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GUEST EDITORIAL

How Many Years Away is Fusion Energy? A Review

Shutaro Takeda[1] · Alexander Ryota Keeley[1] · Shunsuke Managi[1]

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Introduction

Historically, it has been a running quip that 'fusion is always 30 years away.' This is a phrase, or some variation of it, any researcher in fusion energy must have heard of at least once in their career. In fact, fusion energy's promise of clean, safe, and virtually unlimited energy has driven researchers of many generations toward the realization of this future energy source. However, in recent years, efforts toward commercialization have significantly accelerated worldwide, which is exemplified by recent national initiatives like the Bold Decadal Vision for Commercial Fusion Energy in the U.S. [1] and the UK's electricity-generating STEP plant that plans to be completed by 2040 [2]. Further, the private sector is proposing even more ambitious timelines than the UK government, where 3 out of 4 companies are expecting to achieve fusion power generation during the 2030s [3].

Thus arises the following question: is the age-long sarcasm of "*fusion is always 30 years away*" still valid in 2023? This paper answers this question through a literature review of researchers' expectations about when fusion energy will be "ready" for over the past 40 years.

Results

Figure 1 summarizes the evolution of the researchers' remarks on the estimated timing of fusion realization published between 1985 and 2022. The screening protocol for literature is described in the "Appendix". The horizontal axis of Fig. 1 shows the year of publication, and the vertical axis plots the remarks within the given paper about the number of years needed before fusion is realized, i.e., the "*fusion is X years away*" factor.

The authors then performed regression analyses of the review result. Here, the realization of fusion was categorized into two phases: the first transmission of fusion power to the grid, i.e., the realization of a DEMO plant or equivalent, and the introduction of fusion to the commercial market, i.e., the realization of the first commercial plant. Linear regression models, which assume constant progress over the years, are shown as dotted lines (the Constant Progress Model). The model assuming non-constant progress, regression models fitted with cubic functions, are drawn as solid lines (the Dynamic Progress Model). Regression results are summarized in the "Appendix" as Table 2.

Discussions and Conclusion

Progress Towards Fusion Realization

The result illustrated in Fig. 1 is insightful. Referring to the Constant Progress Model, which assumes constant progress toward fusion realization over the past four decades, the slope of the regression line is − 0.4319 for first fusion power generation and − 0.2521 for commercialization. In other terms, scientists' expectations for the first electricity generation plant have shortened by 2.5 years every 10 years since 1985; similarly, expectations for the first commercial plant have shortened by 4.3 years every 10 years. This indicates that the scientists' collective expectation for fusion realization has progressed over the last four decades, as opposed to widespread cynicism.

A further intriguing trend becomes apparent under the Dynamic Progress Model, which assumes a dynamic change in expectations toward fusion. Observing the solid lines in Fig. 1, it is clear that the expectations for fusion energy went downhill from 1985 until 2000s, and then improved afterward. This is a quantitative indication that scientists were optimistic about the realization of fusion until the 1980s, but became pessimistic from the 1990s to the 2000s, and then their confidence returned after the 2010s. The peak of the pessimism was in 2006, with

