The Future of Nuclear Energy in a Carbon-Constrained World

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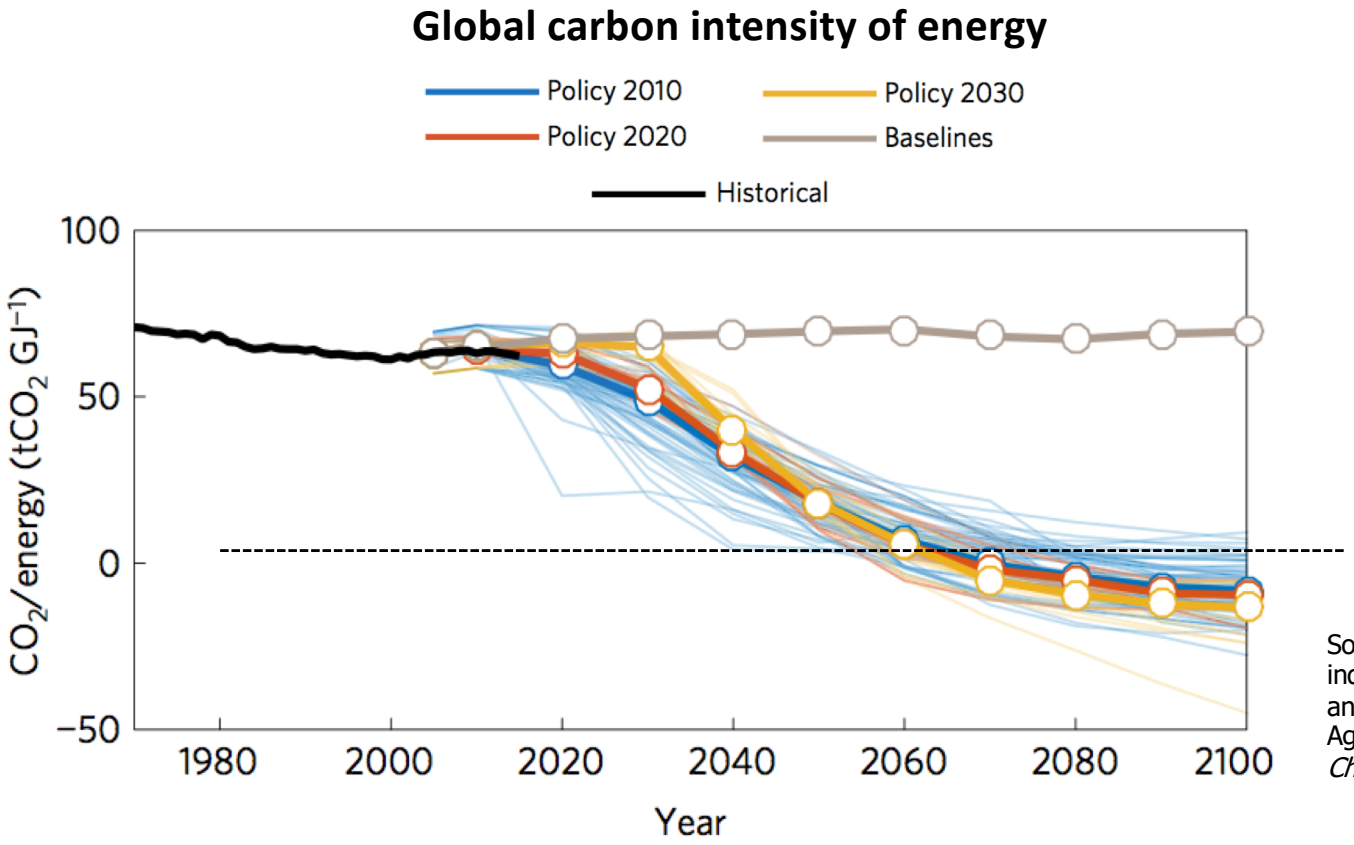
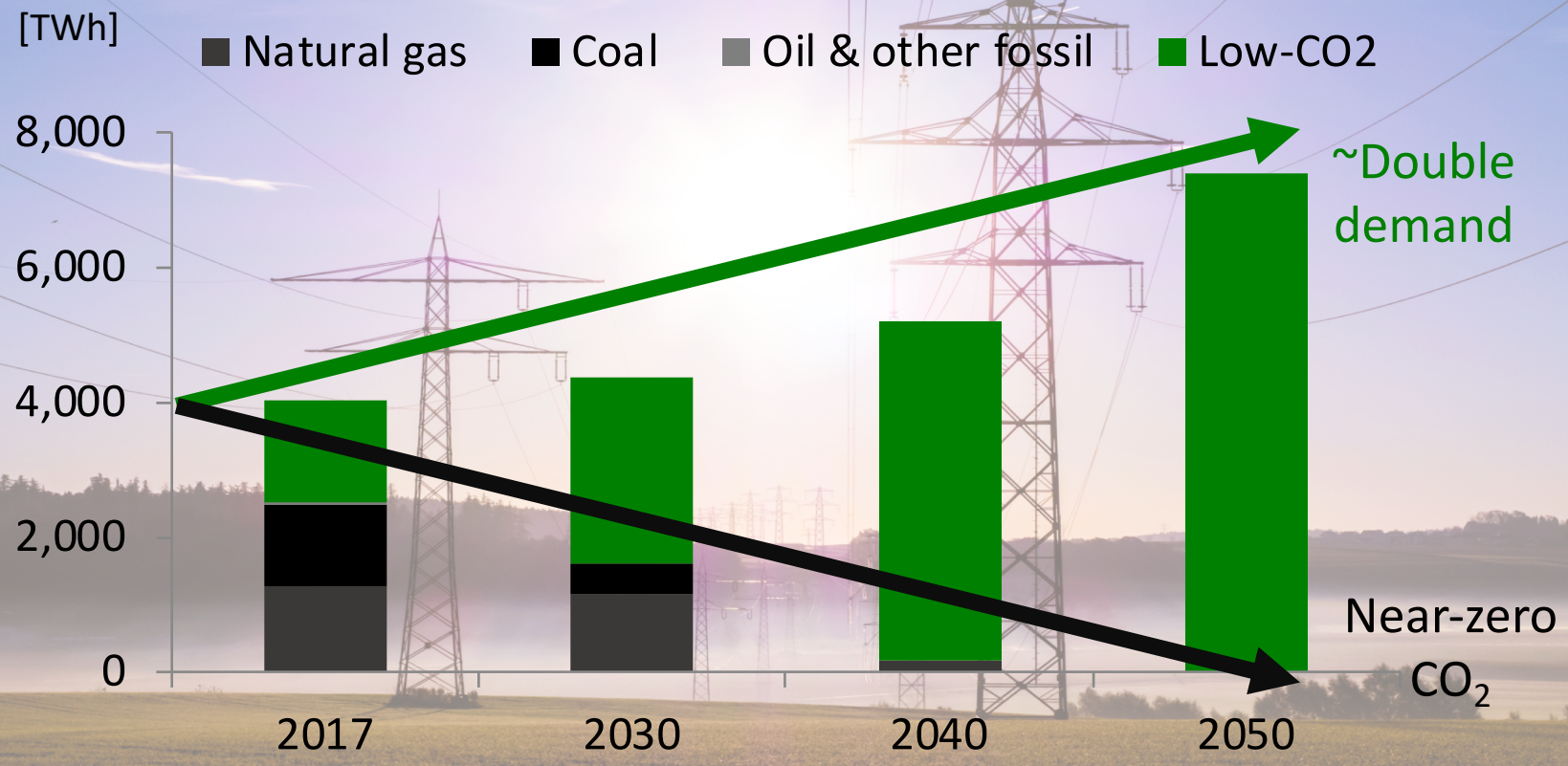
Getting to Zero



