Sustainable Thorium Energy for the World

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1. Sustainability

Nothing is sustainable in the long run, not our sun and, of course, not life on this planet. In about 550 million years, it is expected that photosynthesis will cease through lack of carbon dioxide [1], which is somewhat ironic, given today's worries concerning global warming. Hence, life as we know it will no longer be possible on Earth, and we can only speculate on the fate of humankind, as it is not predictable on such a long timescale. Sustainability only makes sense as a relative concept with respect to the human timescale. The definition of sustainability may become complex when adding environmental, economic, or social considerations. For our purpose, a sustainable energy source could be defined as a source of energy with reasonably manageable impact on the environment, and one that will last long enough for an innovative technology to provide a replacement. A scenario of clear successive energy substitutions has been observed in the past, as shown by Cesare Marchetti [2] (Fig. 1), with energy market niches for wood being successively substituted by coal, oil, and natural gas. The picture has dramatically changed today (Fig. 2), as nuclear energy did not live up to expectations, while newly discovered reserves of coal, gas, and oil have extended the dominance of fossil fuels, and renewable energies have experienced difficulties in conquering a substantial part of the world market.

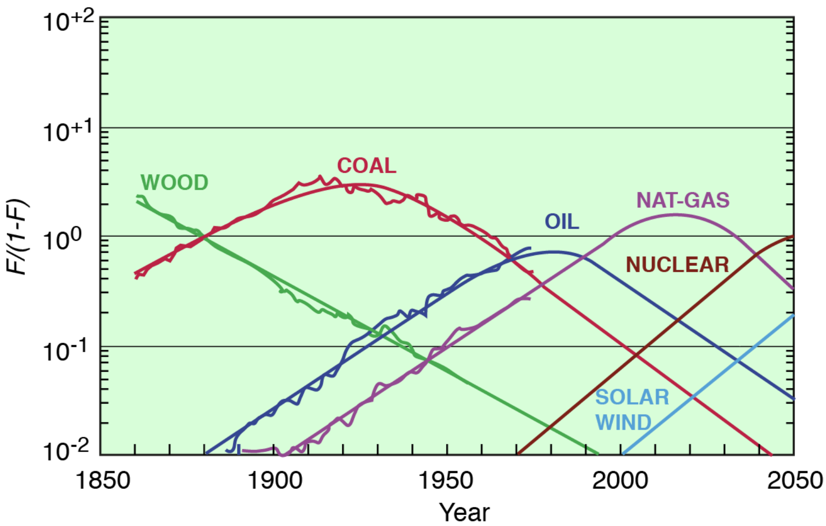

Figure 1. The substitution model applied to the dynamics of energy systems by C. Marchetti and N. Nakicenovic (1979) [2], for the period 1860–2050, where *F* is the fractional market share.

[1] International Thorium Energy Committee, Geneva, Switzerland and Centro Fermi, Rome, Italy

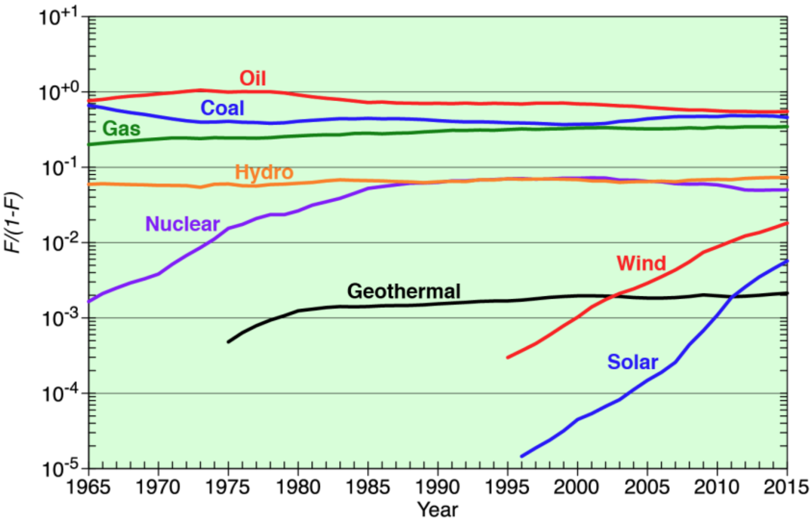

Figure 2. C. Marchetti's quantity *F*/(1–*F*), where *F* is the fractional primary energy consumption as a function of time, using data for the period 1965–2015 from [3].

Sustainability clearly demands an adequate R&D effort for the next innovation to become available in time. In addition, the research effort must include fundamental research, as it is fundamental research that drives innovation. Most importantly, the R&D effort must be accompanied by substantial investment in education in order to provide the required number of researchers, but also to raise the awareness of the public. Without a sufficient effort in education and R&D there is a danger that humankind will exhaust the natural energy resources of the planet before new innovative energy sources are made available.

