Discover Sustainability

Perspective

Fusion breeding as an approach to sustainable energy

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Abstract

This article examines an approach for sustainable energy called fusion breeding. This is the use of 14 meV fusion neutrons to breed fuel for thermal nuclear reactors. Currently thermal nuclear reactors use for fuel, only the isotope of uranium, ^{235}U, which is 0.7% of the total resource. In order for nuclear power to be sustainable, it is necessary to breed nuclear fuel (^{233}U or ^{239}Pu) from fertile material (^{238}U or ^{232}Th). This resource could supply tens of terawatts for thousands of years. By any reasonable criterion, it both sustainable and carbon free. While most efforts at breeding envision fission reactors of one type or another, fusion is also a possible approach to breeding. Not only that, fusion has many advantages as a route for breeding that fission simply does not have. This article makes the case for fusion breeding.

1 Introduction

While sustainable energy might mean different things for different people, for the purpose of this paper we will define it as source capable of delivering tens of terawatts (TWs) for thousands of years in an environmentally and economically viable way. This paper explores one option for energy sustainability, fusion breeding. This is the use of 14 meV neutrons from a fusion reactor to breed fuel for thermal nuclear reactors. A thermal reactor is one that used low energy neutrons, about room temperature to 1000 degrees C for the nuclear reactor. The author has studied this for over 20 years [1] and has recently published three open access review articles on the topic [2–4]. The first is focused on the fusion community, the second on a general technically literate community, and the third on the general physics community. Each one has an Introduction which is a general summary for lay readers. Reference [3] also has a comparison of nuclear power in France with solar power in Germany, indicating that at least at this time, nuclear France easily wins the competition. France has both much cheaper electricity and half the CO_2 emission per capita than Germany. This paper is a much briefer summary, addressed principally to those concerned with sustainability.

An excellent source of relevant energy data is the BP Energy Outlook, which is published every year. Figure 1 is a plot of the energy use by region, end use sector, and fuel as a function of year, taken from their 2019 issue. To the left of the vertical dashed line is the historical record, to the right, their scenarios for the future.

As fossil fuels depend on mined quantities that could well run out in decades, or a few centuries at most, depending on the estimate and rate of usage, the only 'sustainable' fuels on their graphs are hydro and renewables (i.e. solar).

In the more developed parts of the world, virtually all the resources of hydro power have already been tapped. In the less developed parts, there is still considerable potential, especially in Africa. As Fig. 1 shows, the world currently uses about 14 terawatts of total power. However, the power use is very unequal in the world. This is most easily seen in a graph of per capita energy use versus per capita GDP for a variety of countries. These graphs abound on the internet, Fig. 2 is such a graph, produced by Our World Data, based on data from the International Energy Association.

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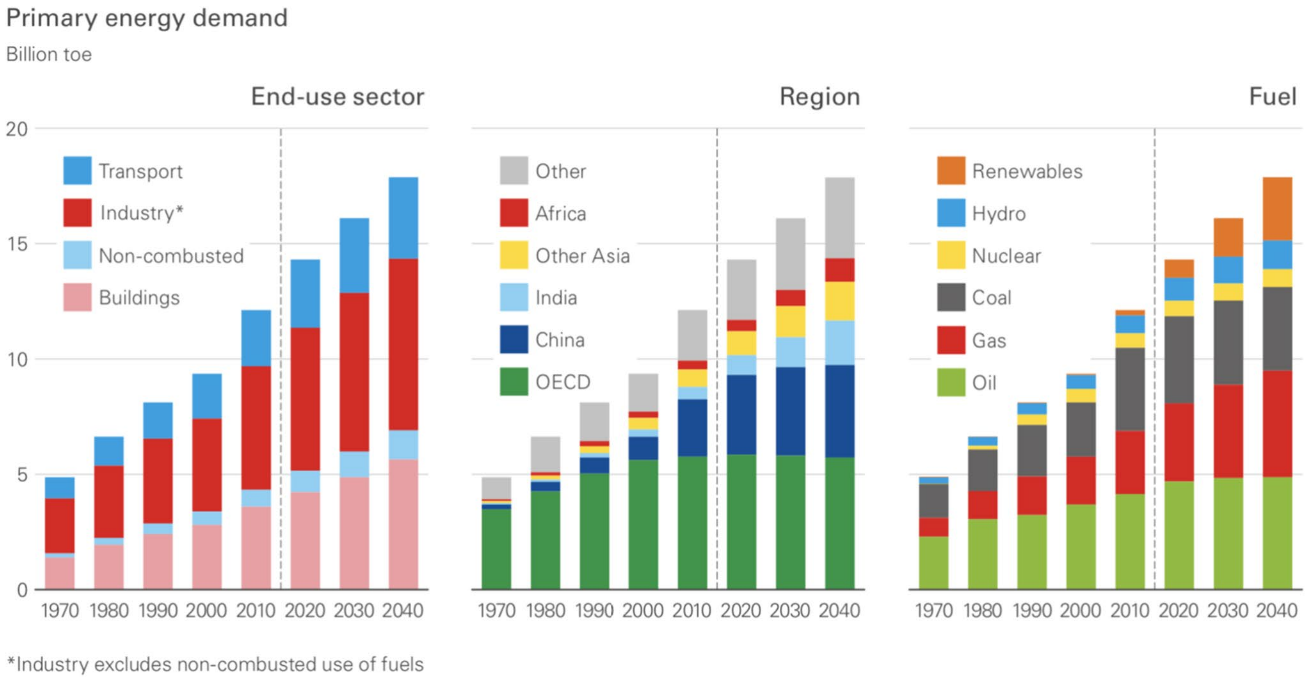

Fig. 1 Plot of energy use from BP Energy Outlook 2019. The vertical scale is in billions of tons of oil equivalent (Btoe) equivalent per year. To switch into more familiar units, 1 Btoe per year is about one terawatt. We will use Watts as our basic unit of power, so that as powers are originally stated in different units, they can be more easily compared. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2019.pdf

The billion or so people in the more developed part of the world use an average about 6 kW per capita (in the USA, we use about 8–10). However, the total world power use is about 14 TW. This is apparent form both Figs. 1, 2. Hence the other 6 billion people in the world share the remaining 8 terawatts, or have a per capita average power usage of just over 1 kW. Note that there is a very strong correlation between average power use and economic well-being. There are no rich countries that use little power.

Notice that power use has leveled off in the more developed countries, while it is growing rapidly in the less developed ones. This is natural, these countries want to share in the life style we in the United States (for instance) enjoy. Who are we to tell them to use only windmills and solar panels when we achieved our lifestyle by using more concentrated forms of fuel, fossil and nuclear fuel? In 2009 I was at a science meeting where a high-ranking member of the Chinese Academy of Science pointed out that in 2000, the average Chinese used about 10% of the power of the average American. He continued saying that they would not rest until our power use and theirs are about equal. Who are we to condemn then for this? They are building many coal fired power plants; now, according to Figs. 1, 2, the average Chinese uses about 30% of the power of the average American. To look at the other end of the spectrum, look at Niger. They only use about 200 W per capita. A person who eats a 2000 cal diet per days, takes in about 100 W. In Niger, human energy would seem to be the main energy used to accomplish their tasks. How long can this be sustained before they demand and build what we have? How can we tell them not to build coal fired power plants?

