Is Fusion Research Worth It?

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Abstract Long-term energy R&D such as fusion needs to be valued in the framework of options analysis. The R&D itself does not provide energy, but rather provides the option to construct and operate energy-producing systems. An initial analysis of this problem applied the Black-Scholes formula based on historical fluctuations in the cost of energy. That study concluded that for reasonable assumptions about the operating cost of fusion power plants, the fusion option was cost effective. Here we use a simpler and more transparent estimate of the future value of energy, but look more carefully at the question of the opportunity cost of engaging in fusion R&D, including the possibility of hedging financially against increased prices for acceptable energy through a savings fund, as compared with the fusion option. We find that the fusion option is very attractive if the probability is more than a few percent that fusion will cost less than the best environmentally acceptable alternative for its potential market share.

1. Introduction

It is generally understood that very long-term financial prediction is highly unreliable, and that projecting discount rates into the distant future is problematic[1,2,3,4]. It is nonetheless necessary to ask the question as to whether, under reasonable assumptions, fusion R&D is a good investment for society. This requires comparing the present value of the cost of the fusion R&D effort with the present value of the option it is to provide to construct and operate future fusion power plants. For this purpose we use the 2003 Fusion Energy Sciences Advisory Committee (FESAC) report “A Plan for the Development of Fusion Energy”[5] as a basis for estimating the cost of fusion R&D. We then invoke a scenario for deployment of fusion energy systems based on the worldwide deployment of fission energy systems. For the value of the fusion energy we compare with the recent Intergovernmental Panel on Climate Change (IPCC) projection[6] for the use of coal with carbon sequestration, a simpler but more transparent model than used in an initial study[7], which applied the Black-Scholes formula based on historical fluctuations in the cost of energy. Both the R&D cost and the energy cost are variables in the final result, so alternative values can be easily substituted. We use a discount rate based on U.S. government borrowing, which allows us also to consider the option of government hedging against future energy prices – for example by not borrowing the funds for fusion R&D but investing in government securities to pay for future energy price increases.

2. The Cost of Fusion Development

The FESAC analyzed a specific future scenario for fusion energy development[5]. In this scenario, the U.S. constructs a fusion demonstration power plant to put electricity on the grid by about 2035. Presumably a more rapid development scenario could be constructed with a higher rate of investment, but such a case has not been analyzed. In the case presented, magnetic and inertial fusion energy (MFE and IFE) are both pursued until 2019, when a selection is made for fusion energy deployment. The U.S. is assumed to participate in the construction and operation of the international ITER project, to construct and operate the U.S. National Ignition Facility (almost exclusively using funds outside of fusion energy development), and to participate in the construction and operation of an International Fusion Materials Irradiation Facility. Domestically at first the U.S. pursues configuration optimization and technology development for MFE and IFE in parallel. After the MFE/IFE selection a substantial U.S.-only Component Test Facility would be constructed, followed by a U.S.-only fusion Demonstration Power Plant. It is assumed that a robust international program moves in parallel with the U.S. program. In particular, it is assumed that multiple countries construct competitive Demonstration Power Plants. Here we will multiply the U.S. costs by a factor of four to account for the assumed robust, competitive international program, for a total development cost of 107B US$2005. The projected world cost of fusion energy development will appear with an adjustable factor in the final result.