With our definition, solar energy clearly is a sustainable source of energy, although present solar energy photovoltaic technologies may not (yet) be sustainable owing to constraints on the availability of rare materials such as indium, tellurium, germanium, and ruthenium if one wants to scale up the solar energy technology to the TW level [4]. Clearly, nuclear energy as we exploit it today is not sustainable. On the other hand, a new source of energy that would last 20 centuries or more and that would meet the basic requirements in terms of environmental impact, would clearly qualify as sustainable. This is potentially the case for thorium energy as will be discussed in sections 4 to 8.

2. Replacing fossil fuels: a major challenge for society

Fossil fuels, which have been dominating the energy market for over 150 years, are present in finite quantities in the Earth's crust and inevitably will run out sooner or later. At the rate they are being used today, the timescale for exhausting these sources of energy is of the order of 50 to 100 years for oil and gas, and 100 to 150 years for coal. If consumption continues to increase, the end of fossil fuels will occur sooner. This should be of significant concern not only because of the short time periods with their attendant implications, but also because it certainly does not make sense to continue burning fossil fuels until supplies run out for several strong reasons:

– In the first place, there is an increasing consensus that global warming as a result of the release of greenhouse gases issuing from human activities is a serious problem. Even if this is still doubted by some, precaution should prevail. We should stop releasing massive amounts of CO_2 and other greenhouse gases into the

Earth's atmosphere. The year 2016 saw the CO_2 concentration exceed 400 ppm [5], a level and a rate of increase unprecedented in at least the past million years.

– Air pollution produced by burning fossil fuels is an immediate, real, and very costly major problem. Burning coal costs Europe alone over 40 billion Euros in annual healthcare expenses [6]. In 2015, the European Environmental Agency declared that: "Air pollution poses the single largest environmental health risk in Europe today". Close to one million deaths per year in China are due to air pollution [7]. The World Health Organization (WHO) estimates that one in eight total deaths in the world are the result of exposure to air pollution [8]. This means that fossil fuels kill twenty thousand people each day. Why is this not the prime reason put forward for wanting to stop burning fossil fuels?

– Remaining fossil fuel reserves could certainly be put to much better use, instead of burning them. For instance, oil is used in the manufacture of plastics, rubber, paints, glue, drugs, cosmetics, detergents, asphalt for roads, etc., and perhaps most importantly, chemical fertilizers, which are crucial to our food supply.

Despite all this, in 2015, fossil fuels still represented 86% of the primary energy consumption [3] (Fig. 3), and because they are cheap and abundant, the current tendency is to increase their consumption (Fig. 4). Assuming a globally rising standard of living and a global population plateauing between 10 and 11 billion inhabitants, it is expected that the world energy consumption would have to increase by a factor of three or more in the next 100 years to keep pace with expected demand. Our civilization would then be powered as a 45 TW engine exceeding the 44 TW geothermal power of the planet.

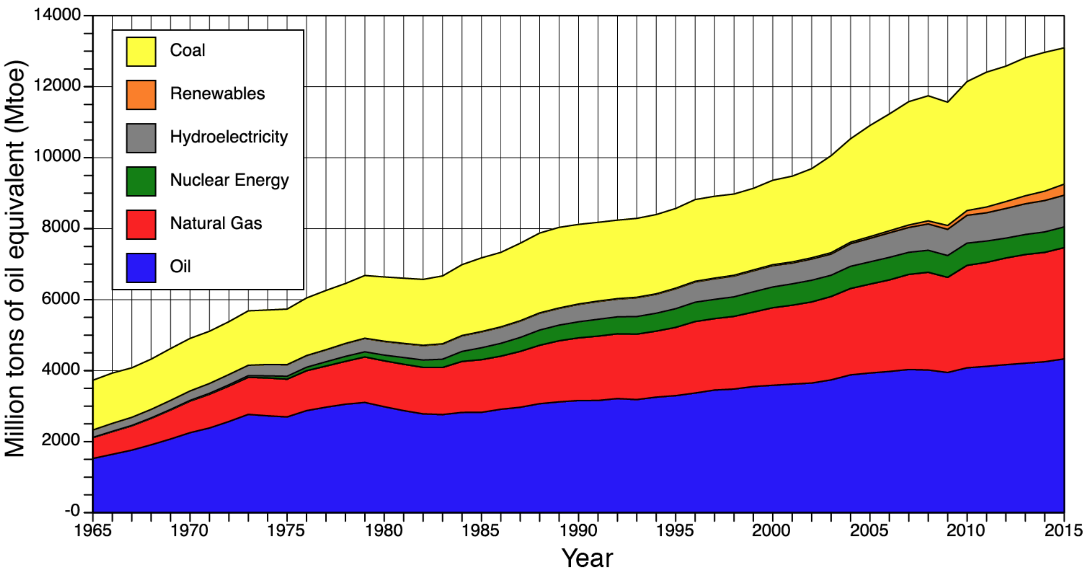

Figure 3. World primary energy consumption [3] for the period 1965–2015. Coal, gas, and oil represent 86% of the supply, hydro 6.8%, nuclear 4.4%, and renewables 2.8%.

