



Financing Fusion Energy

Andrew W. Lo, MIT

6 May 2024

Q Group Spring 2024 Seminar

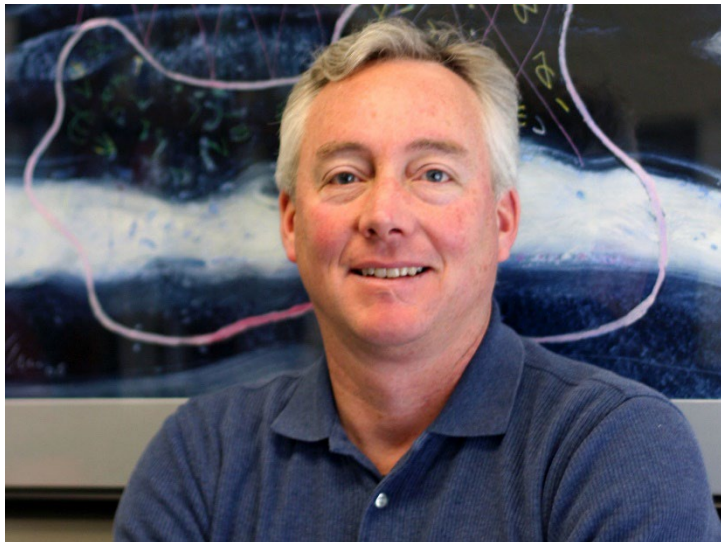
The background image for the bottom right section of the slide features a blue, abstract, digital pattern resembling a circuit board or data flow, with the text "MIT Laboratory for Financial Engineering" overlaid in white and red.

MIT

Laboratory for
Financial Engineering



Collaboration



Prof. Dennis Whyte
MIT Nuclear Engineering

6 May 2024

© 2024 by Andrew W. Lo
All Rights Reserved

Slide 3



JOIM
www.joim.com

JOURNAL OF INVESTMENT MANAGEMENT, Vol. 21, No. 1, (2023), pp. 5-51
© JOIM 2023

FINANCING FUSION ENERGY

Abdullah Alhamsani^a, Zachery M. Halen^b, Irene Hernandez^c,
Andrew W. Lo^{d,e,f}, Manish Singh^g and Dennis Whyte^h

The case for investing in fusion energy has never been greater, given increasing energy demand, high annual carbon dioxide output, and technological wind and solar power. Nevertheless, financing for fusion companies through means has proven challenging. While fusion startups have an unparalleled high upfront costs, lengthy delay in payoff, and high risk of commercial historically restricted funding interest to a niche set of investors. Drawn from investor interviews and case studies of public-private partnerships, megafund structure in which a large number of projects are securitized holding company funded through various debt and equity tranches, with financial guarantees from governments and philanthropic partners. The megafund of the core properties of the fusion industry: the diversity of approaches fusion reactions, the ability to create revenue-generating divestitures in relation to the breadth of auxiliary technologies needed to support a functioning power model expands the pool of available capital by creating tranches with different tradeoffs and providing a diversified "fusion index" that can be viewed as against fossil fuels. Simulations of a fusion megafund demonstrate positive equity (ROE) and low default rates for the capital raised using debt.



1 Introduction

With greenhouse gas levels global warming already extreme weather events, of fossil fuels expected

What Fusion Energy Can Learn from Biotechnology*

Andrew W. Lo^{1-4,†} and Dennis Whyte⁵⁻⁶

¹MIT Sloan School of Management, Cambridge, MA, USA;
²MIT Laboratory for Financial Engineering, Cambridge, MA, USA;
³MIT Computer Science and Artificial Intelligence Laboratory, Cambridge, MA, USA;
⁴Santa Fe Institute, Santa Fe, NM, USA;
⁵MIT Department of Nuclear Science & Engineering, Cambridge, MA, USA;
⁶MIT Plasma Science and Fusion Center, Cambridge, MA, USA;
[†]Corresponding author: Andrew W. Lo alo-admin@mit.edu

This version: 27 February 2024

Abstract

Fusion energy is currently facing many of the same opportunities and challenges as the biotechnology industry of the 1970s: exciting scientific and engineering breakthroughs that could change the course of human history, with sufficient public and private funding, more effective business models, and appropriate regulatory oversight. A number of lessons can be learned from the last 50 years of biotechnology industry history, which lead to five proposed initiatives for accelerating progress in fusion: the creation of a university intellectual-property consortium; the standardization of fusion energy milestones along with fusion rating agencies to certify their achievement; the development of new financing and business models to fund the various stages of fusion progress; a coordinated plan for two-sided outreach, education, and engagement at all levels from K-12 to policymakers and the general public; and managing fusion initiatives as part of a broader ecosystem. Applying these historical lessons today can accelerate the development of fusion towards the same level of commercial success and human impact that biotech has achieved.