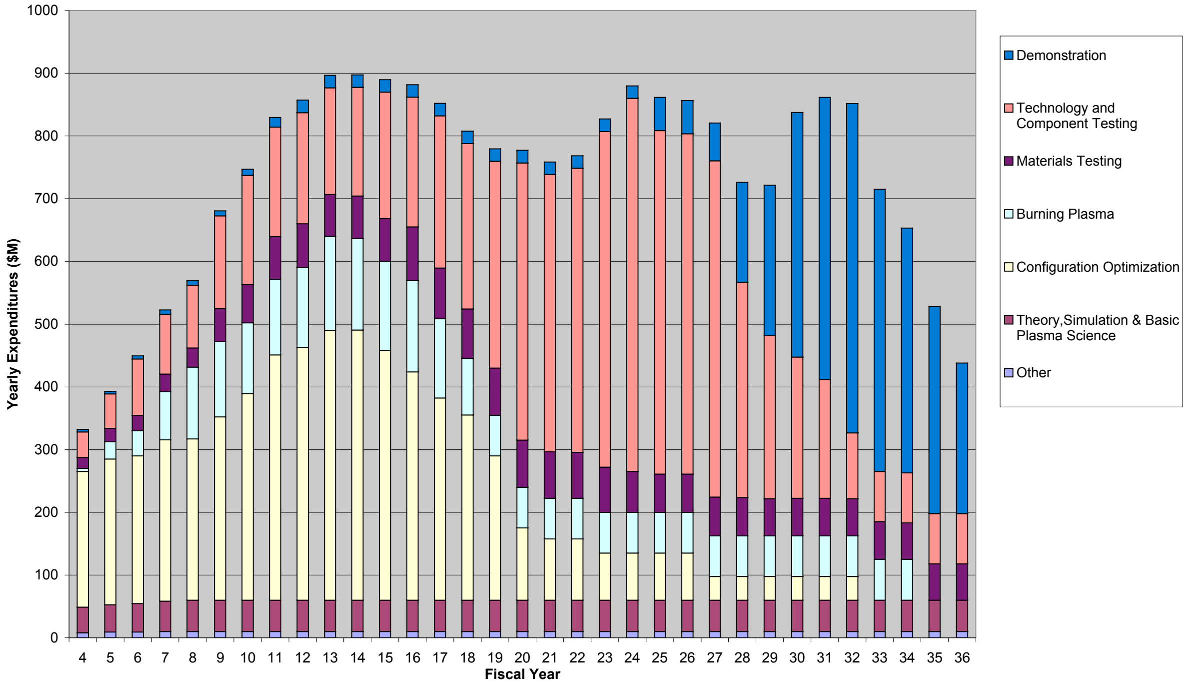

FIG. 1. FESAC projection of U.S. cost for fusion development in US$2002, assumed to be 1/4 of world cost.

3. The Value of Fusion-Produced Energy

To estimate the value of fusion-produced energy we require a reference scenario for potential fusion deployment. President Bush has presented a vision for the U.S. of commercial fusion energy deployment by mid-century, consistent with the demonstration of the economics of fusion power production starting in 2035. We assume a slow start for commercial energy production through 2060, and then project that primary fusion energy production rises at 0.4% of world primary energy use per year until 2200, after which it remains level. 0.4% of world primary energy use per year was the rate at which fission energy penetrated into the world energy market in the period 1975 – 1985, when fission rose from zero to nearly its present steady market penetration. The maximum rate of growth of fusion power, decade to decade, is a factor of 6. If a reasonable tritium excess of 5% is produced in fusion power plants, and the initial startup inventory is set at a reasonable 5 kg, fusion could in principle increase by a factor of 1000 per decade. Fission penetrated the French market at a rate of about 2% per year of primary energy use, which suggests that fusion may be able to penetrate some markets much more rapidly than indicated here. The rate of increase from one decade to the next even in a worldwide 2% per year scenario is at most a factor of 13.

To calculate the reference fusion scenario we need to project world primary energy use into the future, which we do by averaging and extrapolating from scenarios such as those recently presented by the IPPC[6]. This provides an opportunity to compare fusion deployment with the required amount of non-CO_2-emitting energy. Wigley, Richels and Edmonds[8] calculated curves for allowed carbon emissions for different ultimate atmospheric concentrations. These curves can be translated into allowed carbon-emitting energy production by assuming fixed total carbon emission per unit carbon-emitting energy production, and the result can subtracted from total primary energy production to obtain the needed new non-CO_2-emitting energy, shown in Figure 2. Note that some proposed scenarios[9] rely strongly during the period until ~2050 on improved energy efficiency and lowered carbon emissions from non-energy sectors, leaving more of the requirement for new non-CO_2-emitting energy sources to later in the century, when fusion can be made available.