Our vision of global energy issues is obscured by the fact that Europe is not representative of the rest of the world: it is one of the rare regions of the world where the population is expected to decrease [9], there is essentially no economic growth, and European citizens enjoy one of the highest standards of living. Clearly, one cannot imagine applying to the 1.2 billion people in the world still without electricity the same energy measures presently proposed by European politicians.

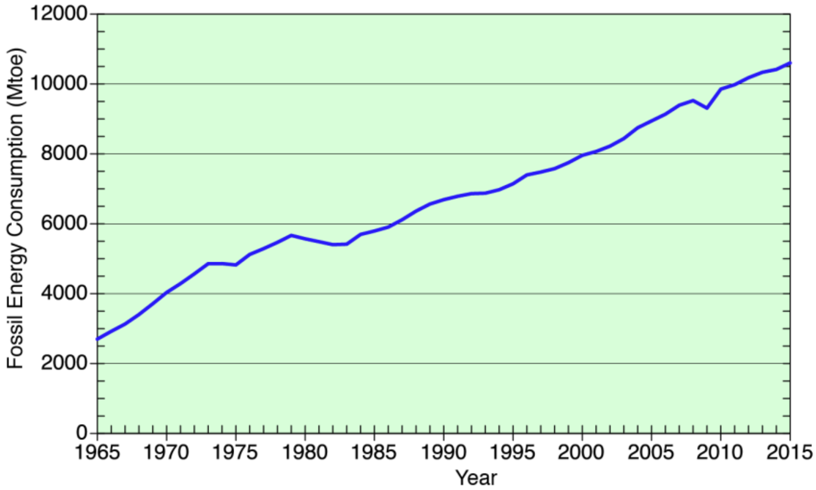

Figure 4. Primary energy consumption of fossil fuels (coal, gas, and oil combined) in million tons of oil equivalent (Mtoe) for the period 1965–2015. Data were extracted from [3].

3. Nuclear fission energy can be exploited in a different way

Solutions to the energy problem can only come from intensive and systematic R&D. Developed countries, which have enjoyed cheap but polluting energy supplies without limit in order to achieve their present level of wealth, have the responsibility to lead the R&D effort and develop innovative solutions. It is clearly a responsibility for the scientist to feed the R&D effort. Politicians cannot invent solutions. Funding does not even seem to be a limitation in Europe, if we may judge from the 600 billion Euros that the EU spent on renewable energies from 2005 to 2013 [10], mostly on subsidies.

Nuclear fission energy must not be left out of the energy R&D effort. Resources are abundant and energy-intensive. For instance, an electric power of 1 GW can be sustained for one year by using only 1 ton of thorium, compared with 3 to 4 million tons of coal or 60 km^2 of solar cells at the latitude of Paris. Nuclear fission energy can ensure base load electricity production, it produces neither greenhouse gases nor air pollution, and it could be made sustainable. If it were not for accidents, waste management, and proliferation issues, there would be no reason to want to stop nuclear power plants. So the question that should be asked is: ***Can nuclear energy be made acceptable to society?*** It is clear that the present way of exploiting nuclear energy was selected for other reasons: the uranium fuel cycle was chosen to produce plutonium for nuclear bombs; Pressurized Water Reactors (PWRs) were invented to fit on a submarine. Is there a better choice for nuclear energy? Prominent physicists, such as Nobel Prize Laureate Carlo Rubbia, answered clearly “yes”, with thorium fuel in fast neutron Accelerator-Driven Systems (ADS) [11]. This is not to claim that thorium accelerator-driven systems could by themselves solve the entire energy problem, but they would make a major contribution to the solution, by allowing nuclear energy to take a major share of the energy mix and by being complementary[2] to renewable energies, while at the same time offering the possibility of destroying a major fraction of nuclear waste. Regardless of national policies, the

[2] Photovoltaic solar energy and wind energy require another source of energy with equivalent power as a backup for when there is no wind or no sun, because of the lack of technology suitable for massive electricity storage. The plan in Germany is to use coal-fired power plants for this purpose.

problem of nuclear waste management must be solved, as waste has accumulated and continues to accumulate (Fig. 5). The added requirement of retrievability makes geological storage more challenging if not questionable; therefore, alternative solutions must be considered.

