's results[3]. Sevior's results for high-grade uranium ore are based on data from an unpublished report by the Swedish electricity utility, Vattenfall (of which only a brief summary[4] is in the public domain). Unpublished sources have low scientific credibility. The actual results are hard to believe: for instance, based on these data, Sevior claims that the energy input to the construction of a nuclear power station is generated in only 1.5 months of its operation. This extraordinarily low result is contradicted by several earlier studies by independent analysts, who find that the energy payback period for the construction of both nuclear and coal-fired power stations (which use similar types and quantities of construction materials) is several years[5].

Sevior dismisses these earlier studies because they use input-output analysis, the standard approach that derives energy consumption from economic data. He argues that it is better to work entirely with empirical data on energy consumption. This may be true in theory, but in practice a complete set of energy data does not exist for the nuclear fuel chain and most other complex processes. There is little choice but to use input-output data. Otherwise, large energy inputs will inevitably be omitted. However empirical data does exist for energy inputs from one part of the nuclear fuel chain, the mining and milling of uranium ore.

For high-grade uranium ore, Sevior uses recent empirical data on fossil fuel inputs to uranium mining and milling and obtains lower energy input and hence CO_2 emissions than Van Leeuwen and Smith, whose data are older. The issue is still not resolved. On one hand, there can be no doubt that Van Leeuwen and Smith are correct that, if uranium ore grade declines by a factor of ten, then energy inputs to mining and milling must increase by at least a factor of ten. ('At least', because more than one process is involved. It is likely that the efficiencies of the other processes decline as ore grade declines.)

There has to be an ore grade at which the CO_2 emissions from mining and milling become unacceptably high. On the other hand, Sevior may be correct in claiming that nowadays the critical ore grade may be lower than the level of 0.01% yellowcake obtained by Van Leeuwen and Smith. The exact value of this critical ore grade is still subject to continuing scientific analysis and debate.

The 2006 Report on *Uranium Mining, Processing and Nuclear Energy* (UMPNER) addresses only part of the issue of CO_2 emissions, evading the issue of the emissions from the use of low-grade uranium ore.[6] Its Box 7.2, citing a consultants' report by the University of Sydney[7], focuses on the energy inputs into construction and demolition of nuclear power stations. Concerning the mining and milling of uranium, UMPNER cites an International Energy Agency (i.e. pro-nuclear) estimate that "known uranium reserves – which are of sufficient quality to give a net energy benefit – could fuel nuclear power for 85 years"[8]. However, it is doubtful whether all of these alleged uranium reserves are high-grade. Furthermore, even if all of these reserves were sufficient to give a net energy benefit, it would be unlikely that all would give a better greenhouse performance in a nuclear power station than an equivalent combined-cycle gas-fired power station. That is the real point, which is addressed neither by UMPNER nor the University of Sydney report. It is still plausible that there are only a few decades of high-grade uranium ore remaining at present consumption rates and therefore that nuclear energy would become a substantial emitter of CO_2 at the end of that period.

Are there alternative future pathways for nuclear energy that could have lower CO_2 emissions?

Are there alternative pathways?

Although there are vast quantities of uranium oxide in the Earth's crust, almost all of such reserves exist at very low concentrations, typically 4 x 10^{-4} %, at which 1000 tonnes of ore would have to be mined to obtain 4 kg of uranium in the form of yellowcake. In this case the energy inputs to extract uranium would be much greater than the energy outputs of the nuclear power station. Sea-water contains uranium at a concentration of about 2 x 10^{-7} %, meaning that 1 million tonnes of sea-water would have to be processed to extract just 2 kg of uranium.

A theoretically possible option would be to switch to *fast breeder reactors*, which produce so much plutonium from U-238 that, in theory, they can multiply the original uranium fuel by 50. The world's last large fast breeder reactor, the French Superphénix, was closed in 1998, after many technical problems and costing about A$15 billion. At present there are no commercial scale fast breeders operating. The Russian 600 MW demonstration fast neutron reactor, Beloyarsk, is operating, but it has a history of accidents and does not seem to have ever operated as a breeder. (The 'fast' refers to the speed of the neutrons produced.) The pro-nuclear MIT study does not expect that the breeder cycle will come into commercial operation during the next three decades[9].

Even if another fast breeder were to be built in the future, large-scale chemical reprocessing of spent fuel would be necessary to extract the plutonium and unused uranium. Since spent fuel is intensely radioactive, reprocessing has its own hazards and costs.