In a midcentury world with 10 billion people, the goal is certainly for everyone live a middle class life style, or to use a power of ~ 6 kW, or 60 TW for the entire world by 2050. As energy efficiency is increasing, typically by about 1% per year [5], this 60 TW could probably be reduced to about 35–40 TW. However unquestionably this is the goal, and it is a laudable one. Who are we to tell the people in, for instance, Niger, not to develop coal fired power, but to use windmills instead, when our own lifestyle depends on the use of fossil and nuclear fuel? As we approach mid-century, when the world will demand a middle class life style, much more power will be needed, not less. Furthermore, the abundance or scarcity of a fuel resource depends on how quickly it is used. Most estimates of fuel resources available are based on current usage. For instance, if the resource will last about a century at a rate of 14 TW, it will only last about 30 years a rate of 40 TW. This is a further argument for developing sustainable energy resources.

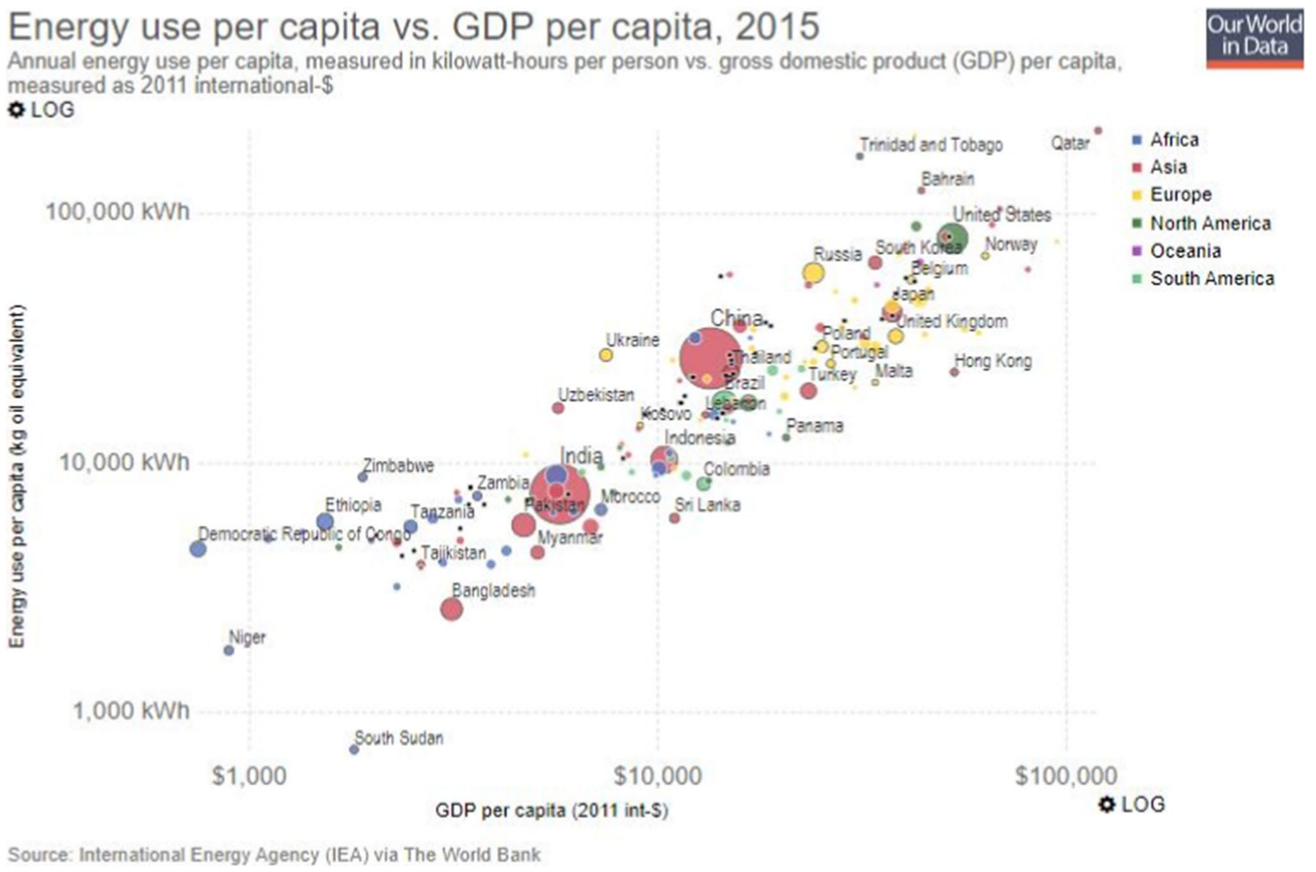

Fig. 2 A graph of the per capita energy use of various countries as opposed to their per capita GDP in 2015. This graph was produced by the International Energy Agency. The vertical axis is kilowatt hours per year. Since there are 8760 h in a year, to get the average power in kilowatts in 2015 divide by 8760, or to get an approximate value, just divide by 10,000. The size of each circle is proportional to the population of the particular country. This is taken from https://sustainingcapabilities.com/2018/07/17/the-energy-development-nexus/

The emphasis recently has been on carbon free solar power, that is solar photovoltaic, solar thermal, wind and biofuel. However, more and more people are beginning to realize that these have not and cannot provide sufficient power and ground truth certainly exist to support this position. Furthermore, windmills and solar panels take up a great deal of land, and there is more and more resistance to having the landscape marred. It is not only what some Americans refer to as limousine liberals on Cape Cod, who object to having their ocean view marred by hundreds of off shore windmills. In the Midwest, opposition to large wind farms is strong and typically popular opposition to them delays or prevents their installation. [6]. Of course, there is local opposition to nearly any nearby power source, coal, nuclear… However solar and wind are unique due to the enormous amount of land they occupy, land which other landowners likely have other plans for. Furthermore, they use an enormous amount of material and have enormous decommissioning costs when they wear out (solar panels and windmills are expected to last 10–25 years). Furthermore, neighbors have a legitimate fear that when they do wear out, they will just be left there, marring the landscapes with enormous, useless white elephants, or else will be dismantled at their expense.

Furthermore, besides the experience of France and Germany, there is much additional experience that solar and wind cannot do the job. California, which is decommissioning its nuclear and many of its fossil fuel power stations in favor of solar and wind, is now experiencing something rare in the developed world, rolling blackouts [7]. Germany is a rich country, and California is a rich state; if they want expensive, unreliable (in the case of California) power, they can certainly have it. But what about poorer areas of the world as they struggle to advance? Can India afford it? Can Niger?

Even the proponents now realize that the cost to transition to solar will be astronomical, assuming it can be done at all. The amount spent currently per year is about $500B worldwide of additional expenditures [8]. Reference [8] specifies how this money is to be divided up now and in the future. While there were many categories, by far the largest 3 were for low carbon transportation, renewable energy generation, and energy efficiency. This is *real money* for a gamble on something whose benefits are at best uncertain, and which may not even be necessary. Yet proponents think this is quite insufficient. Their recent estimates of the cost between now and 2050 are between about \$50 and \$100 trillion [8]! And these are the cost estimates by proponents; the estimates by skeptics are much higher. Recently Mark Mills has written a treatise on the inability of these solar power sources to do the job [9].

