The Role of Fusion in a Decarbonized Electricity System

Summary of Findings

A study from the MIT Energy Initiative in collaboration with
the MIT Plasma Science and Fusion Center

September 2024

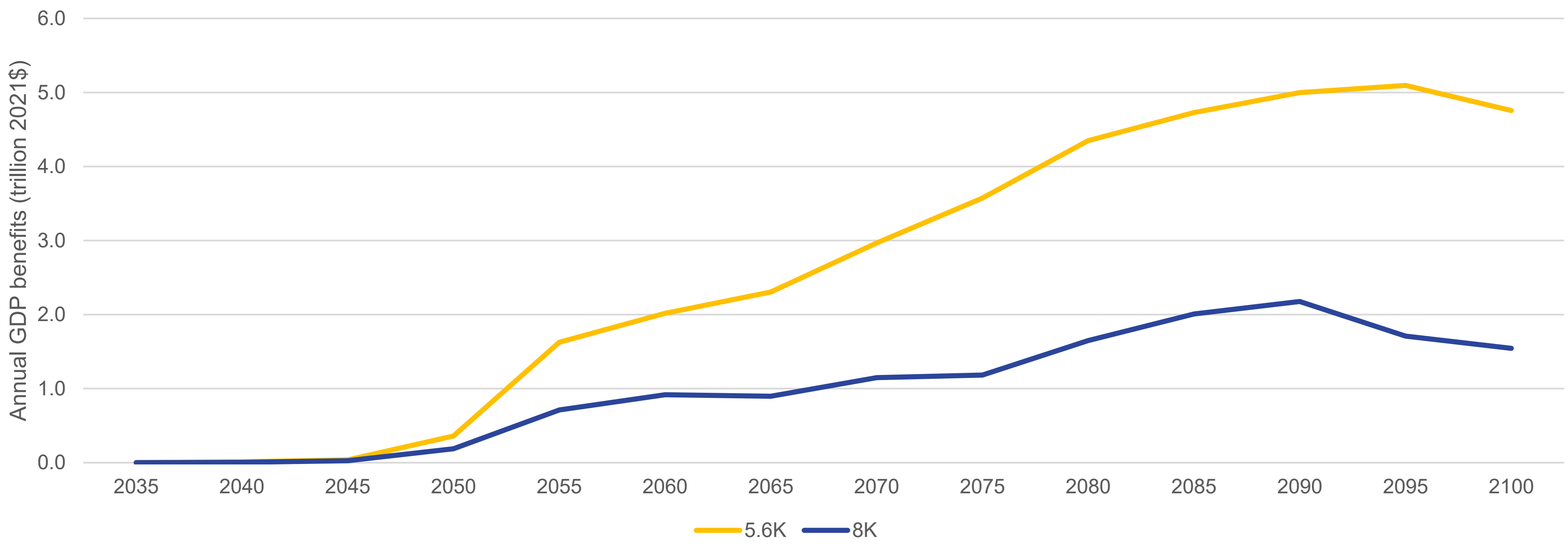
Overview of Fusion - Opportunity and Challenge

- When two nuclei combine they release enormous amounts of energy:
  - More than 1,000,000 times the energy of combustion on a mass basis
  - More than nuclear fission on a mass basis
- Required conditions for fusion:
  - Very high temperatures (>> 100 million degrees C)
  - Confinement of fusion fuels to bring them together long enough to fuse
- Primary confinement methods:
  - Magnetic confinement
  - Inertial confinement
  - Magneto-inertial confinement
- The Challenge:
  - Building an economically viable system that can handle the temperatures and high-energy particles released, plus the ability to convert that energy into electricity

Timeline and Structure of this Study

- Project period: fall of 2022 through spring 2024
- Structured with core workstreams:
  - Global deployment
  - Subregions of United States
  - Critical materials and supply chains
  - Key cost drivers
- We do not predict:
  - When fusion will first be deployed commercially
  - Which fusion technology will deploy first
  - What it will cost
- Instead, we focus on conditions required for fusion commercial viability

