40 Years of Power Plant Studies: Brief Historical Overview and Future Trends

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40 Years of Power Plant Studies: Brief Historical Overview and Future Trends

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Abstract

In addition to the tokamak concept, six magnetic fusion concepts were developed since the 1950s with different levels of maturity: stellarator, spherical tori, field-reversed configurations, reversed-field pinches, spheromaks, and tandem mirrors. Numerous fusion power plant studies (> 50) were conducted worldwide covering all seven concepts. It seems likely that more power plant studies will be developed and future design processes will deliver more efficient, safe, economical, and maintainable designs that operate at peak conditions. Neverthless, the philosophy adopted in international designs varies widely in the degree of physics extrapolation, technology readiness, and economic competitiveness. For this reason, the national roadmap to fusion energy is influenced by the timeline anticipated for the development of the essential physics and technologies for Demo and successor power plants. As such, the various fusion roadmaps developed to date take different approaches, depending on the anticipated power plant concept and degree of extrapolation beyond ITER. Several Demos with differing approaches should be built in the US, EU, Japan, China, Russia, Korea, India and other countries to cover the wide range of near-term and advanced fusion systems. Recognizing the capabilities of the national and international fusion facilities, it appears that, with unlimited funding and a limited timetable, the first fusion power plant could add electricity to the grid by 2030-2035.

1. Introduction

Since the 1958 Second Conference on the "Peaceful Uses of Atomic Energy" held by the United Nations in Geneva, Switzerland, the secrecy surrounding controlled thermonuclear fusion by magnetic confinement had been lifted allowing researchers in the US, Russia, UK, and other countries to freely share technical results and discuss the challenges of harnessing fusion power. In the 1960s, hundreds of fusion scientists were engaged in a variety of theoretical analyses and experiments to more fully understand and advance fusion physics and technology. The energy crisis of the early 1970s encouraged all nations to seriously investigate other nuclear energy sources (like fusion and renewable) to supplement fission. Building on the early progress made in the 1950s and 1960s, the world's fusion researchers realized the need for better understanding of the physics and technology of fusion energy. Numerous fusion studies, extensive research and development (R&D) programs, more than 100 operating experiments worldwide, impressive international collaboration in all areas of research, and a large body of accumulated knowledge have led to the current wealth of fusion information and understanding. For decades, the International Atomic Energy Agency (IAEA) and International Energy Agency (IEA) have organized fusion conferences and workshops and provided a framework for collaborative programs that covers a broad range of fusion topics (such as plasma physics, materials, power plant studies, safety, environmental, and economic aspects, and social acceptance). Just recently in October 2008, the IAEA held its 22nd Fusion Energy Conference in Geneva to celebrate the golden anniversary of magnetic fusion research. As part of the conference, the IAEA produced a CD containing the proceedings of the 1958 Geneva Summit and a 28-page brochure titled: "Fifty Years of Magnetic Confinement Fusion Research – A Retrospective." The brochure is available at: http://www-naweb.iaea.org/napc/physics/2ndgenconf/sets/Home.html.

2. Brief Historical Overview

In the early 1950s, there were only four magnetic confinement fusion concepts pursued internationally: tokamak (a donut configuration with toroidal plasma current), stellarator (steady-state toroid without plasma current), mirror (steady-state linear system with magnetic wells), and pinch (simple toroidal device). The tokamak, stellarator, and pinch concepts have experienced substantial modifications over the past 60 years [1]. The mirror concept was actively pursued in the US, but suspended in 1986 due to budgetary constraints, while continuing at a very low level in Japan and Russia. After the first 1969 "International Fusion Reactor Conference" in Culham, England, more than 50 conceptual power plant design studies have been conducted in the US, EU, Japan, Russia, and China. During the 1970-2010 period, numerous D-T fueled fusion power plant designs were developed for both magnetic fusion energy (MFE) and inertial fusion energy (IFE) concepts, covering a wide range of new and old design approaches: tokamaks, stellarators, spherical tori (ST), field-reversed configurations (FRC), reversed-field pinches (RFP), spheromaks, tandem mirrors (TM), and laser/heavy-ion/Z-pinch driven inertial fusion. Most of the studies and experiments are currently devoted to the D-T fuel cycle, since it is the least demanding to reach ignition. The stress on fusion safety has stimulated worldwide research on fuel cycles other than D-T, based on 'advanced' reactions, such as D-D, D-^{3}He, p-^{11}B, and ^{3}He-^{3}He. In addition, a few smaller-scale projects investigated non-electric applications of fusion along with the technological means to lessen the likelihood of proliferation.