✉ Shutaro Takeda
s.takeda@doc.kyushu-u.ac.jp

1 Urban Institute, Kyushu University, Fukuoka, Japan

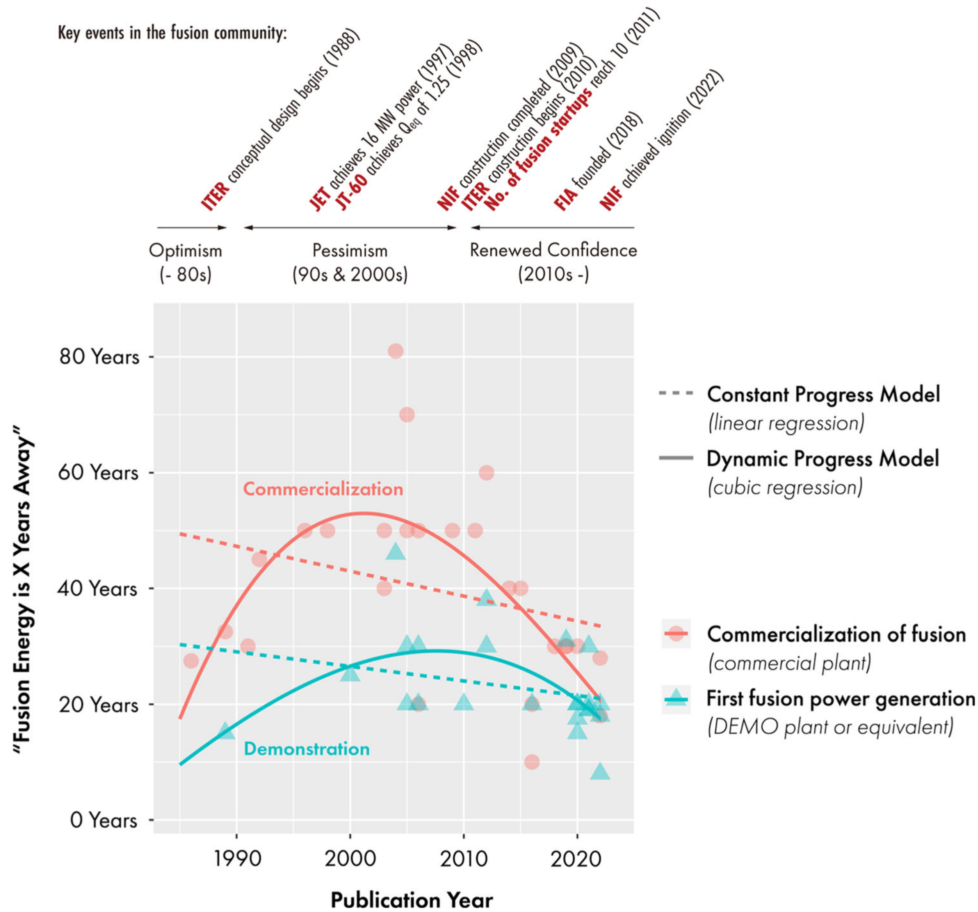

Fig. 1 Researchers' expectations on fusion realization over the past 40 years. (N.B. Drawn by the author based on Tables 1 and 2. JET: Joint European Torus; NIF: National Ignition Facility; JT-60: Japan Torus-60; FIA: Fusion Industry Association.)

"fusion being 29.2 years away" for demonstration, and in 2001, with "fusion being 53.0 years away" for commercialization.

Accelerated Expectations for Fusion

Comparing the R-squared values of the two models (Table 2), it is clear that the Dynamic Progress Model fits the evolution of the expectations for fusion better than the Constant Progress Model. This implies that the change in the expectation for fusion has, in fact, not been constant; rather, it has been accelerated since the 2010s.

What caused these dynamic changes in expectations? Comparing the timelines of the key events in the fusion community and the shifts in expectations, it would seem that the major scientific achievements in the late 90 s (including the successful JET and JT-60 experiments) created the turning point for the expectations for commercialization. Then, milestone achievements of the public programs (including NIF and ITER) as well as the advent of the private sector around the year 2010 coincided with the turning point in the expectation for the first fusion power generation.

It would be difficult to objectively conclude if private enterprises (or the public programs, for that matter) contributed to the accelerated progress or if they are simply benefitting from this trend from this result alone. Personally, judging from Fig. 1, the author would like to believe that private companies are both contributors and beneficiaries of this trend. In the end, the turning in expectations did happen before the advent of the private sector; at the same time, there would be no denying that the accelerated expectations for fusion around the year 2020 owe significantly to the private sector.

Limitations

Before moving into conclusions, it should be noted there are some limitations to the study. The most notable limitation of this review is that, due to the ambiguous nature of the review criteria, the authors could not design a systematic review process. As a result, the authors could not ensure that every published literature that mentions the timing of fusion realization is included in this study. Further, the "fusion is X years away" statements are often subject to biases and opinion of the scientists, rather than scientific assessments. Notwithstanding, the authors made every effort to be comprehensive and impartial in their screening process as outlined in "Appendix", and the extracted literature (N = 45) was sufficient to produce statistically significant regression models. As a result, the authors believe that the result is sufficient to discuss the general trend of the scientists' expectations of fusion energy over the past four decades.

How Many Years Away is Fusion?

