American Journal of Energy Engineering
2025, Vol. 13, No. 1, pp. 1-8
https://doi.org/10.11648/j.ajee.20251301.11

Review Article

Global Fusion Energy R&D Trends and Bangladesh's Current Perspectives: An Overview

Md Mahbub Alam[1,*], Md Shamimul Islam[2], Md Mahbub Alam[2], Nayan Kumar Datta[1]

[1]Software Engineering Division, Institute of Computer Science, Bangladesh Atomic Energy Commission, Dhaka, Bangladesh

[2]Nuclear Cyber Security Division, Institute of Computer Science, Bangladesh Atomic Energy Commission, Dhaka, Bangladesh

Abstract

Sustainable energy associated research and development activities have gained significant popularity among research communities over the last few decades. Nuclear energy, in particular fusion energy can become a promising option to the world's primary energy source. Its fuel reserve, environmental effects and safety features are certainly noteworthy. Now the advancements of fusion energy Research and Development (R&D) progressing it's to economically feasible fusion power. One major step to achieve this goal in a short period of time is the International Thermonuclear Experimental Reactor (ITER) project, a 35-nations collaborative megaproject. EUROfusion is proposed a DEMOnstration power plant as the next step following ITER. Addressing these issues this study reviewed the global fusion energy R&D trends and current perspectives of Bangladesh. Currently, fusion energy R&D activities have been carried out in more than 50 International Atomic Energy Agency (IAEA) Member States. About 94 fusion devices are in operation, 11 fusion devices are under construction and 28 fusion devices are being planned to establish for experiment as well as demonstration purpose. In the Asian region especially in Japan, China, South Korea, India, Pakistan, Iran, Kazakhstan and Thailand fusion energy research has become remarkably popular and spreading up in the recent years. The United States (US) fusion community is conducting fusion R&D from multiple directions. The United Kingdom (UK) has been playing a pioneer role in continuing experiment with fusion since 1960. Several countries in European Union (EU) take initiatives to develop fusion technology. In 2020, scientists of Korea Superconducting Tokamak Advanced Research (KSTAR) achieved high-temperature sustained plasma of above 100 million degrees Celsius for a period of 20 seconds. From the global fusion energy R&D perspectives Bangladesh yet not has started fusion energy R&D in large scale. Only few universities and research organizations have been conducting fusion energy R&D activities in small scale.

Keywords

Fusion Energy, Global, Bangladesh, Fusion Research, Plasma, Thermonuclear

[*]Corresponding author: mahbub.baec@gmail.com (Md Mahbub Alam)

Received: 11 December 2024; **Accepted:** 24 December 2024; **Published:** 14 January 2025

1. Introduction

Fusion energy is the basic form of energy found in the universe. The sun and every star have been generating fusion energy since they were formed. Fusion energy is produced through the nuclear fusion reactions. Several fusion reactions involving Hydrogen and its isotopes can occur throughout the universe. Among them, the deuterium-tritium (DT) fusion reaction is the most promising option on laboratory scale due to its significant cross-sectional value and minimal energy needed to surpass the repulsive force [1]. The DT fusion reaction can be expressed as equation (1).

$$D+T\rightarrow He^4\left(3.5MeV\right)+n\left(14.1MeV\right) \qquad (1)$$

When the nuclei of deuterium and tritium fuse together, they recombined and produced α-particle (He^4) and a fast neutron. The reorganize of these two nuclei decrease the total mass, which in turn releases energy as kinetic energy in the form of the reaction products. The neutron possesses a kinetic energy of 14.1 MeV, whereas the α-particle possesses 3.5 MeV. The overall amount of energy released in each reaction is 17.6 MeV [2]. Figure 1 shows a diagrammatic representation of the fusion reaction between the deuterium and tritium nuclei, along with the released energies and fusion product.

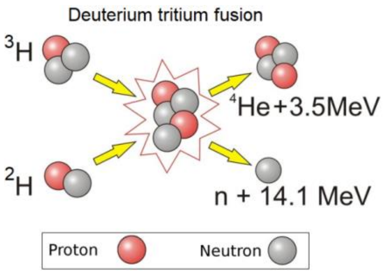

Figure 1. *A diagrammatic representation of the fusion reaction between the deuterium and tritium nuclei; the two nuclei approach sufficiently close to each other against their electric repulsive force; they fuse and produce a new nucleus of He^4 and a neutron along with 17.1 MeV kinetic energy. [Figure courtesy: Loewenhoff, T. W.].*