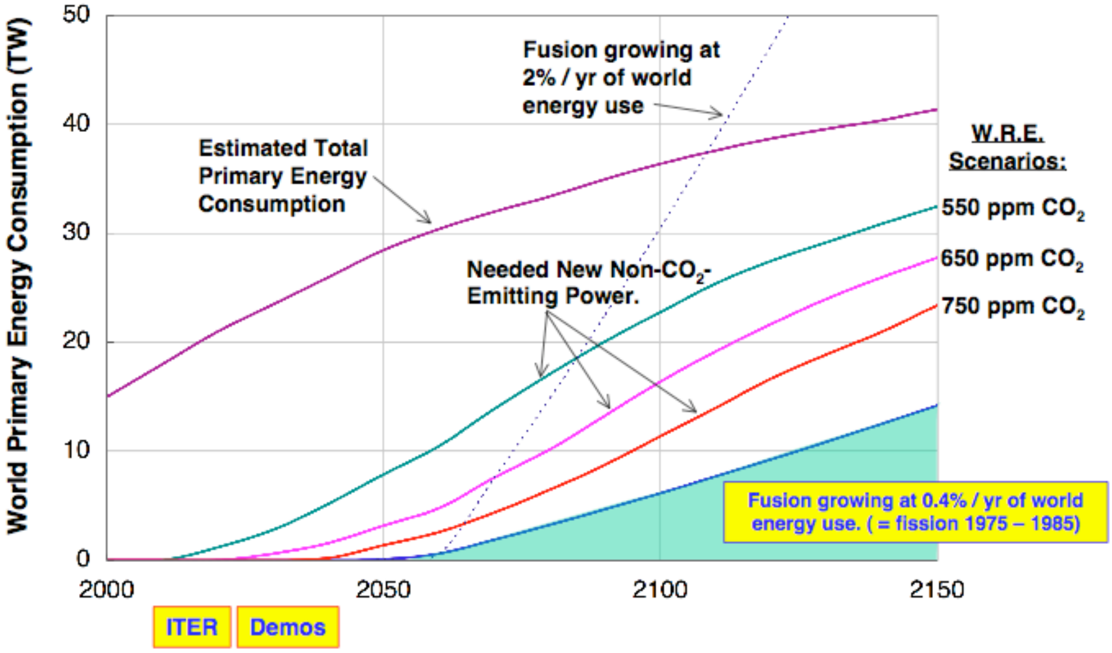

FIG. 2. World primary energy use projected based on IPCC estimates, needed new non-CO_2-emitting power based on W.R.E. scenarios, fusion primary energy based on world fission growth rate, and based on fission approximate growth rate in France (dotted line).

To determine the value of the fusion-produced energy, we compare it with other potential non-CO_2-emitting large-scale baseload energy sources, assuming that the world will find it necessary to move towards the W.R.E. scenario curves. The amount of primary fusion energy shown in the shaded region of Figure 2, out to 2150, is 22,500 EJ. This is greater than the the total “prognosticated and speculative” fission energy resource available without breeding (~7000 EJ)[10], but well less than the total fission energy resource available from U238 and thorium with breeding, and well less than total coal resources. However a low-CO_2 coal-based scenario to produce the amount of energy in the shaded region of Figure 2 would require sequestering 1800 $GtCO_2$, close to the lower IPCC estimate[6] of economically unconstrained total world storage capacity of 1700 $GtCO_2$ in deep saline formations and depleted reservoirs, but less than the upper estimate of possibly 10,000 $GtCO_2$ and much less than the fusion fuel resource, set by lithium on land ($3\ 10^5$ EJ) or in seawater ($5\ 10^9$ EJ)[11].

It is difficult to use fission to set a baseline for the value of the energy potentially produced by fusion because an agreed estimate is not available for the cost of fast-spectrum reactors burning ~$2\ 10^6$ kg of plutonium per year, supplied by an adequately proliferation-resistant fuel cycle of the necessary scale. Comparison with burning coal and sequestering the resulting CO_2 is apparently more straightforward. The IPCC has estimated[6] the cost of electricity from coal with carbon sequestration at 5.5 – 9.1¢/kWh for plants where local sequestration is practical. Using a cost of 7.3¢/kWh and an electrical efficiency of 35%[6] gives a value of 2.55¢/kWh US$2005 for primary energy.