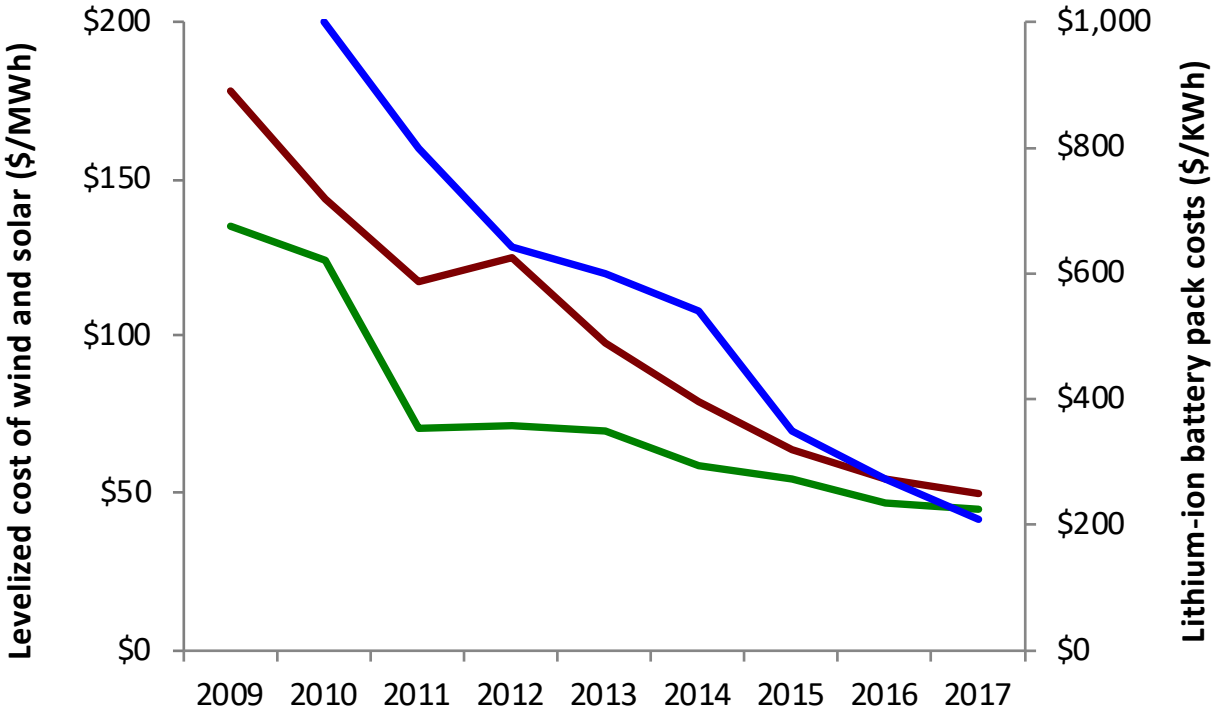
Source: Peters et al. (2017), "Key indicators to track current progress and future ambition of the Paris Agreement," *Nature Climate Change* 7: 118-122