The resources needed for fusion reactions as well as fusion reactors have been extensively studied over the past few decades. The necessary fuel for the deuterium-tritium reactions is sufficiently resourceful. The seawater contains abundant amount of deuterium that occurs naturally and can be obtained easily at a minimal expense. The ration of deuterium and hydrogen in the sea water is 1: 6700. According to the current rate of global energy use, if all of the deuterium stored in the oceans is used in fusion reactors, it will take roughly two billion years to consume it all [3]. The tritium, another fuel of fusion reactions can be obtained from the lithium isotope, Li^6. The lithium isotope is not found naturally on earth but it can be used as one of the components in the fusion reactor's blanket, a heat-absorbing component of fusion reactor's vacuum vessel [4]. The extraction process of tritium from the lithium isotope can be expressed by the equation (2).

$$Li^6+n\rightarrow He^4\left(2.05MeV\right)+T\left(2.75MeV\right) \qquad (2)$$

While lithium is not found in its elemental state in nature because of its strong reactivity, it is available throughout the Earth. It would take roughly 20,000 years to use up all of the Li^6 that is available on Earth if global energy consumption continued at its current rate. Figure 2 shows a diagrammatic representation the tritium fuel production process of the reactor by using Li^6 blanket.

However, three criterions must satisfied to induce fusion reaction; (i) repulsive force among the two nuclei must overcome since both nuclei are positively charged and repel each other due to coulomb's force (ii) reactant nuclei should stay in the reacting region for a sufficient time and (iii) the density of the reacting nuclei must be large enough for the sufficient collision. These criterions can be achieved by heating the deuterium-tritium mixture at a temperature of about 100 million degrees centigrade. At this high temperature the fuel becomes a mixture of equal number of negative electrons and positive nuclei and fusion carried out in this way is known as thermonuclear fusion. As the combustion process needs to be self-sustaining without additional heating, thermonuclear fusion must meet a specific requirement referred to as ignition and expressed by $\hat{n}\tau_E\hat{T}>5\times10^{21}m^{-3}sKeV$, where, $\hat{n}$ and $\hat{T}$ are the pick ion density and the temperature in the plasma, respectively and τ_E is the plasma confinement time.

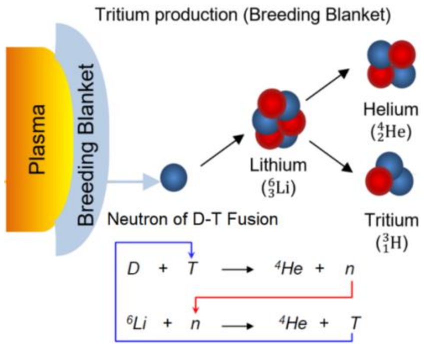

Figure 2. *Breeding of tritium in the deuterium-tritium fusion. Tritium fuel can be produced inside the reactor by using Li6 blanket. [Figure courtesy: Rodney Price].*

The temperature of the thermonuclear fusion or the plasma is so extreme that it cannot be contained within any standard container. So, magnetic field is used for containing such hot plasma. The magnetic field guides the charged particles and prevents them from hitting the surrounding solid walls. This is called magnetic confinement and producing useful amount of energy by magnetic confinement is treated as controlled nuclear fusion. The devices that offer such type of controlled nuclear fusion are known as tokamaks and stellarators. Tokamak is being developed to contain the hot plasma and it is the leading candidate for a practical fusion reactor. Over the last 60 years, tokamak attracts much attention to the fusion research communities across the world to carry out various types of experiments and researches to understand the physics, technological and engineering challenges to achieve fusion energy [5]. The significant progress of fusion researches in tokamak during the last 60 years have been reached at the stage to demonstrate the scientific and technological feasibility of fusion energy through ITER, which is being built in France [6]. ITER is scheduled to produce first plasma in 2025 and start deuterium-tritium operation in 2035 [7]. In parallel, also significant achievements have been obtained in stellarators for the controlled nuclear fusion during the last few decades. The Wendelstein 7-X fusion facility in Germany recently achieved its initial hydrogen plasma production. It is the largest fusion device of the stellarator in the world [8].

2. Tokamaks and Stellarators

A tokamak is an experimental device aimed at realizing thermonuclear fusion. The energy that produced through the fusion reactions inside the tokamak is absorbed as heat by the wall of the tokamak vessel. Fusion power plant uses this heat to produce steam and then electricity, just like a conventional power plant. Tokamak confines the fusion plasma using strong magnetic fields in a donut shape also known as torus. The fusion energy researchers' communities are considering the tokamaks as the foremost fusion plasma confinement device for the fusion power plants. Tokamak has strong toroidal magnetic field (B_t) in toroidal direction (ϕ) of cylindrical coordinate system. The toroidal magnetic field in tokamak forms torus shape, the intensity of the toroidal magnetic field is inversely proportional to the major axis (R). In tokamak, the charged particles gyrate and the guiding center of the particles move along the toroidal magnetic field. But due to the inhomogeneity and curvature of the toroidal magnetic field the guiding center of the charged particles drift. As a result, the plasma can't be confined in the tokamak by only the toroidal magnetic field. A second set of magnetic fields known as poloidal magnetic field (B_θ) or (B_p) should be introduced to overcome this problem. The two field components create a helical magnetic field. Consequently, a magnetic surface is formed that traps the particles within the plasma. In addition, a third set of outer poloidal field is required to control the shapes and positions of the plasma.