*We thank David Cohen-Tanugi, Jayna Cummings, Maria Hancock, Peter Hancock, Andrew Holland, Scott Heu, Brad Smith, and Sam Wurzel for many helpful comments and discussions. The views and opinions expressed in this article are those of the authors only, and do not necessarily represent the views and opinions of any institution or agency, any of their affiliates or employees, or any of the individuals acknowledged above. Research funding for this project was provided by the MIT Laboratory for Financial Engineering and its sponsors (listed at <https://lfe.mit.edu/about/sponsors/>). No funding bodies had any role in study design, data collection and analysis, decision to publish, or preparation of this manuscript. No direct funding was received for this study. The authors were personally salaried by their institutions during the period of writing (though no specific salary was set aside or given for the writing of this manuscript).

© 2024 by Lo and Whyte
All Rights Reserved

Energy Transition

AUGUST 2022

MI

Report

The “Energy Transition” Delusion: A Reality Reset

Mark P. Mills

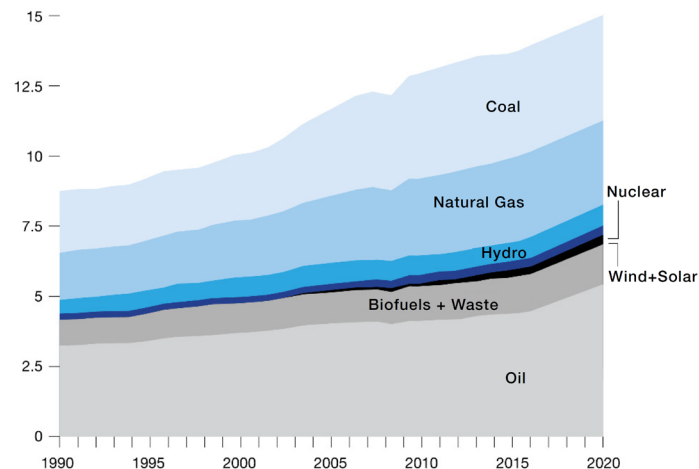
SENIOR FELLOW
Manhattan Institute



1. ENERGY TRANSFORMATIONS ARE SLOW

Growth in Global Energy Supplies

Oil Equivalent (Billion Tons/Year)*



Note: 1 billion tons oil/year = 20 million barrels/day.

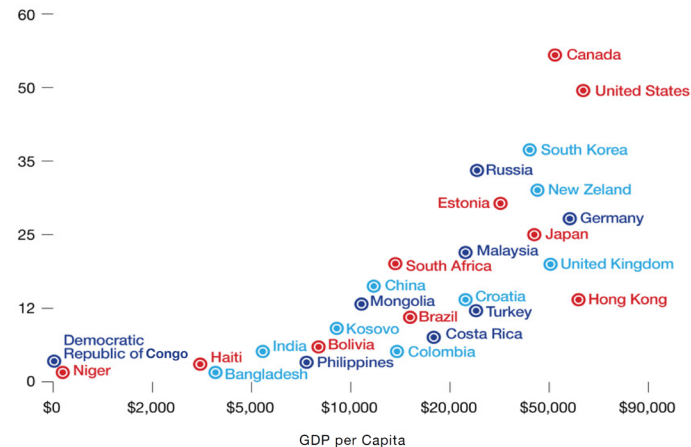
Source: BP, Statistical Review of World Energy 2022