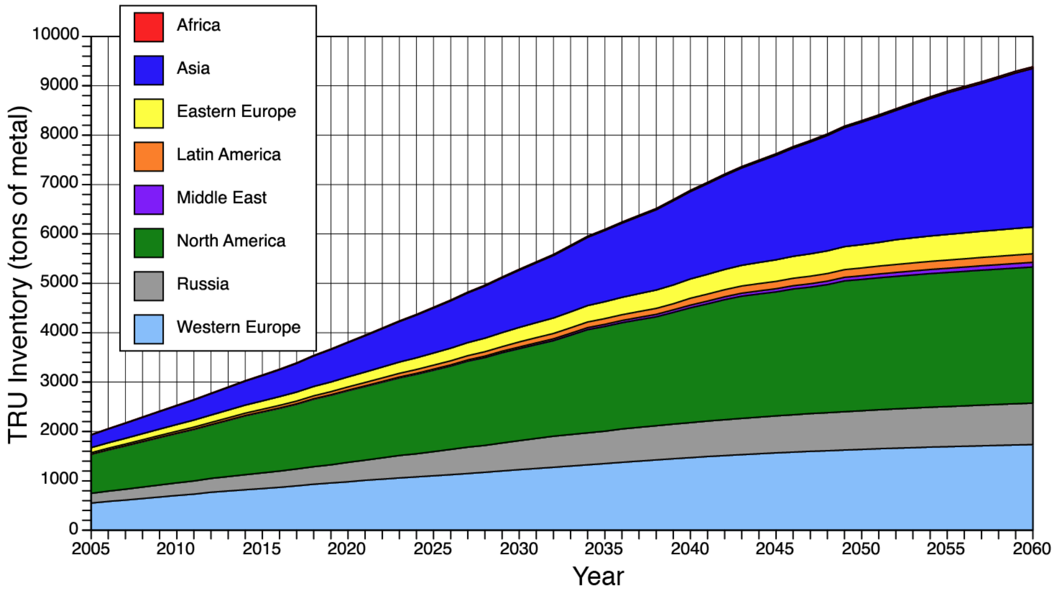

Figure 5. Evolution of the world inventory of transuranium elements (TRU)[3], the long-lived component of nuclear waste, in tons, and projection to 2060, assuming the present number of nuclear reactors and those expected to be commissioned by 2035, showing that TRU waste will exceed 9000 tons by 2060 [12].

4. Thorium: a sustainable source of energy

Given the foreseeable huge energy demand, any potentially important source of energy must be considered, in particular thorium, as the technologies required to exploit it represent only a relatively modest extrapolation of existing nuclear reactor and particle accelerator technologies, in sharp contrast to the development of fusion energy.

Table 1. Estimated world thorium resources in tons [13]. Note that one ton of thorium can generate 1 GW of electric power for one year.

	Country	Quantity (ton)		Country	Quantity (ton)
1	India	846,000	10	South Africa	148,000
2	Brazil	632,000	11	China	100,000
3	Australia	595,000	12	Norway	87,000
4	USA	595,000	13	Greenland	86,000
5	Egypt	380,000	14	Finland	60,000
6	Turkey	374,000	15	Sweden	50,000
7	Venezuela	300,000	16	Kazakhstan	50,000
8	Canada	172,000		Other countries	1,725,000
9	Russia	155,000		**World Total**	**6,355,000**

It is estimated that the Earth's crust contains 1.2×10^{14} tons of thorium [14], which is about the same amount as lead, and three to four times more than uranium. Thorium resources are broadly distributed on the Earth (Table 1), which has

[3] TRU: chemical elements with atomic numbers greater than 92 (the atomic number of uranium).

obvious geopolitical advantages. Thorium is not fissionable, so one must produce the uranium-233 isotope from thorium to obtain fissions (Fig. 6). Breeding of uranium-233 uses essentially all the thorium. In PWRs, it is only uranium-235, present at a level of 0.7% in natural uranium, which is used. As a result, thorium represents a greater energy supply by a factor of 140, which, when combined with the higher thorium abundance, corresponds to an overall factor of 500 times more potential thorium resources compared with uranium.