In Russia, nuclear fusion research began in 1950 and started operation of the world's first tokamak, T-1, in 1958 [9]. Subsequent advances led to the construction dozens of tokamaks around the world by the mid-1970s. By the late 1970s, a new series of tokamaks were designed notably the Joint European Torus (JET) in England, Tokamak Fusion Test Reactor (TFTR) at Princeton Plasma Physics Laboratory (PPPL) in US to achieve practical fusion [10]. These successes led to construct the ITER, a 35-nations collaborative megaproject, which aims to produce 500 MW of fusion power. Figure 3(a) shows a cutaway diagram of the ITER the largest tokamak in the world, which began construction in 2013 and is projected to begin full operation in 2035. It is intended as a demonstration that a practical fusion reactor is possible, and will produce 500 megawatts of power and Figure 3(b) right figure shows Plasma torus with magnetic field coils and plasma current.

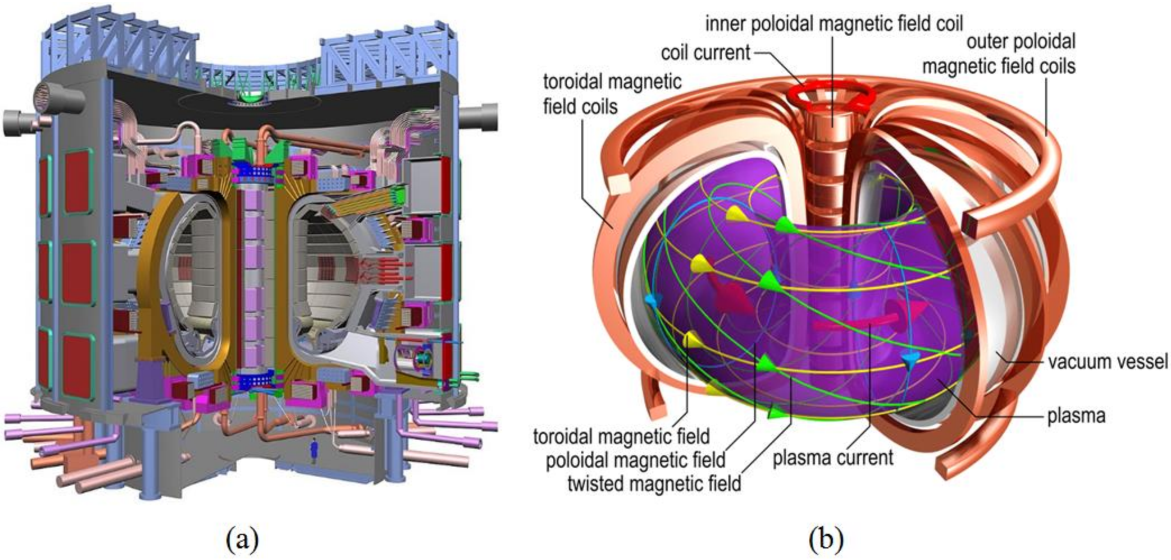

Figure 3. *(a) A cutaway diagram of the ITER [Figure courtesy: ITER]. (b) Plasma torus with magnetic field coils and plasma current (Right Figure) [Figure courtesy: C. Brandt].*

The stellarator is another type of a promising device to achieve the real-world fusion power. The basic concept of confining the plasma in stellarator is very closely related to the tokamak but the only difference between the tokamak and the stellarator are the method of achieving plasma confining magnetic field. In tokamak, the twisted magnetic field is achieved by using a combination of toroidal field coils current and poloidal field coils current as well as plasma current whereas in stellarator the twisted magnetic field line is directly achieved by helical coils. The stellarators have several advantages as well as disadvantage over tokamaks. The stellarator requires less injected power to sustain the plasma but the helical coils design of stellarator is very complex. Despite making stellarator coils is challenging in terms of reactor design, the stellarator may become a promising alternative of tokamak. However, many experimental projects of stellarator are planned and commence over the world. Currently, the world's largest stellarators in operation are the Large Helical Device (LHD) in Japan and the Wendelstein 7-X in Germany. Figure 4(a) shows a schematic view of LHD and Figure 4(b) shows plasma torus of LHD with magnetic field coils. Beside the tokamaks and stellarators, scientists around worldwide are conducting research and experiments with Heliotrons and laser/ inertial electrostatic fusion. Additionally, several alternative concepts such as magnetic mirror machine, dense plasma focus, magnetized target fusion, beam-target, simple magnetized torus, hybrid fusion, spheromak, pinch, reverse field pinch, inertial electrostatic fusion, pulsed power generated electron beam, levitated dipole and so on.

