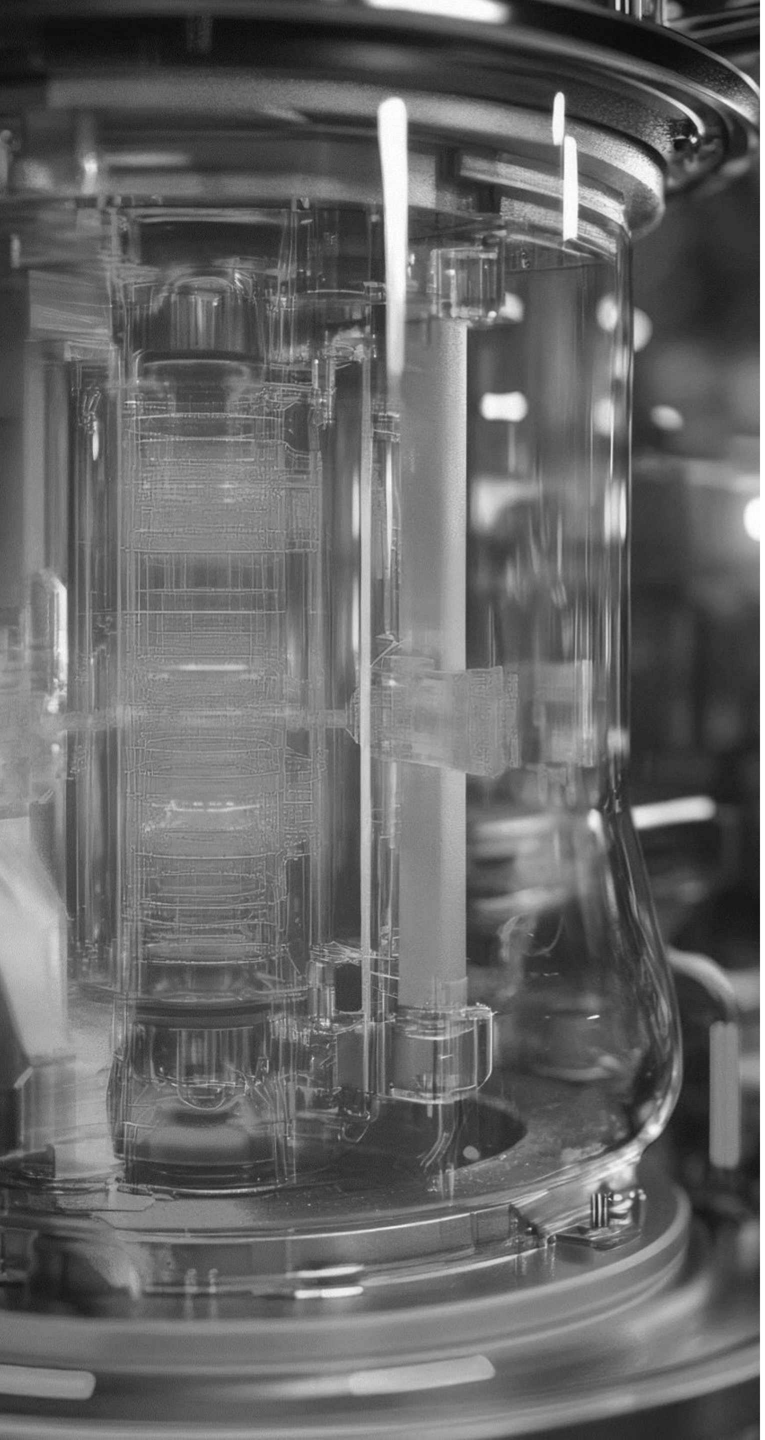


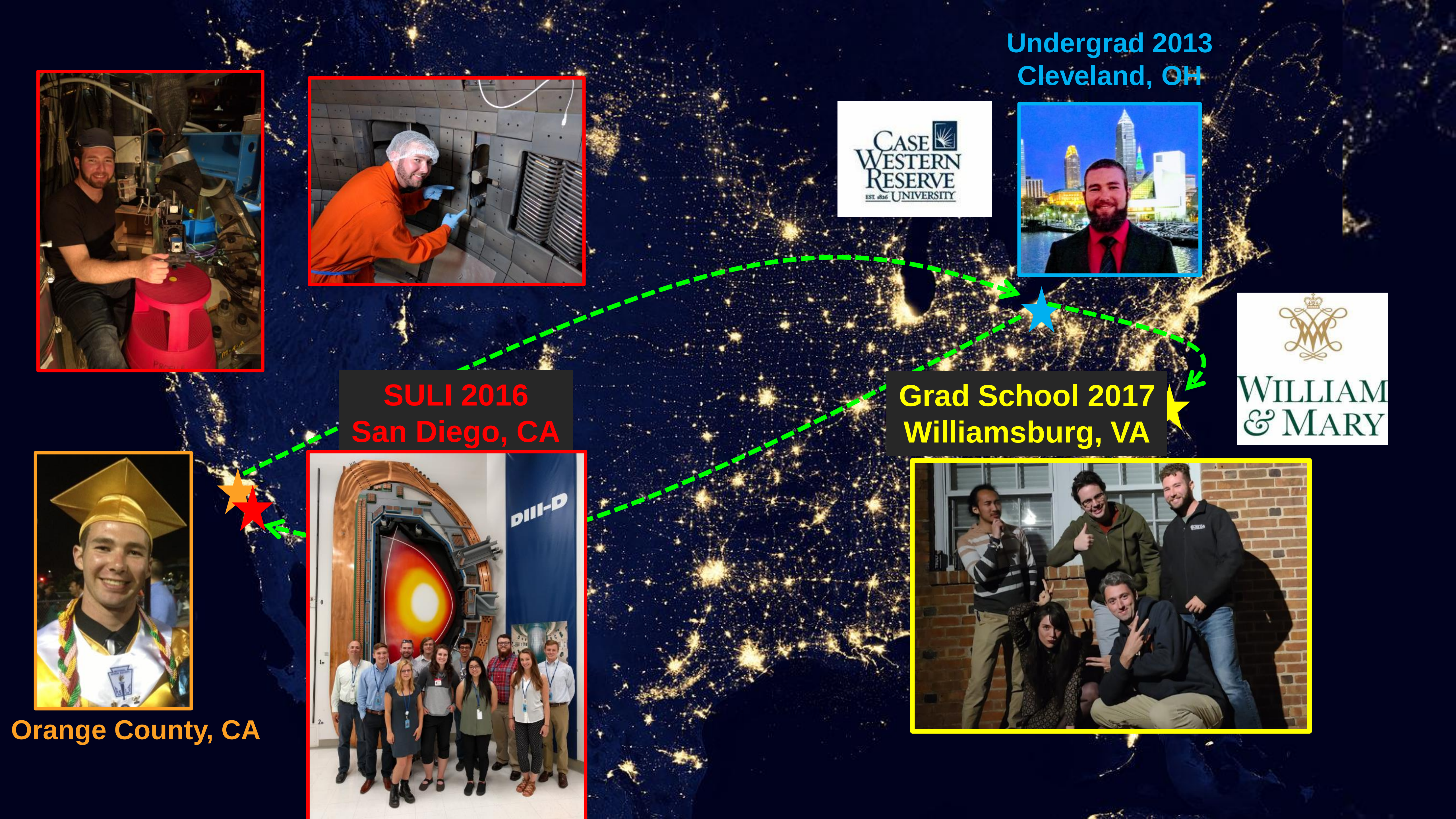
Fusion in a Market Context

Ryan Chaban

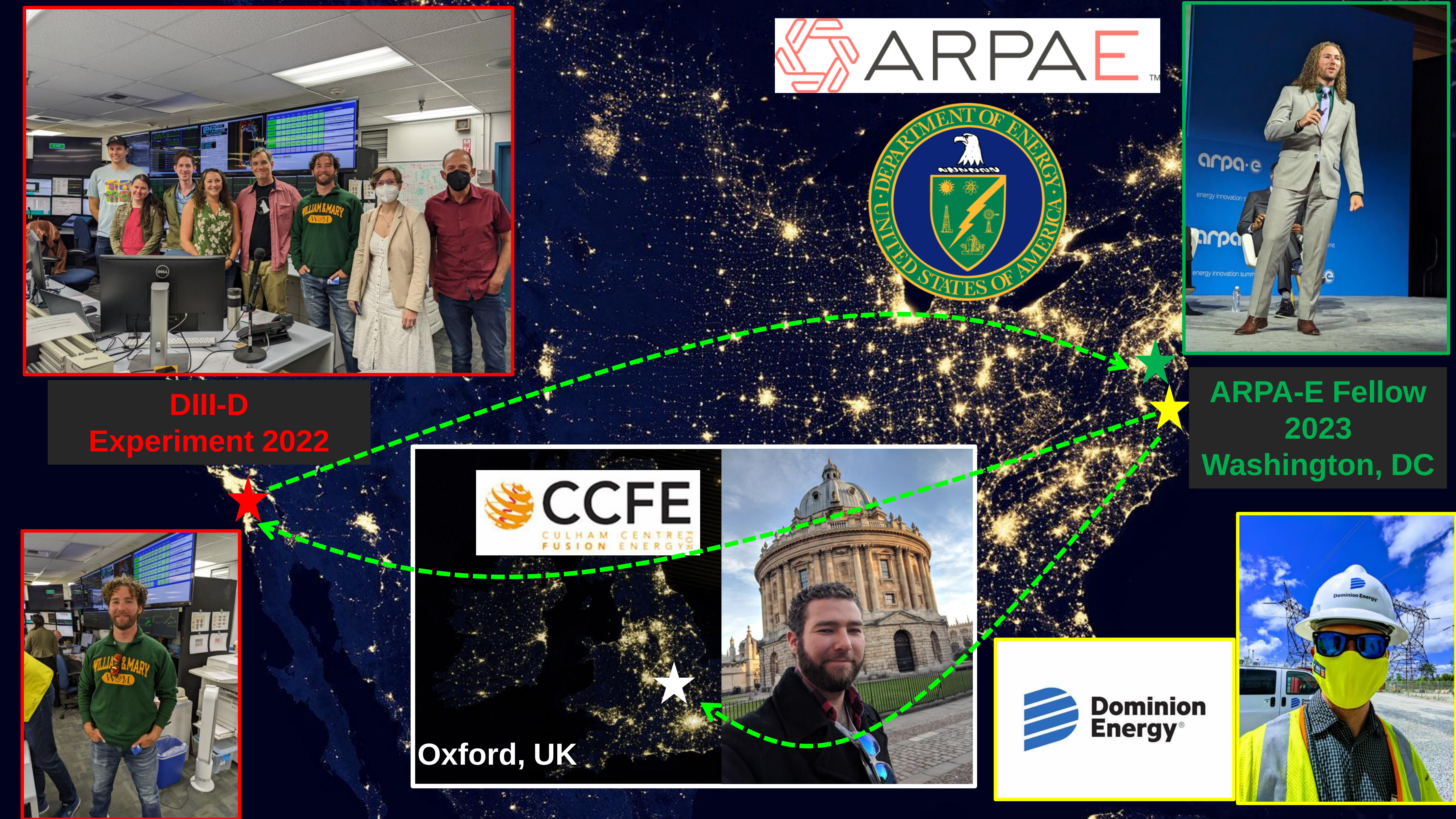
Fellow

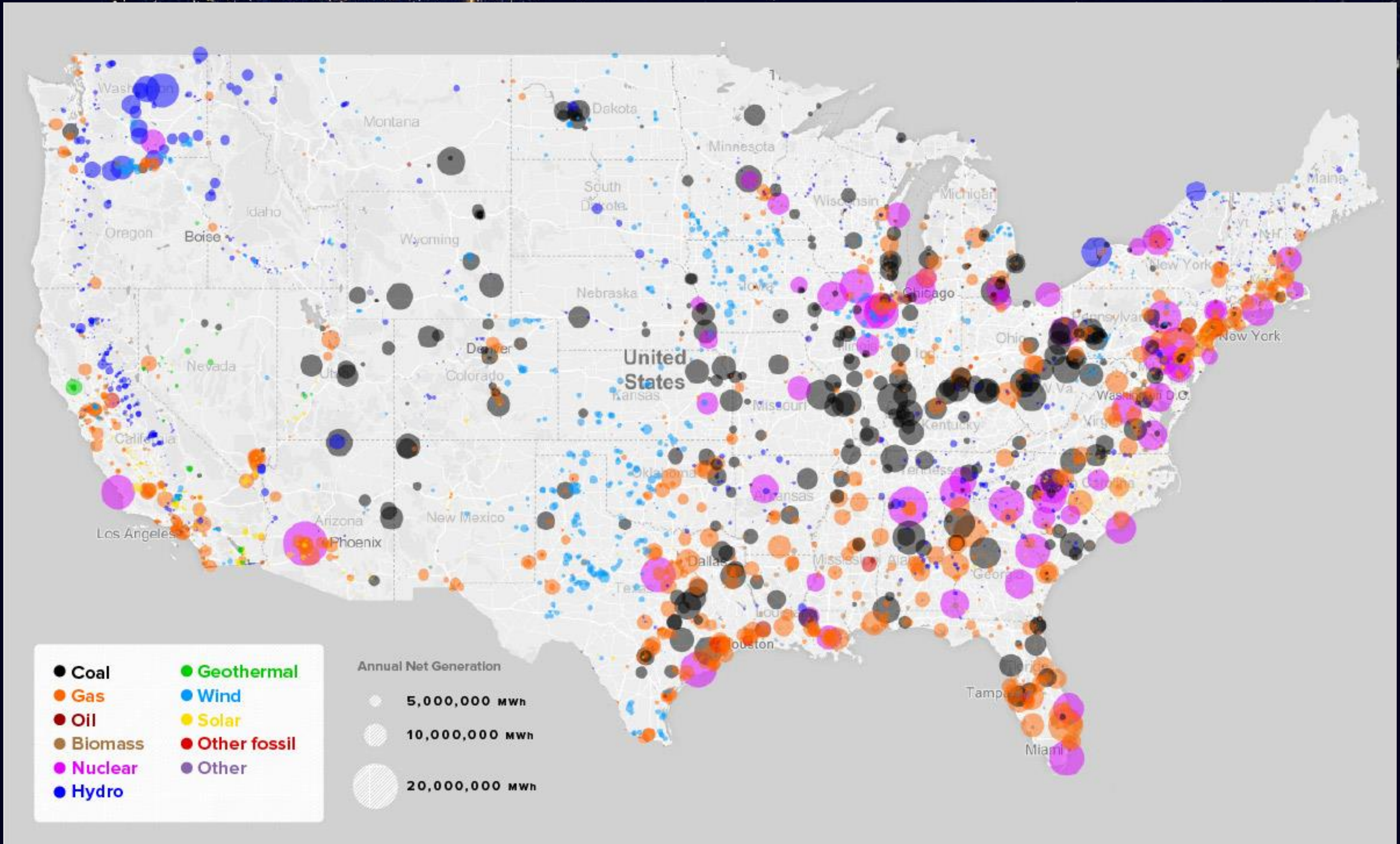
Advanced Research Projects Agency – Energy (ARPA-E)

June 6, 2025



Undergrad 2013
Cleveland, OH
CASE WESTERN RESERVE EST 1826 UNIVERSITY
SULI 2016
San Diego, CA
DIII-D
Grad School 2017
Williamsburg, VA
WILLIAM & MARY
Orange County, CA


ARPAE
DEPARTMENT OF ENERGY
UNITED STATES OF AMERICA
DIII-D
Experiment 2022
ARPA-E Fellow
2023
Washington, DC
CCFE
CULHAM CENTRE FOR FUSION ENERGY
Oxford, UK
Dominion Energy



Montana
Minnesota
Michigan
Maine
South Dakota
Oregon
Boise
Idaho
Wyoming
Nebraska
Chicago
Nevada
Colorado
United States
Kansas
Missouri
New York
Arizona
New Mexico
Phoenix
Los Angeles
Dallas
Tampa
Miami
Coal
Gas
Oil
Biomass
Nuclear
Hydro
Geothermal
Wind
Solar
Other fossil
Other
Annual Net Generation
5,000,000 MWh
10,000,000 MWh
20,000,000 MWh

Why should I build a Fusion Power Plant?