4. Discount Factor

An extensive literature exists on how to project very-long-term discount rates, which are fundamental to the analysis of opportunity cost[1,2,3,4]. This literature relates to questions such as radioactive waste disposal, greenhouse gas emission reductions and the U.S. Social Security trust fund, but can also be applied to long-term energy R&D such as fusion. Intuitions about interest rates *vs.* risk developed from experience with short- and medium-term investments are not directly applicable to very long-term investments. A risk-neutral investor demands equal expected values from risky and non-risky options; the rate of return of a risky option must therefore exceed that of a safe option by x, as given by:

$$x = (1 + y)\exp\left[-\ln(P)/N\right] - 1$$

where y is a required zero-risk annual rate of return, P is the probability of success and N is the number of years of investment. x falls dramatically as N rises. For example for $y = 5\%$, $P = 0.8$ and $N = 5$ years, $x = 4.79\%$; while for $y = 5\%$, $P = 0.8$ and $N = 50$ years, $x = 0.469\%$.

Only governments can take on large-scale investments with significant risk such as fusion because of the size of the required investment, which appropriately makes corporations risk averse, and because of the time scale that reaches beyond the period of protection for intellectual property rights. Note that the following analysis does not apply straightforwardly to smaller, shorter-term government energy R&D investments where private industry can be expected to develop or deploy improvements to existing energy sources, albeit more slowly than with government assistance. In those cases the benefit to the public of government investment is limited to the period of benefit due to the acceleration.

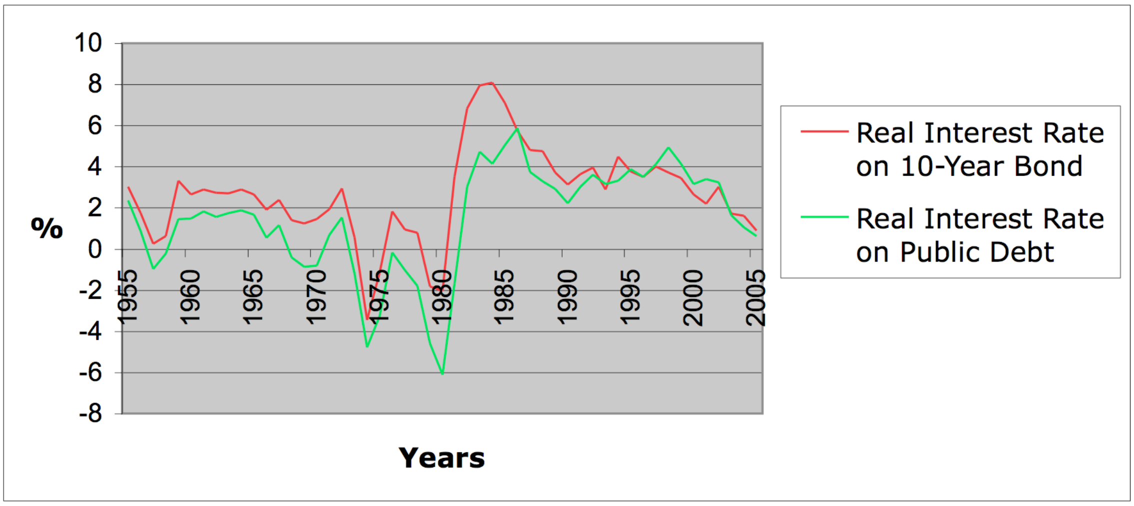

FIG. 3. Real interest rate on 10-year U.S. Treasury Bond and on the total U.S. public debt[12,1314].

Here we consider two alternatives, that the U.S. government borrows money to support the U.S. effort in fusion development, or that it does not borrow this money. Thus the present value of pursuing fusion development, both costs and benefits, should be determined using a discount rate fixed to the real interest rate that the U.S. Government pays to borrow money. This can be seen by considering a variant on the second alternative, demonstrating the opportunity cost of investing in fusion. In this variant the government borrows the same profile of funds as if to develop fusion, but instead invests in a special government savings fund which purchases government securities to insure against future energy prices. The net effect on public ownership of government securities is the same as not borrowing for fusion development, and the "energy insurance" savings fund earns at the government's payment rate on its debt. This is the opportunity lost by the government in choosing to invest in fusion development. We return to analyze its value in Section 6.

