White Paper: When will fusion energy truly become a reality?

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This paper provides up-to-date insights into fusion (thermonuclear) research, detailing ongoing projects and planned devices. The document also explores alternative sources of energy, offering a comprehensive overview of the current landscape. Additionally, notable comments and observations are provided to illuminate key aspects of the discussed topics. Stay informed as we delve into the latest advancements and initiatives in the dynamic field of energy research.

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I. Introduction

The demand for energy, in increasingly greater quantities, appears to be growing more clearly (and unfortunately dramatically) today, both from industrialized Countries and so-called emerging ones. In fact, the former need energy not only to improve their quality of life but also to meet the needs of increasingly sophisticated and necessary industries and services (well-being, medicine, communications, transportation). However, energy is also needed by emerging Countries (third and fourth world), often highly populous, which are following the path previously taken by today's more developed Countries. These Countries, for various reasons, tend to exploit polluting forms of energy derived from fossil sources.

Apparently, today there is, and indeed it is growing in more advanced Countries, a greater sensitivity towards the environment, and thus a tendency to resort to clean and safe sources of energy. However, it is difficult to outright condemn poorer Countries that have fossil resources but cannot afford the costs associated with the development and adoption of sustainable sources. It is not to say that these Countries are devoid of concern for the environment, but the need to survive, even in conditions endangering public health, outweighs the prudence required in the use of energy sources that the West strongly criticizes today and would like to abolish altogether.

While, to the chagrin of staunch environmentalists, so-called alternative sources of clean energy offered by nature (hydroelectric, wind, solar, marine, biomass, geothermal) seem to make a very modest contribution, insufficient for the needs of both developed and developing societies, nuclear energy remains on the table, both from fission reactors (existing), and the one pursued for a long time (although this delay has been caused by unjustified deviations), coming from fusion.

The environmental cost, as well as upstream and downstream pollution and storage difficulties related to various forms of alternative energy, should also be taken into account. Furthermore, these are linked to climatic conditions, which vary in different regions of each Country, whereas a nuclear power plant of any kind would produce a negligible amount of waste, although they do present potential hazards to be assessed.

II. Fission Energy

Fission energy is still viewed today as dangerous, both for the radioactivity that would accompany it in the event of natural disasters or human errors, and for the radioactive waste that would remain hazardous for very long periods. However, there are now several generations of fission reactors considered progressively safer, and perhaps the disasters recorded so far (Three Mile Island, Chernobyl, Fukushima) have been overestimated. Someone has also been proposed to place fission reactors underground, at depths of 200-300 meters.

The average person is not accustomed to "living by statistics" and may not be aware, for example, that the COVID-19 vaccine, opposed by some, carries a significantly lower risk than being struck by lightning or dying from an anaphylactic shock caused by an insect bite.

The most educated individuals and the political class of a modern Country, which, ideally, should be its emanation, should take on the responsibility of *properly informing* the population. Not all decisions can be left to the entire population because specific expertise in every field is crucial.

It is a fact that there is widespread misinformation today, in Italy and in other Countries, the spread of incomplete, incorrect, or deliberately biased information, sometimes by ignorant individuals, often by incompetents, and other times for very specific vested interests. The results are always damaging.

For many years, we have known that splitting atoms (easier if they are heavy like uranium and plutonium) releases energy. Unfortunately, the uncontrolled version of this process has given us the atomic bomb, while the controlled version has provided peaceful energy through appropriate reactors. This is fission.

Today, it seems that a fourth generation of fission reactors, considered safe, is on the horizon. We will see. Meanwhile, even the less safe ones are a source of profit for Countries like France and [at least until recently] Russia, which build and sell them around the world. Does it make sense for a Country like Italy not to want them on its soil, but to purchase fission energy from France, Switzerland, and Slovenia? Would a potential catastrophe just beyond the Alps not spread radioactivity in Italy as well? Or would it stop at the Alps due to a referendum?