The Energy Landscape

- Energy Consumption & Production
- Making Energy
- Selling Energy

Considerations for an Energy Source

- Fusion Advantages (and Disadvantages)

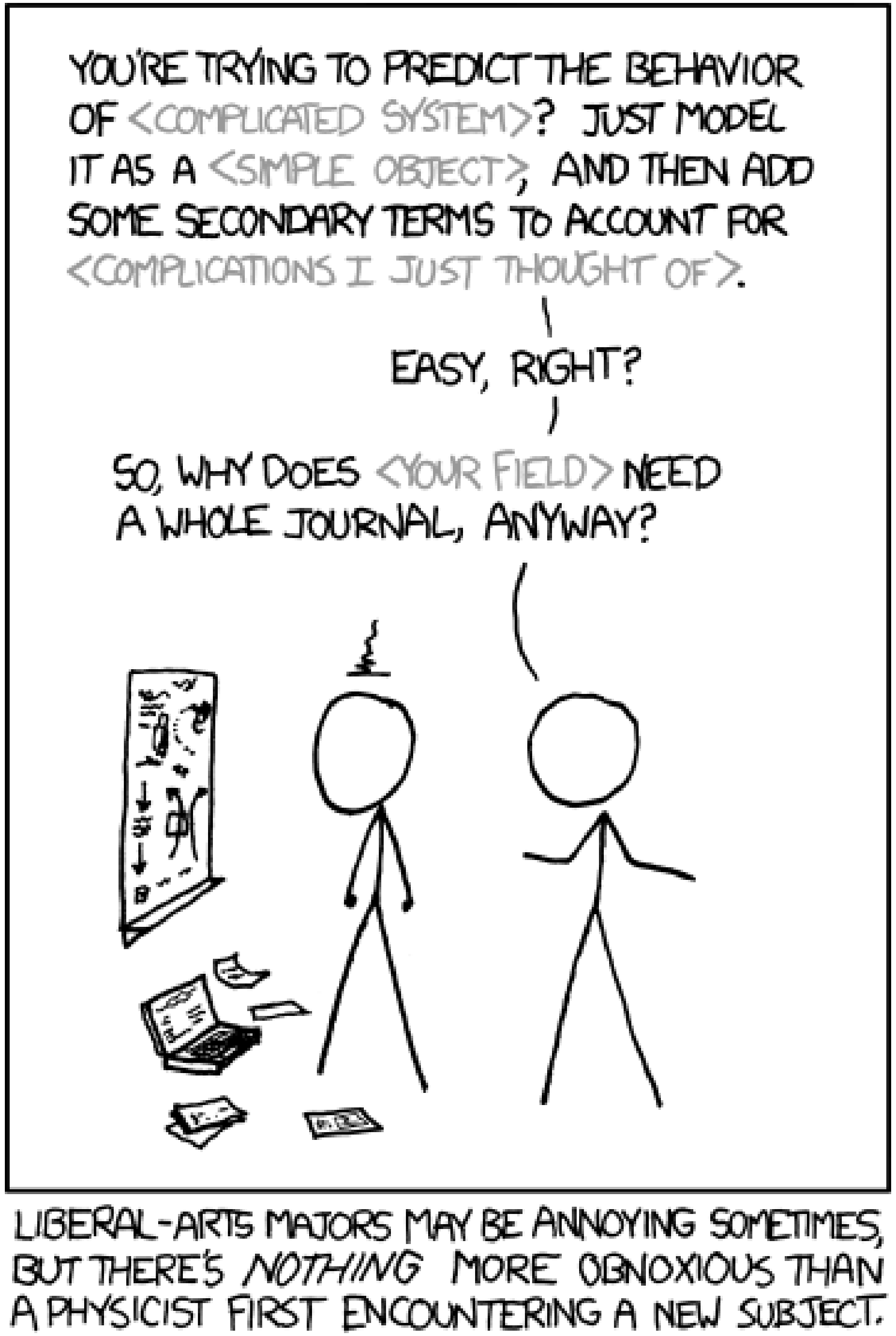
The ARPA-E Fun Show

- Fusion
- Not Fusion

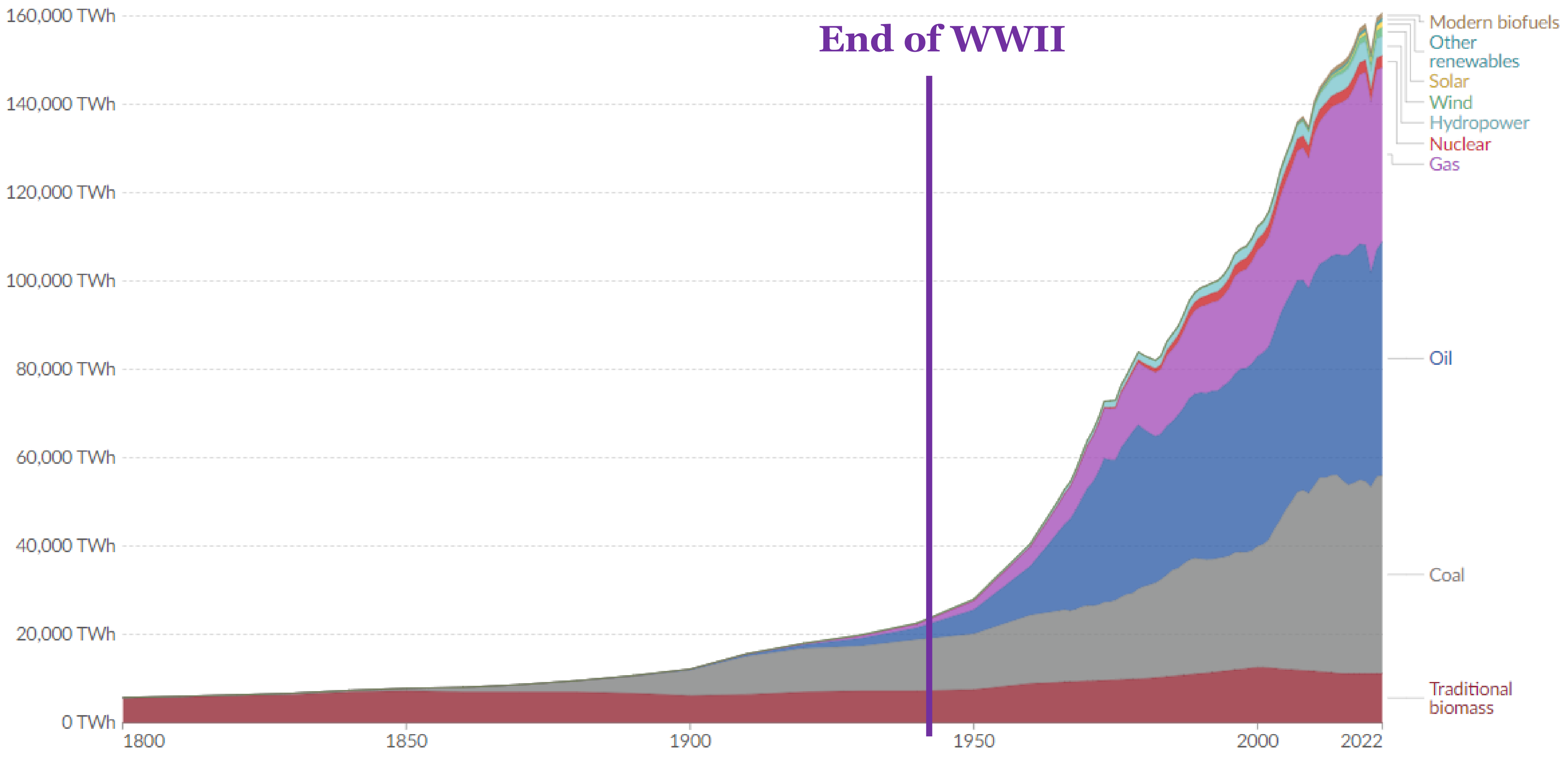
But First: A Disclaimer

1. The opinions expressed in this talk are my own not those of my employer
   (ARPA-E and the U.S. Government)

2. I have absorbed knowledge from experts, but absolutely do not consider myself an expert (see image)



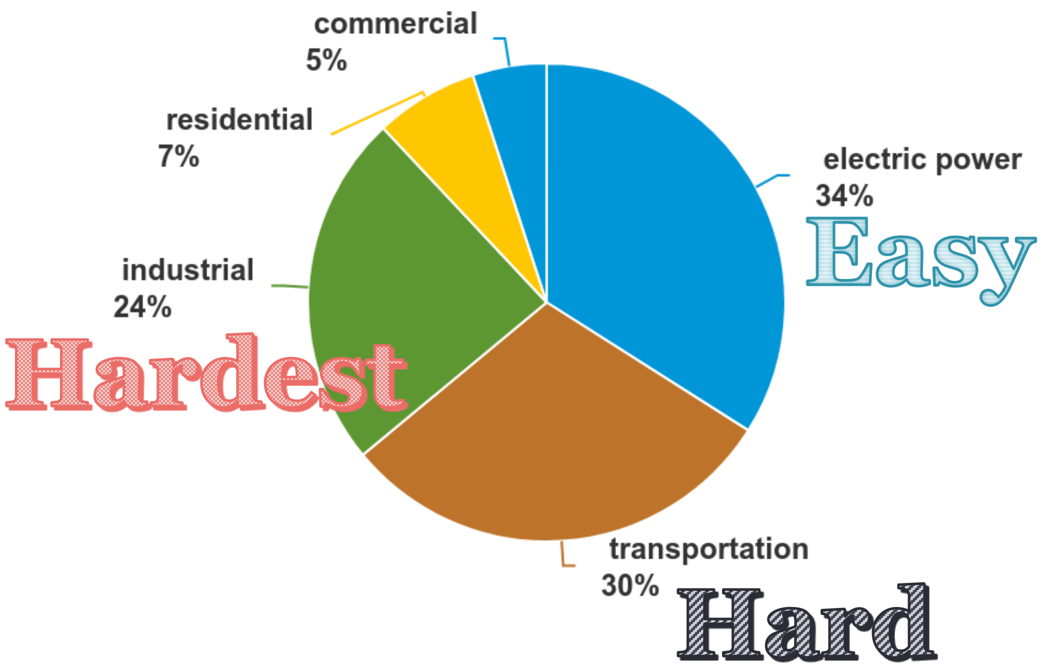
The world uses a lot of energy, and we have a lot of work to do



What types of energy do we need?

The US consumed approximately
94 Quads of **Primary Energy** in 2023

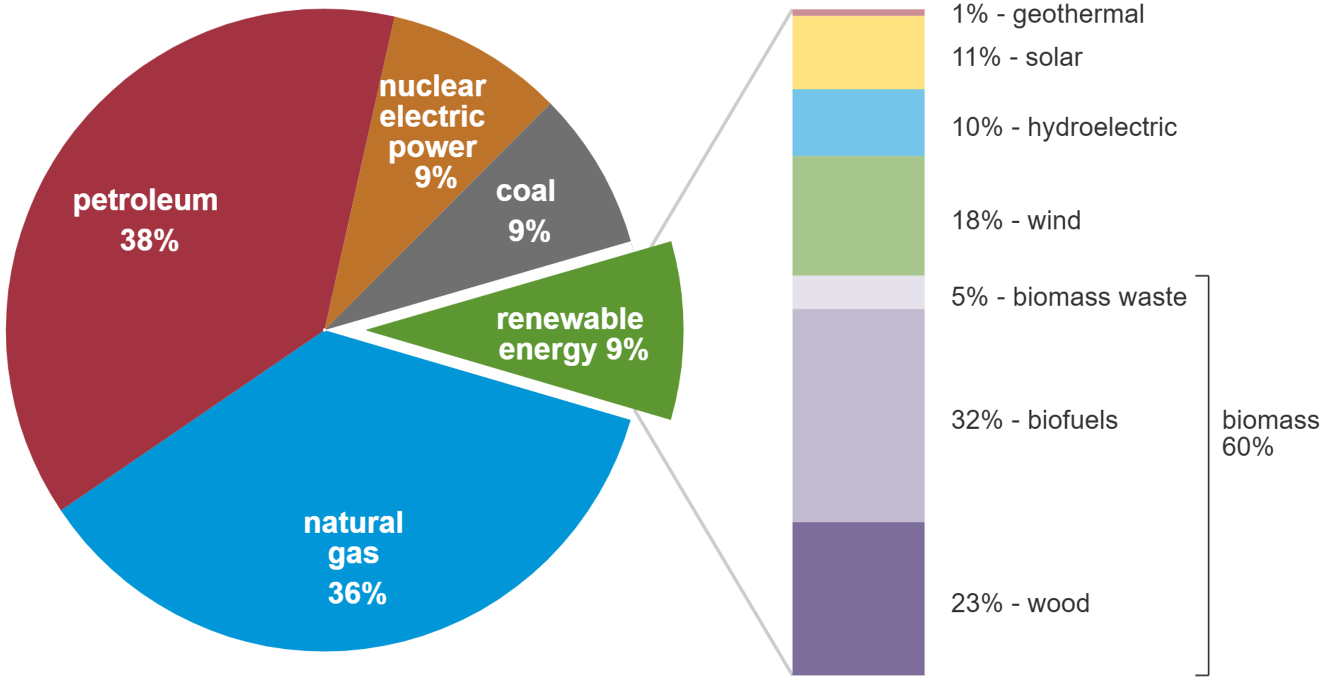
1 Quadrillion BTUs ~ 300 TWh



U.S. primary energy consumption by energy source, 2023

total = 93.59 quadrillion British thermal units

total = 8.24 quadrillion British thermal units



eia

Data source: U.S. Energy Information Administration, *Monthly Energy Review*, Table 1.3 and 10.1, April 2024, preliminary data
Note: Sum of components may not equal 100% because of independent rounding.

But why?

Energy is worth exactly what you can sell it for

What does energy cost to make?

How much can you sell it for?

Levelized Cost of Energy (LCOE)

CAPITALISM

$$\text{LCOE} = \frac{\text{Total Lifetime Costs}}{\text{Total Lifetime Sales}}$$

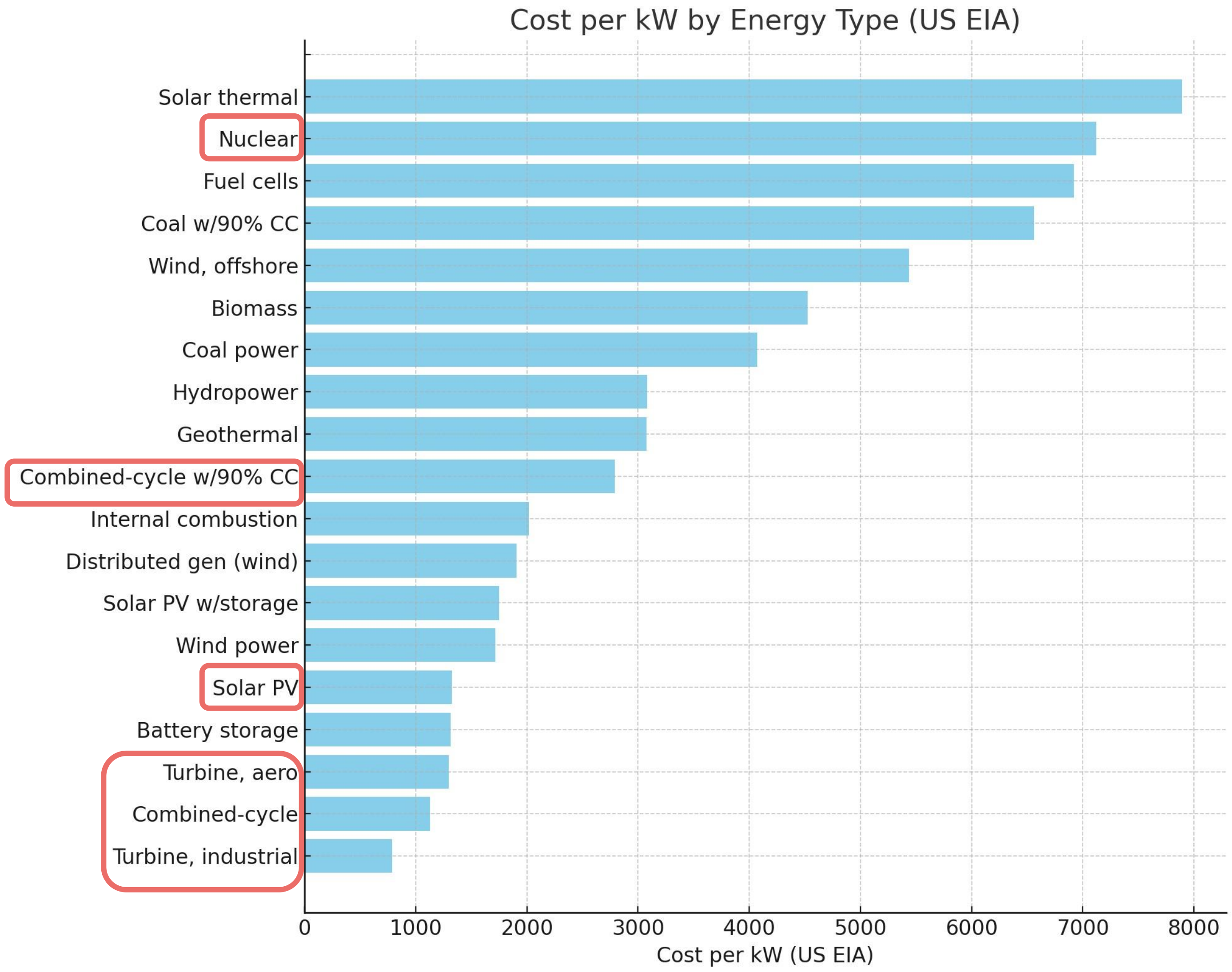
$$= \frac{\Sigma\, I_t + M_t + F_t}{\Sigma\, E_t}$$

Usually expressed in \$/kWh or \$/MWh

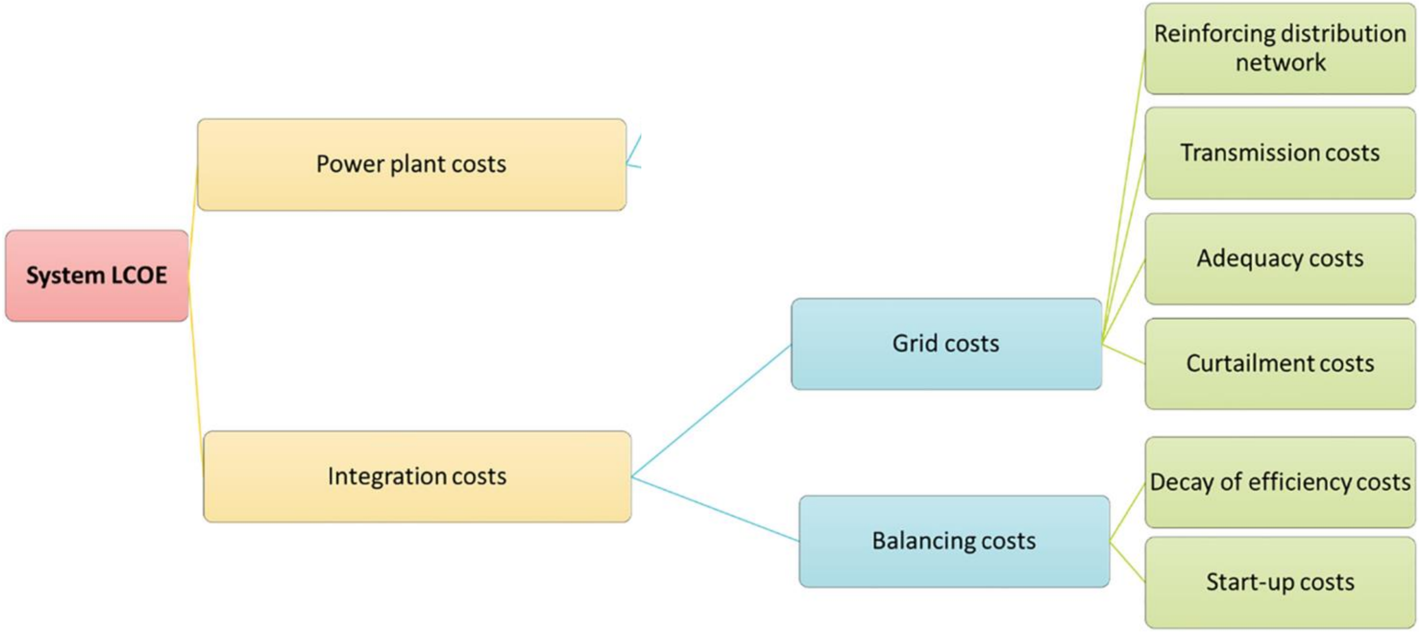
Wholesale grid prices:
~\$0.04 - \$0.40 /kWh
~ \$40 -\$400 / MWh

Gas	Nuclear		
Small	Huge	I_t	= Investment Costs
Medium	Medium	M_t	= Maintenance Costs
Medium - Huge	Tiny	F_t	= Fuel Costs
		E_t	= Energy Sold