Energy Transition

2. ECONOMIC GROWTH CREATES DEMAND FOR MORE ENERGY

Per Capita Wealth vs. per Capita Energy Use

Energy per Capita (BOE/year)*



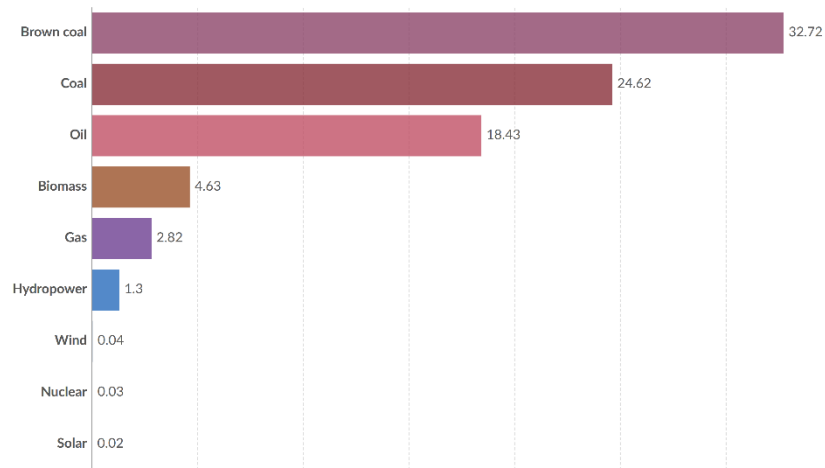
*Note: Total energy measured as barrels-of-oil-equivalent (BOE). Thus, the average person in Japan, where GDP/capita is about \$50,000, uses about 25 BOE per year vs. about 5 BOE in India, where GDP per capita is around \$5,000.

Source: World Bank; Our World in Data

Death rates per unit of electricity production

Death rates are measured based on deaths from accidents and air pollution per terawatt-hour¹ of electricity.

Our World
in Data



Data source: Markandya & Wilkinson (2007); Sovacool et al. (2016); UNSCEAR (2008; & 2018) OurWorldInData.org/energy | CC BY

1. Watt-hour: A watt-hour is the energy delivered by one watt of power for one hour. Since one watt is equivalent to one Joule per second, a watt-hour is equivalent to 3600 Joules of energy. Metric prefixes are used for multiples of the unit, usually: - kilowatt-hours (kWh), or a thousand watt-hours. - Megawatt-hours (MWh), or a million watt-hours. - Gigawatt-hours (GWh), or a billion watt-hours. - Terawatt-hours (TWh), or a trillion watt-hours.

Energy Transition

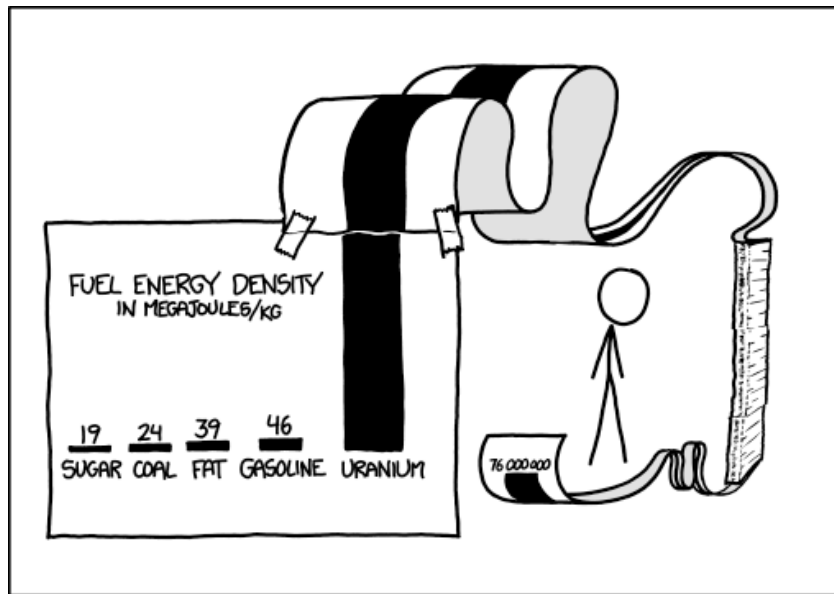
- Everyone agrees that this is important
- But what are we transitioning to??



1. Fission
2. Fusion
3. Geothermal

**Most (politically) realistic
solution: fusion**

Energy Density



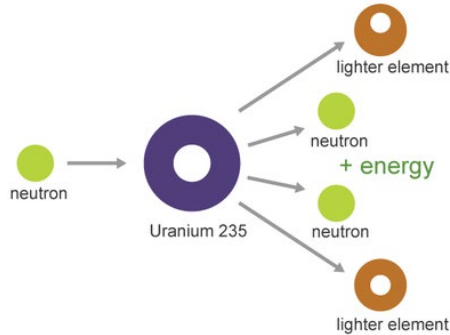
SCIENCE TIP: LOG SCALES ARE FOR QUITTERS WHO CAN'T
FIND ENOUGH PAPER TO MAKE THEIR POINT *PROPERLY*.