The average real interest rate on 10-year U.S. Treasury Bonds from 1954 to 2005 was 2.659%, while the average overall real interest rate paid on the U.S. public debt was 1.426%. There is no evidence to indicate that a decision on whether to invest in fusion development would change the mix of U.S. government borrowing, but for completeness we will carry forward both of these values in predictions of discount factor sequences. The risk associated with the fusion investment will be considered explicitly in the estimation of its probable value. We will assume a risk-neutral stance on the part of the U.S. government.

There is considerable uncertainty in projecting future real interest rates. One method is simply to use the average historical rates, which we employ below. We also pursue a stochastic model proposed by Newell and Pizer[2] which takes into account the fact that using an average interest rate into the future does not give the same result as taking into account the uncertainty in future interest rates and averaging the resulting discount factor sequences from multiple realizations. They make a best fit to historical data using an autoregression model:

$$\varepsilon_t = \rho_1\varepsilon_{t-1} + \rho_2\varepsilon_{t-2} + \rho_3\varepsilon_{t-3} + \zeta_t$$

where ε_t is the deviation from the mean value at time t. The best fit provides a set of values for the ρ's and an estimate of the root mean square value of the error in the fit, ζ. Unlike Newell and Pizer we do not work in log space, since our historical data include brief negative excursions. This approach also avoids the problem of projected drift in the mean interest rate. We find that the best-fit values of the ρ's are below unity, indicating that the trend is better represented by a mean-reverting model than a random-walk model, where the ρ's are forced to sum to unity. The values of the ρ's and normally-distributed values for ζ are used to predict 10,000 stochastic future real interest rate sequences, and so real discount factor sequences, based on the 10-year bond and on the total public debt.

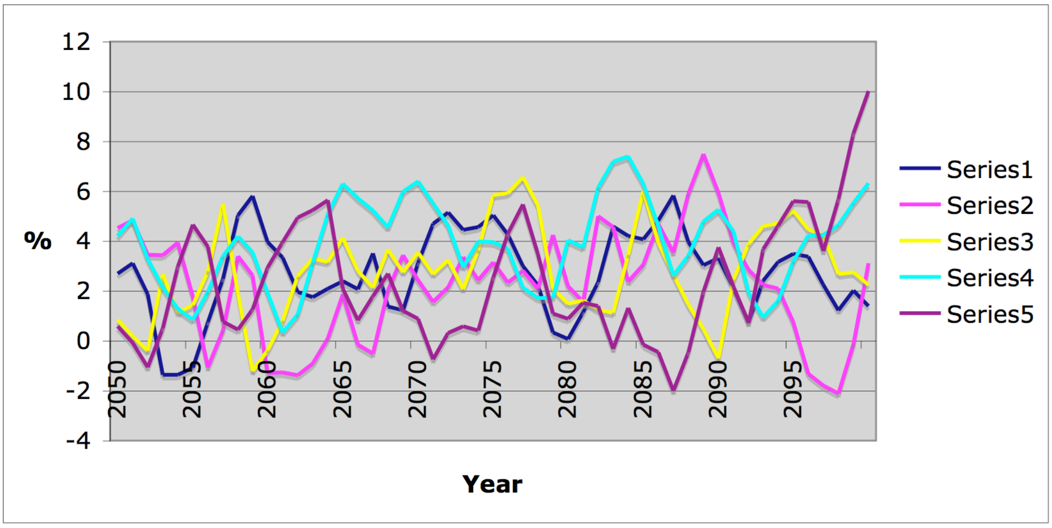

FIG. 4. Five randomly selected realizations of real 10-yr bond interest rates from 2050 to 2100.

We find that the predicted sequences for the mean-reverting model (Figure 4) look much more similar to historical data than the random-walk sequences, which have a tendency to drift to very high and very low (even negative) interest rates for long periods of time.