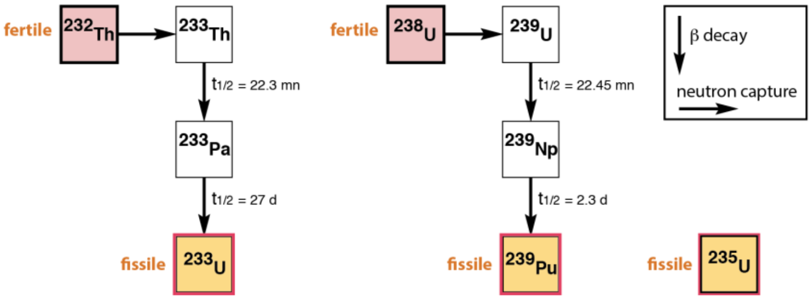

Figure 6. The three main nuclear fuels are U-233, Pu-239, and U-235. The figure shows a comparison of the breeding schemes for U-233 in thorium fuel (left) and for Pu-239 in uranium fuel (middle). U-235 used in present PWRs does not require breeding as it is extracted from natural uranium, where it is present at the 0.7% level. Horizontal arrows represent neutron captures, and vertical arrows β decays.

Assuming the present world electric power consumption of 2.5 TW, the 6.3 million tons of thorium reserves [13] (Table 1), a number probably underestimated given that thorium has not been the object of a systematic search, could electrically power the whole planet for 2500 years. At the ThEC13 international conference on thorium at CERN, Carlo Rubbia stated: “Thorium constitutes a sustainable energy resource on the human timescale" [15].

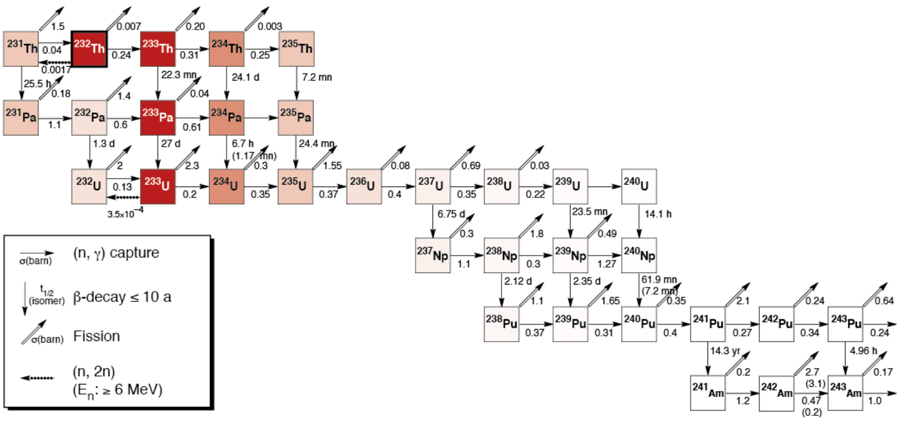

Figure 7. Main elements produced by irradiation of thorium in a fast neutron flux, illustrating why the production of TRU is strongly suppressed, as it takes six successive neutron captures to produce uranium-238 starting from thorium-232. Horizontal arrows represent neutron captures, vertical arrows β decays, and diagonal arrows fissions.

Natural thorium is isotopically pure, found mostly in monazite ores, but also in thorite ($ThSiO_4$) and in thorianite (ThO_2+UO_2), and is relatively cheap as it is often a by-product of rare earth mining. Thorium produces smaller amounts of long-lived nuclear waste (TRU) than uranium, because it is six neutron captures away from uranium-238, the entry point for the production of TRU in the neutron irradiation chain (Fig. 7). In addition, thorium has excellent physical properties such as higher melting points for both the metallic and oxide forms, and better thermal conductivity compared with uranium. This means that there are higher safety margins for design and operation. Most importantly, the thorium fuel cycle has the great advantage of being proliferation resistant, as the production of plutonium is negligible and the uranium mixture in the spent fuel makes it extremely difficult to manufacture a bomb [11].

Because of the need for breeding uranium-233 to obtain fissions, and for neutron inventory reasons, thorium cannot simply be substituted for uranium in critical reactor fuel. Three basic approaches are envisaged today in order to exploit thorium [16]:

a) A three-stage scheme adopted by India [17]. This involves breeding plutonium in CANDU heavy water reactors, then using the plutonium produced as the fuel in fast sodium-cooled critical reactors, around which uranium-233 is bred in a thorium blanket. Finally, the uranium-233 extracted from the blanket is used to manufacture fuel for advanced thermal reactors. This scheme is complicated, as it requires maintaining three different reactor technologies. Moreover, it does not solve the problem of nuclear waste management and it is not sustainable as uranium is needed to initiate the process.

b) Moving the fuel continuously in order to always have fresh fuel in the core. This can be done in pebble-bed reactors [18] or in molten salt reactors [19], both of which have serious technical and safety issues still to be resolved. There exists also the idea, yet to be developed, of traveling wave reactors [20]. In these systems, it is not the fuel that moves, but the neutron breeding and fission wave.

c) Using a particle accelerator to produce the extra neutrons needed to sustain a chain reaction, in so-called subcritical accelerator-driven systems (Fig. 8). This appears to be the most efficient and elegant method for using thorium [11] and, when used in fast neutron ADS, a most efficient method for destroying TRU through fission.