More and more prominent environmentalists and climate experts are realizing this, including Michael Shellenberger, James Hansen, Tom Wiggley, and Kerry Emanuel [10]. This leaves nuclear, which they now favor. Michael Shellenberger is an environmental scientist second to none, and he has come out strongly for nuclear in his new book *Apocalypse Never* [11]. There has been at least a 10-year history of analysts re-examining nuclear power and finding that so far at least, it is more effective in curbing CO_2 emission than solar and wind [12–15]. This is certainly confirmed by the experience of France and Germany.

However nuclear reactors as they are now constructed are thermal reactors using as fuel a mixture of about 4% ^{235}U in 96% ^{238}U. Hence, they are constrained by the supply of ^{235}U. The amount of ^{235}U is subject to some dispute, pessimistic estimates are in the range of 60–300 TW years [16]. This is considerably less than the estimates of fossil fuel. Hence nuclear power, as currently practiced, is not a sustainable technology, at least as sustainable is defined in this paper.

However, there are a variety of ways of breeding nuclear fuel from fertile material, i.e. ^{238}U or thorium. With breeding, the amount of nuclear material is multiplied by several hundred, easily meeting our definition of sustainable. Indeed, with breeding, nuclear power could power the world at 40 TW for thousands of years. These methods include using fast neutron reactions [17] (to be discussed shortly) or using a thermal neutron thorium breeder [18].

This paper hopes to make the case for a very different type of breeding, fusion breeding. While fusion breeding certainly has a longer development path than conventional fission breeding, it has advantages which are simple to state. It takes two fission breeders at maximum breeding rate to fuel a light water reactor (LWR) of equal power, and it takes them about 20 years to double the fuel in the reactor. A single fusion breeder can fuel 5 LWR's of equal power, and do so nearly immediately.

In Sect. 2, we discuss the basics of fusion breeding. Section 3 discusses the fusion project, where it is, where it hopes to be going and Section 4 discusses the 'Energy Park', what this paper sees as a sustainable, economical carbon free energy architecture with little or no proliferation risk. Section 5 gives conclusions.

2 Fusion and fission breeding

To start, we will review the various nuclear processes in fusion and fission. In fusion, the basic reaction is between a deuterium and tritium nucleus:

$$D + T \rightarrow N(14.1MeV) + He(3.5MeV)$$

Hence the reaction produces a 14 meV neutron and a 3.5 meV alpha particle, for a total energy release of 17.5 meV. Since this reaction in a fusion device will occur in a thermal plasma, rather than give reaction cross section, we give the reaction rate, <σv>, where σ is the reaction cross section, v is the particle velocity, and <> is the average over the distribution function of deuterium and tritium, assumed to be Maxwellian at the same temperature. Figure 3 is a graph of reaction rate as a function of temperature. Figure 3 also shows two other fusion reaction rates, the D ^{3}He and DD rates, which we will not discuss here. Clearly the DT reaction rate is the highest, and requires the lowest plasma temperature.

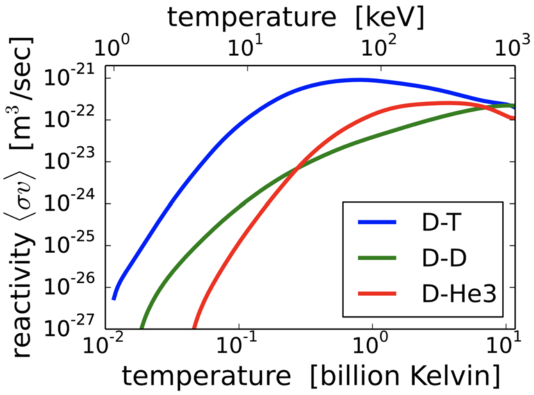

Fig. 3 The reaction rates for 3 potential fusion reactions

Regarding deuterium, there is plenty of it in the world's oceans. However, tritium does not exist on earth, it must be bred from lithium via one of two reactions. The first is exothermic:

$$n + {}^{6}Li \rightarrow T(2.75MeV) + He(2.05MeV)$$

The second possible reaction is endothermic, taking 2.47 meV away from the reacting particles:

$$n + n + +^{7}Li \rightarrow T + He + n$$

Clearly this reaction requires an energetic neutron. However, depending on the breeding blanket and reactions used to breed the nuclear fuel, it may be worth the energy price to price to preserve the extra neutron.

What we call pure fusion is to set up a plasma hot enough to sustain the DT reaction. The 14 meV neutrons are absorbed, they heat the blanket surrounding the reacting plasma, and this generates electricity in the usual way. However, there are other uses for the fusion neutron; it can be used to breed fissile material, ^{233}U or ^{239}Pu from fertile material, ^{232}Th or ^{238}U.

We now discuss the fission reactor and the breeding process. Different isotopes of uranium (or plutonium) behave very differently. Uranium of odd atomic mass, when colliding with a low energy neutron can split into two fragments with a combined energy of about 200 MeV. Also the reaction produces 2 or 3 additional neutrons of energy about 2 MeV each. A plot of the fission cross sections of 4 elements from a collision with a neutron are shown in Fig. 4. At the energy the neutron is produced, ~ 2 MeV, all the fission cross sections are about 1 barn (1 barn = 10^{-24}cm^{2}). However, as the neutron energy decreases, the fission cross section of the odd atomic number elements increases significantly, to about 3000 barns at about room temperature, while the fission cross section of the collision with the ^{238}U remains very low. As the fission reaction produces additional neutrons, there is the potential for a chain reaction, and this is the basis of any nuclear reactor.

Most nuclear reactors can only operate if the neutron slows down. The way to slow down the neutron is to have it collide multiple times with lighter elements like hydrogen, deuterium or carbon. The most effective is hydrogen (i.e. the lightest), and this is the basis of the light water reactor. The neutron slows down by colliding with the hydrogen in the water. The water is also a coolant for the reactor. Since these nuclear reactions are at neutron temperatures corresponding roughly to conventional fossil fuel reactors, they are called thermal reactors.

While the ^{238}U cannot fission at the thermal energies, there is another important reaction. Figure 5 is a plot of the absorption cross section as a function of neutron energy for both ^{238}U and ^{232}Th. The ^{238}U can absorb a neutron to form ^{239}U. However, this element unstable to a double beta decay, finally resting as ^{239}Pu. Thorium can do the same, finally resting as ^{233}U. Hence ^{238}U and ^{232}Th are called fertile, while ^{233}U, ^{235} and ^{239}Pu are called fissile.