Source: <https://xkcd.com/1162/>

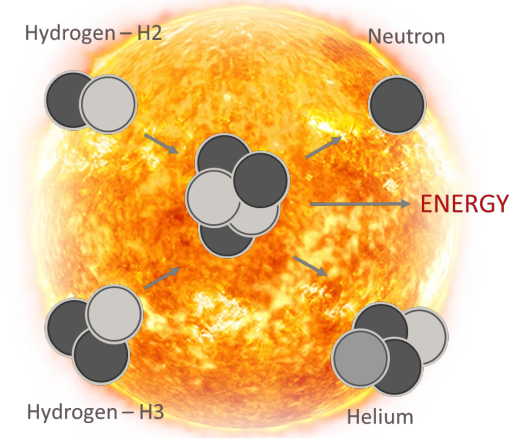
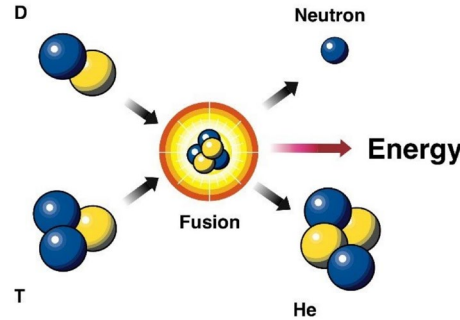
$$E = m c^2$$

Why Fusion?

Fission

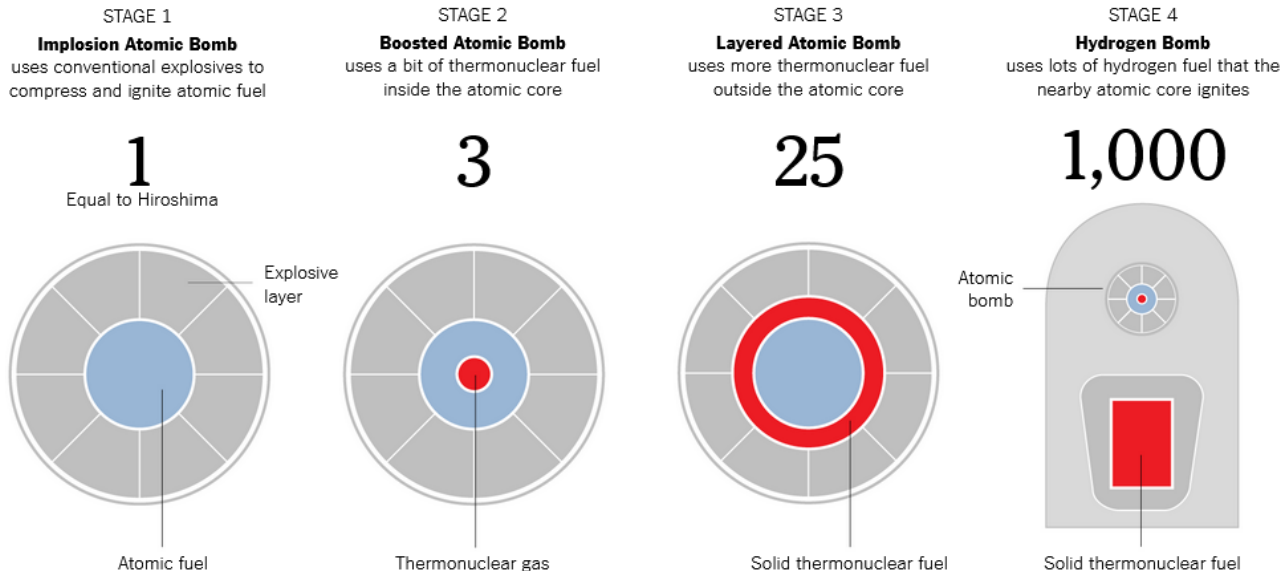


Fusion



- Fusing hydrogen-2 (deuterium) with hydrogen-3 (tritium)
- Fusion can produce 4 times more energy per kg of fuel than fission, with no long-lived radioactive waste (helium + tritium)

Why Fusion?



Note: Destructive power for each stage is based on early tests in the U.S. and U.S.S.R., not on current stockpiles.