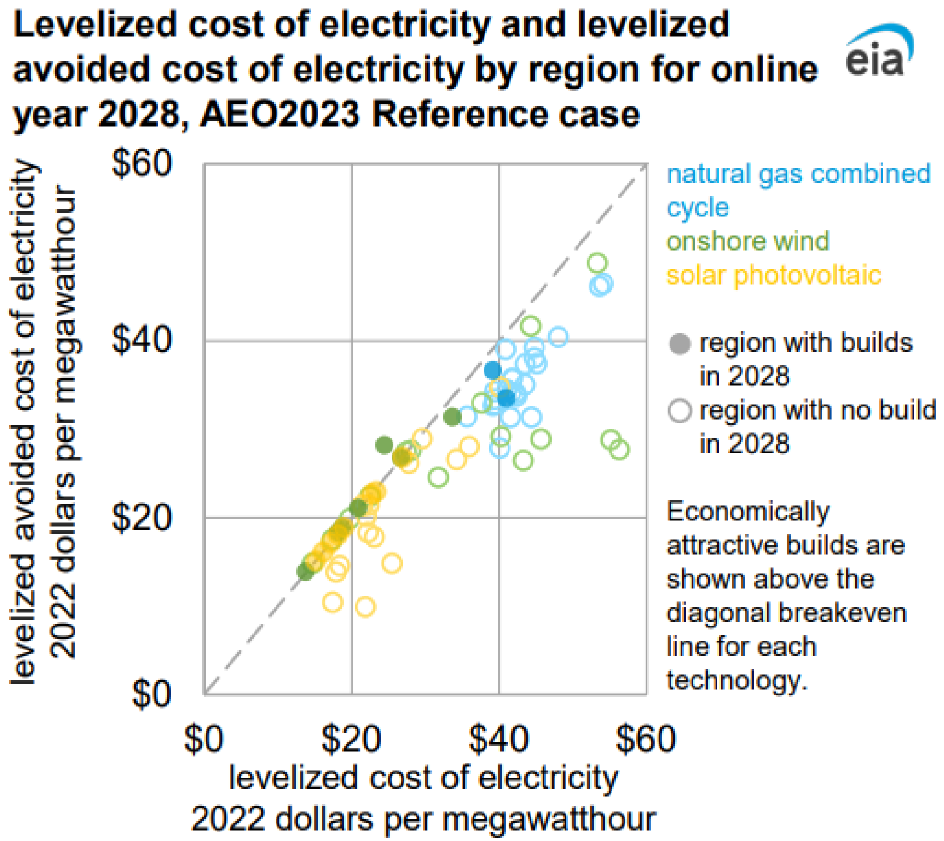
Nuclear is expensive



You need to connect a powerplant to the grid



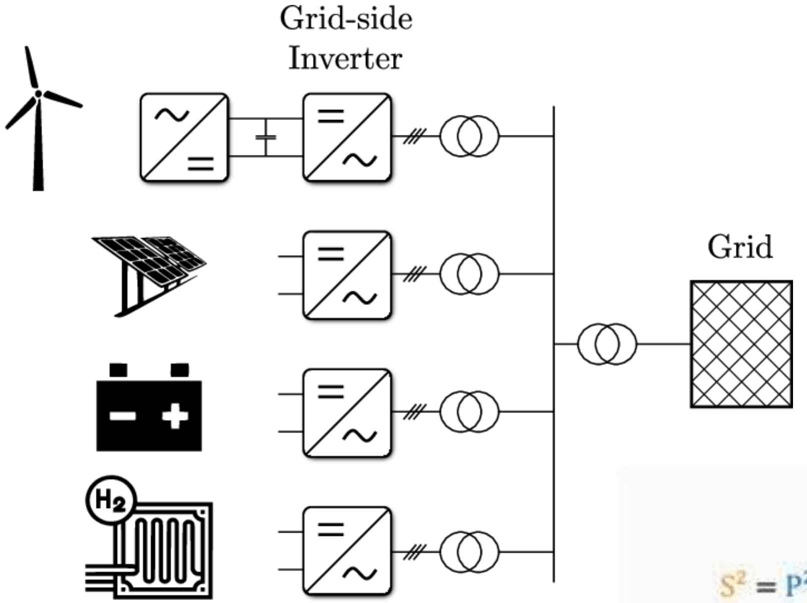
LCOE vs. LACE

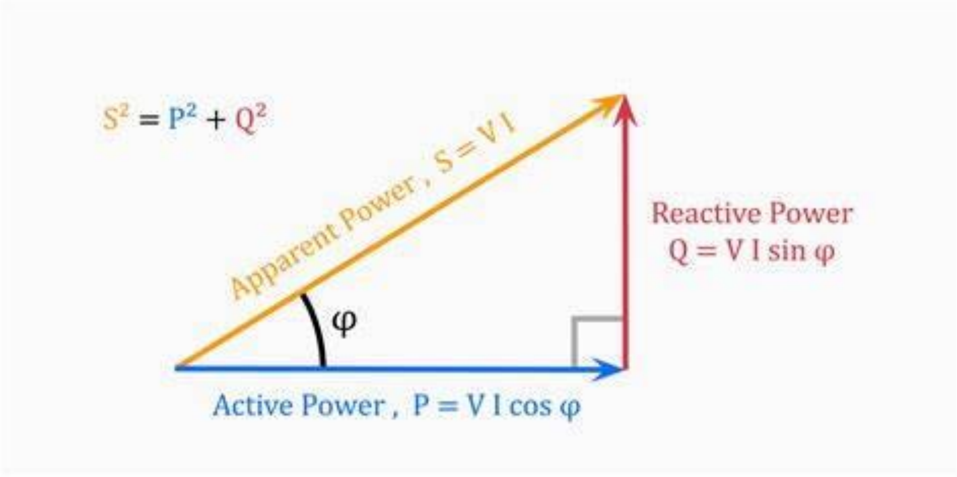


[Improving the traditional levelized cost of electricity approach by including the integration costs in the techno-economic evaluation of future photovoltaic plants - Veronese - 2021 - International Journal of Energy Research - Wiley Online Library]

How good is your power source for the grid?

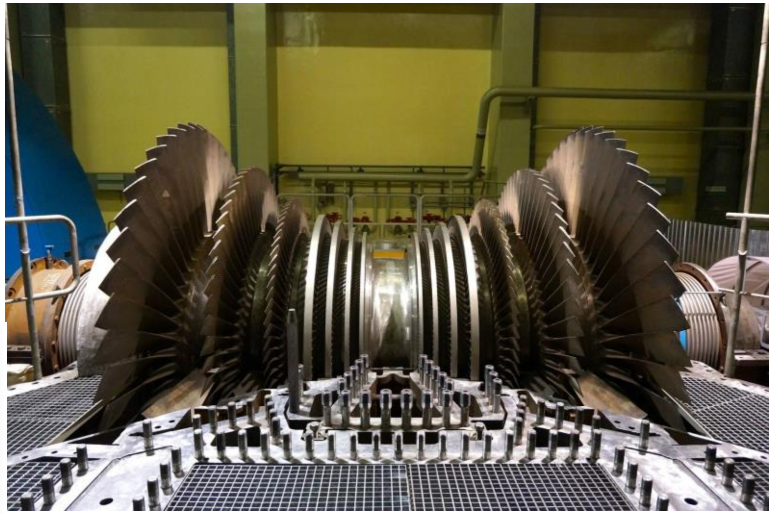
Inverter based resources



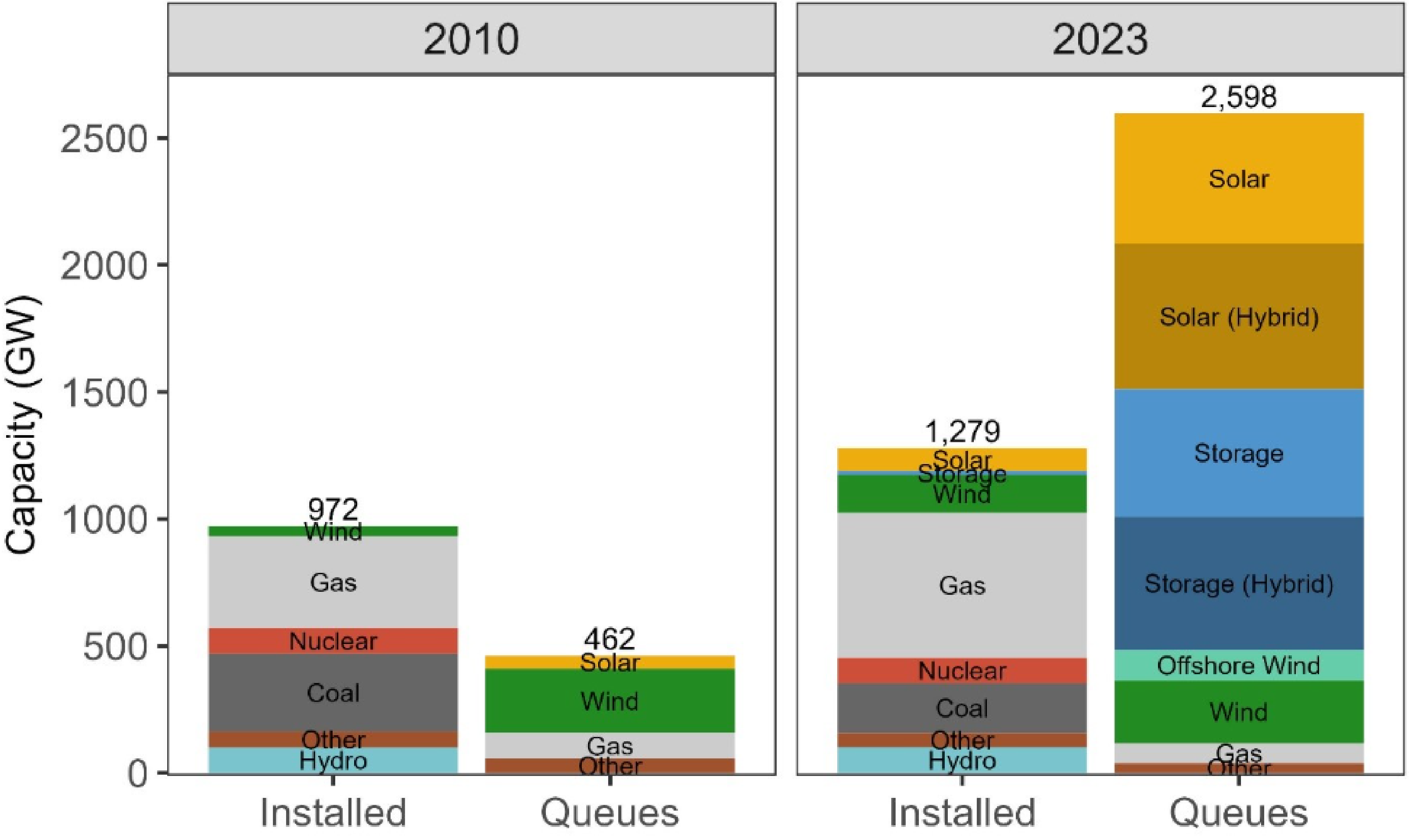


Inertia based resources

“Things that spin”



Grid interconnection queues are growing



- Interconnection queues are now 10-15 years
- Nuclear is baseload generation and provides a lot of "grid services"
- Nuclear can possibly skip the queue
- This is a huge advantage for nuclear over PV and Renewables

CAPITALISM

Levelized Cost of Energy (LCOE)

$$\text{LCOE} = \frac{\text{Total Lifetime Costs}}{\text{Total Lifetime Sales}}$$

$$= \frac{\Sigma\, I_t + M_t + F_t}{\Sigma\, E_t}$$

$$= \frac{\Sigma[\frac{I_t + M_t + F_t}{(1+{\color{red}r})^t}]}{\Sigma[\frac{E_t}{(1+{\color{red}r})^t}]}$$

I_t = Investment Costs

M_t = Maintenance Costs

F_t = Fuel Costs

E_t = Energy Sold

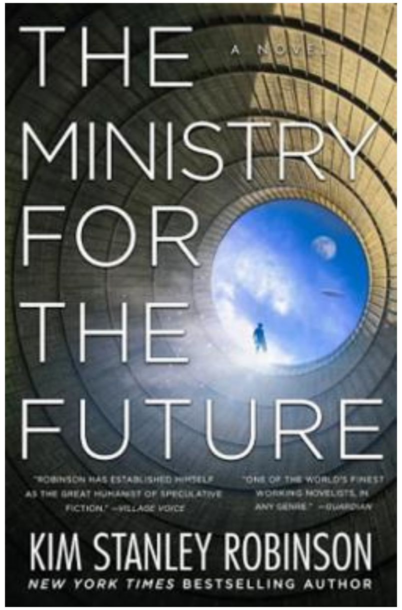
r = Discount Rate

Discount rate: What is the value of money today?

- How much do you value money today vs. how much you value it a year from now

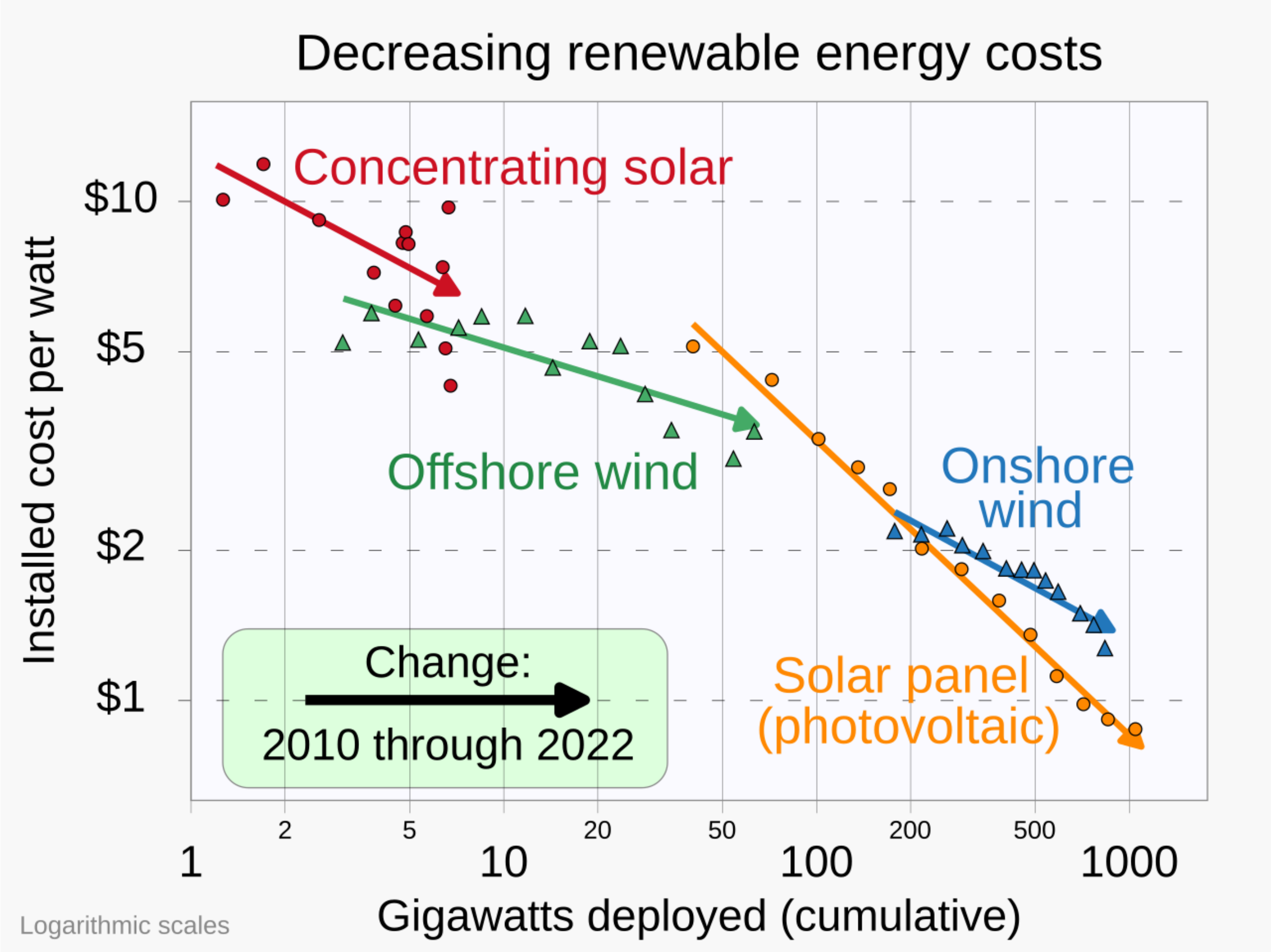
- Discount rate
  - Min: US Federal Interest Rate
  - Max: generally 10%
  - Rule of thumb: weighted average cost of capital (see econ class)

***r* ~ 6-9 %**



*An excellent chapter about how discount rates sell short the value of future generations

Learning rate: how fast do things get cheaper?