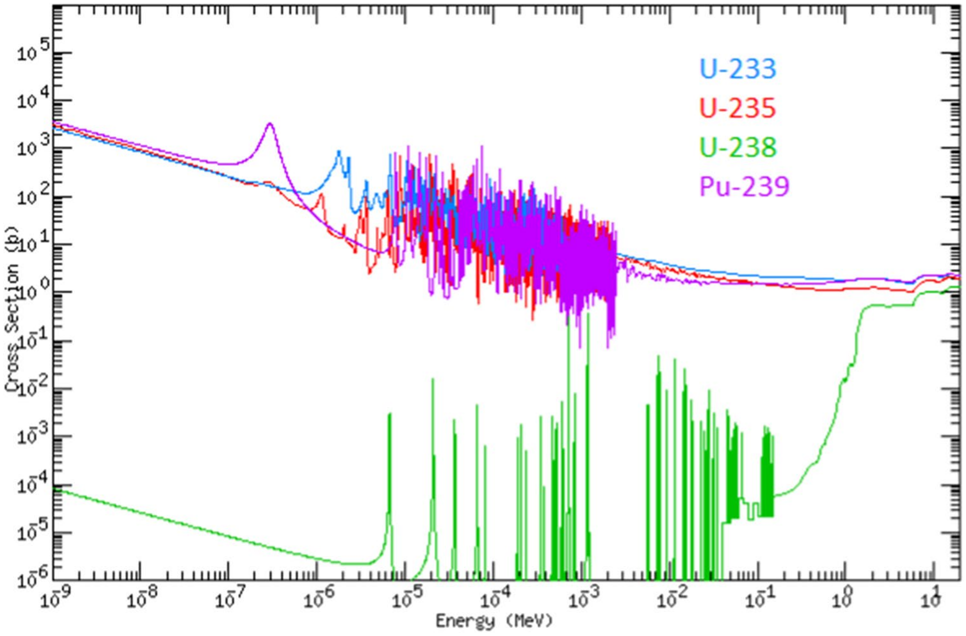

Fig. 4 Fission cross section in barns for as a function neutron of energy in MeV for relevant elements in a nuclear reactor

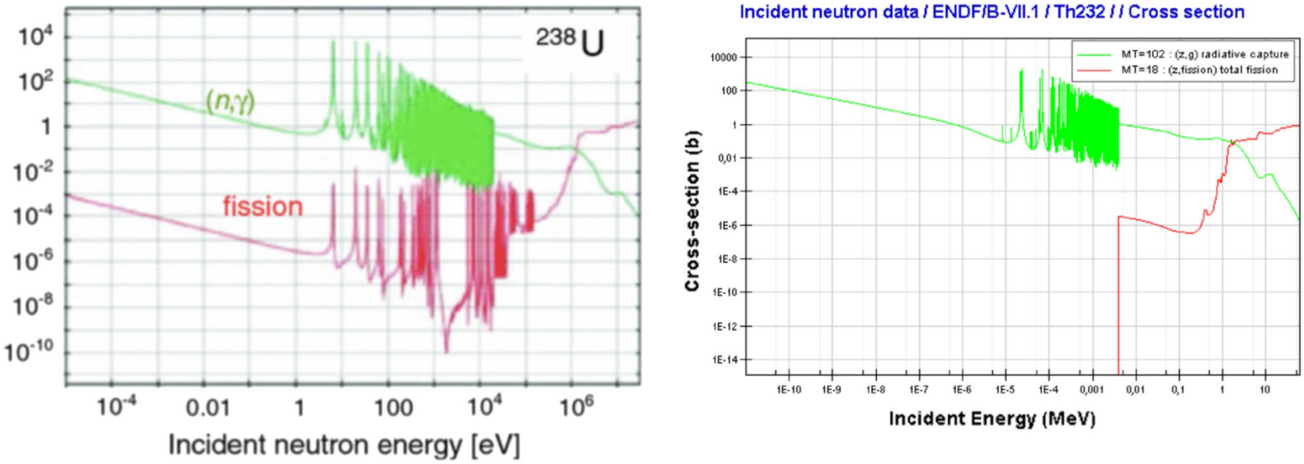

Fig. 5 The absorption and fission cross sections, in barns, of ^{232}Th and ^{238}U as a function of neutron energy

The LWR is typically fueled with a mixture of about 96% ^{238}U and 4%^{235}U. As an LWR operates, the fuel, which starts as pure ^{235}U, becomes a mixture of ^{235}U and ^{239}Pu. Of course, the ^{239}Pu, or the ^{239}U (before the beta decays) can absorb another neutron to form higher actinides. Each year, about 25 tons of used fuel is released from the reactor. This contains about 24 tons of uranium, now enriched at ~ 1%, ~ 200 kg of fissile and fertile higher actinides, ~ 700 kg of a large variety of fission fragments, that is intermediate atomic weight atoms, most of which are highly radioactive with half-life of 30 years or less. About a ton of fissile fuel has been burned.

There are about 440 nuclear reactors worldwide, about 100 in the United States. About 400 of these are LWR's. This is a fuel mixture for which there is no proliferation danger unless the prospective proliferator has isotope separation facilities (a nuclear weapon needs at least 80% fissile material). As an approximate rule of thumb, a ton of fissile fuel supplies about 1GWe (or about 3 GW thermal) for about a year.

To continue we discuss both fusion and fission reactors as potential breeders. As we have seen, when a fertile nucleus, ^{238}U or ^{232}Th absorbs a neutron, it ultimately decays into a fissile nucleus, ^{239}Pu or ^{233}U. It is a double beta decay process, so in each case there is an intermediate nucleus, neptunium before ^{239}Pu, or protactinium before ^{233}U. In breeding the ^{233}U, the intermediate protactinium has a half-life of about a month. For the case of fusion breeding which this article concentrates on, we consider the thorium cycle, since plutonium is an element we would like to avoid as much as possible. For bred plutonium, the raw fuel for an LWR would a mixture of ~ 4% plutonium and ~ 96% ^{238}U; a serious proliferation risk, as the uranium and plutonium can be separated chemically. Also, ^{239}Pu has a half-life of 24,000 years, so any reactor waste has the potential of forming a 'plutonium mine', which stays around virtually forever, at least on human time scale. However, if thorium is used as the fertile material, the final fuel would be a mixture of ^{233}U and thorium, which is also a proliferation risk. This risk could be decreased by adding some ^{238}U to the fertile material. An LWR using 4% ^{233}U or ^{235}U mixed with 96% ^{238}U would minimize proliferation risks. Such a fuel could be exported to many countries.

It is very simple to see why fusion is a much more prolific breeder than fission. The fusion reaction produces a single neutron. However, it is a high energy (14 MeV) neutron, so that it is energetic enough to produce additional spallation neutrons as it collides with materials like beryllium, lead or uranium. Hence each fusion neutron ultimately produces perhaps 3 total neutrons with a properly designed blanket [19, 20]. One of these neutrons must be used to breed the tritium, leaving perhaps 2 for other purposes. Of course, there are loss processes as well, so after these losses, there are perhaps one half to one neutron left for breeding. In the example in Refs [2–4], we looked at fusion blanket calculated to produce 0.6 ^{233}U nuclei, as well as the tritium. However, when this is burned in a conventional fission reactor, an LWR for instance, it releases about 200 MeV, effectively multiplying the fusion neutron energy by about an order of magnitude.

In a fusion breeder, it is important that the blanket be a flowing liquid so that lithium and thorium can be injected into the flow at the input, and tritium and protactinium can be extracted at the output. A molten salt like FLiBe (fluorine, lithium beryllium) has been discussed frequently. The salt itself provides the lithium, and thorium, protactinium and uranium are all soluble in it. Figure 6 is a schematic from an early LLNL report [21, 22] of such a blanket. It has entrance and exit pipes for the lithium and thorium at the entrance, and for tritium and protactinium at the output.