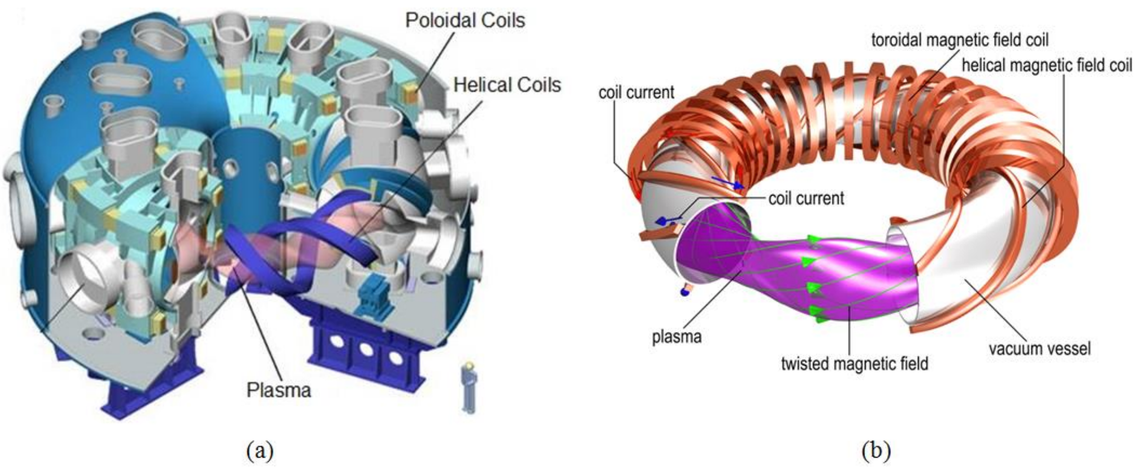

Figure 4. *(a) A schematic view of Large Helical Device (Left Figure) [Figure courtesy: Watanabe Lab, Plasma Physics Group, Nagoya University], (b) A schematic plasma torus of LHD with magnetic field coils (Right Figure) [Figure courtesy: C. Brandt].*

3. Global Fusion Energy Research Trend

Around the world, both public and private sectors are speeding up to grasp a commercially viable fusion energy system. After successfully accomplished the first controlled thermonuclear fusion experiment using Scylla I, a θ-pinch machine at Los Alamos National Laboratory, US in 1958 [11], several countries as well as international cooperation have been providing driving force to enter the global power generation portfolio. Currently, controlled thermonuclear nuclear fusion as well as plasma physics research is carried out in more than 50 IAEA Member States [12]. Figure 5 shows the controlled thermonuclear fusion as well as plasma physics research facilities location on the world map. Now worldwide about 94 fusion devices are in operation, 11 fusion devices are under construction and 28 fusion devices are being planned to establish for experiment as well as demonstration designs. Among them about 73 devices are Tokamaks, 13 devices are Stellarators/Heliotrons, 9 devices are Laser/Inertial and 38 devices are built depend on alternative concepts [13]. Figure 6 shows the numeral of fusion devices organized in four main configuration categories such as tokamaks, stellarators/Heliotrons, laser/inertial and alternative concepts.

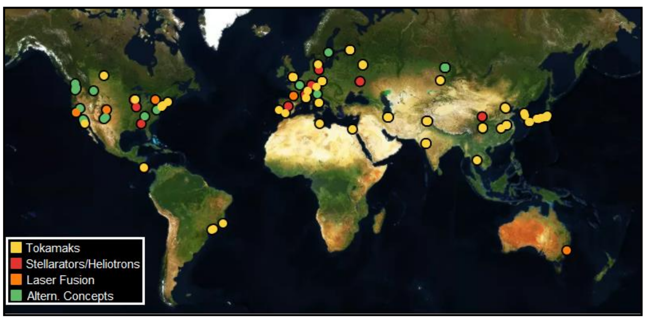

Figure 5. *Controlled thermonuclear nuclear fusion as well as plasma physics research facilities location on the world map [Figure courtesy: Fusion Device Information System (FusDIS), IAEA].*

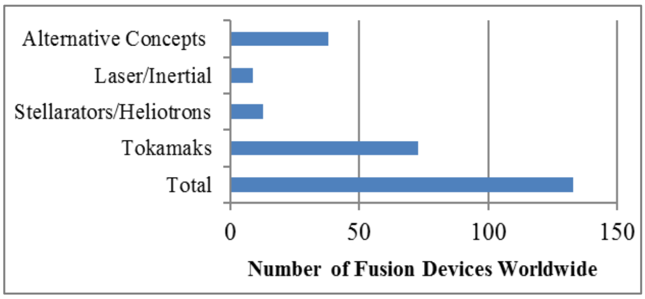

Figure 6. *The numeral of fusion devices organized in four (4) main configuration categories such as tokamaks, stellarators / Heliotrons, la-ser/inertial and alternative concepts [Data Source: Fusion Device Information System (FusDIS), IAEA].*