By The New York Times

Source: C. Buckley, NYTimes 3 Sep 2017

Why Fusion?

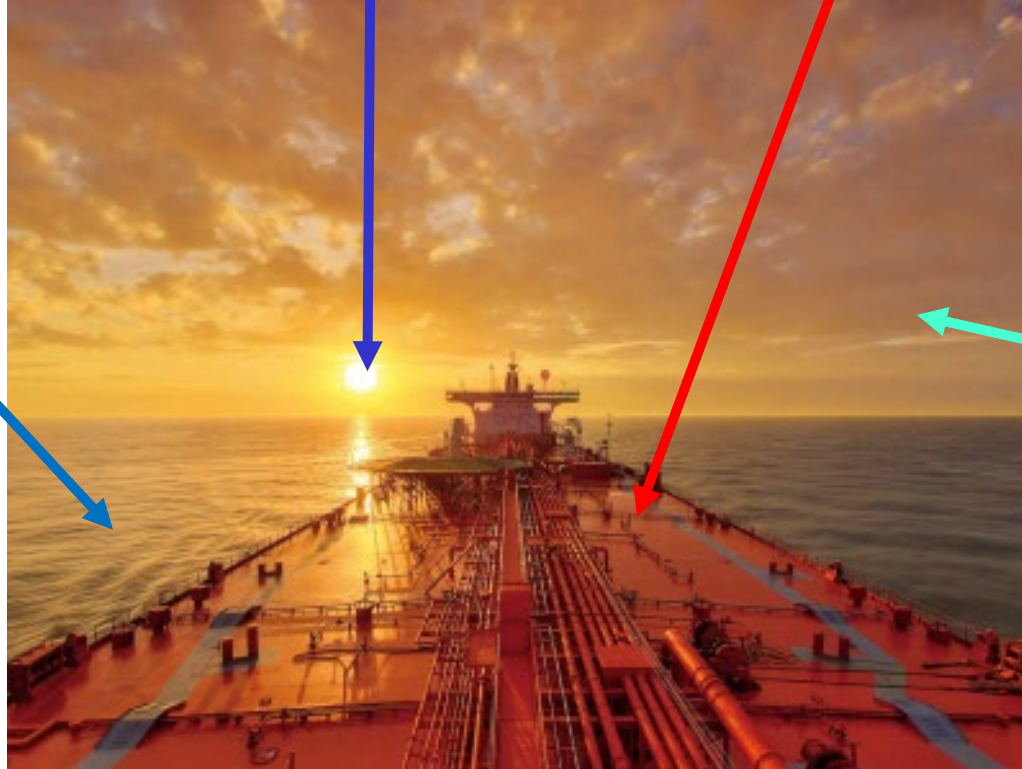
1. Filter 20gal of deuterium from 1/600th of the water displaced by the tanker*



*Or buy it for \$200k

2. Fuse it

3. Produce as much energy as in the tanker's oil**



4. Do not emit 200,000 tons of CO₂

Source: D. Whyte, Feb 22, 2021

** \$750M value

Why Fusion?

- No polluting emissions
- Freely available and inexhaustible fuel supply
- Flexible generation anywhere
- No meltdown or long-lived nuclear waste in fuel cycle
- No fissile material proliferation
- Civilization-scale energy

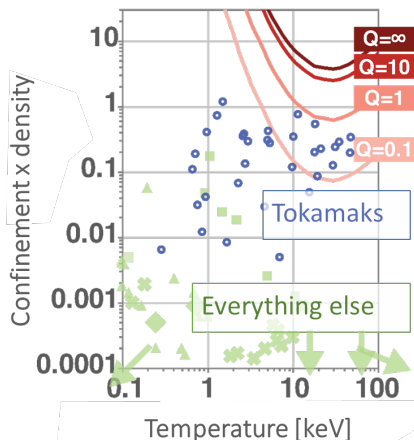
**Addresses climate change, energy security, and equity...
but **when** will it happen??**

Why Now?