We are now in a position to evaluate both the present value of the cost of world fusion development and also the present value of the reference potential fusion energy production. We develop discount factor sequences in four ways:

1) Based on the historical average real 10-year U.S. Treasury bond interest rate
2) Based on the historical average real interest paid on U.S. public debt
3) Based on the averaged discount factors from 10,000 future realizations of 1)
4) Based on the averaged discount factors from 10,000 future realizations of 2)

The results we find for present values are as follows:

US $2005	PV Fusion Development Cost	PV Fusion Energy
10-year Bond Deterministic	$70.8 B	$11.3T
Public Debt Deterministic	$84.8 B	$54.9 T
10-year Bond Stochastic	$75.9 B	$15.7 T
Public Debt Stochastic	$89.7 B	$120 T

The breadth of spread in the discount factor results in a larger present value for fusion energy than is deduced from the fixed interest rate model. The present-value development cost is approximately 80B US$2005, while the present value of the energy in the baseline scenario is in the range of 11T – 120T US$2005, a factor of 140 to 1500 higher.

5. Fusion R&D as an Option

Fusion R&D does not provide fusion energy, but is to provide the option to build power plants that can produce fusion energy. To estimate the value of this option we must average the net present value of the option over future worlds, weighted by our best estimated probability factors. The net present value of the fusion option can be expressed as

$$NPV_{op} = Max\left[(1-\eta_{fe})\eta_E PV_{fe} - \eta_{fd} PV_{fd},\ -\eta_{fd} PV_{fd}\right]$$

where η_{fe} is the ratio of the cost of fusion energy to the best alternative, for the projected market share assigned to fusion in the baseline case. For the case of comparison with CO_2 sequestration this market share might be strongest in regions with limited storage capacity, or more distant from appropriate formations, or with greater environmental risk and/or concern associated with very-large-scale CO_2 sequestration. η_E is a factor to adjust the present value of the baseline amount of fusion energy PV_{fe}, if desired, for example to represent a larger or smaller market share, or a larger or smaller projected cost of the alternative energy source. If fusion costs more than an alternative non-CO_2-emitting energy source which can fill fusion's market share, $1-\eta_{fe}$ will be negative and the present value of the option will be negative, but limited to – $\eta_{fd} PV_{fd}$, the negative of the present value of the cost of fusion development, PV_{fd}, multiplied by another optional adjustment factor, η_{fd}. It is interesting to note that this last adjustment factor could be greater than unity if fusion development proves to be more costly than projected here but the downside risk can be capped at a less negative value in the case where a showstopper appears during fusion development or a demonstrably cheaper source of clean energy is found during this time that can displace fusion's potential market share.