Internationally, the tokamak concept is regarded as the most viable candidate to demonstrate fusion energy generation. The tokamak (acronym from the Russian phrase "Toroidal Chamber with Magnetic Coil") was invented in 1951 by Russian physicists Sakharov and Tamm while named a few years later by Golovin. In 1956, the first tokamak experiment began in Kurchatov Institute, Moscow. Ever since, the confinement concept has been successfully demonstrated with more than 100 worldwide experimental facilities, of which ~35 experiments are currently operational in Russia, US, EU, Japan, South Korea, China, India, and other countries. Over the years, strong domestic and international experimental programs addressed the tokamak physics and technology issues. The collaborative worldwide effort materialized in the design and construction of the International Thermonuclear Experimental Reactor (ITER) – a large burning plasma experiment with ~500 MW of fusion power.

Figures 1 and 2 display the timeline of large-scale magnetic fusion power plants designed since the early 1970s by research teams in the US and worldwide. Numerous conceptual commercial plant designs were developed for all seven confinement approaches, especially for the tokamak. The decade of the 1980s witnessed a transition period aimed at temporarily impeding the US large-scale tokamak studies in order to investigate alternate concepts: stellarator, ST, FRC, RFP, spheromaks, and TM. In the late 1980s, the US had decided to pursue all concepts, except tandem mirrors.