Lawson (1955) Triple Product—Fusion Requires: $n \times T \times \tau_E$

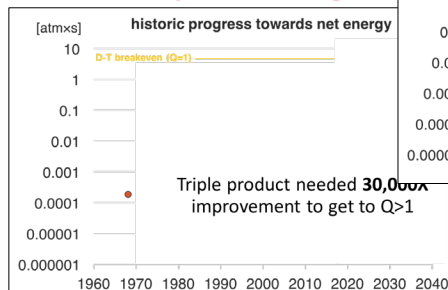
- High temperature (> 100M degrees C)
- Density (pressure)
- Time

$$Q = \frac{\text{Fusion power out}}{\text{Heating power in}}$$

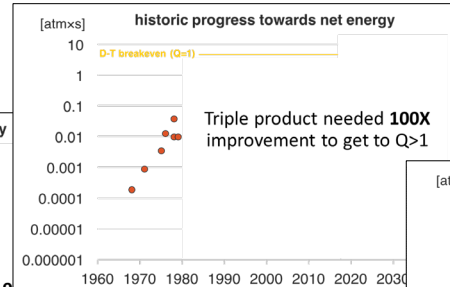


Source: D. Whyte, Feb 22, 2021

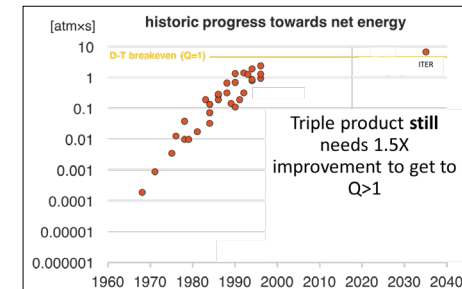
50 years ago



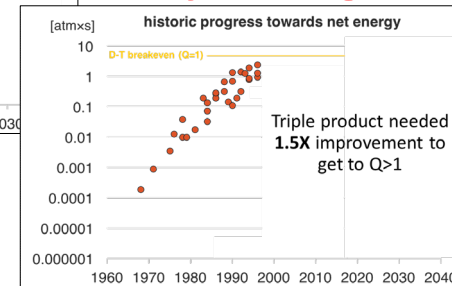
40 years ago



3 years ago



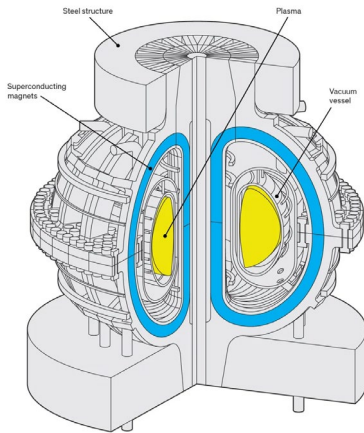
20 years ago



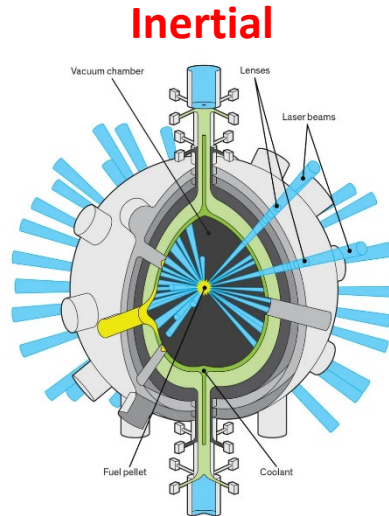
Why Now?

Lawson (1955) Triple Product—Fusion Requires:

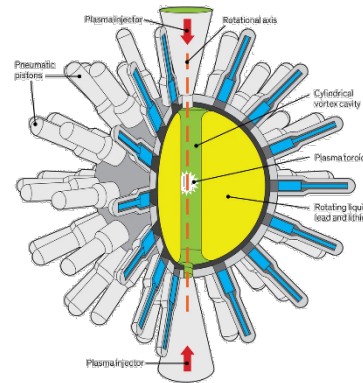
- High temperature ($> 100\text{M}$ degrees C)
- Density (pressure)
- Time