III. Fusion Energy

Fusion energy has been discussed for a long time, and at the moment, there is renewed emphasis on it. What does it consist of? We know that even by "fusing" atoms (easier if they are light like hydrogen and its isotopes, deuterium and tritium, or helium), energy is released. Again, we have seen a military application of this in the so-called hydrogen bomb or "H-bomb." But once again, as evidence that the use of the results and products of Science and Technology depends on responsible human choices, nuclear fusion reactions also have a possible peaceful application. This is the path that we would like to follow by achieving controlled thermonuclear fusion in a "fusion reactor." This, given the absence of inconveniences from reaction products, for example, by using appropriate mixtures of deuterium and helium-3, as well as - in principle - the wide availability of material to use as fuel, would represent the solution to all our problems: a virtually inexhaustible source of sustainable energy. Not insignificant. It should be noted that while deuterium can be easily obtained from water (through distillation), helium-3 is less readily available (it can be obtained from deuterium-deuterium reactions or brought from the Moon, where it is abundant, although this is not currently feasible).

In relation to fusion, it is rightly said to be energy similar to that produced in the Sun. All stars are "kept alive" by thermonuclear reactions, the same ones that occur in the aforementioned fusion. Stars will "die," cease to exist as such, when all their fuel is exhausted, i.e., when there are no more light elements to use for fusion. However, the time required for a star to burn all its fuel is typically measured in billions of years, and it is estimated that our Sun still has 4 or 5 billion years to live.

Achieving fusion on Earth, however, presents non-trivial difficulties. The physical state in which matter appears in stars is that of plasma, i.e., ionized gas: its atoms are divided into ions (positively charged) and electrons (negatively charged). This gas, as one can imagine, tends to expand, to escape, which would prevent the collision of particles (more precisely, ions) that, by doing so, fuse to create heavier ions, while simultaneously releasing fusion energy. In stars, whose mass is considerable, it is gravity that confines the gas, but on Earth, this is not the case. It is not enough: the necessarily modest amount of ionized gas produced in the laboratory cannot be confined by the gravitational attraction of the Earth.

In principle, there are fundamentally two possible solutions to achieve fusion reactions in a laboratory and, hopefully, in a real reactor. One is based on the fact that ionized gas particles are electrically charged and therefore sensitive to the actions of electric, magnetic, and electromagnetic fields. This leads to the conception of, for example (but not only), "toroidal" devices, shaped like a doughnut or a "torus," as mathematicians say, in which charged particles are confined because they are forced to orbit around the lines of the magnetic field created within the "torus." However, the confined plasma must have a sufficiently high density and temperature and remain confined for a sufficiently long time for there to be a sufficiently high probability of fusion reactions taking place. Achieving these conditions in the laboratory is not straightforward.

For a long time, it was believed that building larger machines would produce the desired result, but unfortunately, this does not seem to be true, while the cost of building a toroidal machine increases drastically with its size.

A machine of a certain size, designed to conduct fusion experiments was the JET (Joint European Torus), located at the Culham Centre for Fusion Energy in Culham, U.K. [4]; see Fig.s 1,2. JET has been operational for many years, from 1983 to the end of 2023. It has produced several experimental results by numerous researchers from around the world, but it should be clear that JET was never conceived as a prototype reactor, i.e., a device capable of achieving ignition, thus initiating a thermonuclear reaction, and sustaining such reaction, producing more energy than needed to start the process.

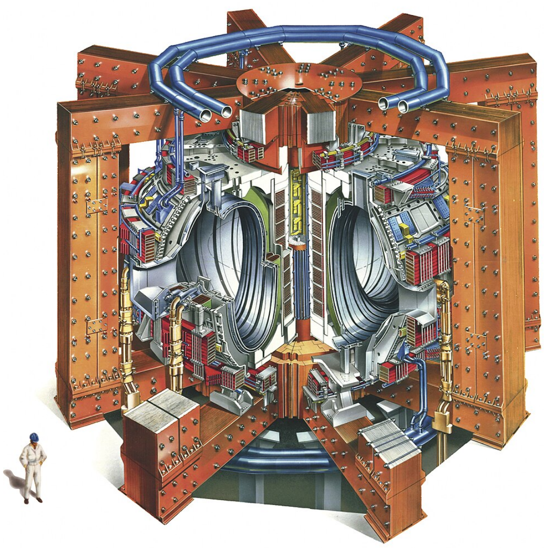

Figure 1: The JET machine (taken from `https://en.wikipedia.org/wiki/Joint_European_Torus`, page last edited on 12 May 2024)