Electricity: the Linchpin



Data source: PNNL "Reference +80%" scenario in GGCAM USA Analysis of U.S. Electric Power Sector Transitions May 2017 performed for the United States Mid-Century Strategy for Deep Decarbonization

Wind, Solar & Battery Costs Plummet



Total cost declines

Solar $/MWh -72%

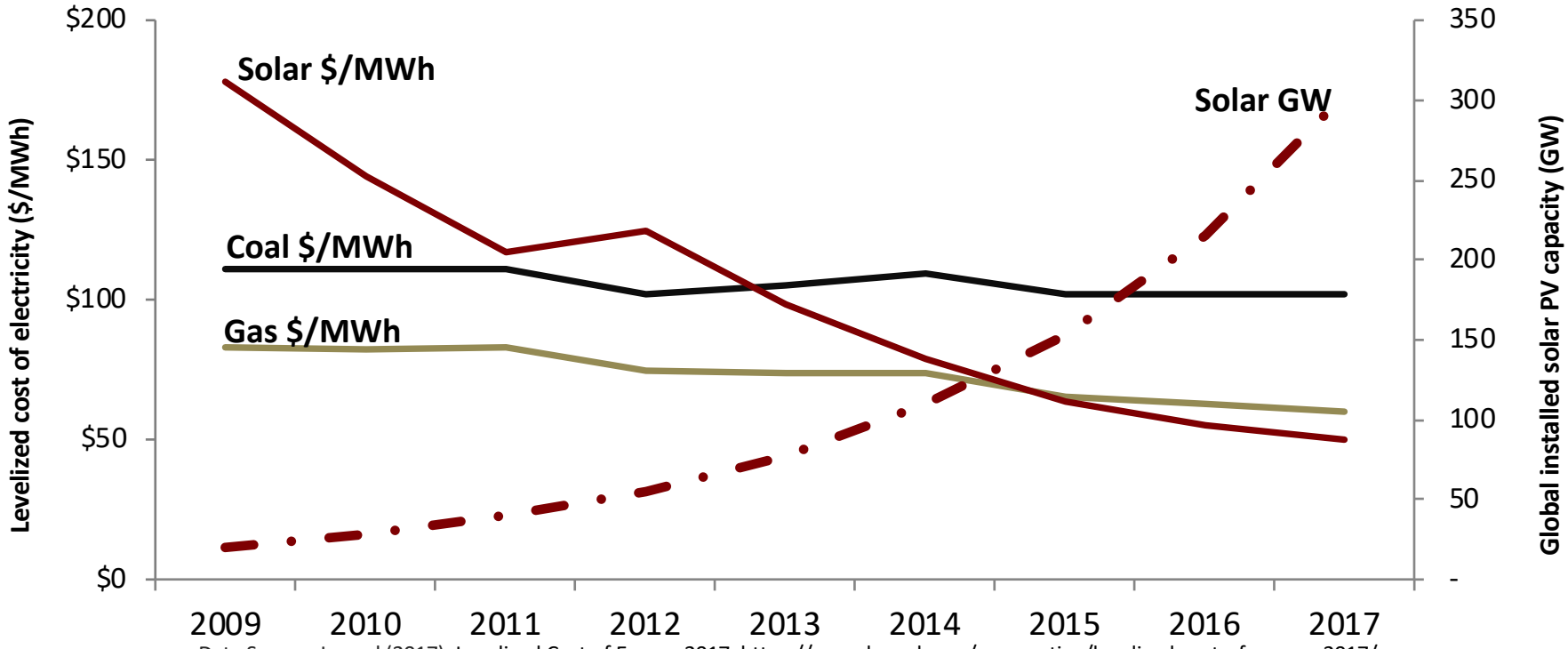
Wind $/MWh -67%

Li-ion packs $/KWh -79%

Data Source: Wind and solar levelized costs from Lazard. Battery pack costs from Bloomberg New Energy Finance