Learning rate (α):

- The cost of your Nth powerplant compared to your N-1 powerplant

We quantify the learning rate roughly as an exponential*

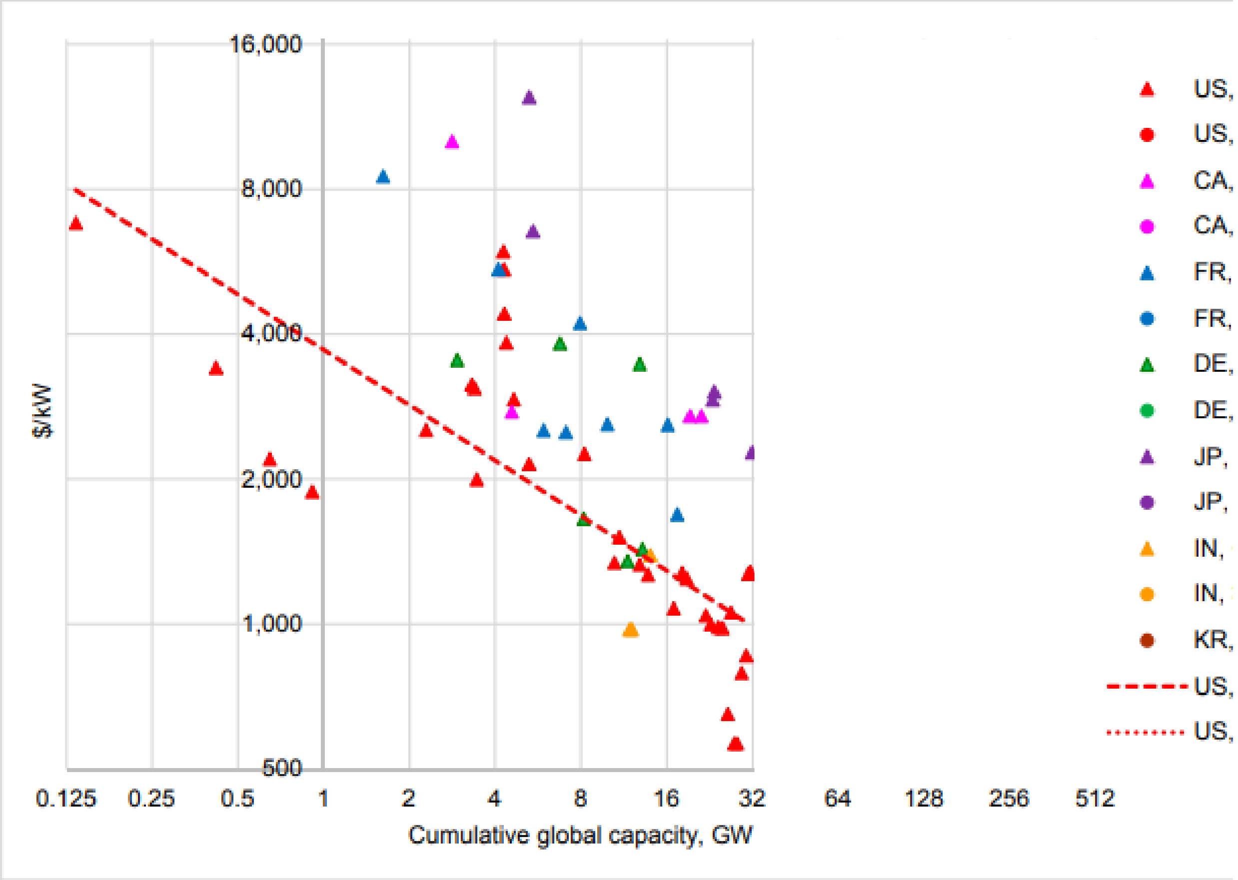
$$C = C_0 e^{-\alpha t}$$

*The cost will never reach zero and approaches a floor. Real systems require more math

Wikipedia

Nuclear has a learning rate problem

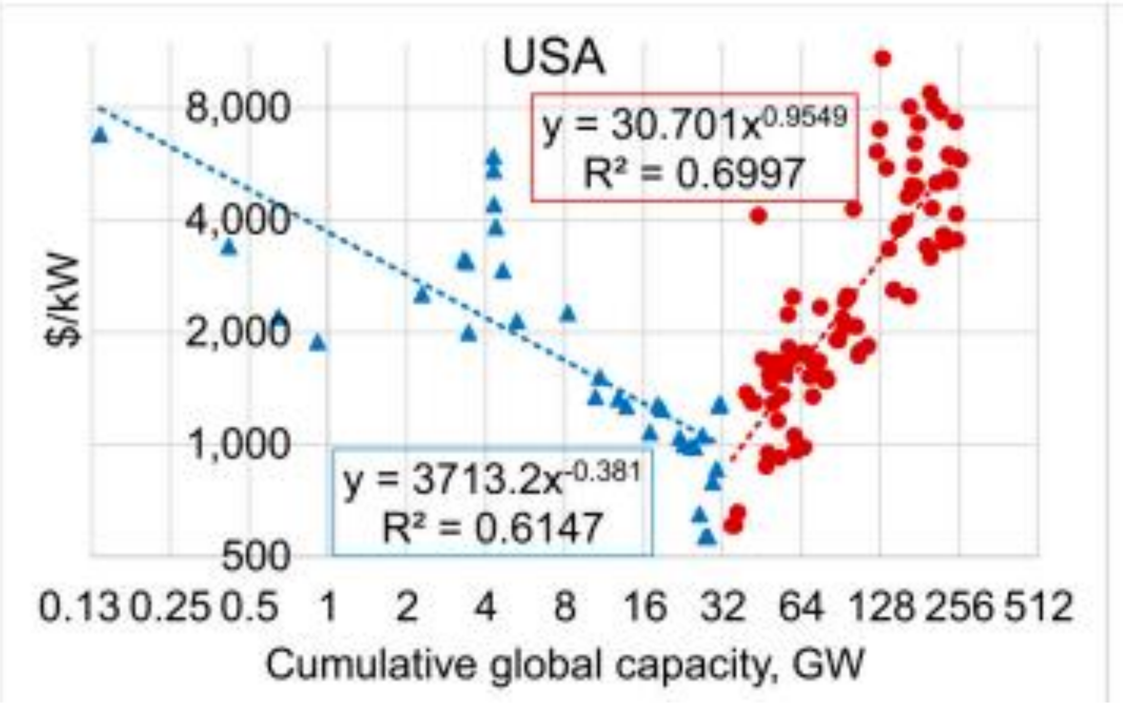
$/kW vs. Global Supply

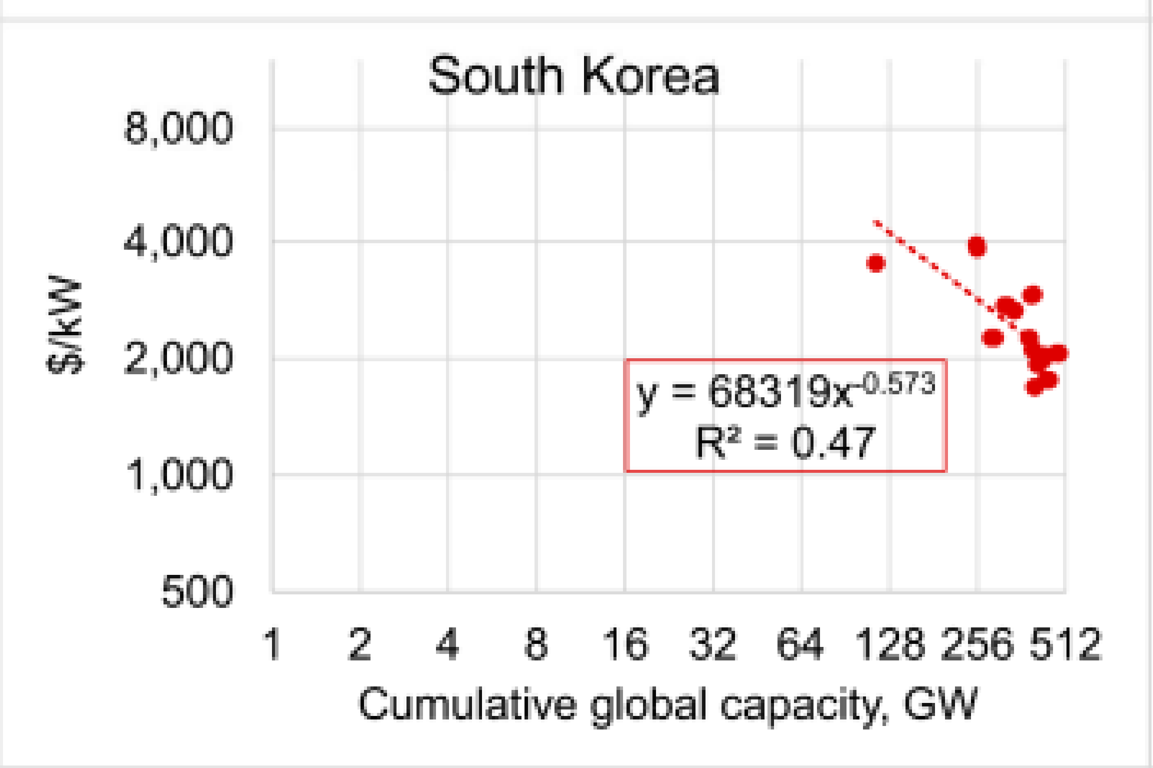


$$C = C_0 e^{-\alpha t}$$

What happens when a learning rate goes negative?

Negative learning rates are not universal





The landscape so far

- Nuclear is expensive
- Nuclear is good for the grid
- Nuclear is not getting cheaper
    - There are places that are building nuclear correctly

But what about CO2 Emissions?!?!?!

Do you see carbon emissions in this equation?

According to the market, emissions don't exist.

$$= \frac{\Sigma I_t + M_t + F_t}{\Sigma E_t}$$

nature

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nature > articles > article

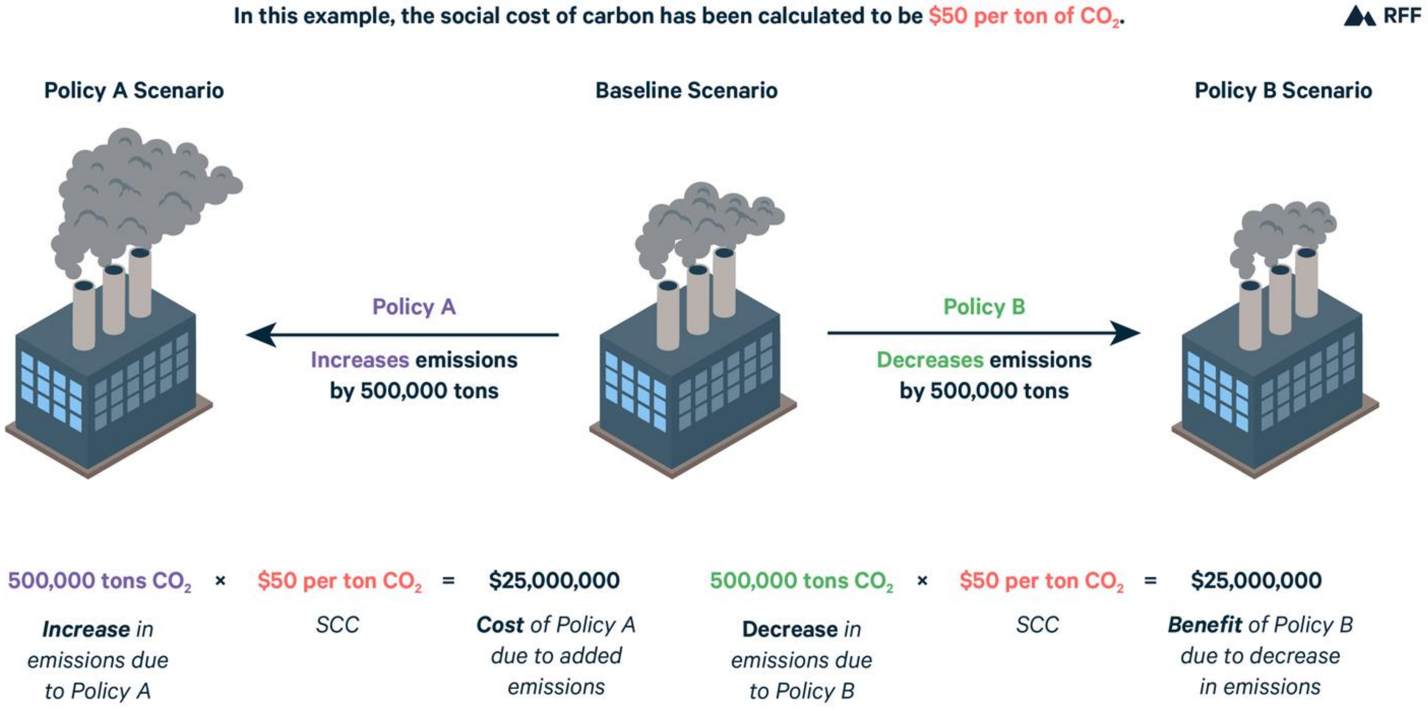
Article | Open access | Published: 01 September 2022

Comprehensive evidence implies a higher social cost of CO_2

Kevin Rennert, Frank Errickson, Brian C. Prest, Lisa Rennels, Richard G. Newell, William Pizer, Cora Kingdon,

Social Cost of Carbon (SCC)

~\$50 - \$185 / ton (Renner et.al)
\$190 / ton (EPA)



https://www.rff.org/publications/explainers/social-cost-carbon-101/

https://www.nature.com/articles/s41586-022-05224-9

https://www.epa.gov/environmental-economics/scghg

Now let’s talk about selling energy

Energy is worth exactly what you can sell it for

What does energy cost to make?

How much can you sell it for?

But why?

CAPITALISM

Energy is worth exactly what you can sell it for

Commodity markets are a race to the bottom in price

Energy $\neq$ Exergy*

*Exergy is defined as the amount of useful work achievable from a given amount of energy.

Exergy ~ Energy * Efficiency

We interrupt this program for a review of the Laws of Thermodynamics

1. **Energy cannot be created or destroyed**
    - *you can never get more energy out of a system than you put in*
        - (you can't win)

2. **Entropy of the universe always increases**
    - *real-world systems are always less than 100% efficient*
        - (you always lose)

3. **Absolute zero can't be reached**
    - *atomic motion stops at T = -273.15 °C (zero Kelvin)*
        - (you can't quit)

Lets have some fun: a completely subjective ranking of exergy

Electricity (lighting)

Heat (2000°C)

Chemical Bonds

Nuclear Potential

Translational Kinetic Energy

Electricity (heat)

Rotational Kinetic Energy

Electrochemical Potential

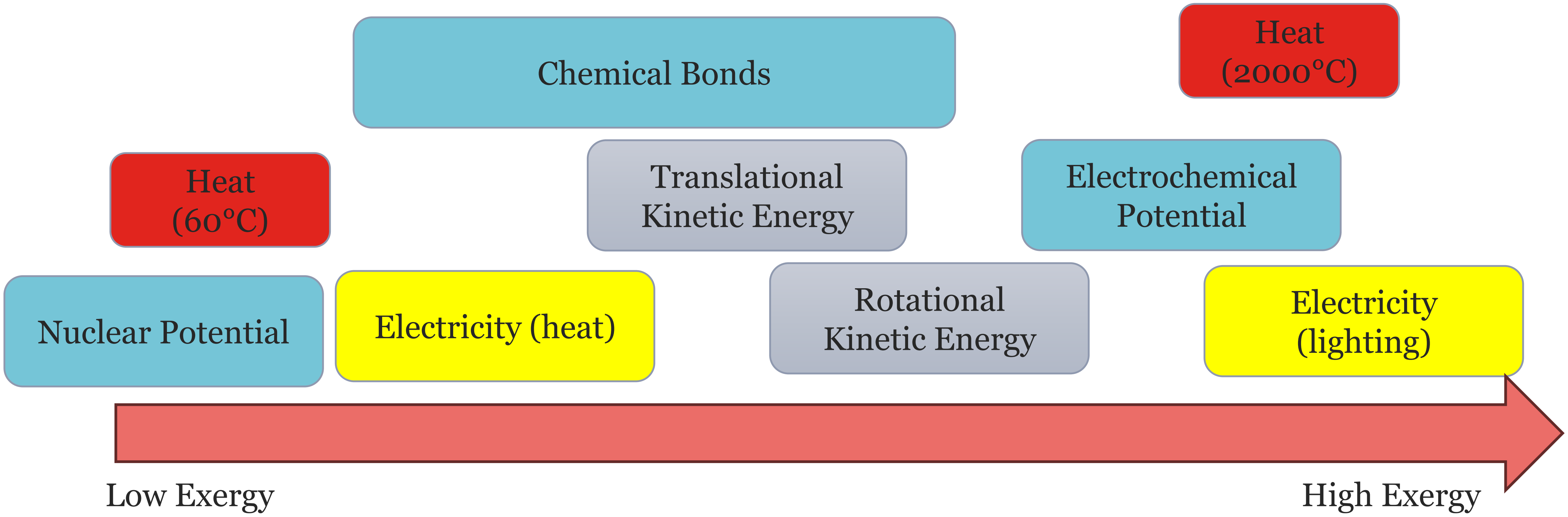
Heat (60°C)

How many times does energy need to be transformed to get to the type I want?