In the Asian region, thermonuclear fusion as well as plasma physics research has become remarkably popular and spreading up in the recent years. Japan, China, South Korea, India, Pakistan, Iran, Kazakhstan and Thailand are providing the leading role for progressive development of fusion research. At present, the world second largest superconducting stellarator the LHD has been operating at National Institute for Fusion Science (NIFS) in Japan in order to conduct fusion plasma confinement research in a steady state for clarify possible solutions to physics and engineering problems in helical plasma reactors. [14]. In recent year, the world's largest superconducting tokamak, JT-60SA as an upgrade of Japan Torus-60 has been completed in Japan and ready for its first plasma [15]. In addition, in Japan both public and private sectors about 21 fusion devices are in operation, 01 fusion device is in under construction and 02 fusion devices are planned to be constructed. Since 2006, an advanced nuclear fusion experimental research device "Experimental Advanced Superconducting Tokamak (EAST)" has been operating for long pulse operation of a high-performance plasma in the Chinese Academy of Sciences, China. As a result, in 2021, EAST achieved a major step toward the test run of the fusion reactor of 120 million degrees Celsius temperature for 101 seconds and temperatures of 160 million degrees for 20 seconds [16]. In addition, about 08 fusion devices are in operation and 02 fusion devices are planned to be constructed in China. Another world class superconducting tokamak developed and constructed by domestic technology; the KSTAR is operating in South Korea to study the aspects of commercial fusion power plants [17]. From 2008, KSTAR has been in full operation with excellent outcomes.

In 2020, scientists of KSTAR achieved high-temperature sustained plasma of above 100 million degrees Celsius for a period of 20 seconds [18]. Currently in South Korea, 02 fusion devices are in operation and 01 fusion devices are planned to be constructed. In the Asian region India has also been playing a vital role for making a fully functional fusion based reactor device. In 2005, India has fabricated a plasma confinement experimental device "Steady State Superconducting Tokamak (SST-1)" for the steady state operation of an advanced configuration ('D' Shaped) plasma [19]. Currently, 02 fusion devices are in operation and 01 fusion devices are planned to be constructed in India. Additionally, in the Asian region, 03 fusion devices are in operation in Iran; 02 fusion devices are in operation, 01 fusion device is in under construction and 01 fusion devices are planned to be constructed in Pakistan; 01 fusion devices are in operation in Kazakhstan; 01 fusion device is in under construction in Thailand.

Across EU member states, multiple private companies and public institutions have been playing a leading role for fusion research. The Max Planck Institute for Plasma Physics (IPP) in Germany operating two most favored fusion devices, tokamak and stellarator, in parallel. From 1988 to 2002, the IPP has been accomplished experiments on "Wendelstein 7-AS", a new class of advanced stellarators to develop a nuclear fusion reactor to generate electricity [20]. Based on the Wendelstein 7-AS experimental outcomes a predecessor stellarator, the world's largest fusion device, Wendelstein 7-X was established in 2014 and the first plasma was produced on 10th December 2015. In 2021, the Wendelstein 7-X reactor achieved of up to 30 minutes of continuous plasma discharge that demonstrated an essential feature of a future fusion power plant [21]. Also at IPP, the Axially Symmetric Divertor Experiment-Upgrade (ASDEX Upgrade) divertor tokamak went into operation at Germany in 1991 to study the interactions between the hot plasma and the walls surrounding it [22]. Based on the roadmap to the realization of fusion energy, in 2014, EU member states with Switzerland and Ukraine formed a consortium "EUROfusion" as an umbrella organization of Europe's fusion research laboratories. The main objectives of EUROfusion network are preparing for ITER experiments and developing concepts for the future Demonstration Fusion Power Plant (DEMO) [23].

In U.S. the government has been supporting for fusion energy research and development from multiple directions since 1950. Currently, about 20 fusion devices are in operations, 01 fusion device is under construction and more than 10 fusion devices are planned to be constructed in U.S. Since the late 1980s, the General Atomics of US has been operating the "DIII-D" tokamak, a world-leading fusion research facility that will enable the development of nuclear fusion as an energy source for the next generation [24]. The US Department of Energy's, PPPL has been running another flagship fusion facility, the "National Spherical Torus Experiment-Upgrade (NSTX-U)" to serve as the model for a fusion pilot plant preceded by an industrial fusion reactor [25]. Recently, the Fusion Energy Sciences Advisory Committee (FESAC) of the DoE and the National Academy of Sciences have been taken initiative for urgent development to enable a test fusion facility is expected to be functioning between 2035 and 2040. [26]. Additionally, several private organizations of U.S. along with some in the UK, the EU and Canada formed a "Fusion Industry Association" which is exploring methods to commercialize fusion [27]. The UK is also playing a vital role in fusion energy research. To the date the world largest and most advanced tokamak JET began operation in 1983 at Culham