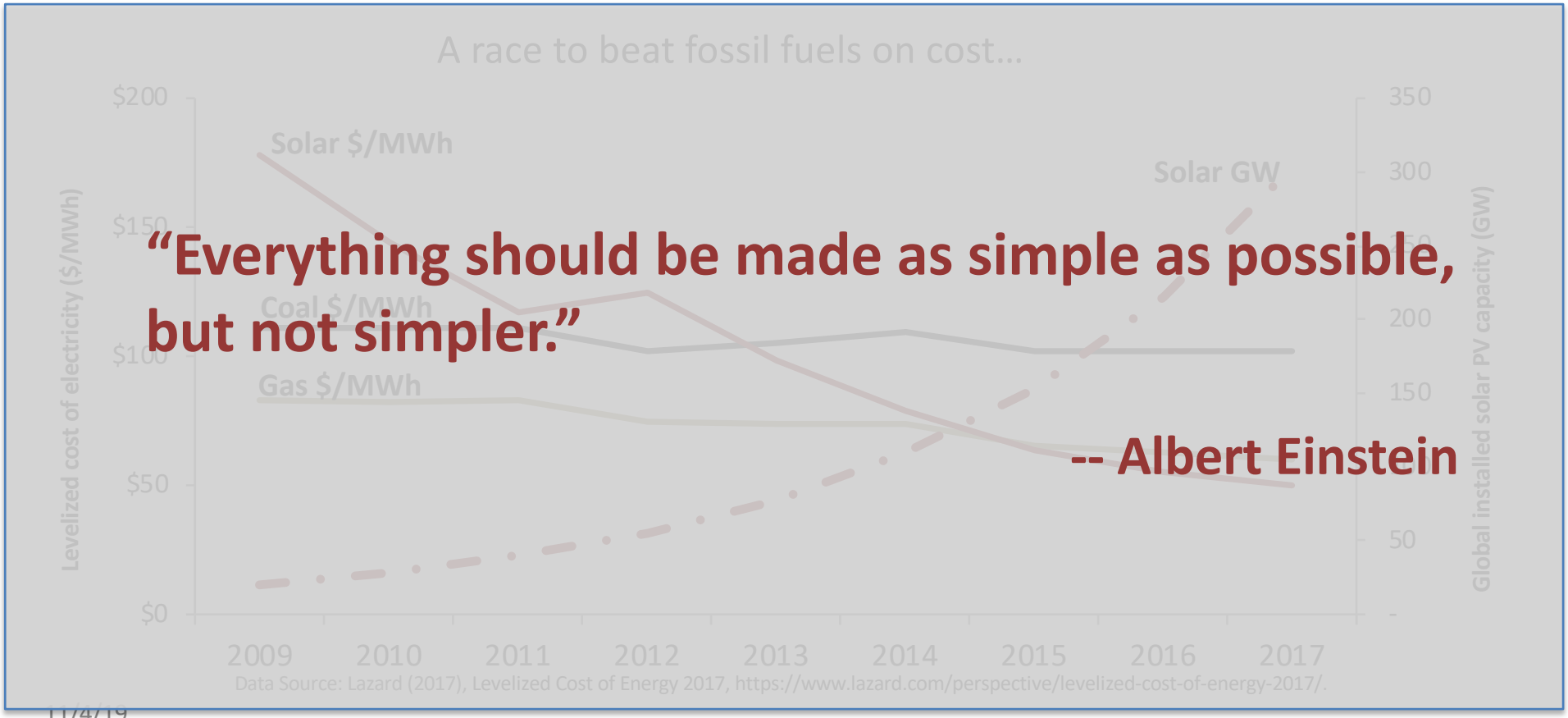
A simple ‘mental model’

A race to beat fossil fuels on cost…



Data Source: Lazard (2017), Levelized Cost of Energy 2017, https://www.lazard.com/perspective/levelized-cost-of-energy-2017/.