In conclusion, according to the collective remarks by scientists, the popular phrase "*fusion is always 30 years away*" is proven wrong, technically speaking. To be precise, we should now say "fusion was said to be 19.3 years away 30 years ago; it was 28.3 years away 20 years ago; 27.8 years away 10 years ago." And now, scientists believe fusion energy is only 17.8 years away. So there *is* a progress, and it is accelerating toward the realization of this ultimate clean energy.

Appendix: Materials and Methods

The authors referred the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) statement [4] to guide the search and screening process, although this review is not intended as a systematic review. Web of Science, Scopus, and Google Scholar were used as search engines for locating eligible articles. The keywords that were used in the search were "fusion energy," "nuclear fusion," and "fusion power." The phrases that were used to search the articles used a combination of Boolean operators AND/OR/IN with English phrases and words such as "years away," "how many years," "always years," "realization," "progress," "breakthrough," "realistic," and "feasible." While priority was given to peer-reviewed articles published in academic journals, gray literature, such as technical reports, government documents, conference papers, editorial letters, and perspectives, were also cited in this study, as these articles also reflect the sentiments of the published era. Other than database search, a snowballing procedure was also used to identify potential sources. The screening process began with title screening, followed by abstract and full-text screening resulting in 45 articles tabulated in Table 1.

Table 1 Tabulated list of screened literature with key quotations

Year	Citation	Key quotations	"X years away"
1986	[5]	The ultimate goal of commercial fusion always seems to be 25 or 30 years away	25 or 30 (Commercial)
1989	[6]	Fusion energy was 10 or 20 years away	10 or 20 (Demonstration)
1989	[7]	The time frame for large-scale commercial application of MFE is, at the earliest, 2015 and beyond, and probably 2030 and beyond	25 to 40 (Commercial)
1991	[8]	Any payoff—no matter how great—that is 30 years away	30 (Commmercial)
1992	[9]	Nuclear fusion appears today to be 40 or 50 years away	40 or 50 (Commercial)
1996	[10]	'Fusion is always 50 years away' syndrome	50 (Commercial)
1998	[11]	Appears to be at least 50 years away from producing a commercially acceptable product	50 (Commercial)
2000	[12]	That prospect is still at least 25 years away	25 (Demonstration)
2003	[13]	Pushed estimates for commercially available fusion power out to the middle of the twenty first century	47 (Commercial)
2003	[14]	Fusion has been 50 years away since I was a boy	50 (Commercial)
2004	[15]	Insertion into the energy offer could take place in the second part of the twenty first century—2010s = ITER R-6.2M; 2030–2070s = Reactor type 1(small extrapolation R-8-9m; 2080–2090s = Reactor type 2 R-6m	26 to 66 years (Demonstration); 76 to 86 (Commercial)
2005	[16]	2025 as the target date for operation of a Demonstration Power Plant, commercial fusion power is still another fifty years away	20 (Demonstration); 70 (Commercial)
2005	[16]	Some believe that commercial fusion power is still another fifty years away	50 (Commercial)
2005	[17]	Power plant could be putting electricity into the grid within 30 years	30 (Demonstration)
2006	[18]	Fusion power station to produce power in 30 years' time	30 (Demonstration)

Table 1 (continued)