Fusion has a potential societal value in the trillions of dollars

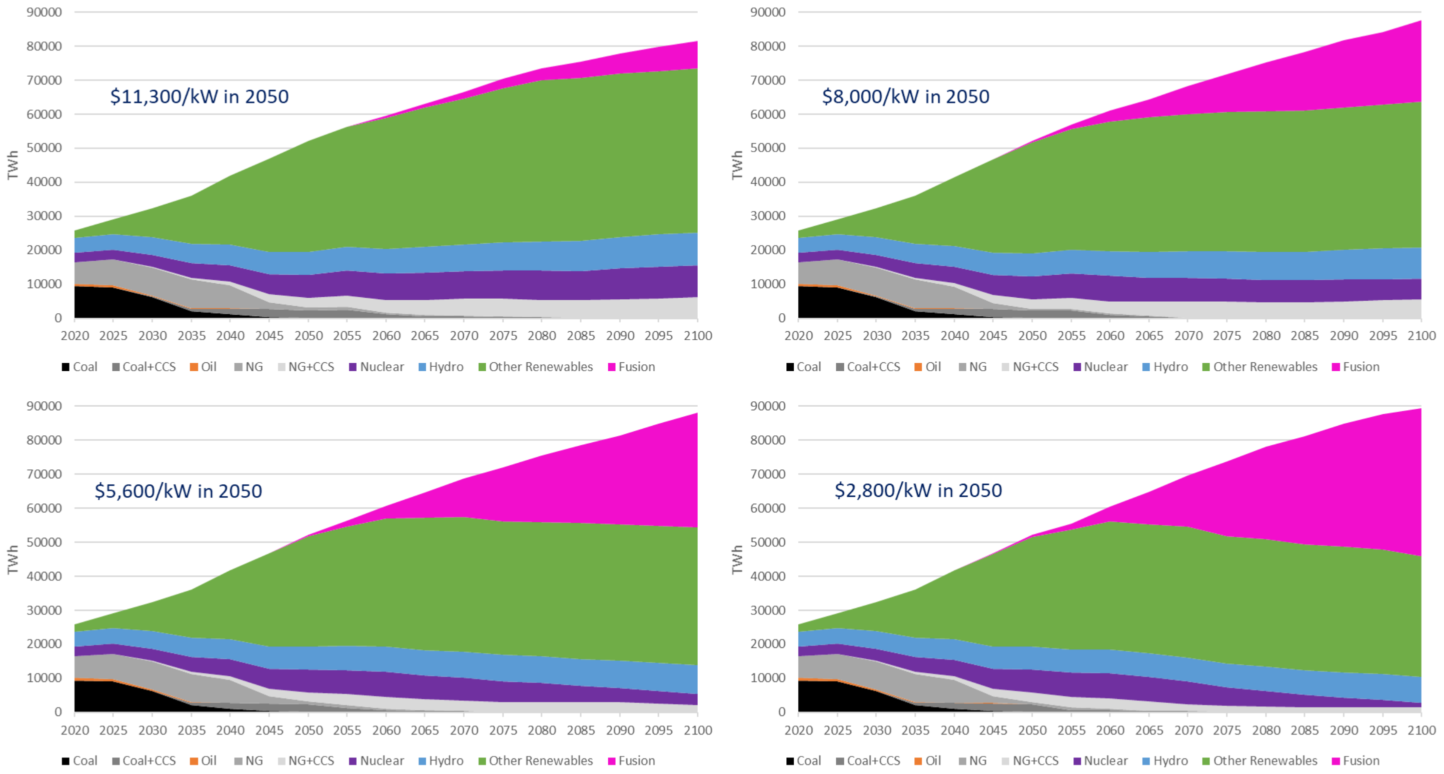


- Fusion technology can reduce the total cost of decarbonization by a cumulative discounted $3.6 trillion if fusion power plants cost $8,000/kW in 2050 and fall to $4,300/kW in 2100
- Fusion technology can reduce the total cost of decarbonization by a cumulative discounted $8.7 trillion if fusion power plants cost $5,600/kW in 2050 and fall to $3,000/kW in 2100

Note: Dollars in this presentation are reported in 2021 dollars, except were explicitly indicated