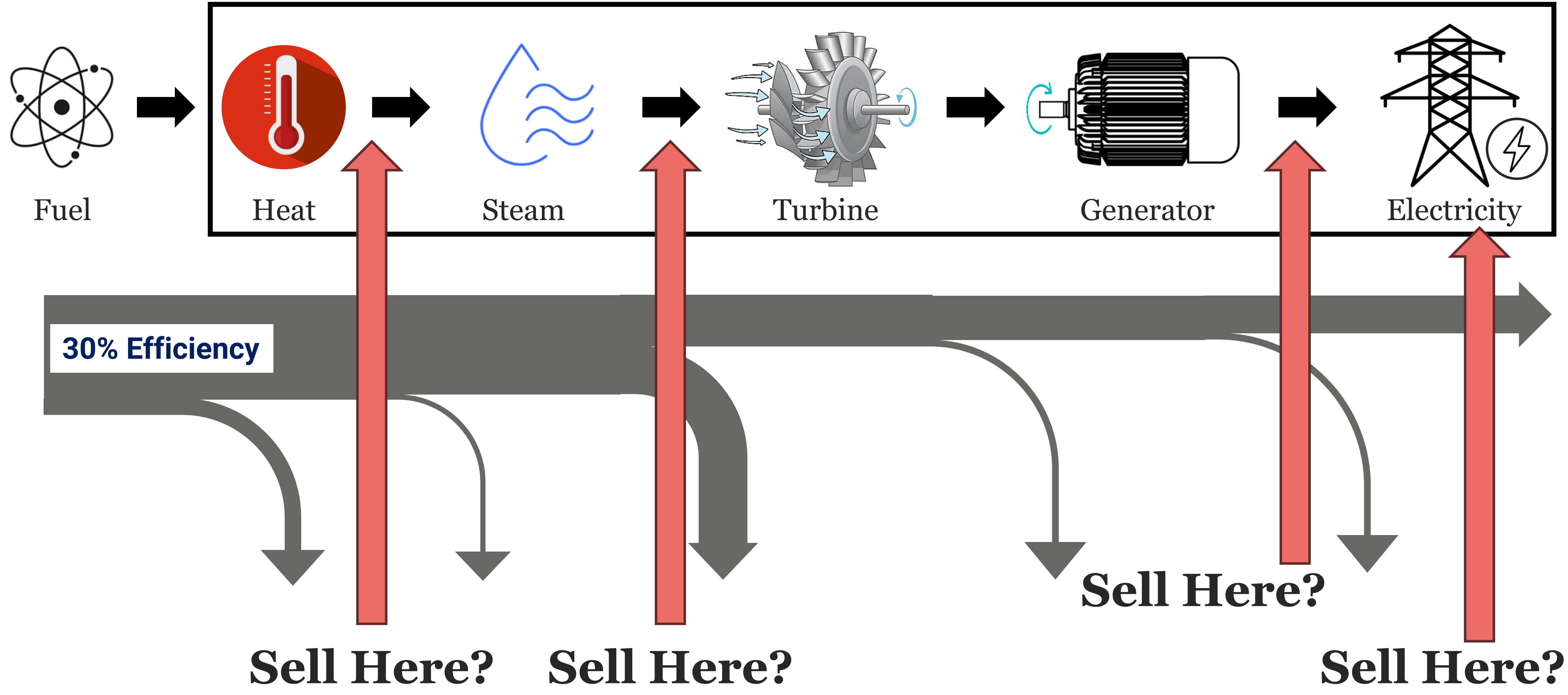
Low Exergy

High Exergy

Lets have some fun: a completely subjective ranking of exergy

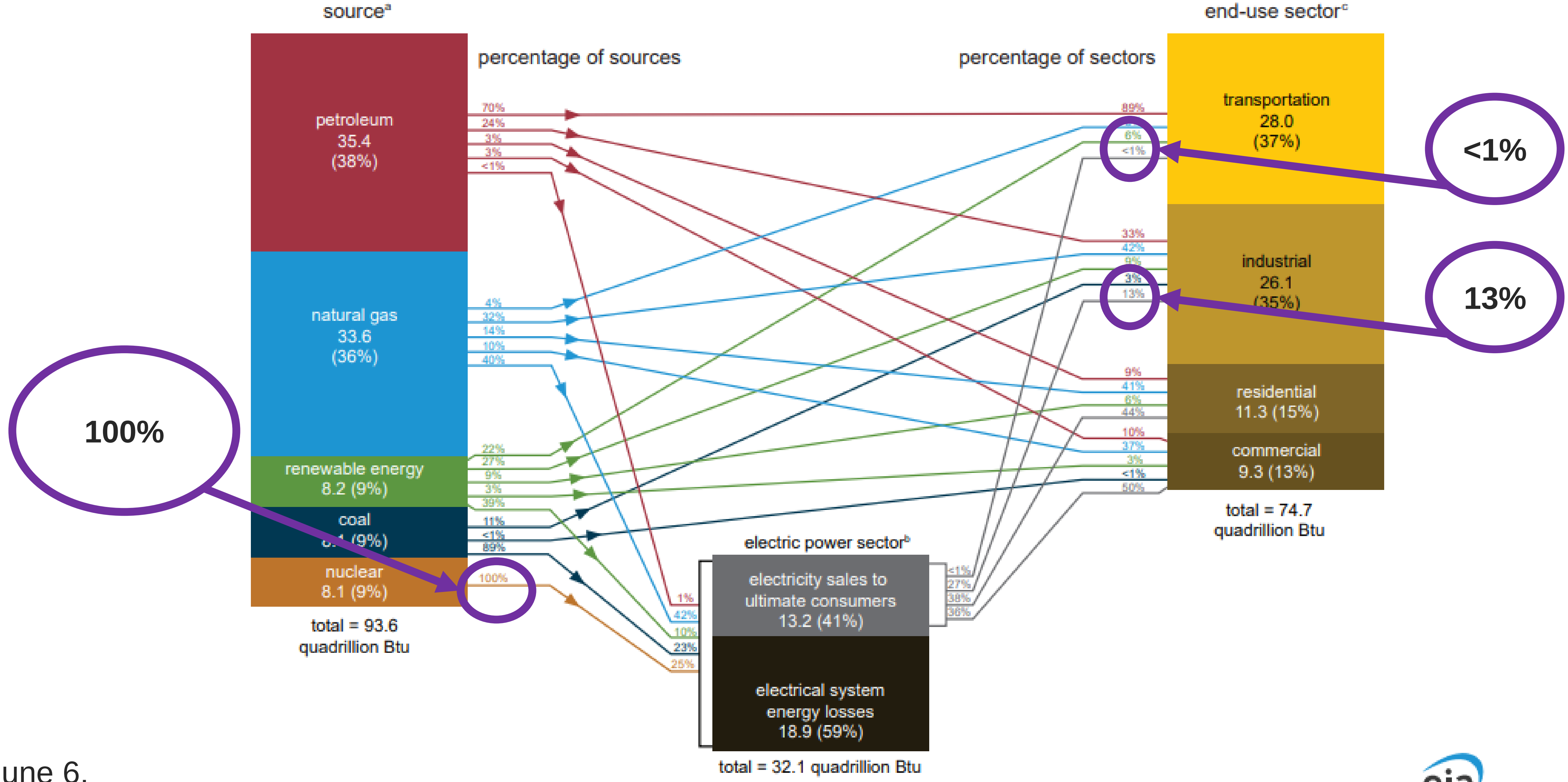


Energy is lost at each conversion step

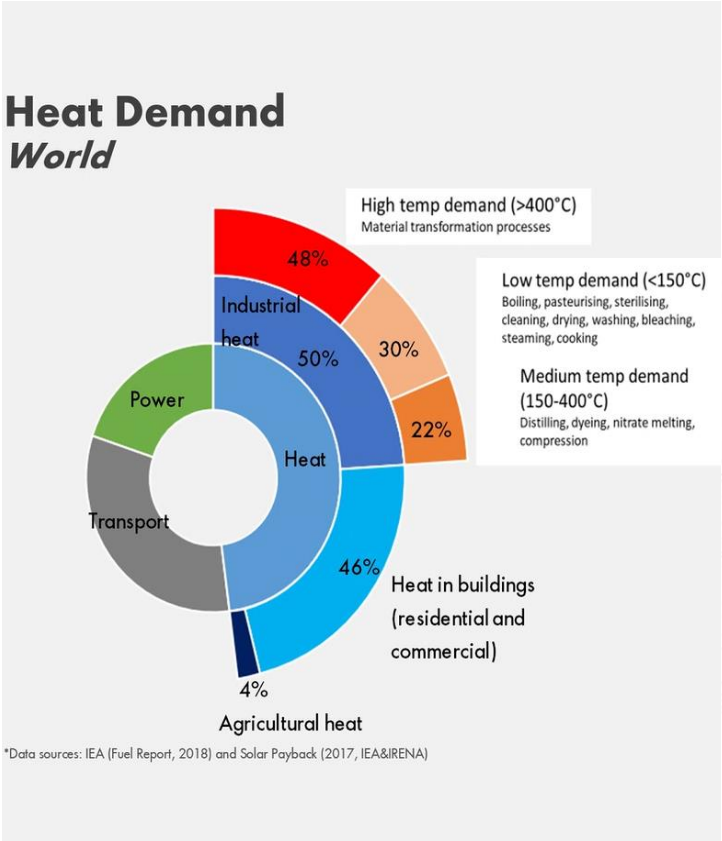


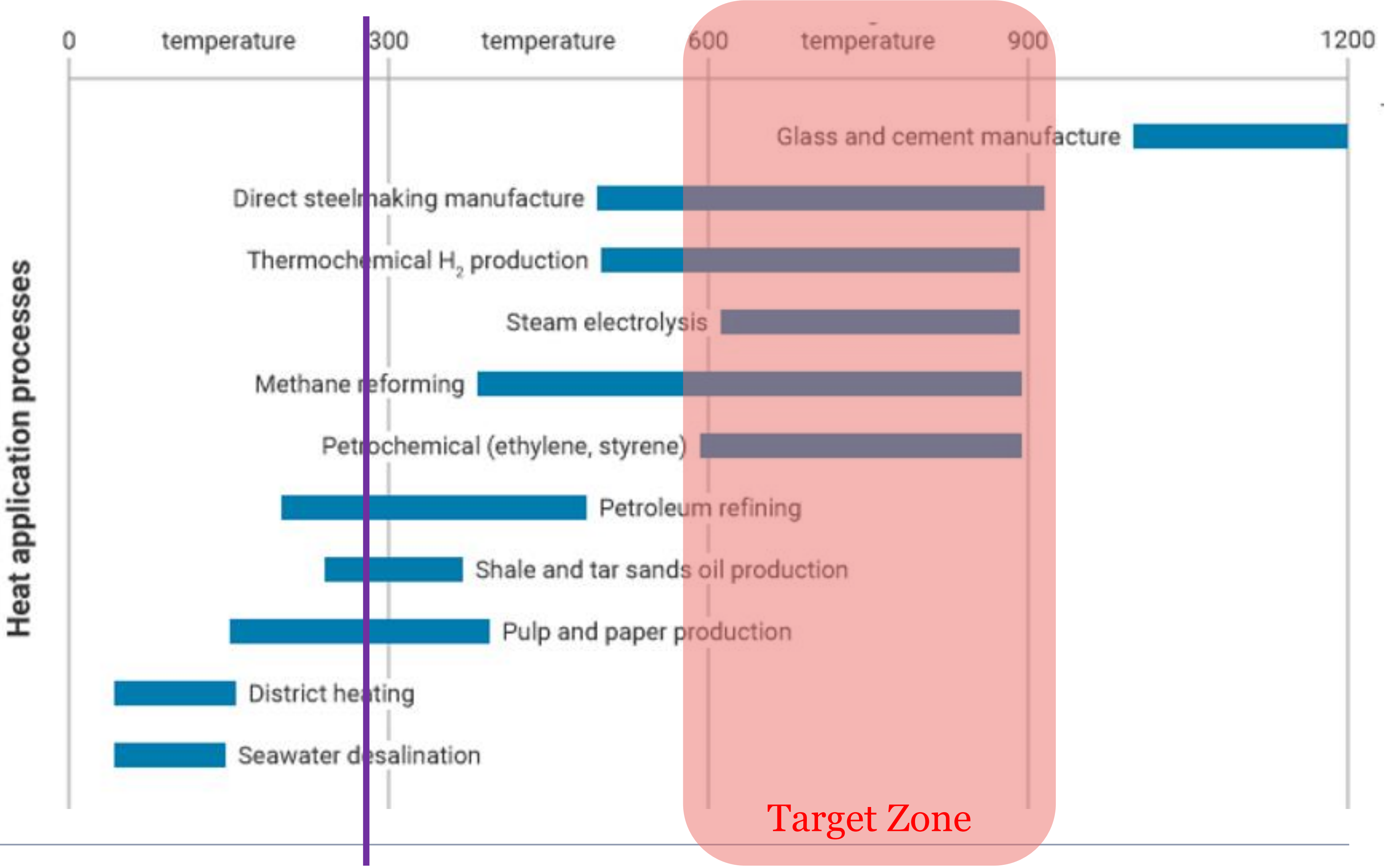
U.S. energy consumption by source and sector, 2023

quadrillion British thermal units (Btu)



If you want to sell nuclear heat it needs to be hot





Current nuclear heat

Further reading if interested:

Joule

CellPress

Perspective

To decarbonize industry, we must decarbonize heat

Gregory P. Thiel[1,4] and Addison K. Stark[2,3,4,*] 2021

https://www.sciencedirect.com/science/article/pii/S2542435120305754

The advantages and disadvantages of Nuclear

Highest Energy Density Fuel

Cheap Fuel

Smallest Energy Footprint

High Capacity Factor

Nearly Infinite Fuel

Radioactive Waste Management

Radiation Management

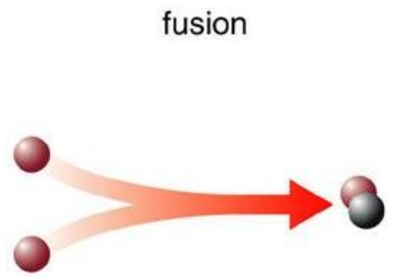
Regulatory Framework

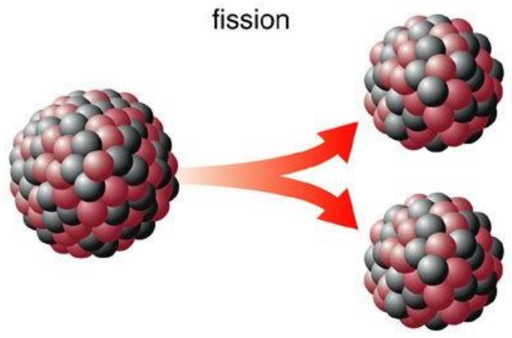
Bespoke Engineering

Rare Elements

Nuclear Accidents

Now let's talk about Fusion vs. Fission





- Inherent Safety - No Meltdowns
- Less nuclear waste*
- Fuel is seawater
- Regulated like particle accelerators
    - Low proliferation risk

- **It works**
- Lower Material radiation requirements
- Basic supply chain exists

“High Level Waste” is a misnomer

“High Level Waste”

Radioactive waste that is highly radioactive and generated as a **byproduct of the reactions that occur inside nuclear reactors or reprocessing facilities.**

HLW is tied directly to nuclear fuel in USA regulations

*This is literally by-definition only in the USA. Fusion will produce a TON of radioactive waste,

**Depending on what you build your reactor vessel out of you can have some serious problems.

But what about CO2 Emissions?!?!

$$= \frac{\Sigma\, I_t + M_t + F_t}{\Sigma\, E_t}$$

Do you see CO2 in this equation?

$$\text{LCOE} = \frac{\text{Total Lifetime Costs}}{\text{Total Lifetime Sales}}$$

$$= \frac{\Sigma\, I_t + M_t + F_t}{\Sigma\, E_t}$$

I_t = Investment Costs

M_t = Maintenance Costs

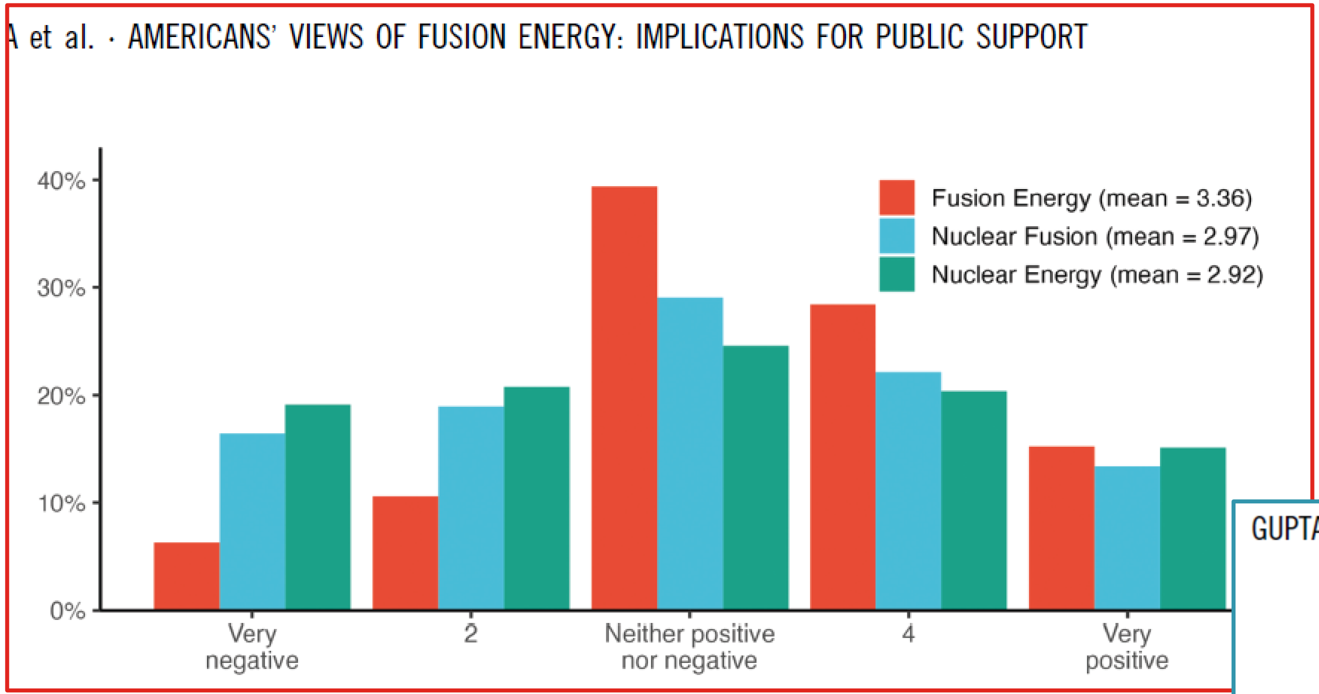
F_t = Fuel Costs

E_t = Energy Sold

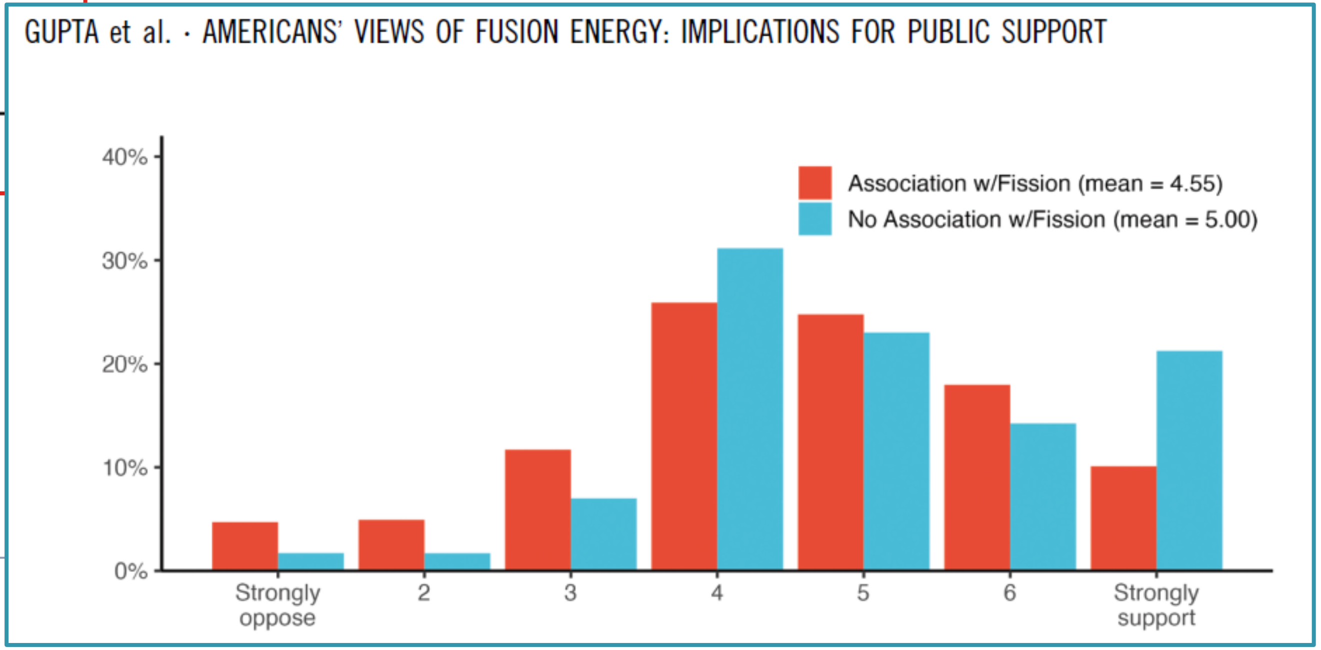
There is no price on Carbon.

How do I get my powerplant built?