Furthermore, the ^{233}U breeding reactions are all exothermic, so that the power delivered by the fusion reactor is multiplied by a factor called M, which is typically about 2. Hence if the fusion reactor delivers ~ 1.5 GW of neutron

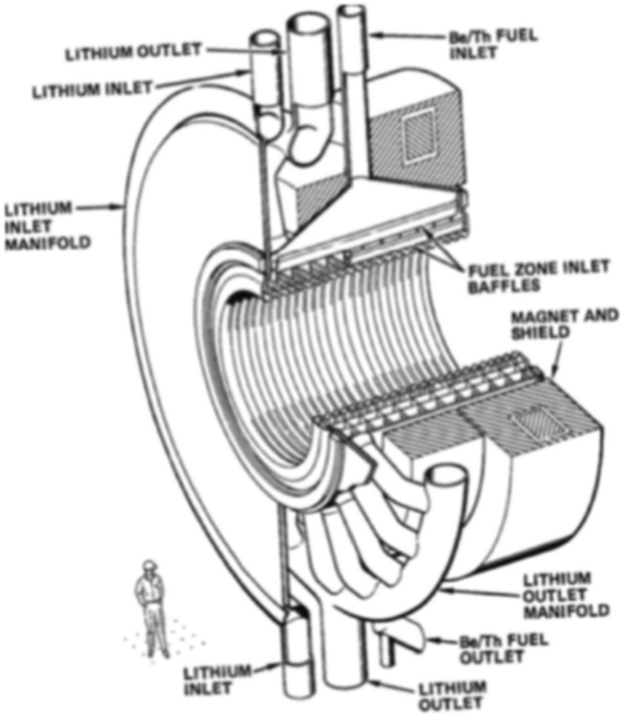

Fig. 6 A schematic of a fusion breeding blanket surrounding a fusion reactor. Notice the input and exit pipes for the flowing lithium and thorium [21, 22]

power, it delivers about 3 GWth of total power, and about 1 GWe when connected to the grid. However, it also produces ^{233}U at a rate which could fuel about 5 LWR's of 1 GWe.

Hence, we see that one fusion breeder, at maximum breeding rate can fuel about 5 LWR's of equal power. For a more advanced fission reactor, with a higher breeding ratio, it could likely fuel more. Furthermore, the fusion breeder fits in well with the existing nuclear infrastructure. After all, LWR's are what the nuclear establishment has chosen so far, after considering all the advantages and drawbacks of that and other reactors. Hence there is no need to develop more and better fission reactors, although if they are developed, the fusion breeder could certainly fuel them as well. The cost of the fusion bred ^{233}U fuel is difficult to estimate as the costs of a fusion reactor is uncertain at best. References [2–4] gave very rough estimates based on the (constantly changing) cost of the ITER tokamak (next section). It estimated the cost of the fuel at about 1–3 cents per kWhr. By contrast, the cost of ^{235}U fuel refined from mined ^{238}U is roughly 0.5–1 cent per kWhr. Either fuel cost, which is just a portion of the total cost, is considerably less than the total cost of nuclear-powered electricity. Hence the fusion bred fuel cost seems affordable.

Now let us consider fission breeding. As we have seen, in thermal reactors, there is some breeding, but not enough to breed extra fuel for other reactors. If the neutrons are not slowed down, but remain at their 2 meV energy until they react with a fuel nucleus, the reaction cross section is much lower, but the reaction provides sufficiently more neutrons, so that they could supply the other reactors as well.

However, fission breeding can never compete with fusion breeding regarding fuel production, and the reason is very simple. The fission reaction produces 2–3 neutrons. One is needed to continue the chain reaction, and another is needed to replace the burned fuel. This takes up at least 2 neutrons. Also, there are a variety of losses, reducing the number of neutrons available for breeding additional fuel to less than one, for a thermal reactor. The extra neutrons produced by a 2 MeV neutron could be sufficient allow the bred fuel to be greater than zero after the reactor refuels itself. There would be at most 0.1 -0.5 fuel atom produced for each reaction producing an energy of ~ 200 MeV. However, the fusion reactor supplies this same extra neutron in a 14 MeV reaction. Hence for a fusion and fission breeder of the same power, the fusion breeder can fuel about an order of magnitude more thermal reactors of equal power. A1GWe fusion breeder can fuel about 5 LWR's of the same power. At maximum breeding rate, it would take two fission breeders to fuel a single LWR of the same power. Hence in a fission breeder economy which fuels LWR's, at least 2/3 of the reactors would have to be breeders, and this would imply a staggering cost. In a fusion breeder economy, only 20% would have to be breeders, and the rest reactors of the type we use today, or an improved version of them.

In other words, fusion is neutron rich and energy poor, while fission is energy rich and neutron poor; a perfect match if the two processes are optimally joined. The position of this article is that the optimal joining is using fusion breeding as a source for fuel for thermal nuclear reactors.

There are other important aspects of a fission breeder to consider. Since the reaction cross section is so low, in the path of the neutron, there can only be material that seem totally transparent to it. The options are few, basically the only such materials are sodium and lead. Hence virtually all built and planned fast neutron reactors use, have used, or will use, liquid sodium as a coolant and element of the heat exchanger. While this is a standard industrial material, it is certainly not the easiest one to use in large quantities. There have been about 30 such fast neutron reactors built, most have been since disassembled. As far as this author is aware, there are only 2 currently running, both in Russia [23].

Since the reaction cross section is so low, the neutron must travel a long distance before it collides and reacts with a fuel nucleus. Hence a great deal of fuel is required in a fast neutron reactor, certainly much more than in a thermal reactor. Also, since the reactor itself produces the fuel, the rate of fuel production is proportional to the amount of fuel present. Hence the relevant measure of fuel production in a fast neutron reactor is the doubling time, the time it takes for the reactor to produce, for a separate reactor, the amount of fuel it was initially fueled with. This doubling time is currently about 20 or more years, with efforts being made to reduce it to 10 years. A fusion breeder, on the other hand, is a completely separate reactor, it produces the fuel needed continuously. To summarize, a fusion breeder, producing fuel for a thermal reactor nuclear economy has enormous advantages over a fission breeder doing the same thing. Of course, a fission breeder exists today, and has a much shorter development path than a fusion breeder.

There is one significant characteristic of a fission breeder which is important to the nuclear economy envisioned here. Notice that in Figs. 4, 5, at 2 MeV, the neutron fission cross section is about the same for all heavy elements, both fissile and fertile. A fast neutron reactor run as a burner can burn all actinide elements about equally. Hence the all actinide discharge of a thermal nuclear reactor can be treated with a fast neutron reactor. For instance, one could take the reactor waste, separate out the uranium, and then actinides beyond uranium with processes called UREX and/or PUREX, store the uranium for further use, and burn the higher actinides in a fast neutron reactor. As we have discussed, each year, an LWR discharges about 20% of its fuel load as higher actinides. Hence one can envision the following nuclear architecture. A single fusion breeder fuels 5 LWR's; and single fast neutron reactor burns the actinide waste of these 5 LWR's. If a more advanced thermal reactor is used, it is likely that more of these reactors could be serviced by the single fusion breeder and fast neutron reactor.