Centre for Fusion Energy in Oxfordshire, UK. JET was designed to operate with the deuterium-tritium fuel mix and to study fusion in conditions required for a commercial power plant [28]. In addition, the UK's national fusion experiment device "Mega Amp Spherical Tokamak- Upgrade (MAST-U)" is also operating at Culham Centre, Oxfordshire, UK. The MAST-U has been particularly focusing on a key issue that must be solved to achieve commercial fusion power [29]. Currently, about 04 fusion devices are in operations and more than 03 fusion devices are planned to be constructed in UK. Russia, Brazil, Canada, Egypt and Australia are also acting pioneer role in the research and development activities of fusion energy. Currently, 08 fusion devices are in operation in Russia. The main directions of Russian fusion program are supporting engineering design and experiments to the ITER project. To promote the research and development activities, in Brazil 03 fusion devices currently are in operation, 01 fusion device is in operation in Canada and 01 fusion device is in operation in Egypt. Figure 7 shows the number of countries based fusion devices dividing into three categories such as in operation, under construction and plan to construction.

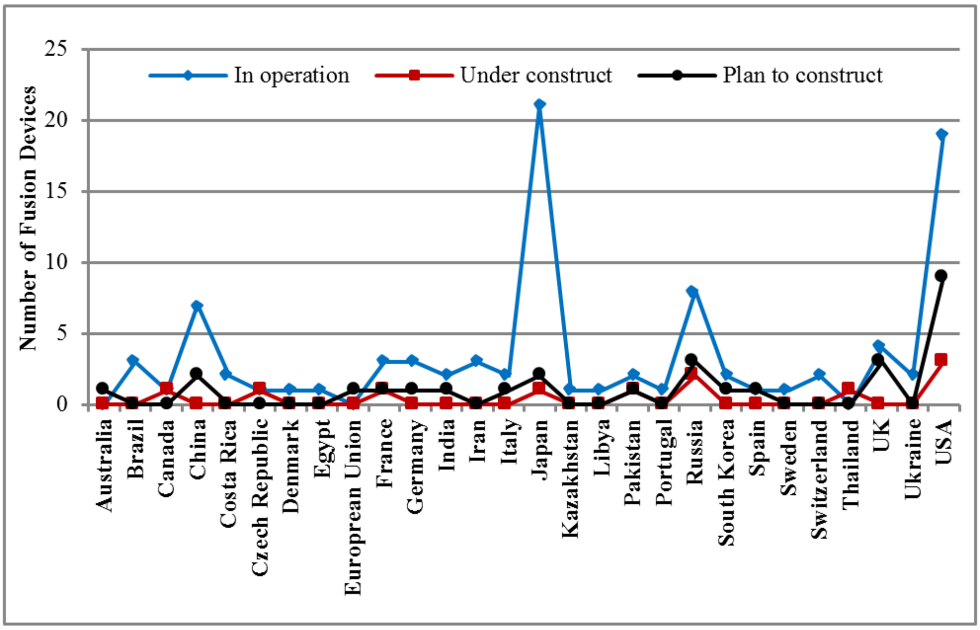

Figure 7. *Number of countries based fusion devices worldwide dividing into in operation, under construction and plan to construction.*

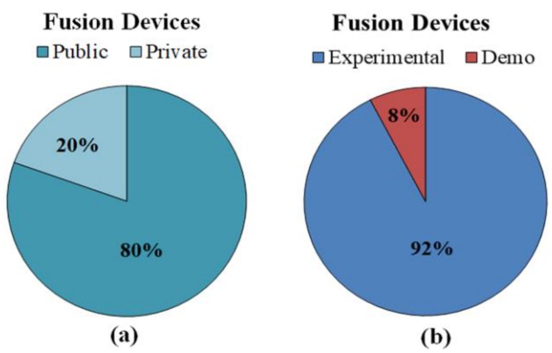

Figure 8. *The worldwide experimental and DEMO fusion devices and privately and publicly operating fusion devices.*

One of the most important steps to achieve fusion power in a short period of time is the ITER project, a 35-nations collaborative and most ambitious energy projects in the world today. Thousands of engineers and scientists around the world have been contributing to the design the world's largest tokamak, ITER. Japan, China, Korea, India, Russia, EU and United states are the signatories and member countries of ITER Agreement. The member countries have been sharing the cost of project construction, operation and decommissioning as well as experimental results and intellectual properties [30]. The project stated in 2006 by the signature of the member countries of ITER agreement and planned to produce its first plasma in 2025. Figure 8(a) shows the pie chart of the worldwide publicly and privately operating fusion devices figure 8(b) shows the pie chart of the worldwide experimental and DEMO fusion devices.