To-“Nuclear” or Not To-“Nuclear”



Fusion gets more support when the word “nuclear” is omitted

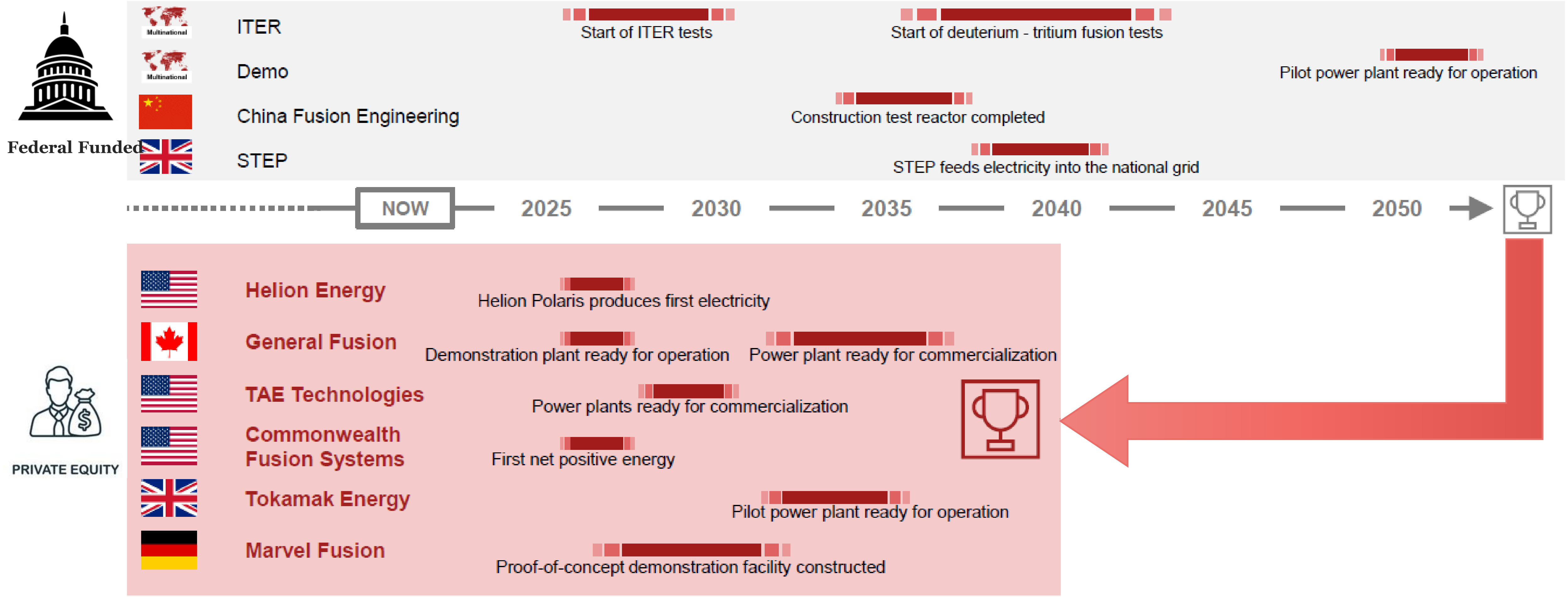


Americans view Fusion more favorably when it is NOT associated with Fission

Conclusions from the first part of talk

- The world and the US needs a lot of energy (not just electricity)
- At the end of the day, the market dictates what gets built
    - You need to make your power cheaply
    - You need to sell as much as you can
    - The market doesn't care about fairness, or carbon emissions (yet)
- Fusion is going to struggle in the same way that fission does
    - Primary advantages are regulatory framework and public perception
    - Primary disadvantages are huge capital costs

There is reason for hope



US bold decadal vision is lead by industry but still require government R&D support for key technologies.

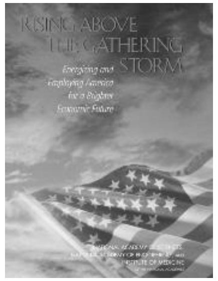
[Fusion energy | Strategy& (koehntopp.info)]

ABOUT

ADVANCED RESEARCH PROJECTS AGENCY – ENERGY

History of the Advanced Research Projects Agency – Energy (ARPA-E)

In 2007, the National Academies recommended Congress establish an Advanced Research Projects Agency within the U.S. Department of Energy to fund and direct advanced energy research & development.



American Recovery & Reinvestment Act **Signed** – Providing ARPA-E its first appropriations of $400 million, which funded ARPA-E's first projects

2007

2009

2025

Rising Above the Gathering Storm **Published** - warning policymakers that U.S. advantages in science and technology had begun to erode

America COMPETES Act **Signed** – authorizing the creation of ARPA-E

1,700+ Awards
87 Programs

Current Funding:
$460M
(FY24)

ARPA-E's Congressional Statute

1. To enhance the economic and energy security of the United States through the development of energy technologies that:

IMPROVE
Energy Efficiency

IMPROVE
Infrastructure Resilience

IMPROVE
Radioactive Waste Management

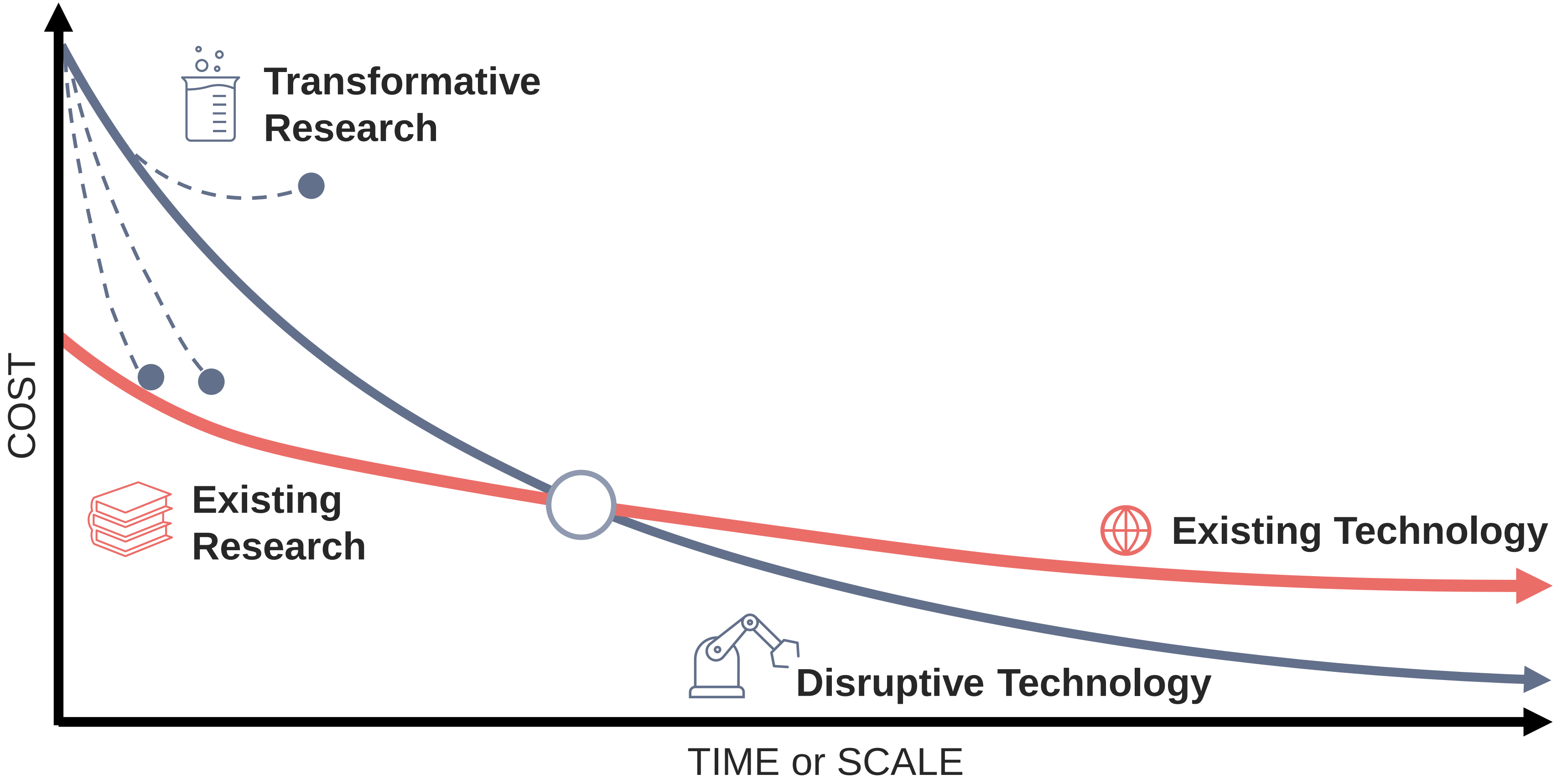
REDUCE
Energy Imports

REDUCE
Emissions

2. To ensure that the United States maintains a technological lead in developing and deploying advanced energy technologies

ARPA-E Funds and Directs Disruptive Energy Technologies

We are positioned to go where others can't or won’t go. Bound by no technical area, ARPA-E programs interrogate unmapped opportunities across the full energy ecosystem.



ARPA-E has two flavors of programs

OPEN
~3 years
Anything goes

Themed
5-8 per year
"Here is a problem we want to solve"

16 Years of Energy Impact

We've always had the same mission: to fund and direct the discovery of outlier energy technologies. Key indicators illustrate how the advanced research and development funded by the Agency translates to scientific, commercial, market, and industry impacts.

SINCE 2009 ARPA-E HAS PROVIDED
$4.21 BILLION
in R&D Funding to More Than 1,700Projects

258 Projects
have attracted more than
$14.6 Billion
in private-equity follow-on funding

167 COMPANIES
Have been formed by ARPA-E projects

34 Exits
MARKET VALUATIONS WORTH
$22.2B FROM MERGERS, ACQUISITIONS, AND IPO'S

382 PROJECTS
have partnered with other government agencies for further development

8,092
Peer reviewed journal articles from ARPA-E projects

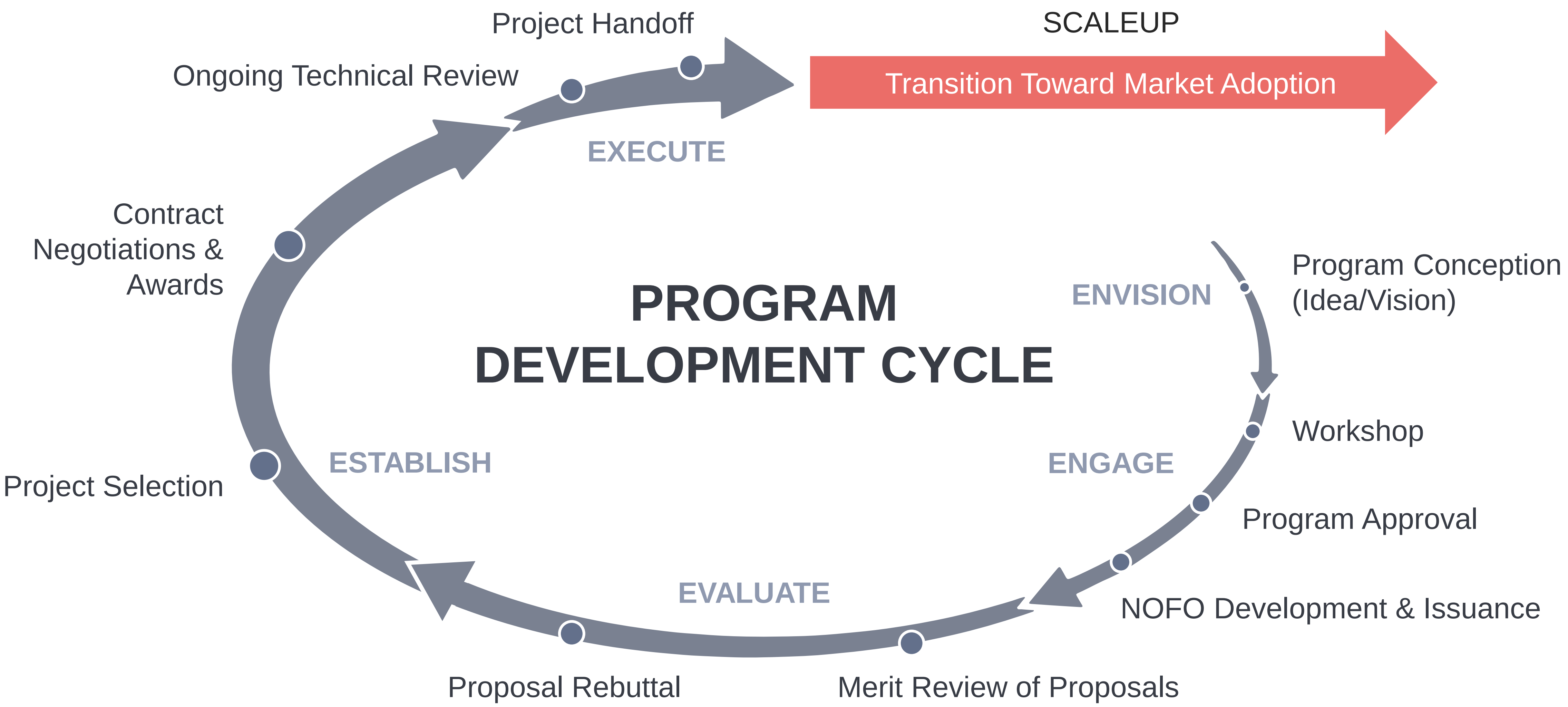
1,225 Patents
issued by the U.S. Patent & Trade-mark Office

452 LICENSES
REPORTED FROM ARPA-E PROJECTS

As of February 2025

The ARPA-E Technology Acceleration Model:

Technical Oversight. Speed. Impact.



OPEN Programs

ARPA-E's OPEN programs support new technologies across the full spectrum of energy applications.

2009
- 41 projects
- $176 million investment
- 10 technical areas

2012
- 66 projects
- $130 million investment
- 11 technical areas

2015
- 41 projects
- $125 million investment
- 10 technical areas

2018
- 77 projects
- $199 million investment
- 13 technical areas

2021
- 68 projects
- $175 million investment
- 13 technical areas

2024
- 49 projects
- $147 million investment
- 18 technical areas

ARPA-E FUSION FUN ZONE

ARPA-E has published a set of retrospectives & articles

arXiv > physics > arXiv:2505.01784

Physics > Plasma Physics

[Submitted on 3 May 2025]

Retrospective of the ARPA-E BETHE-GAMOW-Era Fusion Programs and Project Cohorts

S. C. Hsu, M. C. Handley, S. E. Wurzel, P. B. McGrath

RESEARCH ARTICLE | JUNE 08 2022

Progress toward fusion energy breakeven and gain as measured against the Lawson criterion

Special Collection: Papers from the 63rd Annual Meeting of the APS Division of Plasma Physics

Samuel E. Wurzel; Scott C. Hsu

Retrospective of the ARPA-E ALPHA Fusion Program

Review Article | Published: 08 October 2019

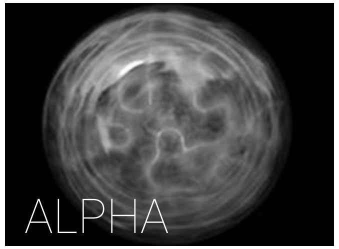
Volume 38, pages 506–521, (2019) Cite this article

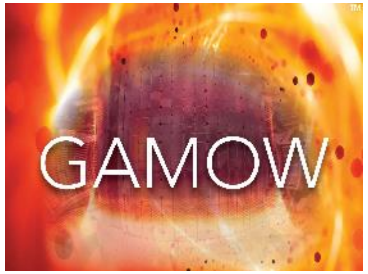
U.S. Fusion Energy Development via Public-Private Partnerships | Journal of Fusion Energy

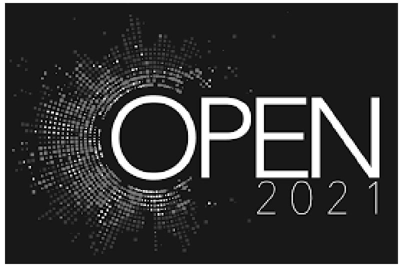
[2505.01784] Retrospective of the ARPA-E BETHE-GAMOW-Era Fusion Programs and Project Cohorts

Retrospective of the ARPA-E ALPHA Fusion Program | Journal of Fusion Energy

ARPA-E Fusion Timeline







ALPHA	OPEN 2018	BETHE	GAMOW	OPEN 2021	CHADWICK
$33M 2014	$11M 2017	$43M 2019	$27M 2020	$9M 2021	$30M 2024

The ARPA-E Fusion portfolio has led the evolution of fusion in the past decade:
New concepts → component technology and teams → system simplification and cost reduction → technology for longer lasting powerplants

At each stage, ARPA-E has catalyzed significant investments from VC through strong thought leadership and sound technical diligence, leading to >$1.5B in private follow-on funding for fusion

ALPHA

ACCELERATING LOW-COST PLASMA HEATING AND ASSEMBLY

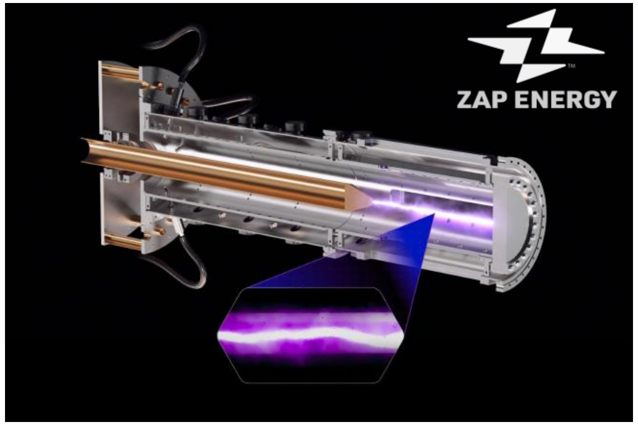
PROGRAM DIRECTOR: Ahmed Diallo
$33M (2014)

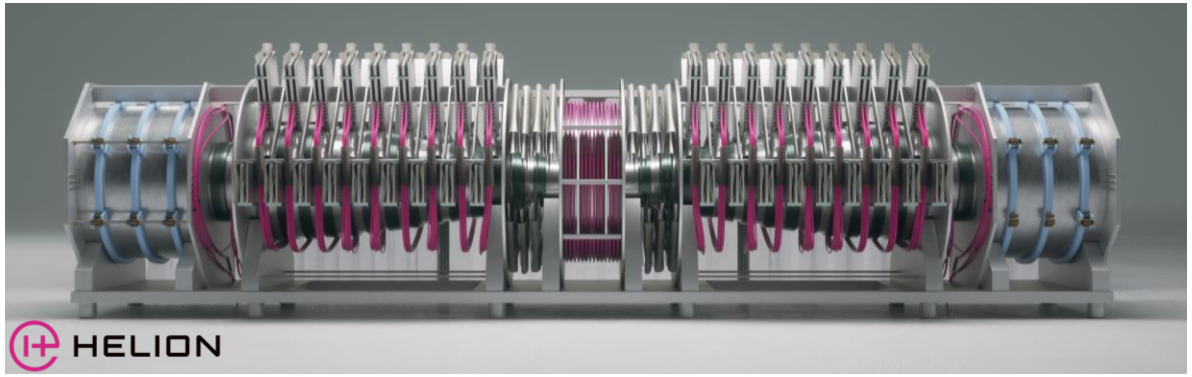
Accelerate fusion energy R&D through new research pathways that are cheaper and faster

Objective
- Validate low-cost pulsed, intermediate-density approaches
- Focus on Z-pinches and magneto-inertial fusion