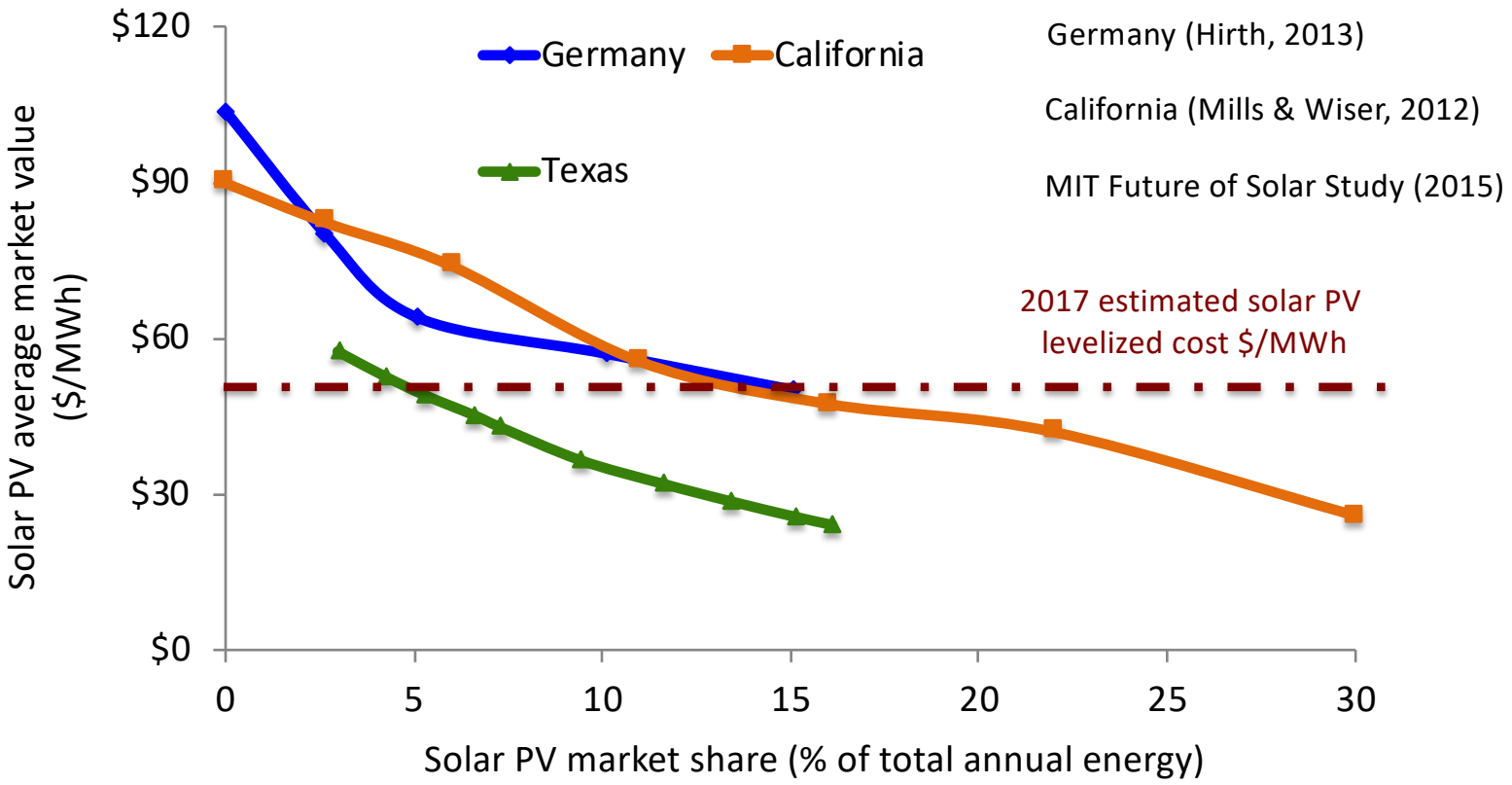
A simple ‘mental model’



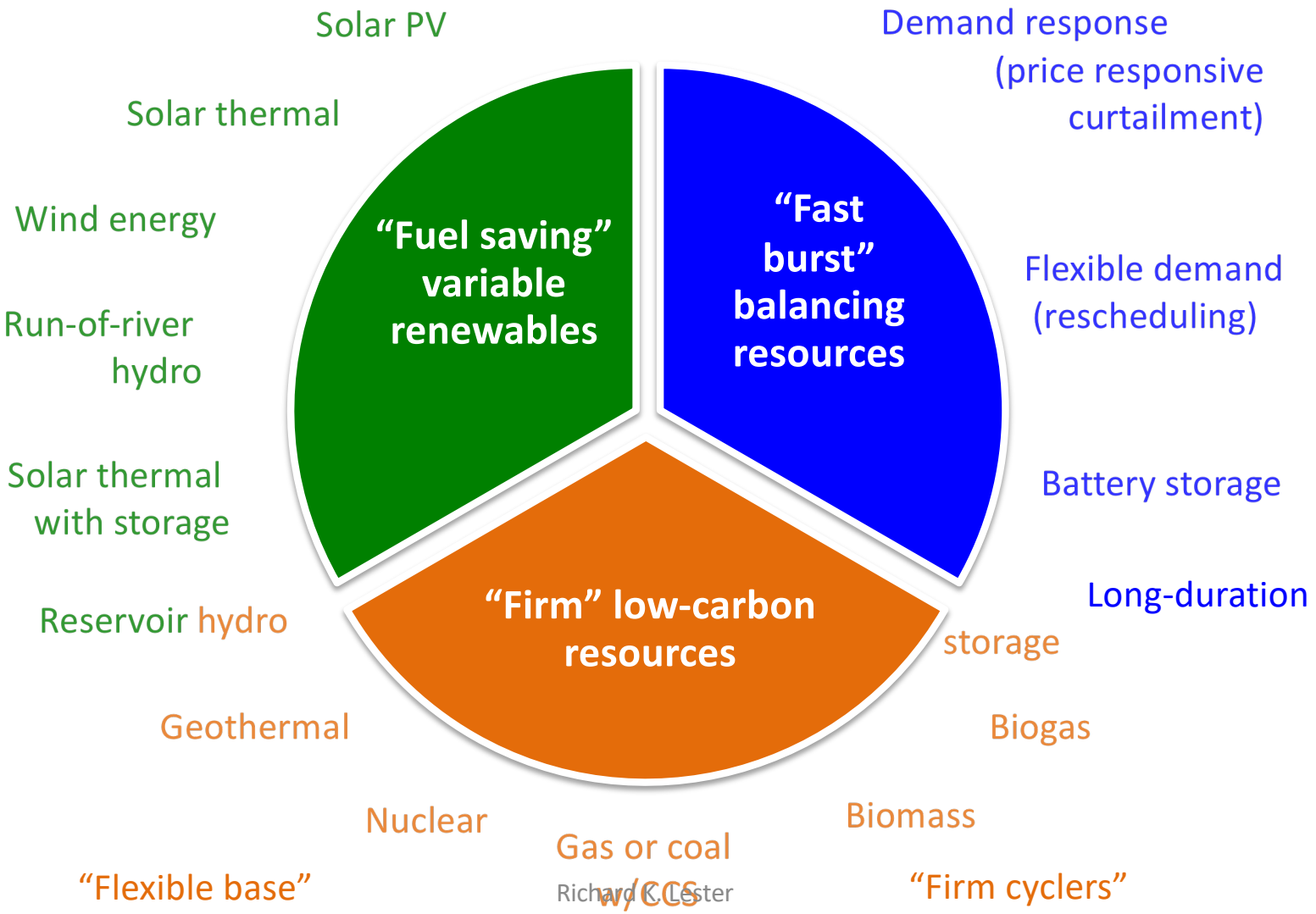
“Everything should be made as simple as possible, but not simpler.”