The scale of fusion deployment will depend on costs

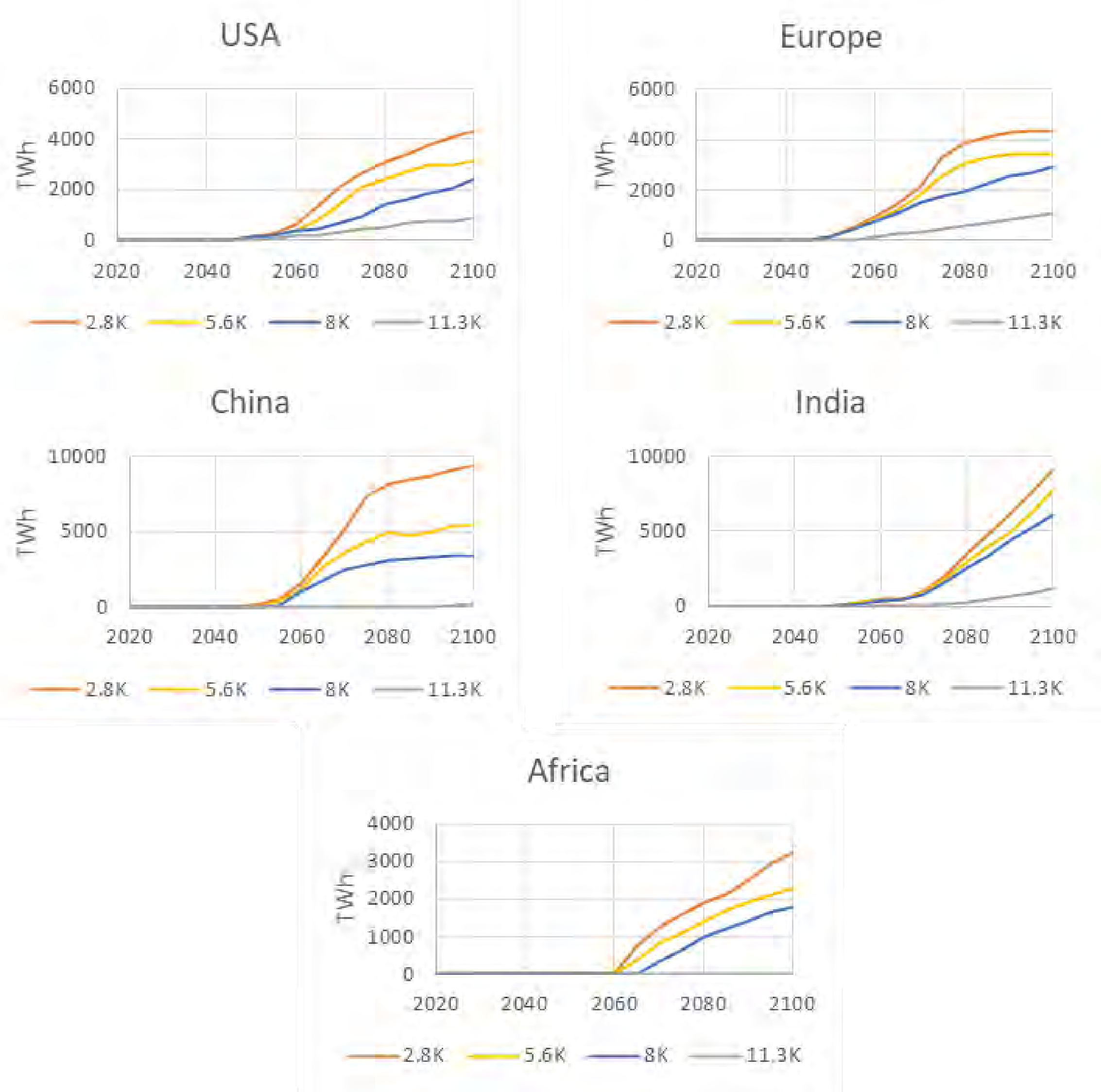
- For a 1.5°C stabilization decarbonization scenario, the total global share of electricity generation from fusion in 2100 ranges from less than 10% to about half depending on the assumed cost for fusion.



- Fusion costs shown are for the overnight cost of constructing a fusion power plant in the U.S. in the year 2050. At the end of the century, costs are about half the assumed 2050 costs.

The scale and timing of fusion deployment is highly variable across regions

- Initial deployment is strongest in the United States and Europe
- Largest increase in fusion takes place in India during the last three decades of the century
- Africa is a late adopter of fusion but sees strong growth late in the century
- These trends are driven by
  - economic growth
  - population density
  - electrification needs
  - regional costs
  - decarbonization targets
  - relative prices of electricity
  - limits on fission-based nuclear generation
  - renewable resource availability