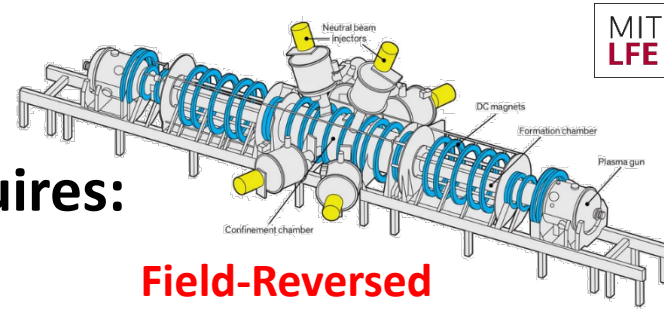
Tokamak



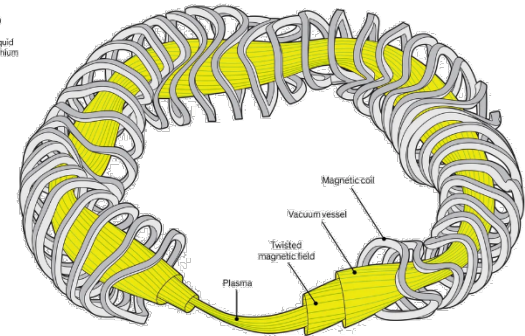
Inertial



Magnetized Target



Field-Reversed Configuration



Stellarator

Source: <https://spectrum.ieee.org/5-big-ideas-for-making-fusion-power-a-reality>

Why Now?

CLEAN ENERGY

Fusion gets closer with successful test of new kind of magnet at MIT start-up backed by Bill Gates

PUBLISHED WED, SEP 8 2021-4:02 PM EDT | UPDATED THU, SEP 9 2021-12:42 PM EDT



Catherine Clifford
@CATCLIFFORD
@CATCLIFFORD

World / Climate

Scientists successfully replicate historic nuclear fusion breakthrough three times

By Laura Paddison, CNN

4 minute read - Updated 1:14 AM EST, Thu December 21, 2023



Dec 21, 2023



See CNN's visit to the nuclear fusion lab trying to replicate the Sun on Earth (May, 2023)

Video Ad Feedback

02:24 - Skunk

The CFS and MIT teams working

Credit: Gretchen Ertl, CFS/MIT - 12/21/2023

[Back](#)

Dec 5, 2022

A shot for the ages: Fusion ignition breakthrough hailed as 'one of the most impressive scientific feats of the 21st century'



Apr 20, 2023

CLEAN ENERGY



REUTERS

World Business Markets Sustainability Legal Breakingviews Technology Investigations

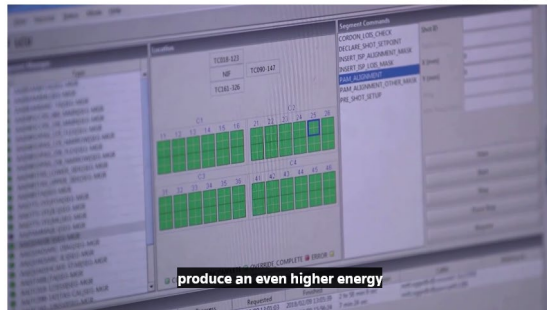
Energy | Grid & Infrastructure | Nuclear

Aug 7, 2023

US scientists repeat fusion ignition breakthrough for 2nd time

Reuters

August 7, 2023 3:07 AM EDT - Updated a month ago





Can Financial Engineering Fund Fusion?



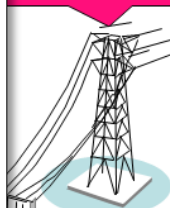
JOURNAL OF INVESTMENT MANAGEMENT, Vol. 21, No. 1, (2023), pp. 5–51
© JOIM 2023

FINANCING FUSION ENERGY

Abdullah Alhamdan^a, Zachery M. Halem^b, Irene Hernandez^c,
Andrew W. Lo^{d,*}, Manish Singh^e and Dennis Whyte^f

The case for investing in fusion energy has never been greater, given increasing global energy demand, high annual carbon dioxide output, and technological limitations for wind and solar power. Nevertheless, financing for fusion companies through traditional means has proven challenging. While fusion startups have an unparalleled upside, their high upfront costs, lengthy delay in payoff, and high risk of commercial failure have historically restricted funding interest to a niche set of investors. Drawing on insights from investor interviews and case studies of public-private partnerships, we propose a megafund structure in which a large number of projects are securitized into a single holding company funded through various debt and equity tranches, with first loss capital guarantees from governments and philanthropic partners. The megafund exploits many of the core properties of the fusion industry: the diversity of approaches to engender fusion reactions, the ability to create revenue-generating divestitures in related fields, and the breadth of auxiliary technologies needed to support a functioning power plant. The model expands the pool of available capital by creating tranches with different risk-return tradeoffs and providing a diversified “fusion index” that can be viewed as a long hedge against fossil fuels. Simulations of a fusion megafund demonstrate positive returns on equity (ROE) and low default rates for the capital raised using debt.