It is a fact that the currently partially constructed ITER *machine (in Cadarache, France)* [3], Fig. 3, *widely publicized in the press, does not, and cannot, according to the the current design, have the objective of achieving ignition*, let alone building a thermonuclear reactor within a couple of decades.

A second way to achieve fusion, distinct from magnetic confinement, is through inertial confinement. In brief, this involves inducing fusion by extreme compression of a mixture of deuterium and tritium using various devices and processes, such as a high-power laser beam or high-energy particle beams.

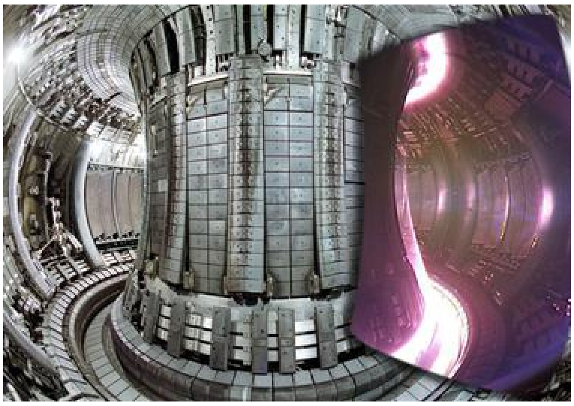

Figure 2: The JET machine (taken from `https://en.wikipedia.org/wiki/\Joint_European_Torus`, page last edited on 12 May 2024)

IV. What happens in the Sun?

Nuclear fusion reactions responsible for the Sun's energy production occur in its core, where temperature and density are higher. In the Sun's core, hydrogen is converted into helium (via deuterium). As of today's knowledge, the Sun's core is predominantly composed of hydrogen. The temperature is around 16 million degrees Celsius, the pressure is extremely high, around 500 billion atmospheres, and the material's density is approximately 150,000 kg/m^3. These conditions are exceptional on a human scale, that is, on Earth, but they are normal in a star.

At these temperatures, hydrogen atoms in the Sun's core cannot remain intact and split into protons and electrons. The thermal energy is so high that when protons randomly encounter each other, they overcome the electrical repulsion between charges of the same sign and merge to form a helium nucleus. Approximately 594 million tons of hydrogen fuse every second, releasing energy equivalent to 386 trillion trillion megajoules. This energy is equivalent to the mass of 4 million tons of hydrogen, while the remaining 590 million tons are converted into helium. Consequently, our Sun loses 4 million tons every second, but its overall mass is so large that even after about 5 billion years of active life, it has only slightly reduced its mass.

In summary, fusion reactions involve the nuclei of light elements like hydrogen fusing into heavier element nuclei like helium at high temperatures and pressures, as mentioned above. It should be noted that hydrogen exists in various forms (isotopes) in the Sun's core, including regular hydrogen (H),

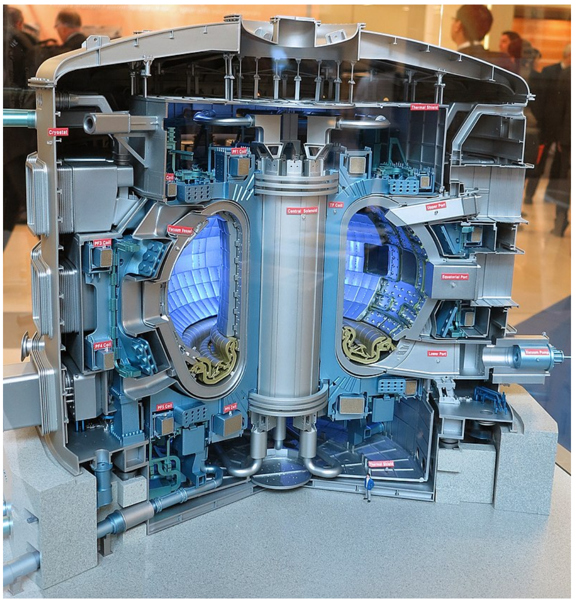

Figure 3: Small-scale model of ITER (taken from `https://en.wikipedia.org/wiki/ITER`, page last edited on 22 June 2024)

