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Promises and limitations of nuclear fission energy in combating climate change[☆]

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ABSTRACT

The most serious problem facing humanity is that we have only a few decades in which to implement effective measures to stop global warming. For these years up to about 2065, fission energy from light water thermal reactors is relevant as an available, developed and proven non-carbon technology with the potential to make an essential contribution to the mitigation of global warming, in addition to renewable energy. Nuclear power is expected to have more economic advantages than intermittent renewable sources for generating base load electrical energy requirements. This would be especially important in the years from about 2025 up to 2065, during which one cannot expect a serious contribution from nuclear fusion and even less from fossil fuels with carbon capture and storage (CCS) facilities. In a strategy to eliminate all non-CCS coal power stations, some 1600 MW of nuclear power would be required and sufficient to cover the base load for the electrical energy supply system. This nuclear expansion should be accompanied by effective international safety assurances, including a mandate to stop construction of unsafe nuclear power plants. In the long term, after 2065, we expect inherently safe molten salt thorium reactors to compete with fusion reactors.

1. Introduction – selection of nuclear technology

Humanity must face reality: the climate is changing and measures to mitigate climate change are imperative. Climate change is predominantly influenced by human activities emitting greenhouse gases (GHG) into the atmosphere (Medhaug et al., 2017; IPCC, 2014), so one mitigation measure is the reduction of these emissions (Meinshausen et al., 2009). As a considerable portion of GHG emissions comes from the production of electricity in the energy sector, a major transformation of the electrical energy supply system is needed. GHG emissions are inherent to the combustion process in fossil fuel power plants. Therefore, these power plants need to be replaced over the next few decades by non-GHG-emitting power plants, unless the fossil fuel power plants are supplied with carbon capture and storage (CCS) facilities. Nuclear technology is the only developed GHG emissions-free energy source capable of replacing fossil fuel energy sources in the given time scale, safely, economically, reliably and in a sustainable way. Consequently, nuclear energy must play a major role in this necessary transformation of the 21st century energy supply system (Brook et al., 2014). The scope of this paper is to analyse which type of nuclear technology could make a substantial contribution to combating climate change.

When selecting the most appropriate nuclear technology to combat global warming, we must consider both nuclear fission and nuclear fusion. Of these two basic forms, we have over fifty years experience with nuclear fission for energy production. Over 400 fission power stations have been in operation for more than half a century and we have decades of experience in their construction and operating problems. Besides experience with nuclear fission reactors in the civil sector, substantial experience has also been accumulated in the military sector. Fusion energy, on the contrary, still faces basic, physical problems as well as many practical ones. In spite of decades of research, it has yet to reach the stage where it can produce a viable, positive energy balance from the fusion device. With fission energy, positive energy balance was achieved in 1942, but heroic efforts to attain the goal of energy gain in fusion have had to focus on plasma physics rather than on the economic and practical problems of constructing and operating fusion reactors.

The initial goal of achieving positive energy balance is pursued in ITER (International Thermonuclear Reactor), the largest current magnetic fusion device under construction. ITER is based on the Tokamak fusion concept, as a follow-up device from the Princeton Tokamak TFTR (Tokamak Fusion Test Reactor) which achieved 10.7 MW of fusion power in 1994 (PPPL, 2017). Assuming ITER successfully achieves positive energy balance, the aim will then be to develop the next fusion

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device, DEMO, into a working fusion power station with all its components of power conversion and tritium production. Whilst achieving positive energy balance in ITER is probably only a question of time, a big question mark hangs over the second goal: the ITER device is based on the Tokamak principle and the essential step in achieving a positive balance in the fusion chamber is to reduce losses of deuterium and tritium from plasma. This could be attained, failing a better solution, by increasing plasma volume with a corresponding increase of the toroidal plasma chamber. Mainstream development, at least with ITER, seems to be heading in that direction. With a big enough plasma chamber, Tokamak fusion will most likely be achieved, but with an installation of elephantine size and complexity. Consequently, Tokamak power plants are unlikely to be built outside a small number of leading, technologically advanced countries. One cannot, therefore, expect Tokamak plants to be built early enough and in sufficient numbers to have a bearing on climate change.

Outstanding problems of a more technical nature with Tokamak fusion are the production of tritium, magnets under strong neutron flux, first wall radioactivity and its replacement. Most of these problems would be associated with any kind of magnetic fusion geometry. New concepts, different from the Tokamak one, are emerging, some of which were described recently (Gibbs, 2016) in the "Scientific American". Regardless of whether these new concepts may have a better chance of achieving fusion, it will be too late for them to have a timely effect on climate change. It is a long and winding road to energy production in large commercial power stations of any type of fusion technology. Laser fusion at the US Lawrence Livermore Laboratory achieved a break-even in pellet burning in 2014 (Betti, 2016). However, that would cover only about 1% of the energy consumed in the whole laser fusion installation. Lengthy and uncertain development would be needed to reach the remote goal of an overall positive balance in laser fusion. That leaves fission technology as the only effective nuclear source for climate mitigation in the time window available to us between now and 2065.