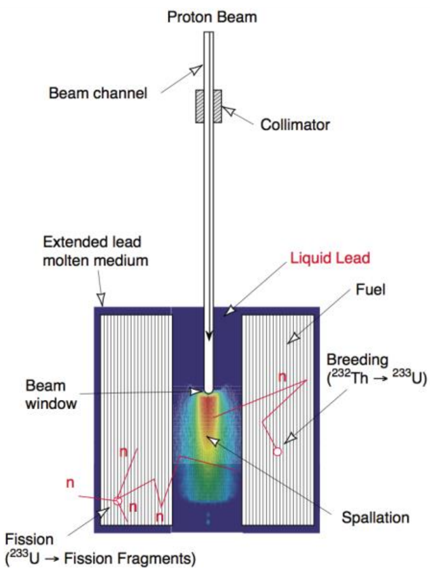

Figure 8. Principle of an accelerator-driven system. A proton beam inserted vertically from the top hits a lead target, producing neutrons through the spallation process. These neutrons travel to the subcritical core, where they are amplified by fission processes similar to those at work in a critical nuclear reactor. The system is called "subcritical" because the chain reaction is not self-sustained; it is powered by the proton beam, which can be switched off in a few microseconds.

5. Fast neutron ADS: a technology feasible today

The ADS idea could perhaps be traced back to the first particle accelerator, in which the radioactive element polonium-210 was used, in 1919, by Ernest Rutherford to bombard nitrogen-14 with 5.3 MeV α particles to produce oxygen-17. An important milestone was certainly 1940, when Ernest O. Lawrence in the USA and Nikolay N. Semyonov in the USSR independently proposed using a particle accelerator as a neutron source. This could be considered as the birth of ADS, and shortly after that, in 1942, Glenn Seaborg produced the first μg of plutonium-239 by using a cyclotron.

Early ADS projects in the 1950s were abandoned when it was realized that the accelerator technology was not yet ready for the required beam power. Renewed interest in ADS in the 1980s appeared under the impetus of Hiroshi Takahashi [21] at Brookhaven National Laboratory and of Charles D. Bowman [22] at Los Alamos, when the USA decided to slow down the development of fast critical reactors.

In the 1990s, Carlo Rubbia gave ADS a major push [11] by launching a vigorous research program at CERN based on the development of innovative simulations of nuclear systems, by using particle physics Monte Carlo simulation methods, and by carrying out specific experiments to test basic concepts (FEAT [23] and TARC [24] experiments). Rubbia is at the origin of the concept, design, and construction of the advanced neutron Time of Flight facility (n_TOF) [25], now in operation at CERN, to acquire neutron cross-section data, crucial for simulating any configuration with new materials.

The conclusion of the CERN study is that thorium must be used in a fast neutron flux ADS to favor breeding (Fig. 9), to allow long burnups for better fuel usage efficiency and longer operation time (neutron captures on fission fragments are much smaller than in a thermal neutron flux), and finally because TRU can fission in a fast neutron flux, and therefore be eliminated by recycling them as fuel. The 9400 tons of TRU expected to accumulate by 2060 (Fig. 5) could power the entire world electrically at the present level of 2.5 TW for 3.7 years.