It is important to note that the British are going down this path. They are constructing a 600 MW fast neutron reactor to treat their plutonium stockpile. Their reactor is called PRISM [24], and it is a scaled-up model of the 60 MW integral fast reactor (IFR) developed by Argonne National Lab [25, 26]. This approach is different from the French approach. The French separate out the ^{239}Pu and burn it in a separate thermal reactor. However, this reactor, like any thermal reactor, produces some additional plutonium while it burns the plutonium is was fueled with. It just ends up with less plutonium than it started with. The IFR, on the other hand, in a burner mode, just burns every actinide it is fueled with without producing any more.

Finally, it is worth pointing out that a thermal reactor using thorium as a fertile material can be a breeder [18]. The relevant cross sections in the thorium cycle are somewhat larger than in the uranium cycle. The Shippensport reactor ran for 5 years, and at the end of the 5 year period, had slightly more fissile fuel (^{233}U) than it was initially fueled with (^{235}U). Hence while it cannot supply other reactors, it can supply itself. This could form a nuclear architecture competitive with fusion breeding. Which of these two possible nuclear architectures is the more advantageous is unknowable at this point, at least to this author. As they both are (hopefully) developed, the advantages and drawbacks of each will become clearer. However, they seem to be only two that are, at reasonable cost, potentially sustainable.

One certain disadvantage of the thorium breeder is that the raw fuel, a mixture of uranium and thorium is a great potential proliferation hazard. The uranium and thorium can be separated chemically. Finally, it is worth noting that of the 30 or so breeders built, only a single one was a thermal reactor using the thorium cycle [16]. All the rest were sodium cooled fast neutron reactors.

3 Fusion reactors

The fusion project has been going on for well over half a century. The motivating idea behind it is that a plasma hot enough to sustain the DT reaction, will produced a large flux of 14 meV neutrons, which will ultimately (for instance) boil water and with a heat exchanger, run an electric power generator. There are two different potential routes to fusion, magnetic fusion energy (MFE) and inertial fusion energy (IFE). MFE attempts to confine the ionized plasma in some type of magnetic configuration. IFE attempts to implode a target microsphere of DT, typically by using a large laser, and have the DT react before the target blows apart.

At this point, magnetic MFE leads by far in neutrons produced. Hence, we concentrate on MFE here, although many of the arguments here apply to IFE as well. Early on in the fusion project, many different magnetic configurations were advocated and investigated. However, as the knowledge progressed, the options have mostly narrowed down to a single configuration called a tokamak. While other configurations, i.e. stellarator, spherical tokamak, reverse field pinch…. get some relatively small amount of support, it is nearly certain that that the first large fusion device producing more neutron than its driving power will be a tokamak.

A tokamak is toroidal container having several magnetic field components. First there are field coils outside the container producing a toroidal, that is a field where the field lines go around the torus. Secondly, the plasma carries a toroidal current. This current produces a poloidal field perpendicular to the main toroidal field. The combination of these two field components can provided confinement of the plasma. In addition there is an exterior field coil producing a vertical field which helps center the plasma in the chamber.

To get feeling for the parameters of the tokamak, large tokamaks today have a major radius of about 1 to 3 m. TFTR, in Princeton NJ (disassembled at ~ 2000); JET, near Oxford, England; and JT-60, in Japan, are the largest with about a 3 m major radius; a minor radius of about 1/3 of the major radius. The plasma current is in the Mega Amp range, and the magnetic field is 3–5 Teslas. The plasma density is about 10^{20} ions per cubic meter, and the temperature is about 5–10 keV. The heating is maintained by Ohmic heating from the plasma current, as well as injected neutral atomic beams and/or microwaves.

An important measure of the performance of the tokamak, operated with a DT plasma, is the Q. This is the ratio of neutron power produced by the plasma, to injected power to heat the plasma and maintain its current. Very few tokamaks have operated with DT, as the labs running the tokamak typically do not have the capability to handle energetic neutrons, or if they had this capability, they did not maintain it. Both TFTR and JET did experiments with DT plasmas; these produced neutrons. JET particularly produced DT plasmas with two different plasma configurations. In each case the plasma was heated principally by beams of deuterium or tritium. In some cases, the neutrons were produced by the beam atoms. Here the Q was about 0.6, but the plasma could not be maintained. The JET group called this plasma a 'hot ion mode'. If the plasma was allowed to thermalize, the Q was reduced to about 0.2, but the reaction could be maintained as long as the discharge existed. TFTR achieved roughly the same results, but only in a hot ion mode. Figure 7 is a plot of the rate of neutron production in the JET experiments for both configurations [27]. These DT experiments were done on JET and TFTR around the turn of the century and have never been repeated.

The success of these tokamak experiments has encouraged the fusion community to come together, worldwide, to build a much larger tokamak called ITER, or international tokamak experimental reactor. Originally ITER was supposed to be an 8 m major radius machine which would produce 1.5 GW of neutron power and achieve Q = 10 and would be powered by 150 Megawatts of neutral beam and microwave power and run for 400 s [28] The original cost estimate in 1998 was $10B for construction and $10B for operation for 10 years. We refer to this original machine as Large ITER. However, as the cost mushroomed, the USA pulled out of the collaboration. Without the United States, the other parties

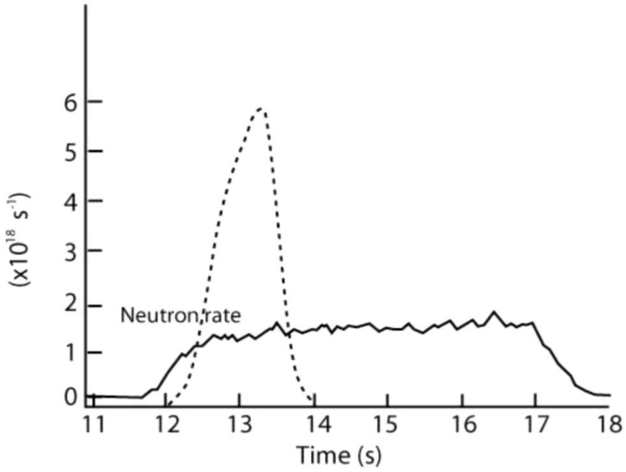

Fig. 7 A plot the neutron production in JET in both the hot ion mode (dashed) and thermal plasma mode (solid)

could not support it, so they came up with a smaller version, a 6-m machine which was still designed to have Q = 10, but only generate 500 MW of neutron power for the same 400 s [29]. The United States rejoined and later India did as well. The project was approved in 2005, and the cost estimate for 10 years was half that of Large ITER. The machine is currently being constructed in Cadarache, in Southern France. The hope is to begin DT experiments in 2035, and complete them, hopefully successfully, in 2040. However, despite being a smaller machine than originally planned, the costs are still escalating in a way that is worrisome to its sponsors and to many others. The current cost estimate to construct ITER is ~ $25B. This is in contrast to the originally projected cost of ~ $5B. An artist conception of ITER is shown in Fig. 8.