4. Fusion Research in Bangladesh

Fusion energy as well as high temperature plasma physics research is not in remarkable stage in Bangladesh. Only few universities and research organizations are conducting research and development activities by addressing these issues. Among them the department of physics of Jahangirnagar

University and Bangladesh Atomic Energy Commission are remarkable. In addition, a lot of Bangladeshi researchers who have been graduated or awarded doctoral degree from foreign universities are individually conducting fusion energy related research and development activities with their own interest as collaborative research to the foreign universities. The authors of this paper proposed that if it is possible to organize all individual researchers in a common platform then it can enrich our current research portfolio. However, to grasp the benefit of endless, clean and sustainable energy, the researchers' communities of Bangladesh as well as the energy authorities of Bangladesh Government should go ahead by focusing fusion energy as well as high temperature plasma physics related research and development activities. Bangladeshi researchers should increase the collaboration work with the international institutions. Bangladesh is a member of IAEA. Being a member, we can access research, technology and expertise related to fusion form IAEA. The IAEA runs a lot of fusion energy related R&D activities and supports to its member country to explore fusion energy.

Since, Bangladesh is investigating a variety of energy sources to mitigate its rapidly growing energy demand. Therefore, considering energy sources without fusion energy is not an option for Bangladesh and long-term planning should be taken in this regard. Bangladesh needs to gradually build its involvement in this emerging field through international collaborations, educational initiatives and participation in the global projects.

5. Conclusions

After successfully accomplished the first controlled thermonuclear fusion experiment using Scylla I, scientists have been working with great effort to avail fusion energy as well as to develop a fusion reactor. Currently both private and public sectors of more than 50 IAEA member states have been conducting research on controlled thermonuclear nuclear fusion as well as plasma physics research. Now worldwide about 94 fusion devices are in operation, 11 fusion devices are under construction and 28 fusion devices are being planned to establish. In the Asian region, Japan, China, South Korea, India, Pakistan, Iran, Kazakhstan and Thailand are providing the leading role for progressive development of fusion energy. Multiple private companies and public institutions have been playing a leading role for fusion research across EU. The US government has been supporting from multiple directions to promote fusion research. Currently 20 fusion devices are in operations in US. The UK, Russia, Brazil, Canada, Egypt and Australia are also playing a vital role in fusion energy research. Several private organizations of US, UK, EU and Canada formed a "Fusion Industry Association" for exploring commercializes fusion.

Fusion energy is a limitless and clean energy sources. It does not produce greenhouse gases as well as long lasting dangerous radioactive waste. Within the context of environmental change fusion energy is a most attractive alternative sources of energy.

Abbreviations

R&D	Research and Development
ITER	International Thermonuclear Experimental Reactor
IAEA	International Atomic Energy Agency
US	United States
UK	United Kingdom
EU	European Union
KSTAR	Korea Superconducting Tokamak Advanced Research
JET	Joint European Torus
TFTR	Tokamak Fusion Test Reactor
LHD	Large Helical Device
NIFS	National Institute for Fusion Science
EAST	Experimental Advanced Superconducting Tokamak
IPP	Max Planck Institute for Plasma Physics
DEMO	Demonstration Fusion Power Plant
PPPL	Princeton Plasma Physics Laboratory
MAST-U	Mega Amp Spherical Tokamak- Upgrade

Author Contributions

Md Mahbub Alam: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing

Md Shamimul Islam: Data curation, Formal Analysis, Investigation, Methodology, Resources, Software, Validation, Writing – original draft

Md Mahbub Alam: Formal Analysis, Investigation, Methodology, Resources, Validation, Visualization

Nayan Kumar Datta: Data curation, Formal Analysis, Methodology, Resources, Software

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] Garry M., Peter S. Man-Made Fusion. The Energy of the Universe. 2nd ed., ELSEVIER, 2013, pp. 31-38. https://doi.org/10.1016/C2009-0-64568-2

[2] John W. Fusion. Tokamaks. 4th ed., OUP, 2011, pp. 1-24. https://doi.org/10.1080/00107514.2012.720285

[3] Jeffrey P. F. Fusion and world energy. Plasma Physics and Fusion Energy. CUP, 1st ed., 2008, pp. 3-20. https://doi.org/10.1017/CBO9780511755705

[4] Yican W., FDS T. Conceptual design and testing strategy of a dual functional lithium–lead test blanket module in ITER and EAST. Nuclear Fusion. 2007, 47(11), 1533–1539. https://doi.org/10.1088/0029-5515/47/11/015

[5] Smirnov V. P. Tokamak foundation in USSR/Russia 1950–1990," Nuclear Fusion. 2009, 50, 014003 (8pp). https://doi.org/10.1088/0029-5515/50/1/014003

[6] Kikuchi M. A Review of Fusion and Tokamak Research towards Steady-State Operation: A JAEA Contribution. Energies. 2010, vol. 3, no. 11, pp. 1741–1789. https://doi.org/10.3390/en3111741

[7] ITER Timeline. ITER. Available from: https://www.iter.org/proj/inafewlines (accessed 08 February 2021).