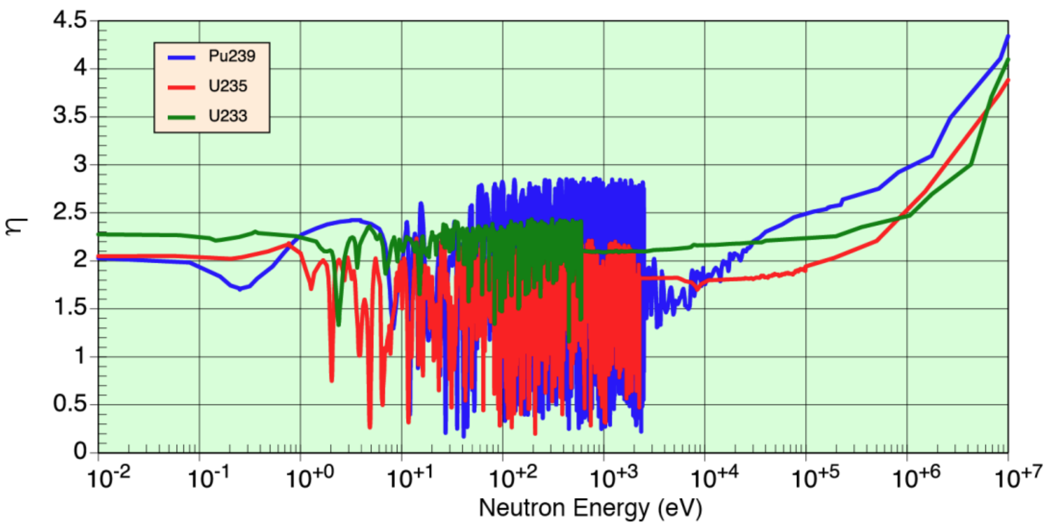

Figure 9. Number of neutrons produced per neutron absorbed (η) in U-233, U-235, and Pu-239, as a function of neutron kinetic energy, taken from [26]. For breeding to be possible, η has to be larger than 2. The fast neutron part of the spectrum is clearly advantageous for breeding, even though, for U-233, breeding is also possible at thermal and epithermal neutron energies.

The first phase of ADS development, which consisted of validating the basic concepts, was completed in the 1990s, in particular at CERN. In the second phase, which was completed in the 2000s, all the basic elements of an ADS were tested separately. Proton beams have exceeded a power of 1 MW, first achieved at the Paul Scherrer Institute (PSI) in Switzerland, with a cyclotron [27]. During the same time period, neutron spallation sources have reached or exceeded the MW regime, first with MEGAPIE [28] at PSI and nowadays with the Spallation Neutron Source (SNS) [29], at Oak Ridge National Laboratory, in the USA, which runs at 1.4 MW beam power. Today, the European spallation neutron source (ESS) [30], with 5 MW beam power is under construction in Sweden and EURISOL [31] is being designed for a beam power of 4 to 5 MW, and is awaiting funding for construction. The proton accelerator community has made decisive progress in the development of high-power superconducting accelerating cavities. EUROTRANS, a major R&D program of the European Union 5th and 6th framework programmes on partitioning and transmutation for the uranium fuel cycle, has addressed all the aspects of the back end of the nuclear fuel cycle, as well as corrosion issues with high-temperature lead or lead–bismuth coolants.

As all the elements of an industrial ADS exist separately, the next step, or phase 3, should logically consist of a first coupling at significant power (≥1 MW) of a proton beam to a fast neutron subcritical core. However, this step is still missing, more than 20 years after the pioneering FEAT experiment. Phase 3 should include the development of an accelerator optimized for industrial applications of ADS.

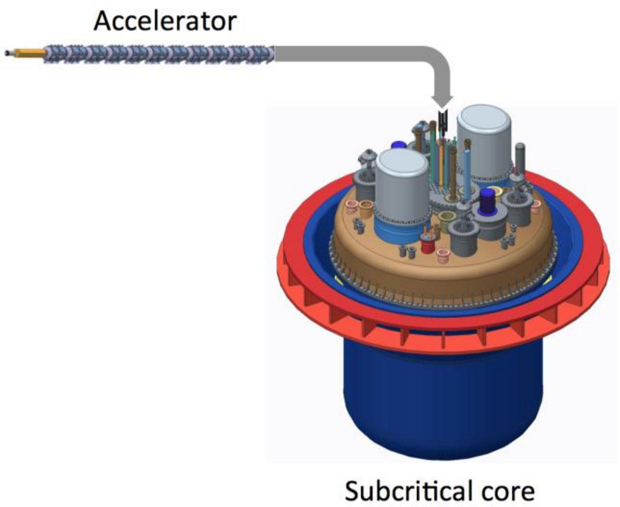

Figure 10. Schematics of the MYRRHA ADS, with a proton linear accelerator (600 MeV, 2.5 mA) driving a subcritical core, cooled with a eutectic lead–bismuth mixture, designed to produce a thermal power of 50 to 100 MW.

The good news is that there are two major ADS projects in the world today, driven by proton linacs (linear accelerators), which are aimed directly at what could be defined as the industrial fourth phase: the MYRRHA project [32] in Europe (Fig. 10), which should be the flagship of accelerator-driven systems, and ADANES [33] in China, which has the goal of reaching 1000 MW of electrical power by 2032. Given their long timescales (for both projects, first operation is not expected before the 2030s) and the large leap into industrialization, both projects would benefit from an ADS phase 3. In India, there is also interest in ADS, and the HISPA project [34] at the Bhabha Atomic Research Center is concentrating on the development of a high-power proton linac, with a first stage goal of a 30 mA, 20 MeV injector, and the ambition to reach 1 GeV and 30 MW beam power for the final stage.

There are also several other on-going ADS-related activities in the world, for instance, in Ukraine, with a 100 kW, 100 MeV electron beam driving a subcritical thermal core [35], just about to be commissioned, and in Japan [36], where ADS research was restarted as a consequence of the Fukushima accident. Given the importance of the energy issue, the lack of coordination and collaboration between these various efforts is regrettable.