Assuming ITER is successful, the proposed next step is to construct a DEMO, a more advanced tokamak that would demonstrate the capability of fusion to power a real power plant. However, there are enormous obstacles between a successful ITER and a real power plant, i.e. the DEMO. To demonstrate these obstacles, let us consider an ITER like DEMO. The neutron power is ~ 500 MW of thermal power, which boils water, or whatever the neutron power is dumped in. This boiling water powers a generator. However, the generator produces electricity with an efficiency of typically 1/3. Hence the ITER like DEMO would only produce 170 MWe. But it needs 50 MW of microwaves or beams to power it. But microwaves and beams are not produced with 100% efficiency either; 1/3 is a more realistic efficiency to assume. This means the power source for ITER will take up ~ 150 MW of wall plug power, leaving virtually nothing for the grid.

To develop into an economical power plant, an ITER like DEMO, would need to increase its power by about a factor of 6, so as to be comparable to a standard nuclear plant, increase its Q by about at least factor of 3 or 4, so the circulating power is well under the delivered power, and reduce its size and cost. However, a smaller, more powerful plant means that the wall loading would be increased by at least an order of magnitude. These are not minor details! They would almost certainly take decades and tens of billions of $$ to accomplish, assuming they could be accomplished at all. To add insult to injury, it is likely that currently understood limitations on tokamaks prevent such an improvement on tokamak performance [2, 4, 30]. Given that the DT experiments will complete no sooner than 2040, and even assuming no additional delays, it is extremely unlikely that an ITER like device will be able to provide commercial power this century.

However, let us look at ITER as a fusion breeder. As we have seen in the last section, the 500 MW of neutron power becomes about 1 GW (~ 300 MWe) due to the breeding reactions. In addition, it would breed enough ^{233}U to burn at 5 GWth, nearly enough to power two 1GWe LWR's. The cost of the bred nuclear fuel is difficult to estimate, due not only to the inherent problems of making a cost estimate for a technology which is itself uncertain, but also in part to the rapidly changing cost estimates of ITER. References [2, 3] came up with a very rough estimate of ~ 1–3 cents per kWhr of electricity. The cost of mined uranium fuel currently is ~ 0.5–1 cent per kWhr. By contrast gasoline or heating oil, at $2 per gallon costs 5 cents per kWhr for the raw energy, or ~ 15 cents per kWh of electricity, if produced by a generator with a typical 1/3 efficiency.

If a more advanced thermal reactor is used, perhaps one with a larger breeding ratio, a fusion breeder might be able to power more thermal reactors. On the other hand, if we are still using the LWR's of today, one could develop a fusion breeder based on Large ITER and power 5 conventional 1GWe LWR's. If the ITER DT experiments are successful, this could be accomplished not too long after mid-century.

Concluding this section, we discuss what looks to this author like a role for the American MFE program, a path he has argued for 20 years [1–4]. In 2003, he gave it its name, 'The Scientific Prototype' [31], and in 2013 he published a short article arguing that it is by far the best of many choices for the American MFE program [32]. The two things ITER will

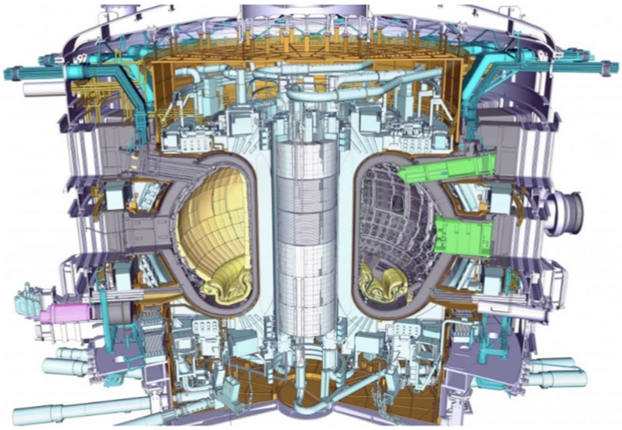

Fig. 8 An artist's conception of ITER, a tokamak with a major radius of 6 m, and when run with a DT plasma, will hopefully generate 500 MW of neutron power and have a Q ~ 10 for 400 s

not and cannot do are to run true steady state (days, weeks, months, not 400 s) and breed its own tritium. The Scientific Prototype, about the size of TFTR, JET or JT-60, and run with Q ≤ 1, but would do both.

4 The energy park

This section introduces what could be a sustainable energy architecture that could be set up not too long after midcentury called "The Energy Park". Inside a low security fence are 5 thermal nuclear reactors of 1 GW each. In our example, we consider these to be LWRs, although a more advanced thermal reactor may be available at the appropriate time. These provide either electricity or possibly serve as power sources for artificial liquid or gas fuel production, for instance for transportation or space heating. Each year about a quarter of the fuel load is removed as highly radioactive waste. This effluent is then taken inside a high security fence where any material with proliferation risk can be separated out and treated. The released material contains three very different types of material. First there is the unaffected uranium which went along for the ride. Second there are the higher actinides, such as the plutonium. These are separated out by (for instance) the PUREX and UREX processes. The uranium would be stored for future use. The higher actinides would be burned on site. Thirdly there are the fission products, cobalt 60, strontium 90….. These are mostly highly radioactive with half- lives of ~ 30 years. Some of these may have commercial application, for instance medical applications; they would be separated out and sold. The others are the true waste, and would be stored in cooling pools until they become inert for practical purposes. This would be 10–20 half-lives, or 300–600 years. This is a time scale human society can reasonably plan for, unlike the half million years or so, which the plutonium would have to be stored. The half-life of plutonium, 24,000 years.

Inside the high security fence there is a fast neutron reactor, for instance a 1 GWe IFR like PRISM. This would be used to burn the actinide wastes of the 5 LWR's. Recall that each year, an LWR discharges about 20% of its fuel load as plutonium and higher actinides. Hence the actinide wastes are burned, and produce an additional GW of power. Hence there is ultimately no proliferation risk from the material discharged from the thermal reactors.

Inside the high security fence there is also a 1 GWe fusion breeder, which breeds the fuel for the 5 LWR's. It breeds ^{233}U which is immediately mixed with ^{238}U to form a fuel mix for the LWR's. Hence any material with proliferation risk is almost immediately burned or diluted inside the high security fence. There is neither long time storage, nor long distance travel for any material with proliferation risk. Figure 9 is a schematic of 'The Energy Park'. It generates 7 GW of electric power and/or liquid of gaseous fuel. It does so without any CO_2 input into the atmosphere or half million year storage of plutonium nuclear wastes in for instance a Yucca mountain. It is a sustainable energy architecture, capable of providing many terawatts of power as far into the future as the dawn of civilization was in the past.

The Energy Park is more than a dream, but much less than a careful plan. It is one of very few possibilities for sustainable, economical, carbon free power, with little or no proliferation risk and without long term storage or long distance travel of fissile waste material.

5 Conclusions

The goal is to find a sustainable, carbon free, economically viable technology to power a mid-century world of 10 billion people. We begin with Nobel Prize winning physicist Richard Feynman's statement on the Challenger disaster:

> "When introducing a new technology, reality must take precedence over public relations, for nature cannot be fooled".