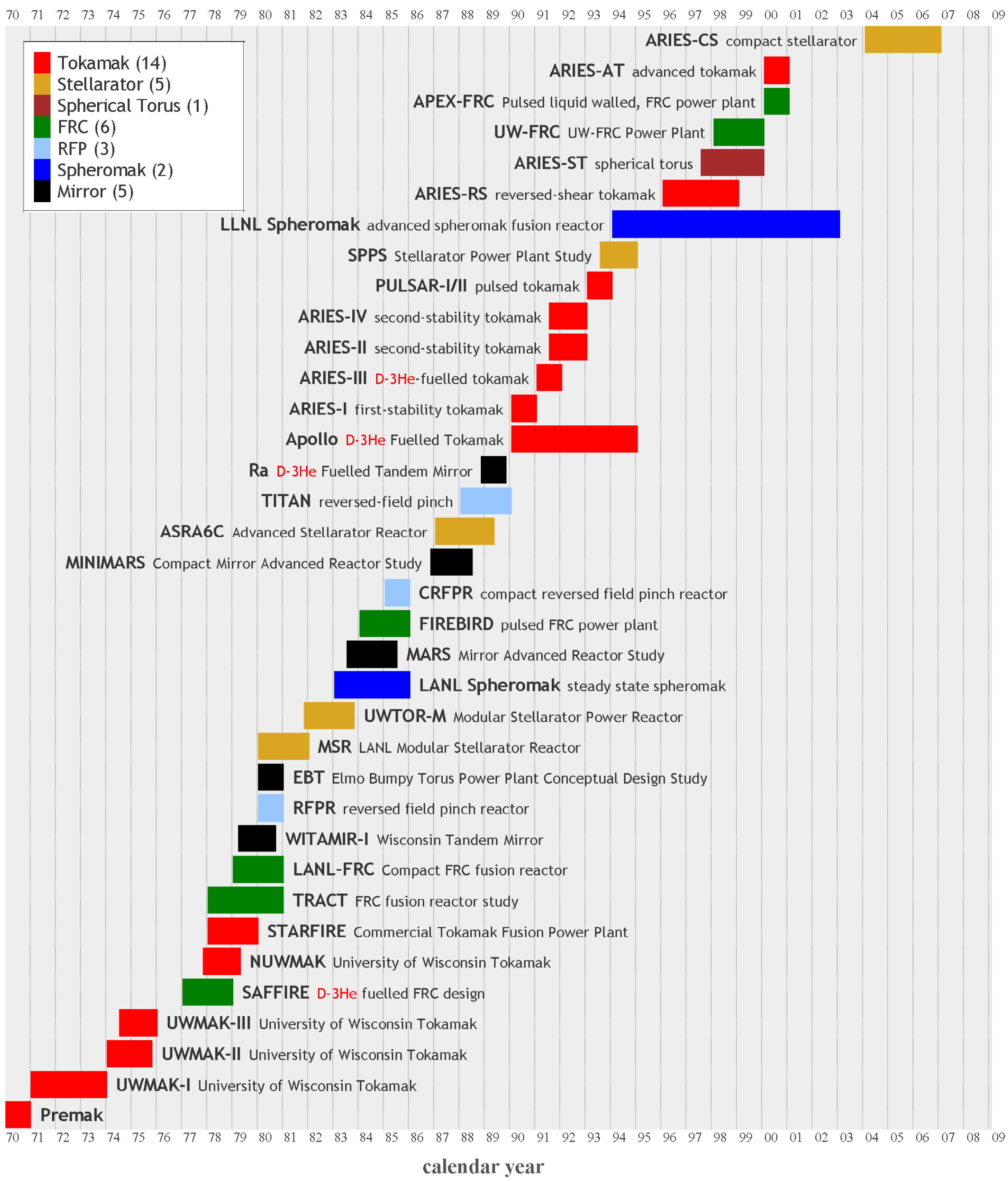

Figure 1. Timeline of large-scale US conceptual power plant designs.

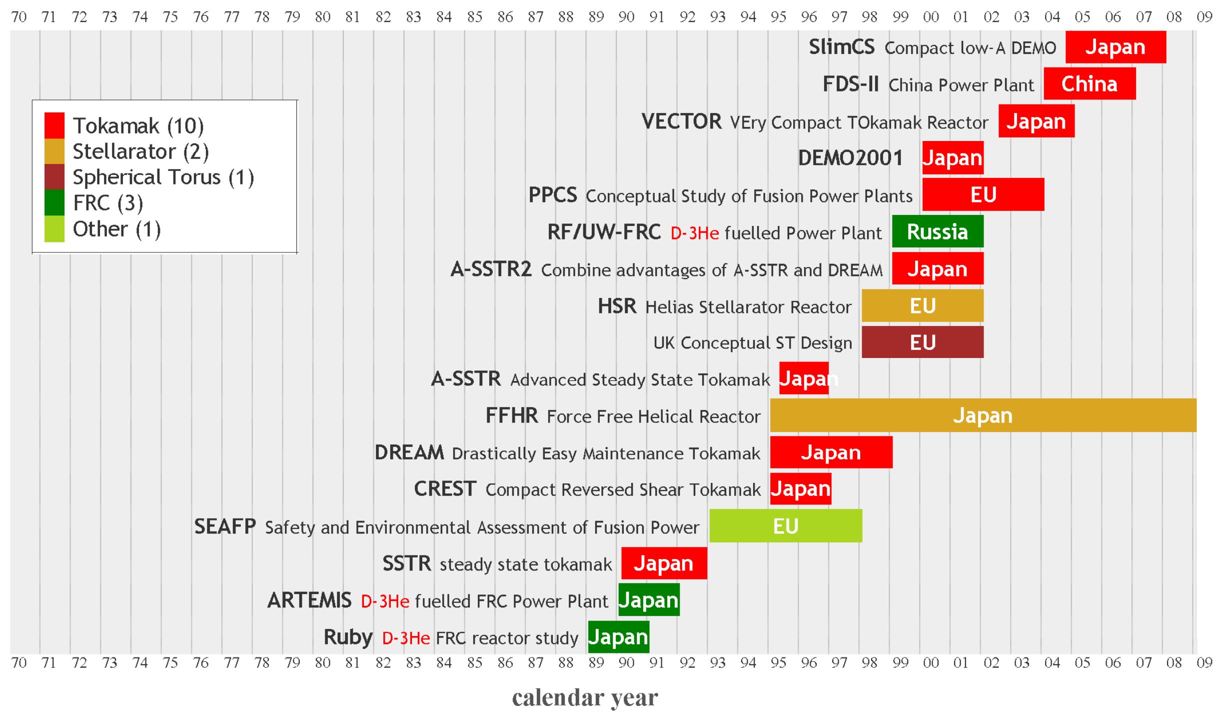

Figure 2. Timeline of selected power plants recently designed in EU, Japan, China, and Russia.