Another possible response to the shortage of high-grade uranium arises from estimates that there is about three times as much thorium in the Earth's crust as uranium. Although thorium itself is not fissile (that is, cannot be split), it can be converted into an isotope of uranium, U-233, which is fissile, by bombarding it with neutrons. In a conventional approach, the neutrons would be produced by fission of a mixture of U-235 and Pu-239. This would be a complicated system involving a type of breeder reactor, which takes us back to the problems outlined above. India is attempting to develop such a system.

A simpler thorium reactor design would use a particle accelerator to produce the neutrons. This has the advantage that the reactor is fail-safe. Unlike an ordinary uranium reactor, the accelerator-driven thorium reactor can be shut down by simply switching off the particle beam. Furthermore, the nuclear wastes produced by this kind of reactor have much shorter half-lives than from a uranium or plutonium reactor.[10] However, with some difficulty, the U-233 could be extracted to make nuclear bombs.

A potential technology for the long-term future is controlled nuclear fusion, in which the nuclei of light elements, such as deuterium and tritium (isotopes of hydrogen), are fused to form heavier elements with the release of energy. This is the same type of nuclear reaction that occurs in the interior of our Sun and in hydrogen bomb explosions. For nearly half a century, research has continued on the fundamental problem of creating a controlled nuclear fusion reaction and containing it in a laboratory. In stars, the very hot ionised gas or plasma undergoing the reaction is contained by the force of gravity; in the laboratory, high magnetic fields are used. Plasmas in the laboratory are prone to many instabilities which terminate the containment of the plasma. As a result, scientists have been unsuccessful in achieving a controlled nuclear fusion reaction in which more usable energy is created than the energy input required to maintain the plasma.

Despite this fundamental shortcoming, several countries are combining their resources to build an experimental fusion reactor called ITER[11]. The initial cost estimate was about US$5 billion, but some recent estimates are much higher. The proponents claim that they are technically ready to commence construction of the reactor and that it could begin to operate in 2016. ITER is not designed to generate electricity – that task would be reserved for the next phase, a prototype nuclear fusion power station, that would be constructed commencing in 2026, if ITER is successful. Then, if this prototype turns out to be successful during its ten-year trial commencing around 2035, commercial fusion reactors might commence operation around 2045.

In theory, by scaling up from laboratory to large fusion reactor, it may be possible to obtain a net energy gain. But it is also possible that the scale-up will introduce new kinds of instability. Clearly, nuclear fusion would not be a commercial prospect for at least four decades, if ever. Even if it does eventually generate more electrical energy than the fossil energy inputs for containing the plasma, it may still require quite large fossil energy inputs for building the power station and preparing the initial fuel charge.

None of the above proposed ‘solutions’ is commercially available and some are several decades away from commercial operation. So, on the basis of present nuclear technology and the small existing high-grade uranium reserves, the potential contribution of nuclear power to the reduction of CO_2 emissions is limited.

Slow deployment

With growing evidence that global climate change may be accelerating, it is essential that the principal technologies for replacing coal-fired power stations can be implemented rapidly. Nuclear power stations have long planning and construction periods: 8–10 years or more, in total. For Australia, which lacks the infrastructure for nuclear power, even Government Ministers have admitted that the first nuclear power station would take at least 15 years to build and commission.

Fortunately most of the improvements in efficiency of energy use and several of the renewable energy alternatives have very short construction periods: for example, large wind farms can be planned approved and installed in less than two years and small bioenergy plants in less than three.

Conclusion

As uranium continues to be mined, its ore-grade will continue to decrease and therefore fossil fuel inputs and CO_2 emissions from the mining and milling of uranium will increase. On the basis of existing studies, it is likely that within a few decades total CO_2 emissions from the nuclear fuel cycle will become comparable with those of an equivalent combined-cycle gas-fired power station. Therefore, with existing technology, nuclear power cannot be part of a long-term solution to global warming.

For at least the next two decades and possibly much longer, neither fast breeders nor thorium reactors nor nuclear fusion will be commercially available to overcome this limitation. With substantial infrastructure requirements and long construction times, nuclear power is also not a short-term solution to global warming.

The suitability of nuclear energy as a means of reducing CO_2 emissions could be re-examined if and when new nuclear technologies are introduced that are lower in life-cycle CO_2 emissions, safer and less expensive.

This article is based on part of Chapter 12 of the author's new book[12].

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