[8] Wendelstein 7-X fusion device produces its first hydrogen plasma. Available from: https://www.ipp.mpg.de/4010154/02_16 (accessed 03 February 2024).

[9] Smirnov, V. P. Tokamak foundation in USSR/Russia 1950–1990. Nuclear fusion. 2009, 50, 014003(8pp). https://doi.org/10.1088/0029-5515/50/1/014003

[10] Tokamak. Available from: https://en.wikipedia.org/wiki/ Tokamak (accessed 03 February 2023).

[11] J. L. Tuck. Review of Controlled Thermonuclear Research. Los Alamos Scientific Laboratory. 1965, 107, 111. http://lib-www.lanl.gov/cgi-bin/getfile?00403625.pdf

[12] International fusion activities and the IAEA's role. Accessed from: https://www.iaea.org/topics/fusion (accessed 30 September 2023).

[13] Fusion device information system (FUSDIS). Accessed from: https://nucleus.iaea.org/sites/fusionportal/Pages/FusDIS.aspx (accessed 30 September 2023).

[14] Large Helical Device. Accessed from: https://en.wikipedia.org/wiki/Large_Helical_Device (accessed 07 September 2023).

[15] JT-60SA. Accessed from: https://www.jt60sa.org/wp/ (accessed 12 September 2023).

[16] Xinhua. Global Link. Chinese artificial sun sets new world record. Accessed from: https://global.chinadaily.com.cn/a/202112/31/WS61ceca11a310cdd39bc7e947.html (accessed 31 December 2021).

[17] KSTAR Project. Accessed from: https://www.kfe.re.kr/eng/pageView/103 (accessed 4 October 2021).

[18] Korean artificial sun sets the new world record of 20-sec-long operation at 100 million degrees. Accessed from: https://phys.org/ (accessed 04 October 2021).

[19] SST-1 (tokamak), Accessed from: https://en.wikipedia.org/ (accessed 23 December 2024).

[20] Wendelstein 7-AS (1988 - 2002). Accessed from: https://www.ipp.mpg.de/ (accessed 6 October 2023).

[21] Wendelstein 7-X. Accessed from: https://www.ipp.mpg.de/w7x (accessed 6 October 2021).

[22] Bradshaw, A. M., and I. Milch. Fusion research at the Max Planck Institute for Plasma Physics. Atw. Internationale Zeitschrift fuer Kernenergie. 2002, 47(1), 37-42. http://inis.iaea.org/search/search.aspx?orig_q=RN:33019515

[23] Contract between EC and EUROfusion is signed. Accessed from: https://fusenet.eu/ (accessed 06 October 2021).

[24] DIII-D National Fusion Facility. Accessed from: https://www.ga.com/magnetic-fusion/diii-d (accessed 12 December 2023).

[25] NSTX-U. Accessed from: https://www.pppl.gov/research/nstx-u (accessed 19 November 2023).

[26] US scientists introduce new fusion reactor concept. Accessed from: https://world-nuclear-news.org/Articles/US-scientists-introduce-new-fusion-reactor-concept (accessed 28 November 2023).

[27] Fusion Industry Association. Accessed from: https://www.fusionindustryassociation.org/ (accessed 19 November 2023).

[28] JET is the world's largest and most advanced tokamak. Accessed from: https://ccfe.ukaea.uk/research/joint-european-torus/ (accessed 12 December 2023).

[29] MAST Upgrade is the UK's national fusion experiment. Accessed from: https://ccfe.ukaea.uk/research/mast-upgrade/ (accessed 21 November 2023).

[30] ITER MEMBERS. Accessed from: https://www.iter.org/proj/Countries (accessed 19 November 2023).

Research Fields

Md Mahbub Alam: Artificial Intelligence and Machine Learning, Numerical Simulation, Fusion and Energy Engineering, Scientific Computing and Data Science, Software Engineering, Cyber Security

Md Shamimul Islam: Artificial Intelligence and Machine Learning, Cyber Security, Energy Engineering, Data Analytics, Nuclear Knowledge Management

Md Mahbub Alam: Artificial Intelligence and Machine Learning, Cyber Security, Energy Engineering, Data Analytics, Nuclear Knowledge Management

Nayan Kumar Datta: Artificial Intelligence and Machine Learning, Nuclear Knowledge Management, Energy Engineering, Data Science, Software Architecture, Nuclear Cyber Security