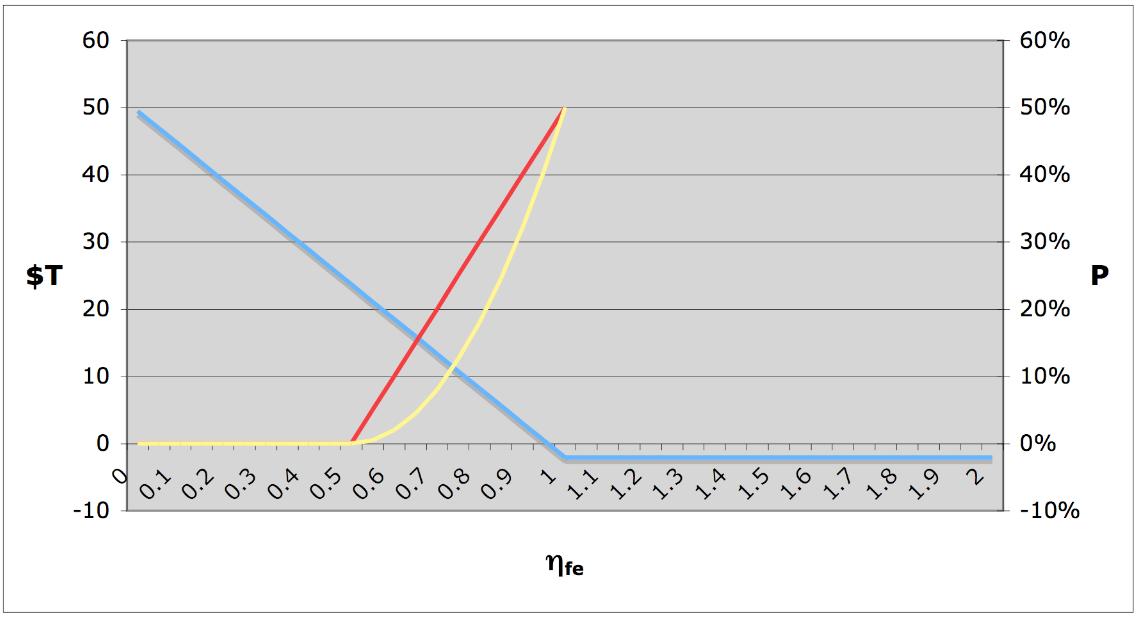

FIG. 5. Present value of the fusion option (blue) in T vs. η_{fe} *for the deterministic public debt case.* $\eta_E = 1$. $\eta_{fd} = 25$ *for clarity. Also shown are two putative probability distributions (red / linear and yellow / quadratic) for the cumulative probability of* η_{fe} *falling below a given number.*

We assume a linear or quadratic cumulative probability distribution for $P(\eta_{fe})$ starting at $P = 0$ for $\eta_{fe} = 0.5$ and rising to $P = P_1$ at $\eta_{fe} = 1$, in order to represent the conservative position that fusion will not be less than half as expensive as the best alternative for its market share. This makes it straightforward to integrate over all cases to find the average present value of the fusion option, retaining P_1 as a variable. The results are

$$\langle NPV_{op} \rangle = \frac{P_1}{4}\eta_E PV_{fe} - \eta_{fd} PV_{fd} \quad (linear); \quad \langle NPV_{op} \rangle = \frac{P_1}{6}\eta_E PV_{fe} - \eta_{fd} PV_{fd} \quad (quadratic)$$

The requirement for $\langle NPV_{op} \rangle$ to be positive can be expressed as a condition on P_1:

$$P_1 > 4\eta_{fd} PV_{fd} / (\eta_E PV_{fe}) \quad (linear); \quad P_1 > 6\eta_{fd} PV_{fd} / (\eta_E PV_{fe}) \quad (quadratic)$$

Taking $\eta_E = \eta_{fe} = 1$, we can then determine the required "breakeven" P_1 for the different evalutions of present value discussed above. The result can be scaled as η_{fd} / η_E, if required.

P_1 for breakeven	Linear	Quadratic
10-year Bond Deterministic	2.51%	3.76%
Public Debt Deterministic	0.616%	0.923%
10-year Bond Stochastic	1.93%	2.90%
Public Debt Stochastic	0.299%	0.449%

This analysis indicates that if the probability that fusion will cost less than the best environmentally acceptable alternative for its potential market share is more than a few percent – the option purchased through fusion R&D is "worth it." Because PV_{fe} is in the range of \$11T to \$120T, and PV_{fd} is in the range of \$80B, the payoff for fusion coming in below η_{fe}= 1 is very large indeed. For η_{fe}= 0.9, using the Public Debt Deterministic model, the NPV for the fusion development option is 5.4T US\$2005, 67 times its cost.

6. Insuring against high costs for clean energy through savings

As discussed in Section 4, an alternative to investing in the option of fusion development would be for the government to establish a fund that would invest in government securities, in order to have a low-risk hedge against high prices for acceptably clean and safe energy. We have calculated that PV_{fe} is in the range of \$11T to \$120T. This stemmed originally from an assumption that electricity would cost 7.3¢/kWh, US\$2005. If we wanted to hedge against an increase in cost of only 2¢/kWh for the baseline fusion share of the energy market, the PV of the insurance fund would need to be in the range of \$3T to \$33T. Said differently, choosing not to invest in fusion energy development, but rather to invest the same 80B US\$2005 in such a fund, would provide insurance against an increase of only 0.0048 to 0.053¢/kWh.

7. Conclusions

We have developed an approach to assessing the present value of fusion energy development using an options analysis framework. Since only governments can make large, long-term investments with significant risk, we take the opportunity cost to be the real interest paid on government securities. Due to the large size of future energy markets the investment in fusion development is very attractive if the probability is more than a few percent that fusion will cost less than the best environmentally acceptable alternative for its market share.

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