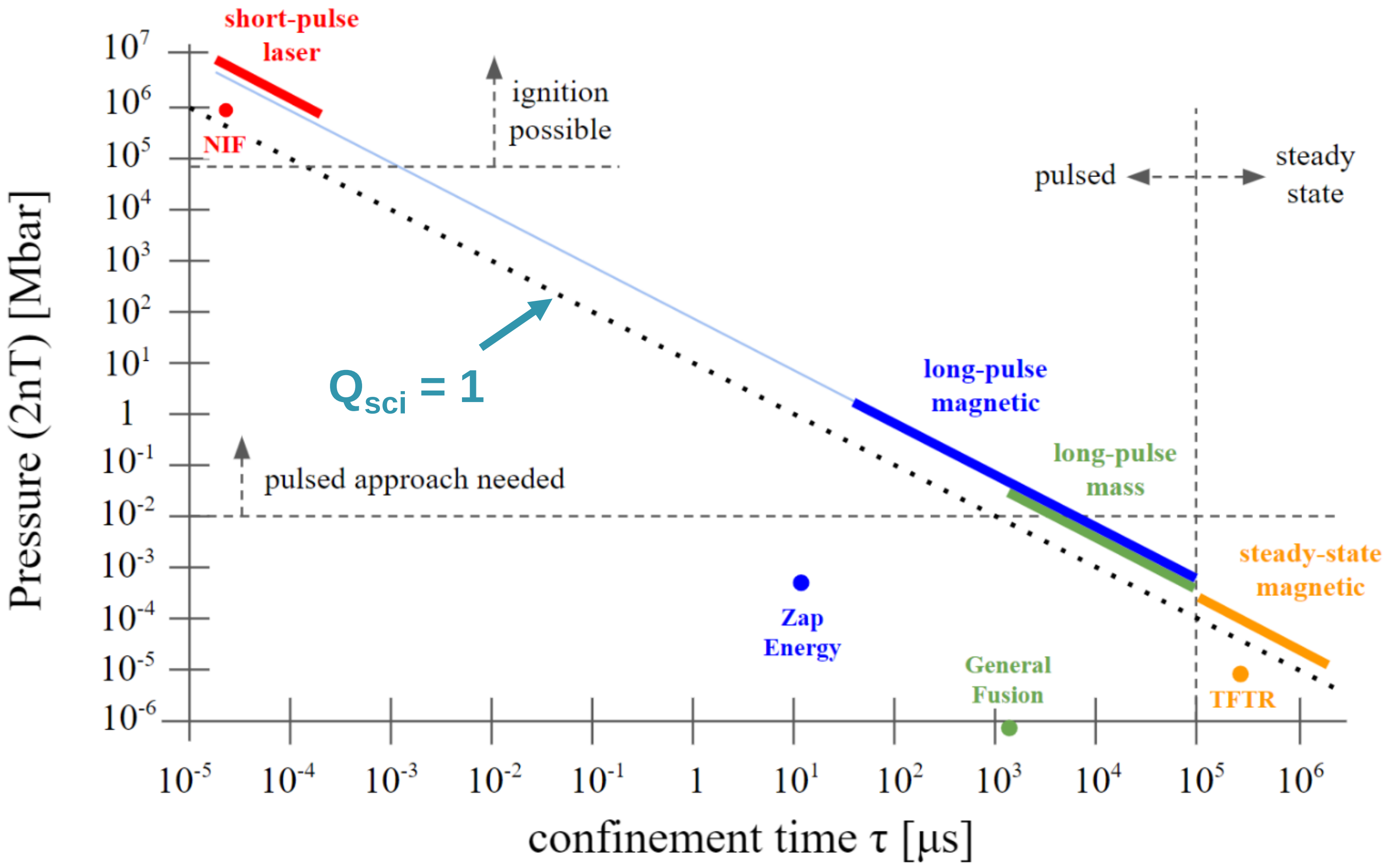
Key Innovations
- Sheared-flow stabilized Z-pinch achieving keV (11M °C) temperatures
- Imploding plasma jet liners enabling rapid experimentation
- Cost modeling show pathways to commercially competitive capital costs

Impact
- 9 projects completed
- 2 new spinouts, including Zap Energy
- $1.3B+ in private follow-on funding
    - $324M to Zap Energy
    - $1B to Helion
- Proof-of-concept for scalable pulsed systems





The theory behind ALPHA



Assumes ideal DT fusion temperature ~15-25keV

Science For America whitepaper 2023

BETHE / OPEN 2018

BREAKTHROUGHS ENABLING THERMONUCLEAR-FUSION ENERGY

PROGRAM DIRECTOR: Ahmed Diallo
BETHE: $43M (2019) / OPEN: $11M (2017)

Support the development of timely, commercially viable fusion energy

Objective

- Develop lower-cost fusion concepts
- Advance component technologies for mature systems

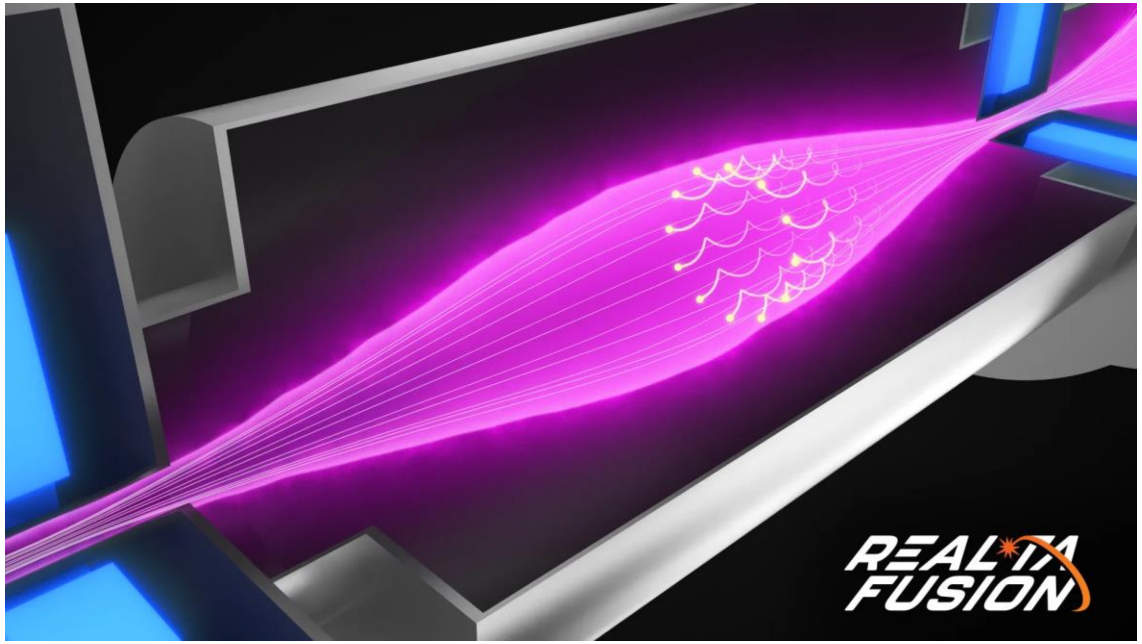
Key Innovations

- Concept Development: Zap Energy achieved multi-keV (up to 3 keV / 37M °C) temperatures
  - Simplest, smallest and lowest cost device to do so
- Component Tech: CFS HTS magnets >20 T at 20 K
- Capability Teams: Enabled cross-sector collaboration

Impact

- 21 projects completed
- $223M+ in private follow-on funding
- 6 teams advanced to DOE's Milestone Program:

Commonwealth Fusion Systems, THEA ENERGY, REALTA FUSION, TYPE ONE ENERGY, ZAP ENERGY



GAMOW / OPEN 2021

PROGRAM DIRECTOR: Ahmed Diallo
GAMOW: $27M (2020) / OPEN $9M (2021)

GALVANIZING ADVANCES IN MARKET-ALIGNED FUSION FOR AN OVERABUNDANCE OF WATTS

Innovative subsystem and cross-cutting R&D towards commercial ready fusion energy

Objective

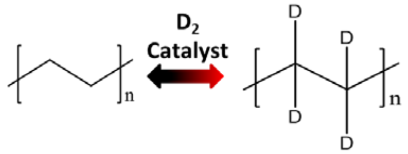
- Advance materials and fuel cycle
- Develop enabling technologies for D-T and advanced fuels

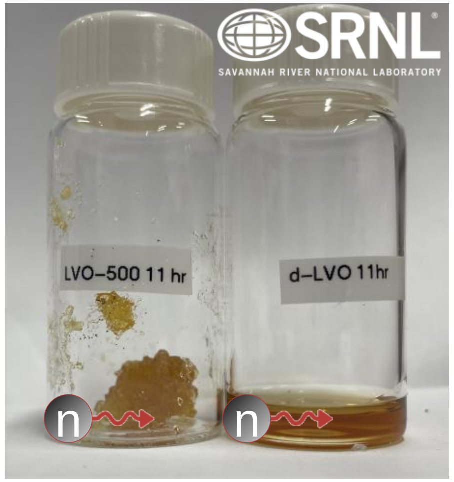
Key Innovations

- Developed radiation resistant, tritium compatible oils for pump, seal, lubricant and fusion fuel capsule applications
- Demonstrated production of 5-ton custom formulated castable nanostructured alloy (CNA) material
- Achieved 20x reduction in cost along with 10x increase in critical current for HTS tapes

Impact

- 17 projects addressing critical challenges
- Advancing tritium self-sufficiency





CHADWICK

PROGRAM DIRECTOR: Ahmed Diallo
$30M (2024)

CREATING HARDENED AND DURABLE FUSION FIRST WALL INCORPORATING CENTRALIZED KNOWLEDGE

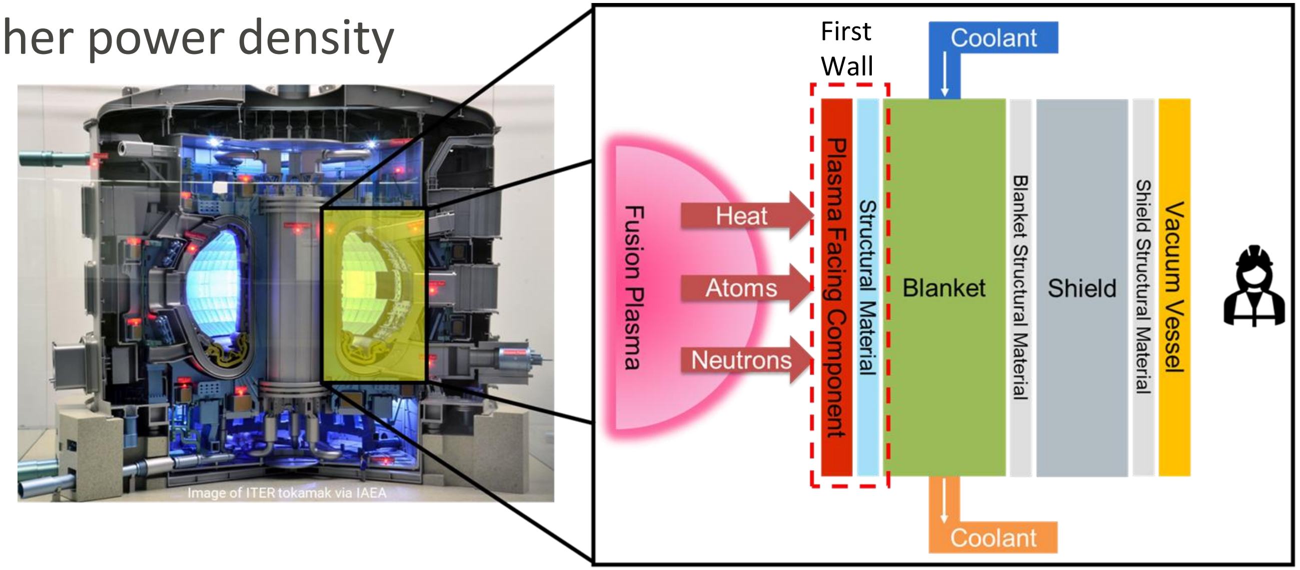
Discovery of transformational durable first-wall materials for fusion power plants

Objective
- Develop radiation-resistant, low-activation first-wall materials

Focus Areas
- Tungsten-based high-entropy alloys for extreme neutron fluence (50 dpa)
- Additive manufacturing of graded materials

Potential Impact
- Enable compact fusion energy systems with higher power density
- Achieve 30+ year fusion power plant lifetimes

Projects
- 13 projects
  - 5 High-Entropy Alloys
  - 2 High Temperature Ceramics
  - 1 Liquid metal
  - 4 Microstructure Engineering



Lets talk about the future…

Disruptive Opportunities

Spin-Polarized Fuels

- 50% reactivity boost via aligned D-T spins
- Early R&D in polarization techniques

Aneutronic Fuels

- p-^{11}B and D-^{3}He options
- Challenges in T_i > 100 keV confinement

Efficient Heating Systems and Laser Fusion Drivers

- Solid-state RF and particle beam heating systems for magnetic fusion energy
- Solid-state diode pumped and excimer laser systems for inertial fusion energy
- Heating systems: >70% wall-plug efficiency
- Laser systems: >16% wall-plug efficiency

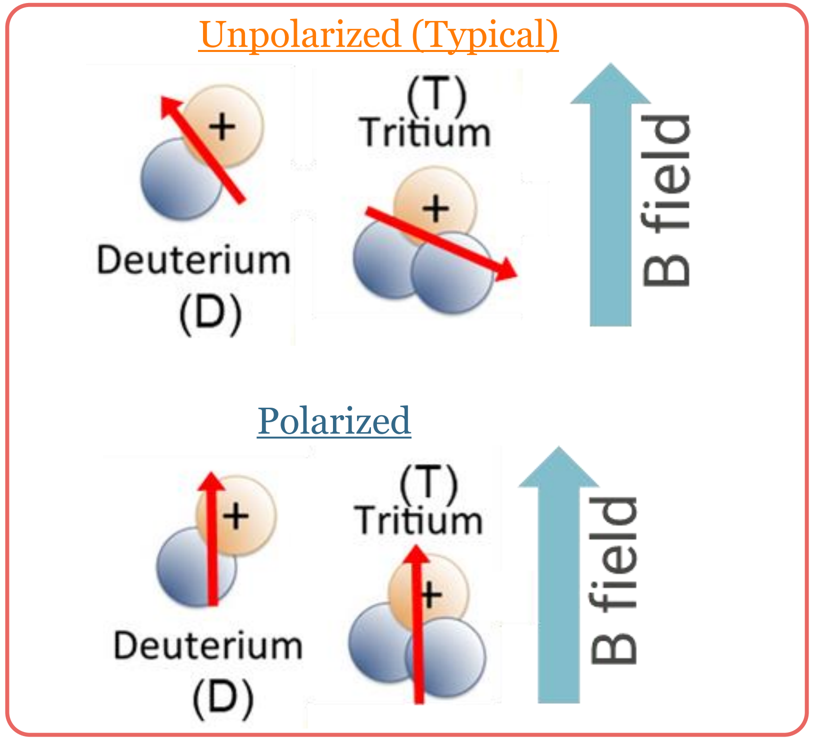
Spin Dependence in Fusion Reactions

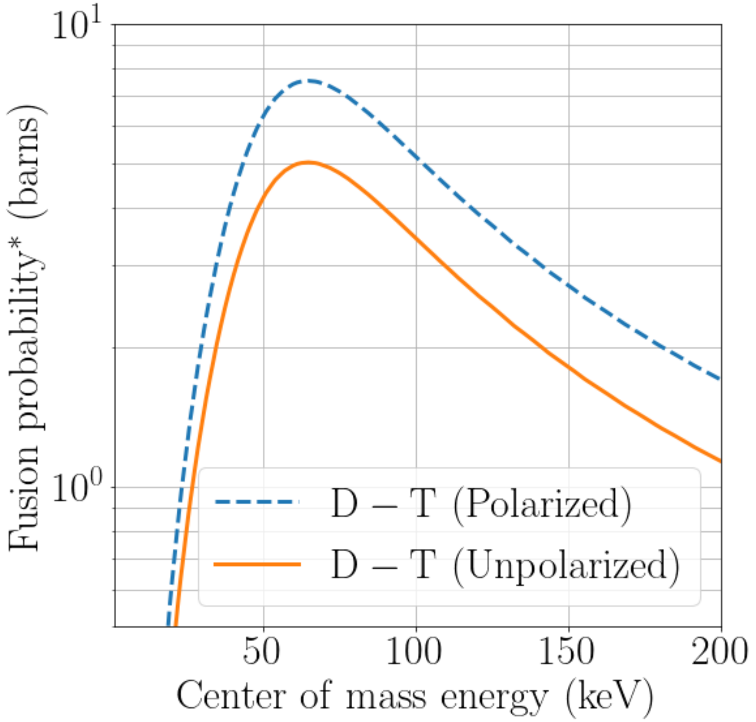
Nuclei have quantum spins!