deuterium (D), and tritium (T). In the D-T thermonuclear reaction, for example, between a deuterium nucleus and a tritium nucleus, a helium nucleus (alpha particle) and a neutron are generated. The total mass of the reaction products is less than the sum of the masses of the interacting particles, which is why energy is released, according to the mass-energy equivalence principle.

V. But can fusion be achieved on Earth?

Decades of experiments have alternately generated the illusion of imminent success and the discouragement of not being able to achieve fusion in a laboratory on Earth. However, the latter is not the opinion of the international scientific community.

Agreeing with Niels Bohr, it is not easy to make predictions, especially about the future, but there are serious indications of what may happen regarding fusion.

The common press occasionally but recently quite frequently reports apparent successful advances, i.e., that China has reached exceptional temperatures for extended periods (but with not very dense plasmas, and the journalist does not specify), or that a machine (yet to be built) will bring "the Sun into our homes" within a few years, or that the private English company Tokamak Energy has reached 100 million degrees in an experiment conducted on a spherical tokamak (without specifying plasma density and confinement times). The outcome of an experiment conducted at the National Ignition Facility (NIF), Fig. 4, located at the Lawrence Livermore National Laboratory in California, announced in August 2021, seems instead to have received little publicity. In fact, here, using the inertial confinement method, there has been substantial evidence that the aforementioned ignition has indeed been achieved. The result is exceptional because it demonstrates, at least, that indeed *nuclear fusion can be achieved in a laboratory on Earth*.

Figure 4: The target assembly of the NIF device (taken from `https://en.wikipedia.org/wiki/\National_Ignition_Facility`, page last edited on 8 June 2024)

What about fusion in magnetic confinement machines? After the European JET initiative, the construction of a larger machine, ITER (International Thermonuclear Experimental Reactor), was scheduled in Cadarache, France, in 2007. According to what is read on Wikipedia, ITER, *also intended in the original Latin sense of "path" or "journey," is an international project aimed at building an experimental nuclear fusion reactor capable of producing a fusion plasma with more power than is required to heat the plasma itself.*

From what has been subsequently declared by the designers themselves (the machine is still in the construction phase, but the design itself does not seem to have been completed), it does not appear that ignition is among the achievable goals of ITER.

If this is the case, in the face of a construction phase lasting at least three decades (the scheduled year for the start of the first plasma experiments has currently been pushed to December 2025), and an expenditure that has risen from 5-10 billion to 60-65 billion Euros or more, we may end up with a machine that could provide less than JET! This is an even more serious problem if we consider that ITER was intended to be followed by a true prototype of a thermonuclear reactor, named DEMO (DEMOnstration Power Plant).

It is worth noting that if ITER *were to fail, the enormous expense and time invested would likely lead almost all Countries in the world to halt significant funding for fusion research for who knows how long.* The economic damage would be enormous.

Over the years, while the USA have substantially reduced its funding for the ITER program, many Countries, through political figures and members of the scientific community, have openly supported it.

In light of the previous criticisms, the strong support for ITER seems somewhat inexplicable, unless it is due to a limited or outdated scientific vision or economic interests, such as favoring the sale of fission reactors (delaying fusion), or benefiting industries present in various Countries, but all of this has nothing to do with the realization of a true fusion reactor. The fact is that the validity of a different paradigm from that followed by ITER has been consolidated by several parties, namely that of *compact machines*, relatively *small in size* and with *high field* strength, that is characterized by particularly high magnetic confinement fields. Ignitor, Fig. 5, 6, is an example of such a machine, earlier based on an Italo-Russian agreement, but also involving the USA, that was signed some time ago. It certainly does not aim to be a reactor, but one of its objectives is the concrete possibility of approaching *ignition*. To confirm this, the machine should be built, and its core is estimated to cost no more than about 78 million euros (to be compared with the total estimated cost of 65 billion euros or more for ITER, which does not even have the goal of ignition).