6. iThEC's initiatives: a first accelerator–subcritical core coupling experiment

iThEC, the international Thorium Energy Committee [37], is a Geneva-based, non-profit association, founded under Swiss law in 2012, with the goal of promoting R&D in the use of thorium to transmute nuclear waste and produce safe, clean, and abundant energy, in particular with accelerator-driven systems.

Figure 11. Photograph of the INR Troitsk beam target area showing the proposed ADS pit (1), the presently operating pulsed neutron source cell (2), and its beam line (3). Taken from [38].

iThEC became convinced of a rather unique opportunity in Russia, at the Troitsk INR laboratory, where the existing infrastructure (Fig. 11) would allow, for the first time at significant power (a few MW), the coupling of a proton accelerator to a fast neutron subcritical core. The accelerator exists and needs only a relatively modest refurbishment to operate at a beam power of 30 to 90 kW, with 300 MeV protons. Troitsk is already operating a neutron spallation source. A beam line toward an available experimental pit could be implemented quickly. In addition, the infrastructure exists for the manipulation of radioactive materials. In five years' time a landmark experiment could be carried out, which would measure the properties of a MW fast neutron thorium ADS, demonstrate its safety, demonstrate the destruction of minor actinides, and test new possibilities for the production of radioisotopes for medicine. This would be at a cost of less than 4% of currents projects such as MYRRHA, and would provide invaluable information for the current large projects in Europe and China. The political impact of a first demonstration of destruction of nuclear waste would probably be very important. A road map of the project has been prepared jointly by INR management and iThEC. The Troitsk experiment would constitute, in addition, a versatile fast neutron test facility, the subcritical character of which guarantees safety. If approved by Russian authorities, the project is expected to get international support and a collaboration on the CERN experimental collaboration model would be possible. However, at this time, iThEC is still looking for a funding scheme to initiate the project.

7. iThEC's initiatives: an innovative high-power superconducting cyclotron

The second iThEC initiative is a project to be submitted to the European Union under the framework of the Horizon 2020 FET program [39]. It is a collaboration with CERN, PSI, ENEA [40] in Italy, and leading European industrial companies to design an innovative single-stage, high-power superconducting cyclotron [41] (Fig. 12). Reliability, minimal beam losses, and a much lower cost than other technologies are the main goals of the study. The ultimate goal of the project is to demonstrate that, for industrial applications, the cyclotron option is favorable.

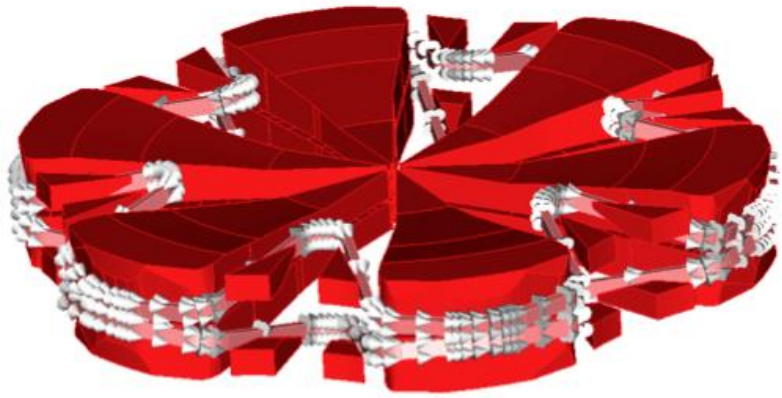

Figure 12. 3D view of the six-sector, single-stage cyclotron with reversed valley B-field (patented under the name S2CD by AIMA DEVELOPPEMENT), considered for the Horizon 2020 FET proposal [41].

8. Conclusion

Sustainability requires innovation. Sustainability of the world energy supply can only be achieved through a vigorous and systematic R&D effort, including R&D in the domain of nuclear fission energy, in order to develop acceptable methods for its safe exploitation. Fossil fuels are not a sustainable source of energy and they have a disastrous impact on the environment, however, replacing them to achieve a zero-carbon society is probably one of the greatest challenges faced by society today.

Whether a country decides to stop or continue its nuclear program, or in the case of developing countries, to start a nuclear program, the issue of nuclear waste management remains to be resolved.

ADS with thorium fuel offer the possibility to destroy a major part of the long-lived waste inventory to reduce the need for long-term storage, while at the same time producing energy. For energy production, there would be synergy between renewables and thorium ADS, as the power from ADS can be modulated to follow the fluctuations of wind and solar energies.

Thorium is an abundant and sustainable source of energy for the future, one that society cannot afford to ignore.

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