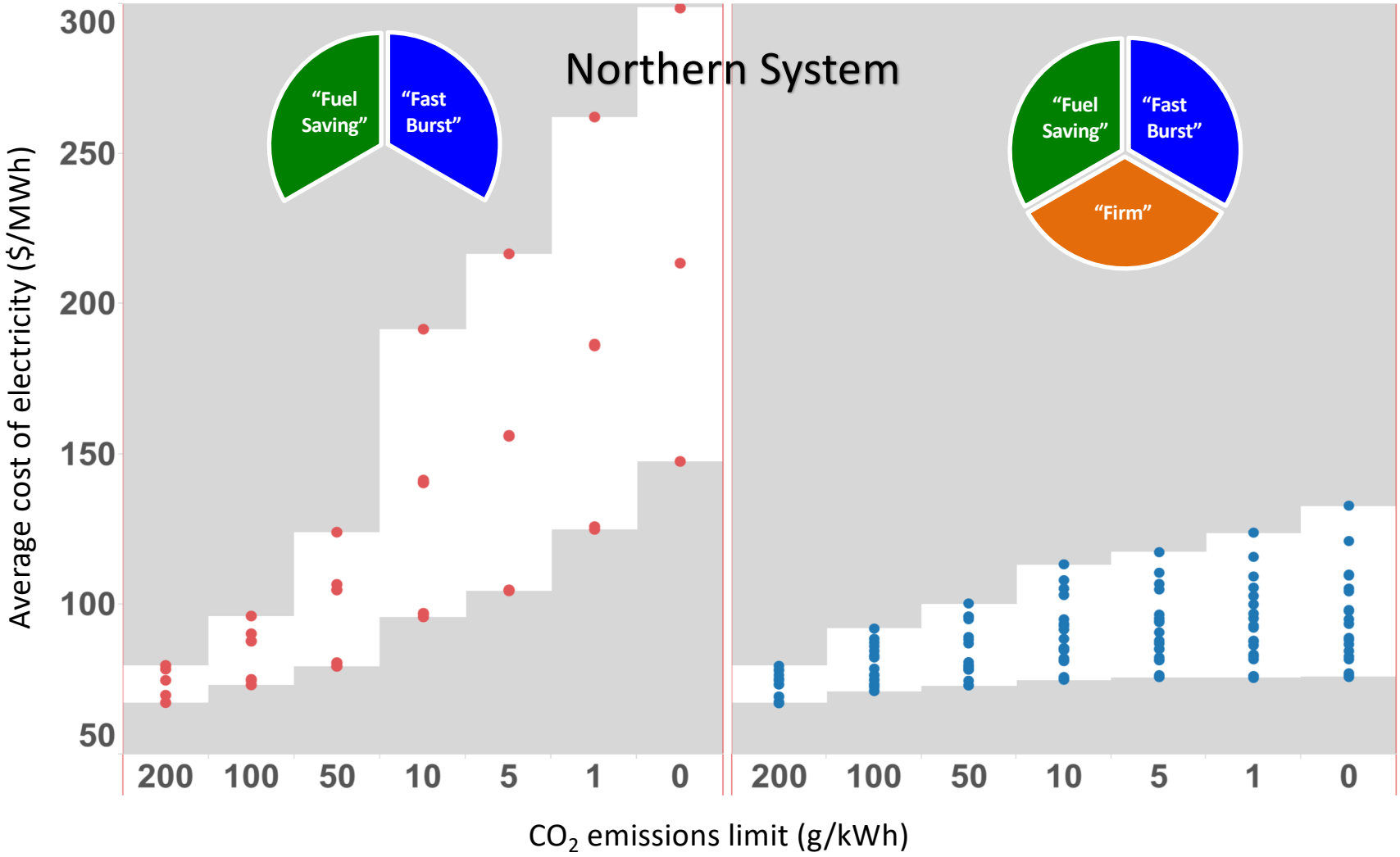
-- Albert Einstein

A Race Against Declining Value

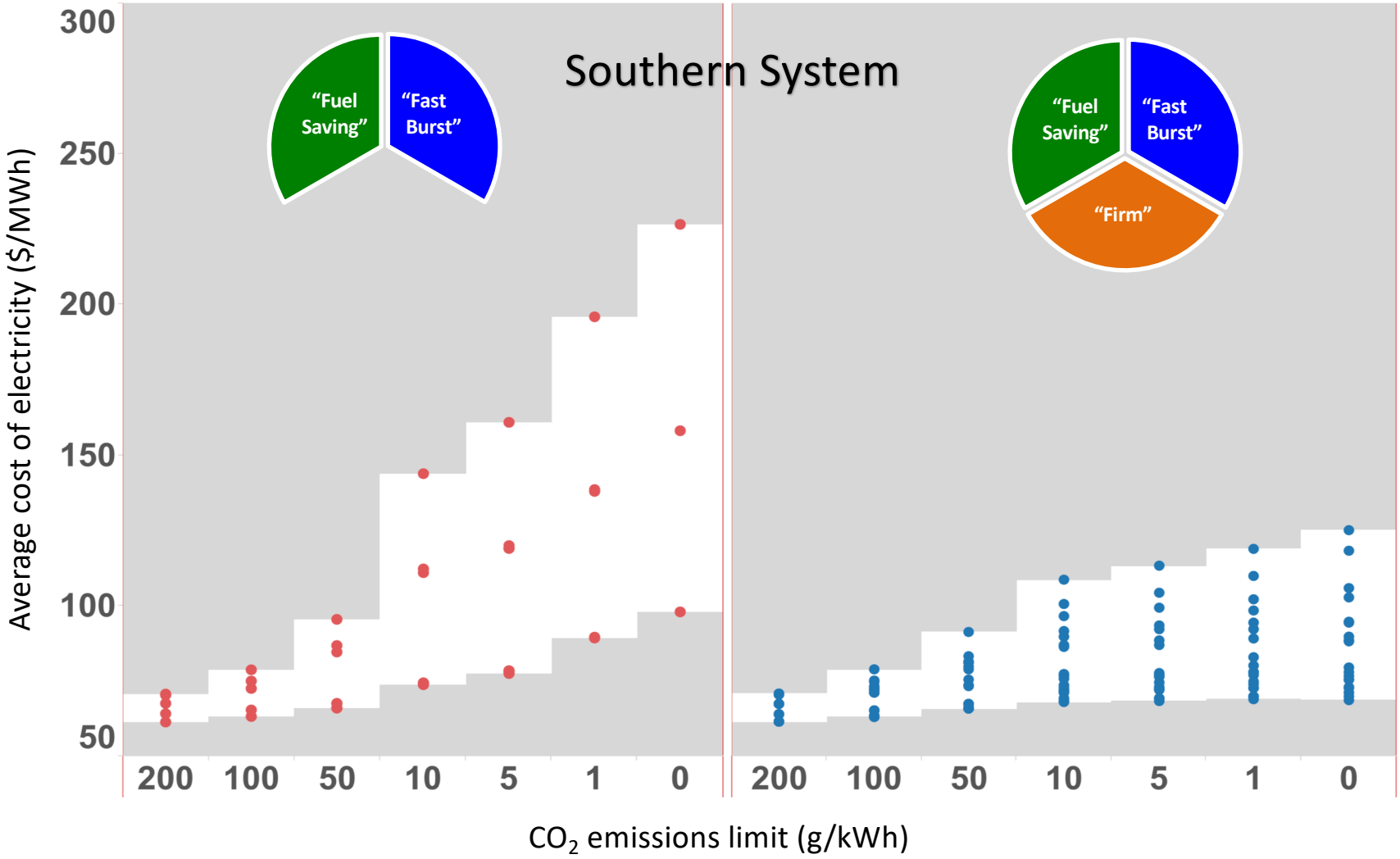


Data Source: Sivaram & Kann (2016), Solar needs a more ambitious cost target, *Nature Energy* Vol. 1 (April 2016).