Why does Ignitor cost so little? First of all, the sites designated to host the machine are already available (e.g., in Caorso, in Italy, while initially Troisk in Russia was considered), the design cost has already been almost entirely paid, and many people working on it do so without pay, as they are researchers and University Professors who already receive a base salary. The 78 million euros, which were allocated to Ignitor (and after these years of waiting, they can be considered not more than 100 million), would be used for the construction of the machine's core, i.e., the machine itself, without considering the infrastructure. Its various parts were intended to be built by Italian industries, with a small part of the cost allocated to updates and design checks by qualified professionals (engineers) in Italy.

Ignitor *is a scientific experiment*, based on a machine whose construction is possible, albeit with numerous bureaucratic obstacles, and it was part of an agreement signed by Italy and Russia in 2011 (with the approval of the USA), during the time of Berlusconi's and Putin's governments. The agreement envisioned the construction of various parts of the machine by Italian industries, after which these parts should have been shipped to Russia and assembled in Troisk, where a suitable site existed to host and power the machine.

Unfortunately, the dramatic events related to Russia's invasion of Ukraine have likely strained relations with Russia, even in the scientific field, and this will likely last for an indefinite period. However, the urgent need to meet energy demands should

Figure 5: The Ignitor design (see `http://personalpages.to.infn.it/~fre/\RTIgnitor/about_ignitor.htm`)

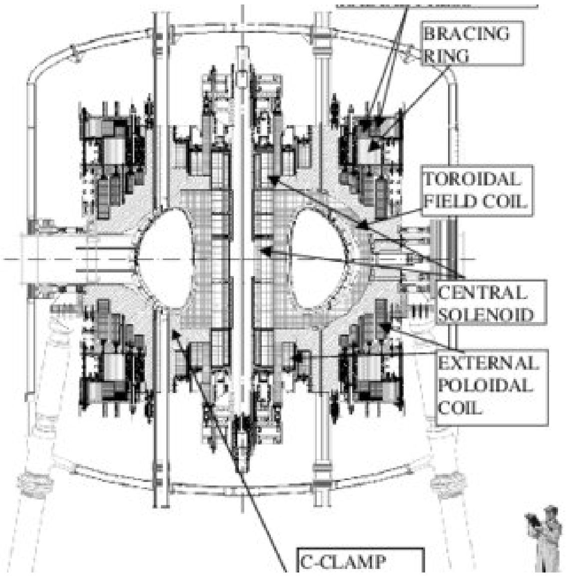

Figure 6: Ignitor (taken from `https://www.researchgate.net/figure/Cross-sectional-view-of-the-Ignitor-machine_fig1_242616001`)

push Italy to build *and* then eventually operate Ignitor *in* Italy. Moreover, the idea and project are the work of Bruno Coppi, an Italian Professor at MIT in Boston, and Italian industries have always been planned to build various parts of Ignitor. Therefore, with a more than suitable site like Caorso, there is no reason to delay. We do not need Russia to move forward.

But why was such a modest amount as the one requested by Ignitor - the 78 million euros, allocated during Minister Gelmini's time as part of the "flagship projects" - mostly re-allocated elsewhere by Minister Fedeli, without even consulting the project's leader, Bruno Coppi? And why has ENI (the Italian multinational energy company) been participating in the Commonwealth Fusion Systems (CFS) consortium since 2018, a kind of MIT spin-off, with at least already 50 million euros paid, to build SPARC, a machine that is essentially an attempt to copy Ignitor, without even consulting the originator? All of this remains a mystery.