3. Fusion Power Plant Studies

Power plant studies help the fusion community and the funding agencies understand the major technical issues involved in fusion and provide guidance for the R&D program to deliver an attractive and viable end product. Any fusion power plant must be safe, reliable, economically competitive, maintainable, environmentally attractive, and meet public acceptance. The philosophy adopted in international fusion power plant designs varies widely in the degree of physics extrapolation, technology readiness, and economic competitiveness. Some designs are viewed as a roll-forward step with a modest extrapolation beyond ITER. Other designs suggest using the cost of electricity with its underlying factors as a figure of merit measured against competing energy sources, mandating advanced physics, high performance hardware with related future technologies to be competitive.

As Figs. 1 and 2 indicate, numerous tokamak conceptual design power plant studies were developed over the last four decades to assess the viability of different approaches and recommend productive R&D directions. In the US, the conceptual studies progressed steadily from the early 1970s pulsed UWMAK series, to the 1980 STARFIRE that first promoted steady-state current drive, to the more advanced 1990s steady-state ARIES series. International institutions, particularly in Europe, Japan, and China, carried out a number of tokamak fusion power plant studies. There are technical similarities and differences between these studies. Some of the underlying differences are related to strategic objectives and technology readiness. For instance, the emphasis given to the economic competitiveness of power plants varies significantly between countries. The US is highly motivated to obtain a fusion power plant that is at least as economically competitive as other available electric power sources. On the other hand, Europe and Japan take the view that the first generation of fusion power plants will enter the energy market because of the major safety and environmental advantages and large fuel reserve, even if they produce electricity at a somewhat higher cost. Overall, improvements were apparent and the recent studies stressed the practicality, safety, and economic competitiveness of fusion power, taking into consideration the fabricability, constructability, operability, and maintainability of fusion devices.

The stellararor concept was one of the first approaches proposed in the US by Spitzer in 1950. The prime interest in stellarators stems from their potential physics advantages over tokamaks. Stellarators are inherently steady-state devices with no need for large plasma current, no external current drive, no risk of plasma disruptions, low recirculating power due to the absence of current-drive requirements, and no instability and positional control systems. For these attractive features, stellarator power plants have been studied for decades in the US, Europe, and Japan to optimize the design parameters and enhance the physics and engineering aspects. Recently, compactness was promoted as an economic advantage for future stellarators, allowing direct comparisons with tokamaks. Although the stellarator concept has been around for several decades, very little in the way of conceptual design studies has been performed compared to tokamaks, of which many studies have taken place in the US and abroad. During the decade of the 1980s and continuing to the present, six large-scale stellarator power plants have been developed: UWTOR-M, ASRA-6C, SPPS, and ARIES-CS in the US, and the most recent HSR in Germany and FFHR in Japan. The six studies vary in scope and depth and encompass a broad range of configuration options.

Worldwide interest in the ST concept began in the the US in 1980s when Peng identified unique physics features of ST as a low aspect ratio device. Key ST features include good plasma confinement, high toroidal beta, and naturally large elongation that allows operation with high bootstrap current (> 90%). Initiated in the late 1990s, two power plant studies have been made of the ST concept: the US ARIES-ST study and the UK conceptual ST design. The limited number of studies reflects the much smaller ST database compared to tokamaks.

The FRC concept was originally invented in the 1950s. It represents one of the simplest configurations that can be envisioned for a fusion device. Geometrically, it is a linear, open-ended cylindrical system, quite different from tokamak, stellarator, ST, and RFP. In the 1970s and 1980s, researchers examined the potential of the FRC concept as an energy producing power plant. The latest design of the 1980 series, the FIREBIRD power plant, is a D-T fueled, pulsed device. Some of the more recent FRC designs examined its steady-state operation with D-T and D-^{3}He fuel cycles.

The RFP is an old concept, first studied in the early 1960s as an axisymmetric, toroidal geometry. At present, the RFP physics is more mature than FRC and spheromak physics. The RFP configuration is much like a tokamak except for the more than 10-fold weaker toroidal magnetic field. The potential advantages of RFP as a power plant have been demonstrated during the 1980s through a few conceptual studies. The earlier 1981 design operated in a pulsed mode and utilized superconducting magnets. Later, steady-state designs were developed and the full advantages of RFP were examined in 1990 by the ARIES team through the large-scale, self-consistent TITAN study.