Electricity Supply



Powering facility

Electrical Output

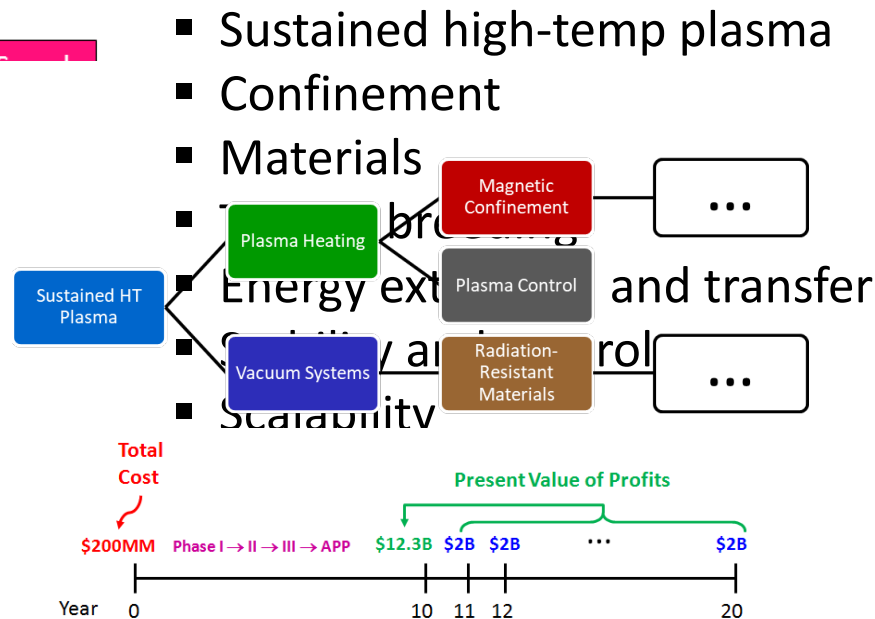
- Sustained high-temp plasma
- Confinement
- Materials
- Tritium breeding
- Energy extraction and transfer
- Stability and control
- Scalability
- Fuel cycle management
- Economic viability
- Regulation and licensing

Source: <https://www.qst.go.jp/site/qst-english/>

Can Financial Engineering Fund Fusion?

superconducting coils

- Plasma heating systems
- Advanced vacuum systems
- Advanced magnetic confinement
- Plasma control techniques
- Improved divertor technology
- Fusion ignition



Can Financial Engineering Fund Fusion?

Imagine a \$10 Billion Fusion Megafund

- Imagine creating an advisory board of experts:
 - Mike Campbell, Steven Chu, Rob Goldston, David Larbalestier, Ernest Moniz, Tom Todd, Dennis Whyte, Scott Wilms
 - Bill Ackman, Warren Buffett, Jeff Bezos, Bill Gates, Vinod Khosla, Bob Merton, Elon Musk, Peter Thiel, Bill Sharpe, Stephen Schwarzman, David Shaw, Jim Simons
- Imagine energy companies, sovereign wealth funds, pension funds, and even mutual funds investing in the fund

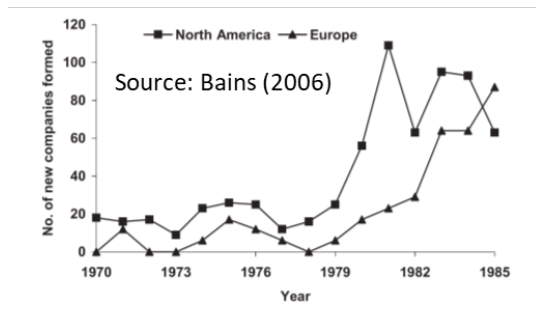
Would You Be Willing To Invest \$1,500 of Your 401(k)?

Private Fusion Companies Today



Source: <https://www.fusionindustryassociation.org/about/members/>

Fusion and Biotech



Biotech startups



Fusion startups

What's Needed:

1. Discrete milestones
2. Third-party certification (e.g., FDA, Moody's, S&P)
3. Access to public markets
4. Government support (e.g., NIH)
5. Outreach (e.g., public, policymakers)
6. **INVESTORS!**

- Fusion today is where biotech was in the 1970s

Conclusion

“Can We Afford Not To Try?”

- Cancer, Alzheimer’s, dementia, diabetes, obesity, pandemics, climate change, energy crisis, etc.

With the Proper Financial
Structure, Anything Is Possible...

Carpe Finance!



Thank You!