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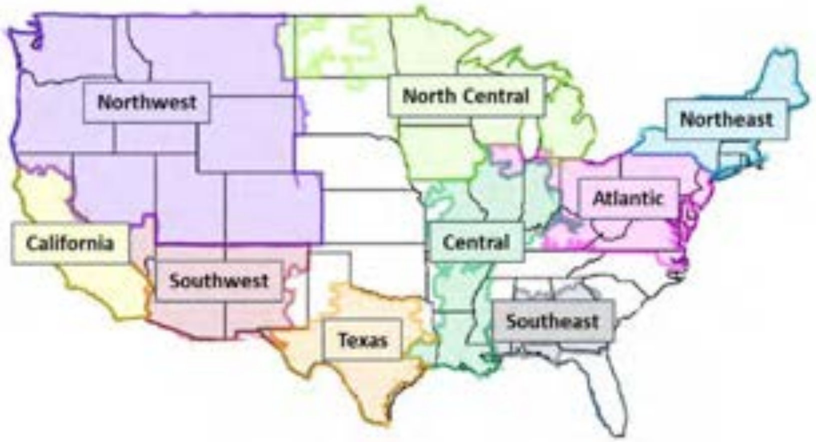
Fusion deployment will highly depend on the availability and cost of other low-carbon technologies

	High Penetration, Low Sensitivity*	Medium Penetration, Medium Sensitivity*	Low Penetration, Low Sensitivity*	Low Penetration, High Sensitivity*
U.S. Subregions	Atlantic and Southeast	California, Northeast, Southwest	Northwest	Central, North Central, Texas
Renewable attributes	Poor onshore wind, hydro, and geothermal resources	Northeast has best offshore wind; California has best geothermal; Southwest has best solar; all three have modest onshore wind capacity or quality	Below average solar and wind resources, but excellent diversity of renewable resources including good hydro and moderate geothermal	Abundant, high-quality, and low-cost onshore wind; limited renewables beyond onshore wind and solar
Fusion penetration at $6,000/kW	Required at all emission caps from 1 to 50 gCO_2/kWh	No penetration at 50 gCO_2/kWh, but capacity reaches 33%–55% of demand at 1 gCO_2/kWh	Required at all emission caps 1–20 gCO_2/kWh but capacity is never more than 26% of demand	Required only at 4 gCO_2/kWh and below, but capacity reaches 25%–45% of demand at 1 gCO_2/kWh

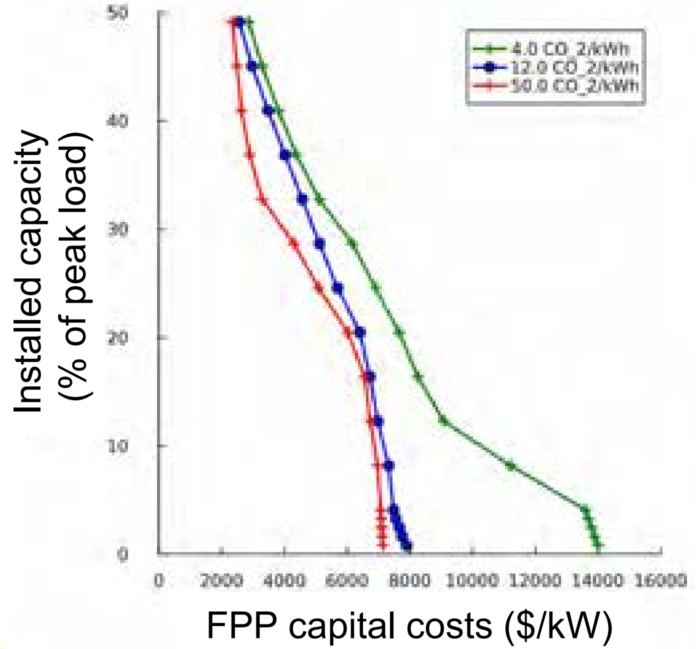


* **Sensitivity** refers to the sensitivity of fusion penetration with respect to changes in the emissions cap

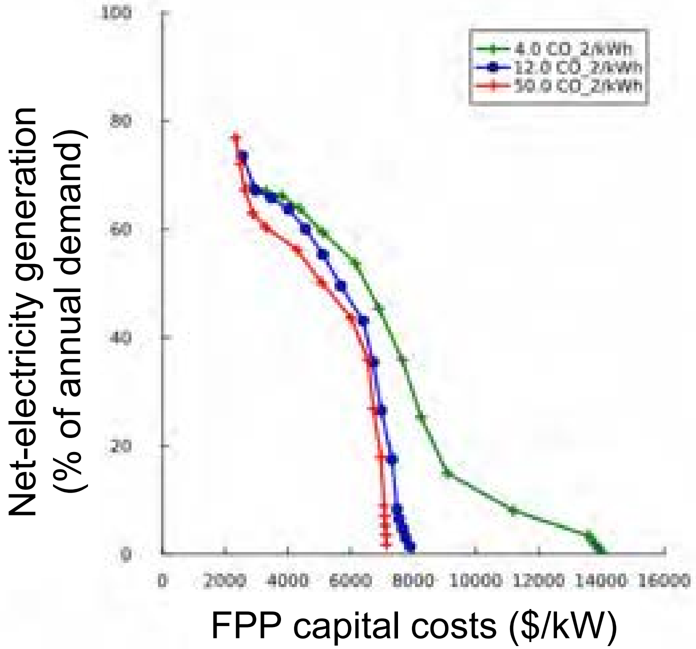
The role of fusion power plants is also highly sensitive to costs