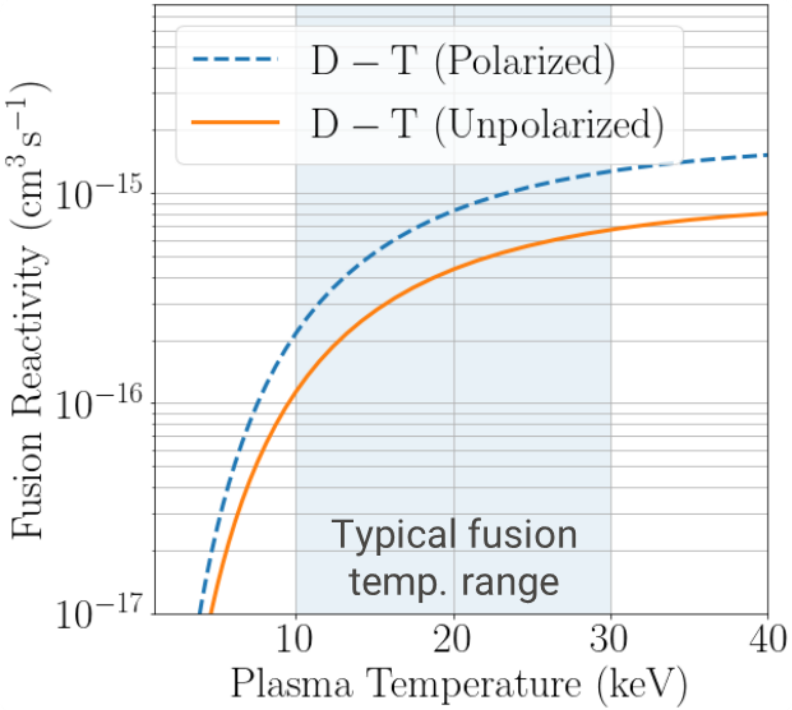
Nuclear fusion probability between atomic nuclei **depends on their relative spin directions**

Aligning deuterium (D) and tritium (T) spins (i.e., spin polarizing the fuel) provides a **50% increase in fusion probability**

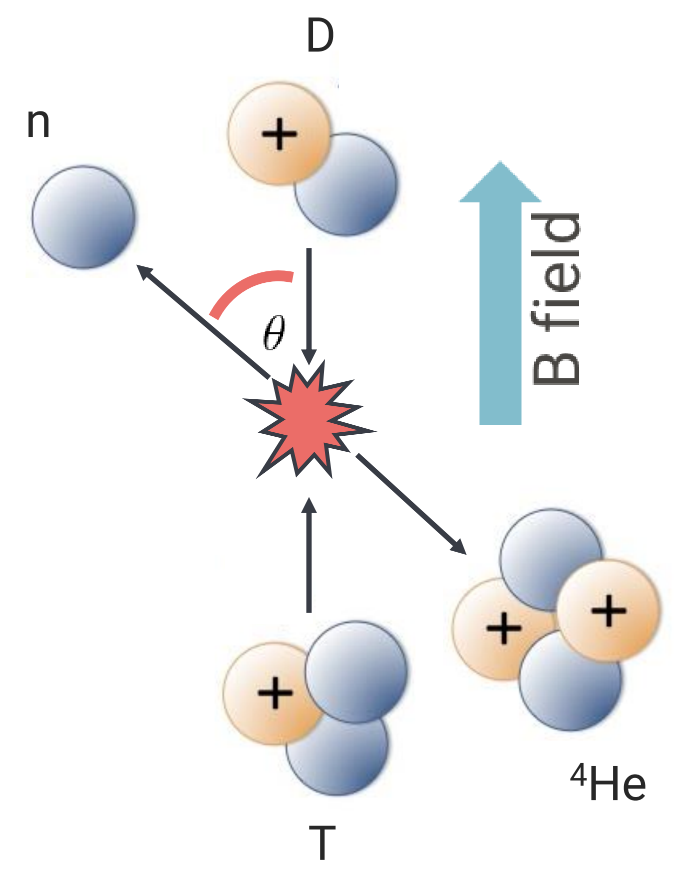
This leads to ~ **2x increase in reactivity,** meaning **increased tritium burn efficiency** *or* **2x in fusion power output** & upwards of **3x in power to the grid**!





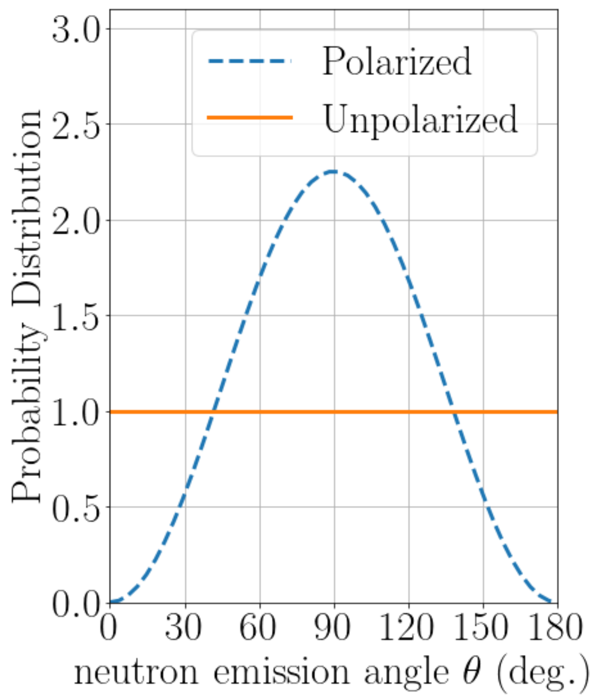


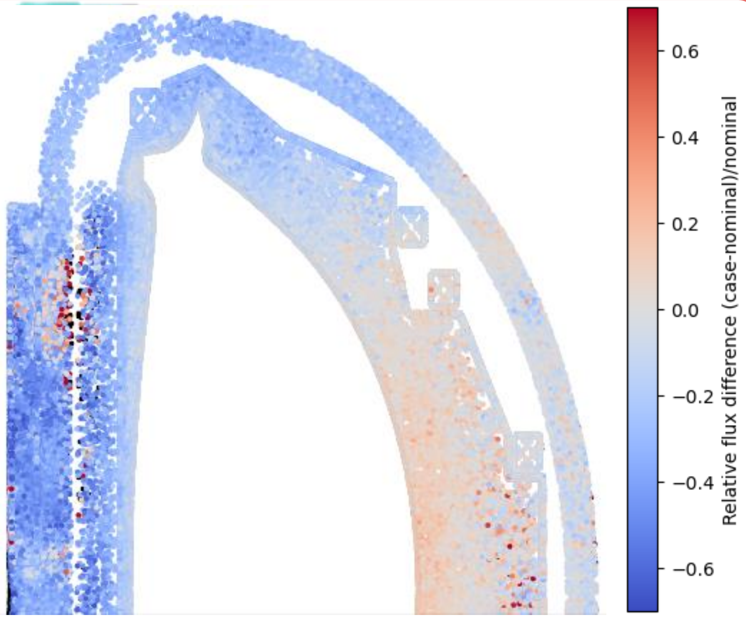
Spin Dependence of Fusion Product Angular Distribution



Angular distribution of emitted fusion products is also spin-dependent
unpolarized = isotropic (4π)
polarized = anisotropic (2π)

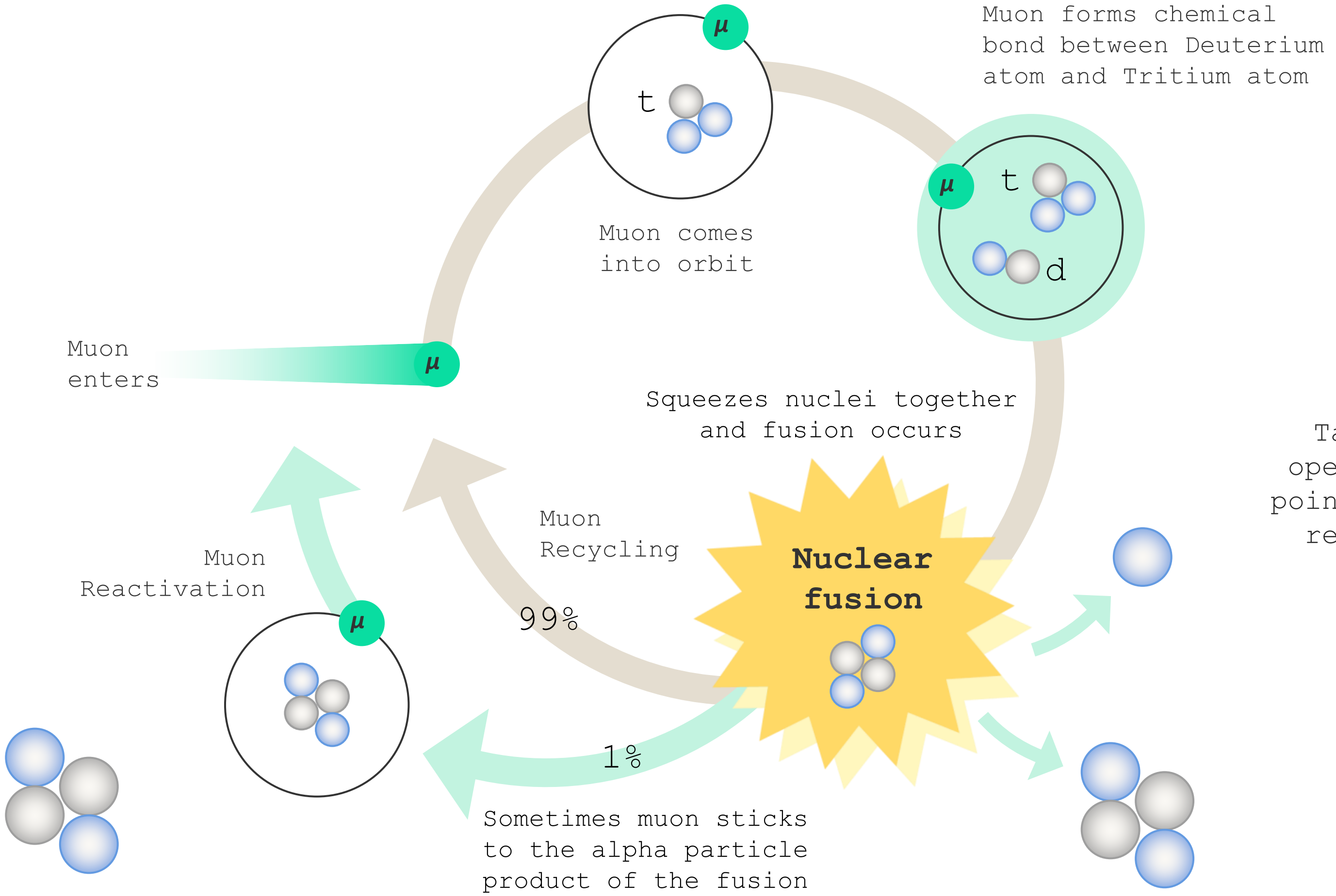
Unlocks new design options to **simplify subsystems** and **reduce costs**





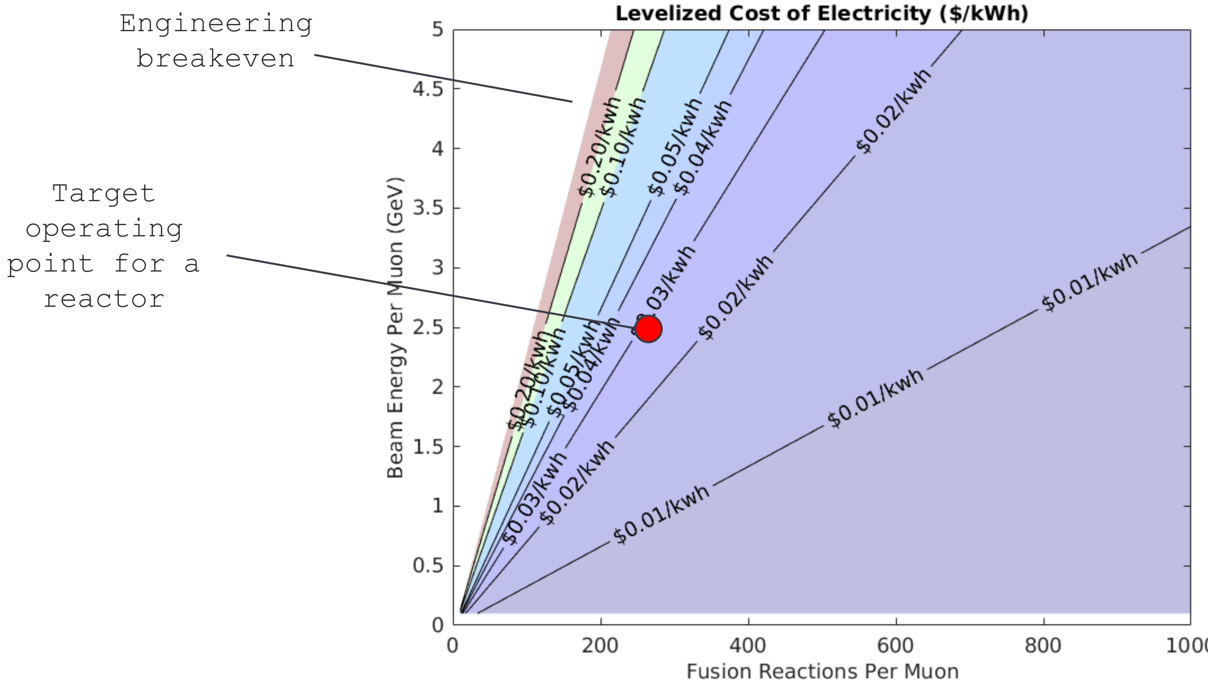
Illustrative simulation of neutron flux change in tokamak subsystem materials, comparing polarized and unpolarized fuel scenarios acceleron

Muon-catalyzed fusion



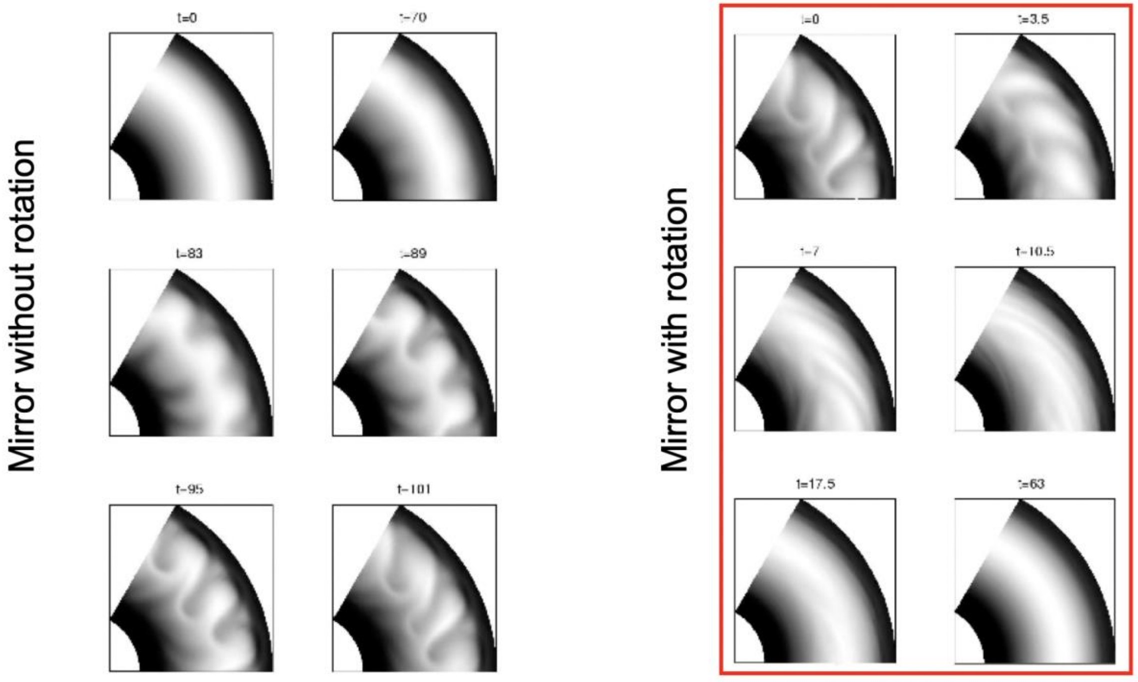
Critical Values:

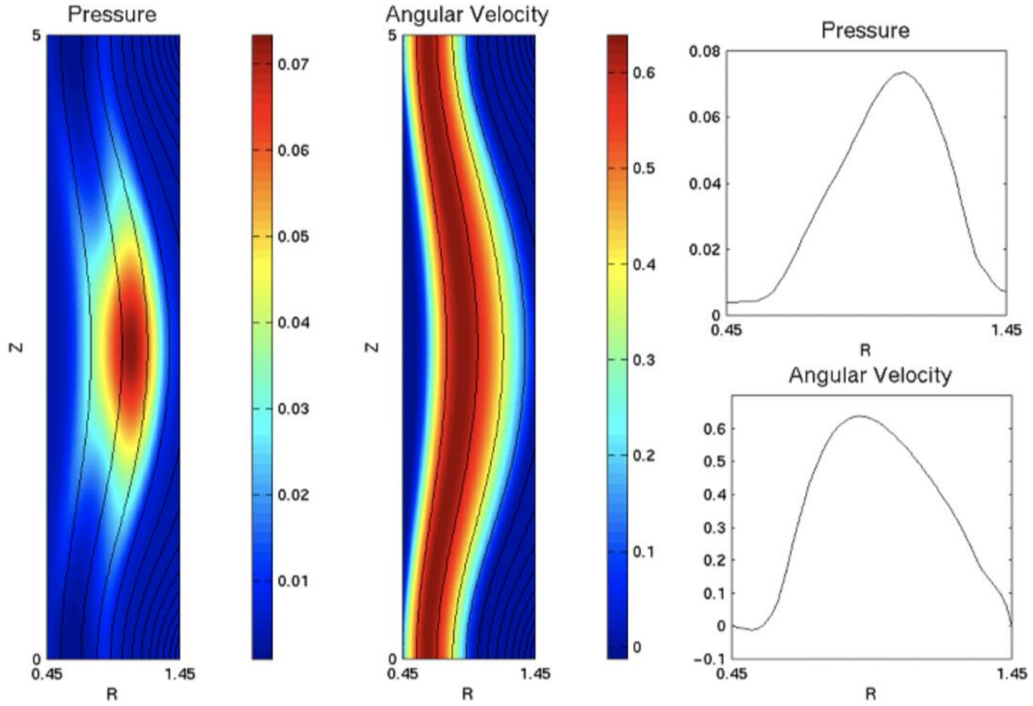
- 250 GeV / muon
- 300 Fusions / muon



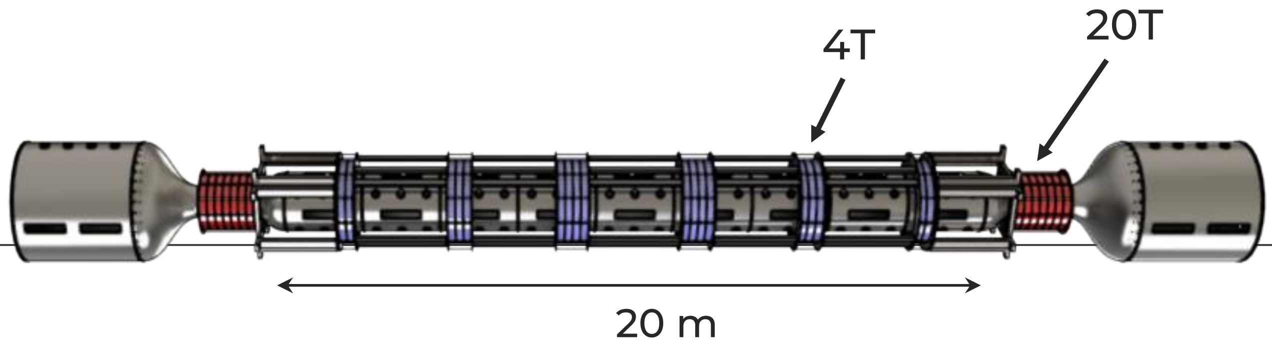
Centrifugal Mirror Fusion eXperiment (CMFX)

Lets take a mirror and spin it!





~200-400M for a Q_{eng} >1 experiment!



In conclusion…

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ARPA-E Fellows are Early-Career Innovators

ARPA-E Fellows have the freedom to discover and develop their technological passion. They work closely with brilliant minds to solve urgent energy challenges and shape tomorrow's energy future and are not confined by a singular project.

"The only problem with this job is figuring out a next step that can possibly measure up to it."

- Dr. Ashwin Salvi, Former Fellow

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