The spheromak is a toroidally symmetric configuration distinguished from STs and tokamaks by the simple, compact geometry without toroidal field coils and with no inboard materials, offering a truly compact fusion device with low aspect ratio, high beta (10-20%), and comparable toroidal and poloidal fields. Although the overall design is simple, the plasma dynamo behavior is very complex and difficult to predict or control. Over a period of three decades, numerous scientists believed the simpler spheromak configuration made a better power plant with much lower cost than tokamaks. Two conceptual designs were launched by the US in the 1980s and 1990s to explore the potential of a steady-state spheromak power plant. The simplicity, compactness, and absence of toroidal field coils make the constructability of spheromaks relatively easy and inexpensive compared to tokamaks.

Substantial interest has been generated in tandem mirrors over the two decades of the 1970s and 1980s. In contrast to tokamaks, TM is linear in nature. The basic configuration is a long central cell (90-170 m) terminated by end cells. There are many configurations for the latter, each offering merits and drawbacks. TM is more amenable to maintenance compared to toroidal systems. Other positive attributes include the high beta (30-70%), no driven plasma current eliminating disruptions, the potential for direct conversion of charged particle power into electricity at high efficiency, and the expandable magnetic flux tube to reduce the heat flux on end cell walls. Historically, TM research embarked on decades of single-cell mirror physics beginning in the 1950s. The TM-based activities of the 1980s delivered four conceptual power plant designs fuelled with both D-T and D-^{3}He. In 1986, the US terminated the TM program in favor of tokamaks and non-TM alternate concepts.

4. Fusion Roadmaps and Timeline of Fusion Power

Power plant studies normally identify the ultimate characteristics of fusion power plants in a fully mature, commercial fusion market (tenth of a kind plant). Since the early 1970s, researchers have been developing roadmaps with the end goal of operating the first fusion power plant in 50 years (i.e., by 2020), believing strongly that fusion should be an option in the 21st century energy mix. But this has been a sliding scale vision with the current expectation still remaining at 50 years in many countries. Recently, optimism about fusion has resurfaced with the construction of ITER in France. Nevertheless, developing fusion energy will cost billions of dollars and would span decades. The key strategic questions are: what technologies remain to be developed and matured for a viable fusion power plant, what other facilities will be needed between ITER and the first power plant, what will it cost, and how long will it take, assuming the existing social and political climate continues? On the other hand, if the social and political climate creates a demand-pull situation, how long will it take to construct the first fusion power plant if the fusion program is treated as an "Apollo" project with unlimited funds and a limited timetable?

The Demo is viewed as the last step before the first commercial power plant. Assuming ITER operates successfully, several countries recommended constructing a few MFE facilities before Demo: International Fusion Materials Irradiation Facility (IFMIF), Component Test Facility (CTF), and Advanced Physics Testing Facility. In each country, the pathway to fusion energy is influenced by the timeline anticipated for the development of the essential physics and technologies for Demo and power plants as well as the demand for safe, environmentally attractive, economical, and sustainable energy sources. Expectedly, the international roadmaps will take different approaches, depending on the anticipated power plant concept and degree of extrapolation beyond ITER. Figure 3 depicts the projected, unofficial timeline for constructing Demo and first power plant in various countries. Clearly, several Demos with differing approaches should be built in the US, EU, Japan, China, Russia, Korea, India and other countries to cover a wide range of near-term and advanced fusion systems. Recognizing the capabilities of national and international fusion facilities, it appears that, with unlimited funding and a limited timetable, the first fusion power plant could add electricity to the grid by 2030-2035. On the other hand, with limited funding and no clear vision, the timetable could extend beyond the proverbial 50 years.