- Fusion power plants serve as
  - Low-capacity-factor, dispatchable electric generation when fusion costs are high
  - Baseload resource when FPP costs are moderate
  - Dispatchable generation with a moderate capacity factor when FPP costs are low.
- This trend was observed in our analysis of the New England subregion of the U.S.

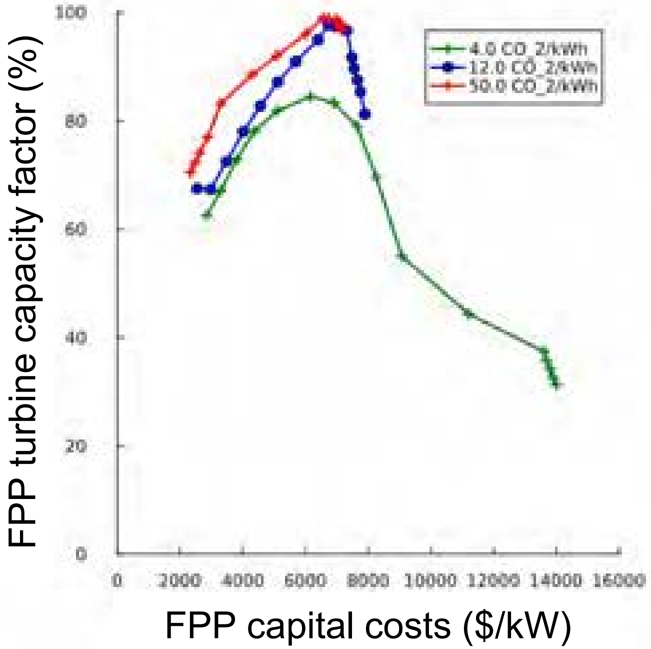
Fusion installed capacity as % of peak load