Let's take a look at wind and solar energy sources, keeping this in mind, and see what is reality, and what is public relations.

Reality is that the French, ~ 75% nuclear pay about half as much per kwhr as the ~ 25% solar Germans. Reality is that the French emit about half the CO_2 per capita into the atmosphere as the Germans. Reality is that California, which is ~ 15% solar and wind from in state sources (it imports ~ one third of its power from other states), while decommissioning its nuclear and coal fired power plants is now having rolling blackouts. Yet California pays more per kwhr than nearly all other states. This is all reality, there is no denying it.

Now let's take a look at public relations. Here are some recent headlines from a simple Google search.

Solar and wind costs continue to fall as power becomes cleaner [33].

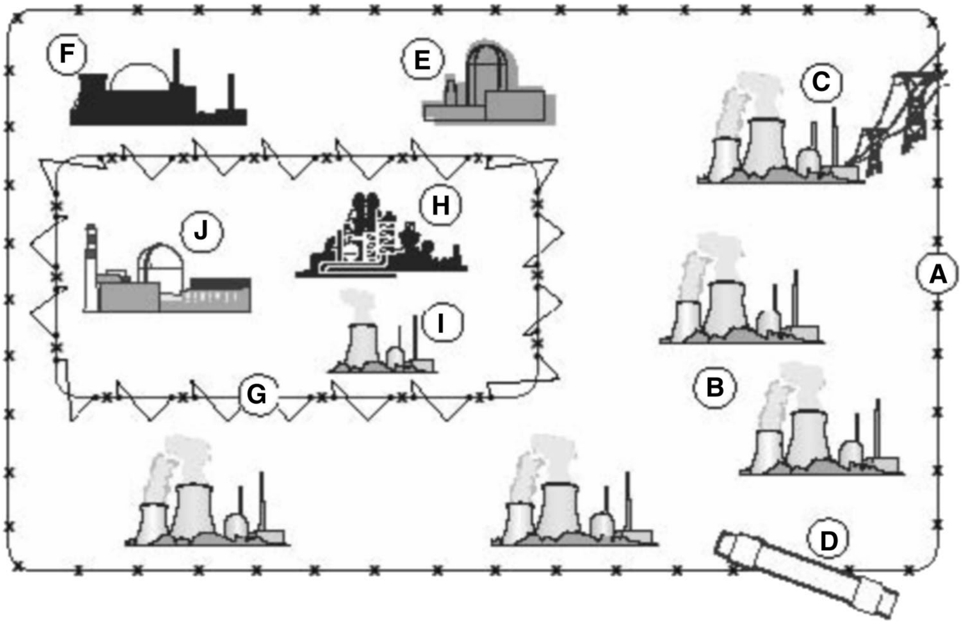

Fig. 9 The energy park: **a** low security fence; **b** 5 thermal 1GWe nuclear reactors, LWRs or more advanced reactors; **c** output electricity; **d** manufactured fuel pipeline, **e** cooling pool for storage of highly radioactive fission products for 300–600 years necessary for them to become inert; **f** liquid or gaseous fuel factory; **g** high security fence, everything with proliferation risk, during the short time before it is diluted or burned, is behind this high security fence; **h** separation plant. This separates the material discharged from the reactors (B) into fission products and transuranic elements. Fission products go to storage (E), transuranic elements got to (I); I, the 1GWe IFR or other fast neutron reactor where actinides like plutonium are burned; J. the fusion breeder, also producing 1GWe itself and also producing the fuel for the 5 thermal nuclear reactors for a total of 7 GWe produced in the energy park.[2–4]

Solar power will cost less than coal [34].

Solar and wind power will cost less than coal by 2030 according to one analyst's math [35].

Wind and solar plants will soon be cheaper than coal in all big markets around the world, analysis finds [36].

Wind power price now lower than cost of natural gas, ARS Technica [37].

Renewable energy costs take another tumble, making fossil fuels look more expensive than ever [38].

If the claims of these headlines are really true, they are certainly not reflected in the experience of Germany and California. More likely they are all arise from public relations. Nature cannot be fooled.

Now let us consider pure magnetic fusion. This project has been underway for more than half a century. It has had constant delays and cost overruns. If ITER, by 2040 achieves its goal, the fusion project will be nearly a century old. Yet pure fusion will still have many enormous hurdles to clear before it can provide economic power. Realistically magnetic fusion cannot be a twenty-first century power source.

This leaves nuclear power, and the conclusion of this paper is that it is the only realistic option for sustainable, economical carbon free power in this century. However, nuclear power as currently practiced uses only the very scarce isotope ^{235}U. This is certainly not sustainable by any measure.

Nuclear power can only be sustainable if it can tap the potential energy of fertile materials ^{238}U and/or ^{232}Th. One way to do this is with fast neutron breeders. This is possible, but they are very expensive. On paper these reactors cost at least double that of conventional LWR's [39, 40]. But these are paper studies of the cost of fast neutron breeder reactors, versus experience with the actual cost of constructing LWR's. Who knows what the cost of breeders will be once we start laying bricks and cutting metal.

The other possibilities are fusion breeding, the subject of this article, and thermal thorium breeders. Both could be viable options. Fusion breeding certainly has a longer development path, but if ITER is successful, one can see light at the end of the tunnel. It certainly has significant advantages. It is a much more prolific fuel producer. Also, it fits in well with existing nuclear infrastructure.

This author has spent a good part of his career on fusion. Accordingly, we conclude with recommendations for how the magnetic fusion effort should proceed. Since ITER is already more than half built, and there is no other device anywhere on the horizon which can make a credible claim that it can equal ITER's hoped for performance, ITER should proceed to completion. Then what is needed at this point is a change in psychology in the MFE effort. There should be a realization that fusion breeding is a different, perfectly acceptable, and perhaps even a better option for fusion. It is certainly one that is more achievable.

Once the MFE program realizes that breeding is the way to go, there are a few changes to make in the ITER project. First of all, since a DEMO capable of pure fusion becomes unnecessary, and is likely impossible anyway; design efforts on the DEMO capable of pure fusion should be dropped and these resources added to the actual ITER effort. Secondly, since a breeder appears to make sense only if there is a flowing liquid blanket, probably a molten salt, ITER should be designed only with such a blanket. Any resources in the project dedicated to designing a solid blanket should be reprogrammed to the design of a liquid blanket.

The American MFE program, instead of being fragmented into several small projects should unify and construct a tokamak which the author has called "The Scientific Prototype" [32]. This is a tokamak which has roughly the parameters of TFTR, JET and JT-60. Possibly it would use the new high temperature, high field superconducting magnets [41]. It would have Q ~ 1, or even less than 1, but run steady state for days, weeks or months in a DT plasma, and breed its own tritium. These are important issues with ITER will not and cannot address. If both ITER and the scientific prototype are successful in the 2040 time frame, a credible path to large scale fusion breeding truly opens up.

To summarize, fusion breeding is one of the very few options for large scale, economical, sustainable carbon free power, and it could be achieved not too long after midcentury. It can tap the potential of all the uranium and thorium energy, and power the world at 40 TW at least as far into the future as the dawn of civilization was in the past.

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