In addition to the *scientific* value of the experiment and its potential *economic* benefits, with the ongoing energy crisis and over 40% of Italy's energy needs dependent on Russian gas, the diplomatic value of the aforementioned Italo-Russian agreement (concluded with the approval of the USA) should have been taken into greater account. The agreement, which had already been signed but never fully honored, could also have been interpreted as a cooperative action in favor of nuclear peace, as this had already begun with Coppi and his Russian counterpart, Professor E. Velikhov. Unfortunately, this latter goal now seems to be obsolete.

VI. The idea of "hybrid reactors"

There is a possibility that would allow the use of fission reactions with reactors having more advanced characteristics than those currently built. These are the so-called "hybrid reactors," machines in which the source of neutrons needed to produce fission reactions is a fusion machine, without the need for the latter to reach ignition. The most desirable fissile materials would be thorium and plutonium. This innovative solution would combine the reliability of traditional fission reactors with safety.

The remarkable fact is that, unlike fusion, *the technology required to build a hybrid reactor already exists today*. Moreover, Italy would be in a pole position in this field, since the aforementioned technology follows that already developed to build experimental machines such as Alcator A (in operation from 1973 to 1979), Alcator C (from 1978 to 1987), and Alcator C-Mod (from 1991 to 2016), named after the Italian wording "Alto Campo Toro," which operated at the Plasma Science and Fusion Center at MIT in Boston, as well as FT (Frascati Tokamak) and FTU (Frascati Tokamak Upgrade), which started operating in 1977 and 1989, respectively, at ENEA in Frascati, and concerning the aforementioned Ignitor project. It is no coincidence that Russia has already decided to develop an experiment along these lines.

VII. But where are we really at?

Unfortunately, for reasons sometimes known and sometimes not, it is a fact that we are surrounded by considerable misinformation.

What is comforting is the result of NIF, which at least shows that nuclear fusion is feasible in a laboratory on Earth using inertial confinement. Less promising are the results obtained or expected so far with magnetic confinement. In summary:

● ITER: Apart from the considerable cost and estimated completion time, it does not even plan to achieve ignition, which does not provide much hope that the subsequent DEMO might truly be a reactor. The Russian invasion of Ukraine, with the consequent sanctions imposed by the EU and the USA, will probably cause further damage to ITER.

● DTT (Divertor Tokamak Test): It is supposed to be realized at ENEA, in Frascati (Italy), along with ENI and the CREATE Consortium, but there is still not enough justification for proceeding with it. Regarding DTT, it has been stated explicitly that, "at an estimated cost of approximately 600 million euros, ENEA and ENI will build it in Frascati over the next seven years, with substantial national funding (10% provided by the EU), a project aimed at creating a "divertor," a device designed to expel the energy - mostly heat - and the products of nuclear fusion generated inside the tokamak. It would be a very flexible machine in operational scenarios and represents a significant advancement in terms of performance compared to machines conceived over 40 years ago. DTT's purpose is to qualify the divertor prototypes for DEMO (the demonstrative fusion machine that would follow ITER), but its operation will also allow the growth of new generations of scientists, capable of working on ITER and DEMO.” In reality, the cost has already increased to 650 million euros, but it is a common opinion that after the project is completed, it will increase to at least double that amount.

Unfortunately, these are just hypotheses. If ITER is not completed according to the plan, the idea of DEMO and, consequently, the DTT, which would serve it, would be of little use. Only the fact that “new generations of scientists” can grow, as happened with JET, working on fusion scientific experiments remains. But at what cost to taxpayers? In reality, continuing down this path will leave Italy without significant experiments for who knows how many years, such as FT and FTU at ENEA in Frascati, which have operated for decades.

• SPARC, the machine of the aforementioned Commonwealth: it tries to reproduce (well?) the machine already designed for the Ignitor Program, but for the moment, only one of the numerous coils necessary to form a superconducting coil has been built. It is not even clear if there is enough of the required materials worldwide, as they are very rare elements. While Ignitor would use superconducting MgB2 ceramics, it would be much more problematic to use ReBCO superconductors (barium and rare earth copper oxide). What is more realistic is to hope for the development of new superconducting materials that are more accessible, for which there have been recent developments at Princeton.