2. A comment on carbon capture and storage (CCS)

Most people lack a correct appreciation of the quantities involved in CCS. Coal production is a massive industry worldwide. Thousands of trains and ships transfer coal from mines to power stations. The amount is staggering: annual consumption is close to ten billion tons. The mass of emitted CO_2 obtained by coal combustion amounts to up to three times the mass of coal used, so storing some twenty billion tons of CO_2 every year defies imagination. Experimental installations have not achieved economic viability. Some are quite large, sequestering several million tons of CO_2 annually, but with inefficient CO_2 removal. There is no chance of increasing the scale a thousand-fold, no idea of where to store tens of billions of tons of CO_2 per year, or, on that scale of storage, how to prevent it from escaping. As one author, independent of the coal industry, surveying the CCS efforts puts it (Biello, 2016), one gets the impression that basically the idea of CCS for climate mitigation is just an alibi for the coal industry to continue burning coal regardless of the effect it has on the climate. An additional argument to our statements regarding CCS is the failure to demonstrate a clean coal technology in the Kemper County plant (Wagman, 2017).

3. Understanding the urgency of the climate situation

The time left to humanity before uncontrollable physical and consequently social changes take place is estimated at only a few decades. A report by the IPCC (International Panel on Climate Change) AR 5 WG 3 (IPCC, 2014) states that between 2000 and 2010 GHG emissions grew at 2.2% a year, almost twice as fast as in the previous 30 years. At that rate, the report states, the world will pass the 2 °C temperature rise by 2030. The last GHG emission figure for the period 2000–2010 is (49 ± 4.5) Gt CO2 eq/year. The connection between carbon concentration in the atmosphere and global temperature rise has been disputed in recent years. The so-called "global warming hiatus" between the years 1998 and 2012 appears to show a slower global temperature growth than would be expected from climate models and the rise of carbon concentration. This has been used by some climate change sceptics to deny that the rise of carbon concentration in the atmosphere is the cause of global warming. However, ocean scientists claim that the hiatus can be explained by the "Decadal Pacific Oscillation" phenomenon. The years 2015, 2016, and part of 2017, the hottest years recorded, show the end of the oscillation period, with a return to faster temperature rise leading to general agreement about long-term trends. The chief scientist at the British Meteorological Office, Stephen Belcher, thinks that with warming after 2015 global temperature rise will follow the long-term trend. A detailed account is given in Nature (Medhaug et al., 2017). In the light of new data on the climate during the years 1998–2012, authors Medhaug et al. think they understand the cause of the hiatus and "are more confident than ever that human influence is dominant in long-term global warming".

Important quantification, based on long-term trends, of the limits to future carbon emission is provided in the paper by Meinshausen et al. (2009). To compare the data, we note that, in the period 1970–2010, the share of fossil fuel combustion in the total GHG emissions was 78%. We quote the following extremely important results: "Limiting cumulative CO_2 emissions over 2000–2050 to 1000 Gt yields a 25% probability of warming exceeding 2 °C and the limit of 1440 Gt yields a 50% probability - given a representative estimate of the distribution of climate system properties." As the emission of CO_2 during the interval 2000–2006 amounted to 234 Gt of CO_2, the magnitude of the problem is apparent. Assuming a continuation of average annual emissions amounting to 36.3 Gt from fossil fuels, forestry and land use, we will exhaust our emission budget by 2027 or 2039 (for respectively 25% or 50% probability exceeding 2 °C). The current global temperature increase is close to 1 °C, yet we are already witnessing an abundance of unpleasant climate changes. The latest instances are the floods in Texas, Florida, and the Caribbean islands. Informed people and scientists dread a future when the world will be confronted with damaging climate changes: floods, droughts, hurricanes, unbearable temperatures, with multitudes of millions migrating in search of a better place to live. That future is only a few precious decades away. A return to pre-global warming conditions is probably already impossible. The alarming new United Nations (UN) Environmental Report 2017 (UNEP, 2017) shows a wide discrepancy between annual carbon emissions predicted for 2030 and the emissions consistent with the long-term 2 °C global temperature increase. The gap (excess of predicted emissions) is estimated at 11.0–13.5 Gt CO_2.

4. Arguments for nuclear technology

Given that the time left for effective action to mitigate future trends is at most two or three decades, what measures can be taken? Renewable energy should be developed as fast as possible. Many people hope that the practically unlimited capacity of solar energy will be the saving grace. However, solar energy is not developing fast enough, as its proponents warn (Koningstein and Fork, 2014). Although solar energy might provide a practically unlimited resource, the effective rate of construction of solar devices is technically limited by the energy consumed in their production, as several studies have shown (Murphy and Hall, 2010). Additionally, solar energy is dependent on a daily cycle and requires expensive energy storage. Nuclear fission energy, providing a base energy load at all times, should be cost effective when compared with intermittent sources requiring additional energy storage. Consequently, nuclear fission, with its potential for a large-scale build-up not later than 2025, cannot be left out of the equation. Unlike nuclear fusion, improved nuclear fission is ready for expansion. Technical advances and cost reductions are possible with unification of design and by developing licensing procedures within a large-scale nuclear programme proposed for combating climate change.