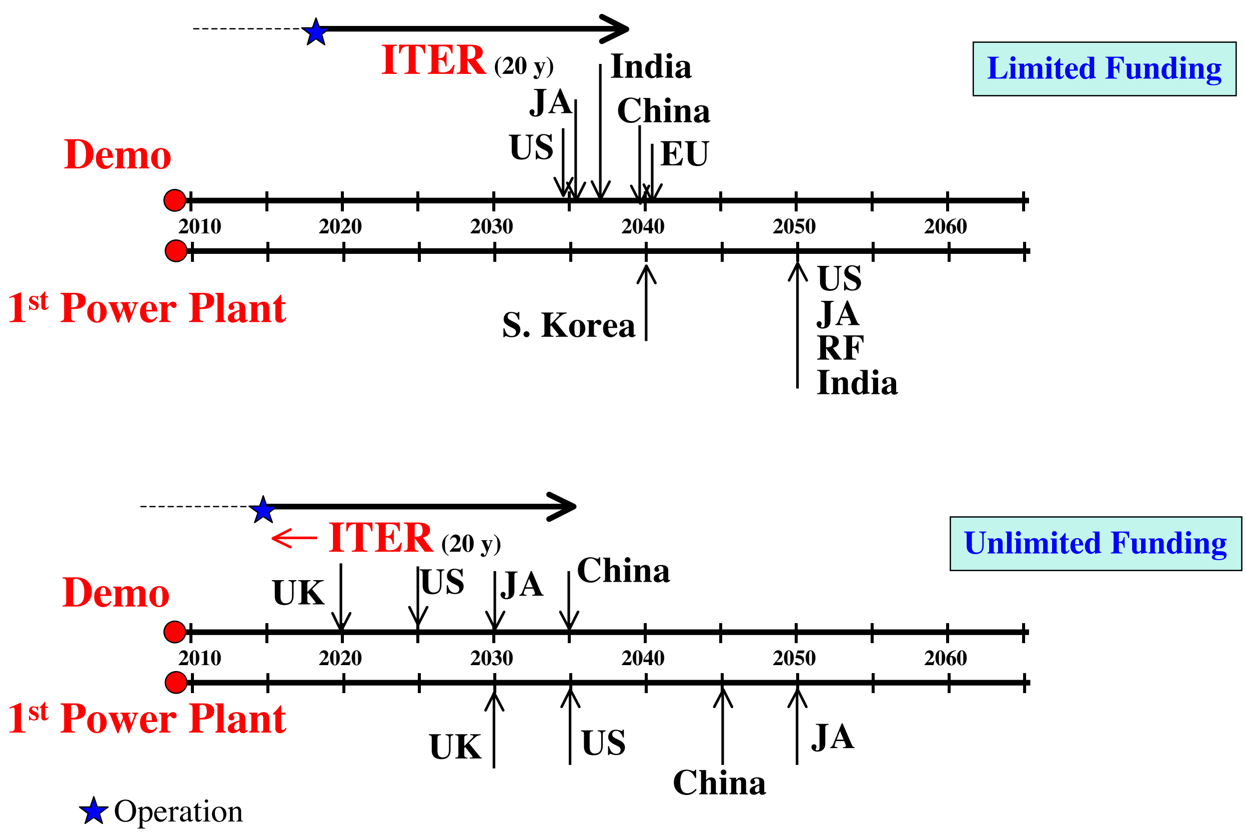

Figure 3. Projected timeline of Demo and power plant constructions with limited and unlimited funding.

5. Conclusions

During the 1970-2009 period, more than 50 conceptual power plant design studies have been conducted in the US, EU, Japan, Russia, and China for magnetic confinement concepts, covering a wide range of new and old design approaches: tokamaks, stellarators, spherical tori, field-reversed configurations, reversed-field pinches, spheromaks, and tandem mirrors. Internationally, the D-T fuelled tokamak is regarded as most viable candidate for magnetic fusion energy generation. Its program accounts for over 90% of the worldwide magnetic fusion effort. The R&D activities for the alternate concepts are at different levels of maturity. Even if these alternate concepts are not successful in realizing the path to a power plant, their physics and technology database will offer possible improvements for tokamaks and fusion sciences in general.

The worldwide fusion roadmaps take different approaches, depending on the degree of extrapolation beyond ITER. Several tokamak Demos should be built in the US, EU, Japan, China, Russia, Korea, India, and other countries to cover a wide range of near-term and advanced fusion systems. With limited funding and no clear vision, the timetable to build the first fusion power plant could extend beyond the famous 50 years that fusion researchers have been envisioning since the early 1970s. Nevertheless, with unlimited fusion funding and a limited timetable, the first fusion power plant could add electricity to the grid by 2030-2035.

Reference

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