• JET: The machine’s operations, permanently closed at Culham at the end of 2023, has produced widely publicized results. Unfortunately, these are not as remarkable as claimed: far more than 30-35 MW of power have been injected generating a total fusion power (neutrons plus alpha particles) of 10 MW. Furthermore, it should be clarified that only one-third of this power can be considered directly “usable.” Anyone understands that to gain an advantage, the ratio between the useful power obtained and the power supplied must be greater than 1.

The BBC has raised some doubts about the recent touted success, and indeed, an informed source reportedly said that the ratio of energy input to energy output in the JET facility has unfortunately remained unchanged compared to the past. Other experts have pointed out that the purpose of the JET experiment was actually to reproduce the result (i.e., gain) obtained 20 years ago but with higher power injection, as well as to do it with a new inner wall made of beryllium and tungsten. This was done in preparation for future experiments on ITER. From a technical point of view, this latter point was interesting because it is known that carbon (graphite), used in the past on the JET’s inner wall, retains Tritium, and there are various differences in the physics that occur in the two different conditions mentioned.

• Ignitor: The reasons why work on its construction is effectively hindered at various decision-making levels are not disclosed. The machine has also been imitated (at a much higher cost) by SPARC, near Boston, not to mention the feasible development of hybrid reactors, which are based on the same technology and existing knowledge of physics.

Regarding Ignitor, L.J. Reinders writes in his recent book “*The Fairy Tale of Nuclear Fusion*” [5, par. 6.5, page 165]: “Finally, we mention the joint Russian-Italian project on the IGNITOR reactor, which has evolved out of Bruno Coppi’s activities at MIT (see Chap. 5). It is part of the line of research that started with the Alcator machine at MIT in the 1970s, and continued with Alcator C/C-Mod at MIT and the FT/FTU experiments at Frascati. *It is so far the first and only experiment proposed and designed to obtain physical conditions in magnetically confined D-T plasmas that sustain the plasma under controllable conditions without the addition of extra heat, i.e., to achieve ignition.* It is a compact D-shaped fusion reactor with a total plasma volume of just 10 m^3. So far, only model calculations have been carried out [1], and construction of the reactor itself at the TRINITI site in Troisk (Russia) is long overdue.”

The observations made in the present article are not meant to be entirely negative, hypercritical, or overly pessimistic, but the fact remains that only serious *scientific knowledge* and *accurate information* are the basis for solving and publicizing such important and no longer avoidable problems as those of energy. Disinformation can only harm by deluding taxpayers and directing public and private funding toward less appropriate and promising paths. This is also because alternative solutions for obtaining gas energy do not seem to provide large quantities or to do so in the short term. On the one hand, it is estimated that increasing gas extraction in Italy, especially around the coasts, besides presenting well-known environmental risks, would only produce 10% more. On the other hand, as pointed out by Romano Prodi, the practical use of gas extracted elsewhere, far from Italy, requires three phases: (1) it must be transformed into liquid form for transport; (2) transportation must be done through special gas pipelines or methane carriers; (3) the liquid gas must then be transformed back into gas (regasification). At the moment, there are not enough facilities or ships equipped for all of this in Italy, and it certainly cannot be organized overnight. From the point of view of users, however, it should not be forgotten that the cost of energy on bills is not determined only by the cost of energy itself but also by significant tax contributions, partly justified for social expenses.

VIII. Conclusions

It seems advisable not to risk losing, in Italy, the opportunity to play a central role on the international stage once again, as happened in the regrettable cases of Chemistry, during Giulio Natta's time, and with computers, during Adriano Olivetti's time. There are all the prerequisites for proceeding toward successful objectives. From an operational point of view, a coordinated intervention that includes the participation of five of the current ministries would be advisable: the Ministry of Ecological Transition, the Ministry of Economic Development, the Ministry of Economy and Finance, the Ministry of University and Research, and the Ministry of Foreign Affairs and International Cooperation, probably by creating an ad hoc agency.

IX. Acknowledgments

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