Year	Citation	Key quotations	"X years away"
2006	[19]	So that the design of the first commercial the demonstration power plant could be finalized in twenty years	20 (Demonstration)
2006	[20]	The joke has long been that commercial fusion energy was only fifty years away	50 (Commercial)
2006	[21]	It appears that commercial fusion energy is still at least 20 years away	20 (Commercial)
2009	[22]	Fusion has always been 50 years away, and always will be', as the old joke goes	50 (Commercial)
2010	[23]	That fusion is 20 years away	20 (Demonstration)
2011	[24]	The idea of hydrogen fusion as well as its difficulties are presented in non-technical language to dispel the notion that fusion is always 50 years away	50 (Commercial)
2012	[25]	Even according to the most favourable predictions of the experts, fusion power is still 60 years away	60 (Commercial)
2012	[26]	Plant could be putting electricity into the grid within 30 years	30 (Demonstration)
2012	[27]	Technical roadmap to fusion electricity by 2050, third period (2031–2050): Complete the ITER exploitation; construct and operate DEMO	38 (Demonstration)
2014	[28]	'Always 40 years away' from the goal of fusion power	40 (Commercial)
2015	[29]	Fusion has been "forty years away", that is, forty years to implementation	40 (Commercial)
2016	[30]	Realistically, the first commercial fusion power plant is still at least 25 years away	25 (Commercial)
2016	[31]	Fusion promises unlimited clean energy, but the reality has hovered just out of reach, 20 years away	20 (Demonstration)
2016	[32]	Commercial fusion electricity is probably still 10 years away	10 (Commercial)
2018	[33]	With the longstanding quip that it is 'always 30 years away'	30 (Commercial)
2019	[34]	The development of practical, controlled fusion energy is still at least 30 years	30 (Commercial)
2019	[35]	Fusion always seems to be 30 years away	30 (Commercial)
2019	[36]	DEMO operation is expected to start in the 2050s	31 (Demonstration)
2020	[37]	Recent advances in fusion science and technology could potentially put the first fusion power on the grid as soon as the 2040s	20 (Demonstration)
2020	[38]	Nuclear fusion is that it has always been 30 years away	30 (Commercial)
2020	[39]	Attaining the first sustained fusion reaction, or burning plasma is scheduled to occur in 2035 at the earliest	15 (Demonstration)
2020	[40]	Scientific and technological innovations enable a unique US vision for economically attractive fusion energy, with the goal of a fusion pilot plant by the 2040s	20 (Demonstration)
2020	[41]	Compact and commercially attractive fusion reactor that can be operational in the next 15–20 years	15 to 20 (Demonstration)
2021	[42]	National academies lay out a to-do list to build the multibillion-dollar plant by 2035, start construction of the pilot by 2035, and to have it running by 2040	19 (Demonstration)
2021	[43]	It is scheduled to start operating in 2025, and the company aims to have reactors for sale in the early 2030s… Private firms are making bold promises about delivering commercial fusion reactors in the 2030s	19 (Demonstration)
2021	[44]	For the first time in decades, the 20-year figure may prove to be correct	20 (Demonstration)
2021	[45]	A working fusion reactor is always just 30 years away	30 (Demonstration)
2022	[46]	Most fusion companies operating today in the world believe fusion will not power any grid anywhere in the world until the 2030s at the earliest	8 (Demonstration)
2022	[47]	One estimate suggests maybe 20 years	20 (Demonstration)
2022	[48]	Spherical Tokamak for Energy Production began in the U.K., and proponents claim it could operate by 2040… And researchers at a demonstration reactor in Japan claim a fusion generator there should be feasible no later than the 2050s	18 (Demonstration); 28 (Commercial)
2022	[49]	There are currently 38 private fusion energy companies worldwide aiming to commercialize fusion energy in the early 2030s and 2040s	8 to 28 (Commercial)

Table 2 Regression results for scientists' expectations on fusion realization, based on Table 1

	Demonstration plant		Commercial plant	
	Constant progress model	Dynamic progress model	Constant progress model	Dynamic progress model
Intercept	5.308×10^{2}	-1.898×10^{5}	9.068×10^{2}	-1.365×10^{7}
Year	-2.521×10^{-1}	1.892×10^{2}	-4.319×10^{-1}	2.024×10^{4}
Year^2	–	-4.715×10^{-2}	–	-1.001×10^{1}
Year^3	–	N/A	–	1.649×10^{-3}
R-squared	0.0745	0.3350	0.0785	0.4529
p Value	0.2076	0.0169*	0.1656	0.0036**

* and ** represent significance level at 5 and 1%, respectively

Then the authors conducted a manual full-text search to identify the key quotations regarding the timing of fusion realization to extract the "X years away" factors. One important caveat of this full-text search is that, for this study, the authors presumed that technical assessment, educated guesses, and quotations were all reflective of the sentiment of the scientists at the time. This presumption was applied even for quotations from previous works, as authors of the paper can arbitrarily cite previous works that state "fusion is 30/40/50 years away." As such, it would be reasonable to assume that the cited number would reflect the authors' own sentiment on the expectation of fusion realization. When the literature estimates the timing of fusion realization with a range, the median value for the expected range was used for regression. When the article does not specifically mention if the prediction is for the demonstration or for the commercialization, the authors manually determined the category carefully from the context of the remark. The key quotations, along with the "X years away" factors, are tabulated in Table 1. Regression results are summarized in Table 2.

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