Fusion fleet generation capacity as % of annual demand

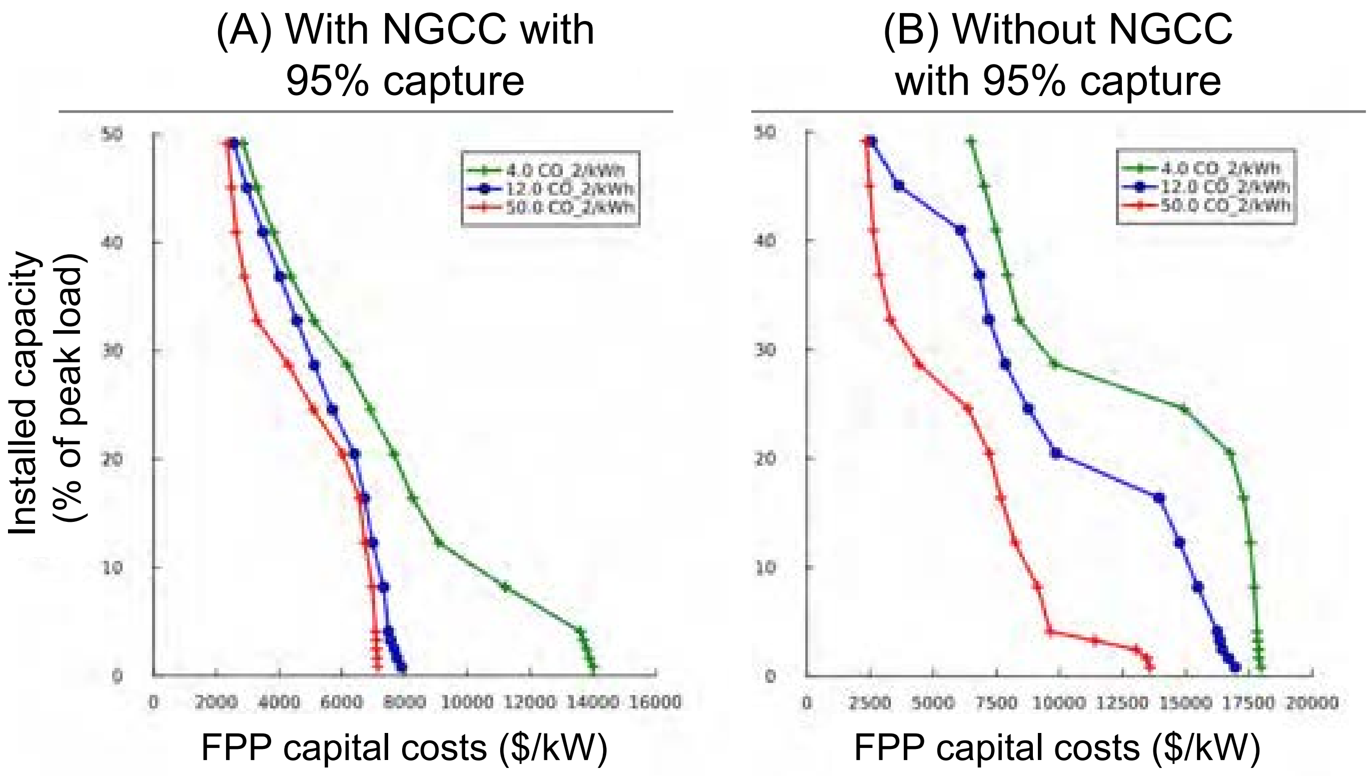


Fusion annual capacity factor



The availability of firm, low-carbon natural gas power plants can have a large impact on the deployment of fusion power plants

- NGCC power plants with high carbon capture and low upstream methane emissions can have a large impact on fusion deployment
- Threshold cost point at which fusion becomes competitive is $4,000/kW lower when NGCC with 95% carbon capture is available than when NGCC with 95% carbon capture is not available.



Supply chains for the processed materials and manufactured parts needed to build fusion power plants vary widely in maturity

- Different technologies are at varying stages of maturity with identifiable issues and bottlenecks

- R&D is needed to develop materials and manufacturing capabilities essential for fusion at the scale outlined in this report

- Fusion components can be broken up into two categories:
  - Niche (e.g. tungsten heavy) with limited non-fusion market opportunities
  - Components (e.g. high-temperature superconductor, radio-frequency devices) with strong potential for commercial non-fusion use

- For raw materials, there are no anticipated showstoppers, however beryllium resources and markets remain an uncertainty

Key cost drivers for fusion power plants include reactor equipment cost, regulatory considerations, and operations and maintenance costs

- Fusion reactor equipment is the leading cost contributor at 30% to 65% of the total capital cost
- Regulation can be a potentially large cost driver and motivates
  - fusion companies to minimize their footprint with respect to fuels and activated materials
  - governments to adopt appropriate and effective regulatory policies to maximize their ability to use fusion energy in achieving decarbonization goals
- Operating and maintenance (O&M) costs can be significant for a fusion power plant

Key Takeaways

- Fusion has potential societal value in the trillions of dollars in a decarbonized world.
- Deployment and operation of fusion power plants is highly dependent on:
  - Fusion costs
  - Cost and availability of alternative low-carbon technologies in each region
  - Carbon emission constraints
  - Economic and electricity demand growth
  - Market design
- The ability of fusion to scale requires development of materials and manufacturing capabilities for niche components
- For raw materials, there are no anticipated showstoppers

Acknowledgements

Study Participants

Robert Armstrong
Randall Field
John Parsons
Koroush Shirvan
Nirmal Bhatt
Sara Ferry
Theodore Mouratidis
Jeffrey Freidberg
Dharik Mallapragada
Jennifer Morris
Elsa Olivetti
Tim Schittekatte
Robert Stoner
Dennis Whyte
Ruaridh Macdonald
Sergey Paltsev
Layla Araiinejad
Amanda Farnsworth
Angelo Gurgel
Y.-H. Henry Chen
Emre Gençer
Samuele Meschini
Matthew Munderville
Richard Roth
Michael Short

Subject Matter Experts

Zachary Hartwig
Alexander Molodyk
Keith Smith
Steve Wukitch
Stuart Malloy
Daniel Ng
Lance Sneed
Yifei Zhang

Project/Report Team

Gail Monahan
Tom Witkowski
Elizabeth Hamblin
Kelley Travers
Kelly McGinity
Marika Tatsutani

Funding

MITEI and PSFC gratefully acknowledge Eni for supporting this research and for engaging in discussions with MIT during this research project.