Solar PV
Solar thermal
Wind energy
Run-of-river hydro
Solar thermal with storage
Reservoir hydro
Geothermal
Nuclear
Gas or coal w/ CCS
"Flexible base"
"Fuel saving" variable renewables
"Fast burst" balancing resources
"Firm" low-carbon resources
Demand response (price responsive curtailment)
Flexible demand (rescheduling)
Battery storage
Long-duration storage
Biogas
Biomass
"Firm cyclers"

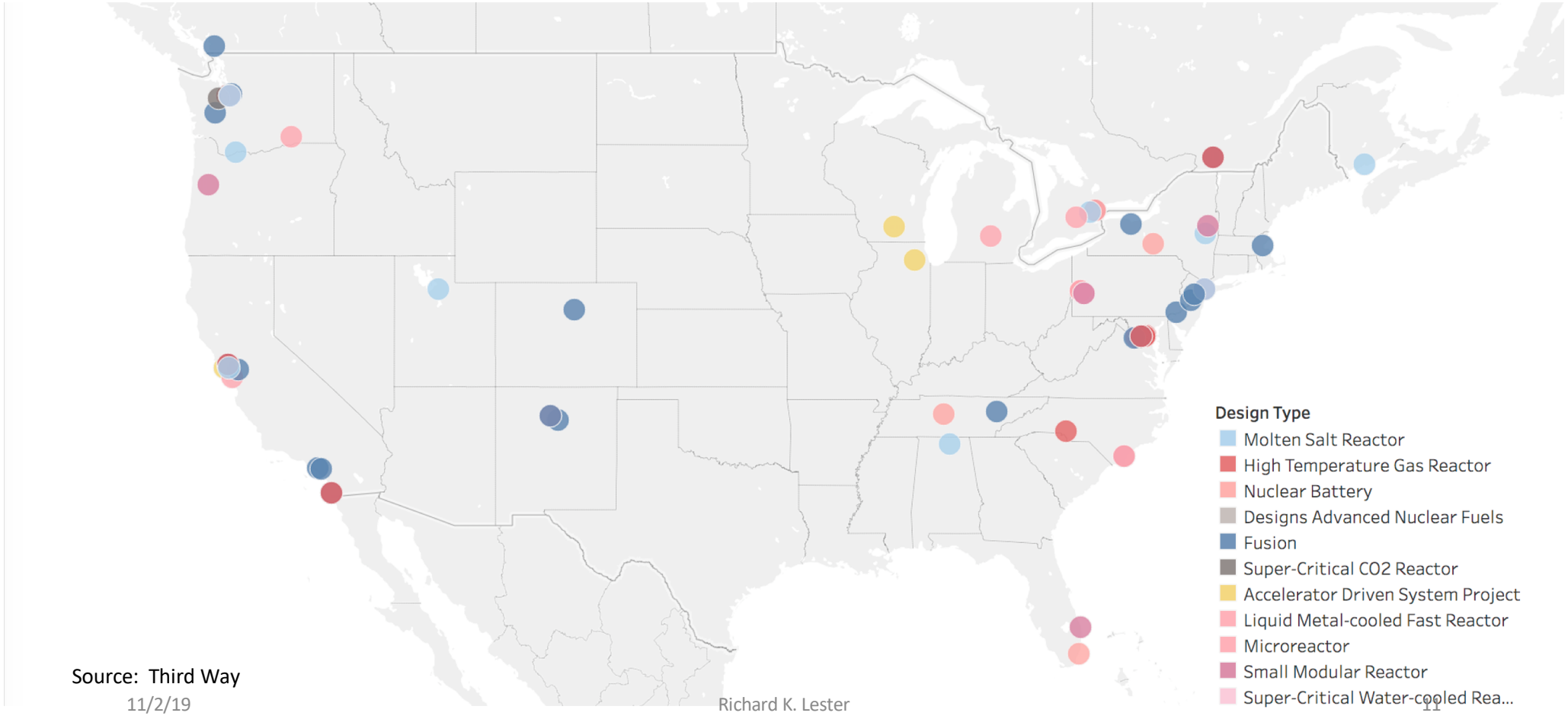


Data source: Sepulveda, Jenkins, de Sisternes, & Lester (2018), "The role of firm low-carbon resources in deep decarbonization of electric power systems," *Joule*



Data source: Sepulveda, Jenkins, de Sisternes, & Lester (2018), "The role of firm low-carbon resources in deep decarbonization of electric power systems," *Joule.*

Advanced Nuclear Projects in the United States (2019)



Source: Third Way

New Priorities for Nuclear Innovation

- ✓ Lower (and more predictable) capital cost
- ✓ Shorter (and more predictable) construction times
- ✓ Enhanced safety
- ✓ Reduced proliferation and security risks
- ✓ Optimized waste streams for geologic disposal
- ✓ New markets (beyond baseload power)
  - ✓ Fluid fuels production
  - ✓ Industrial heat
  - ✓ Grid services (load following, load shifting, etc.)
- ✓ Sustainable uranium and thorium usage

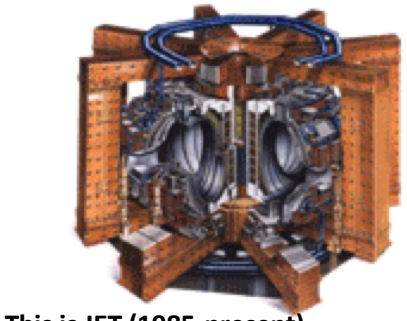
Fusion holds the possibility for producing virtually limitless, clean, safe energy

- The tokamak concept has brought fusion to the brink of achieving net energy production
- Scientists and engineers around the world are coming up with ways of optimizing the tokamak
- A fast path to fusion is needed to ensure that fusion power can help mitigate the effects of climate change

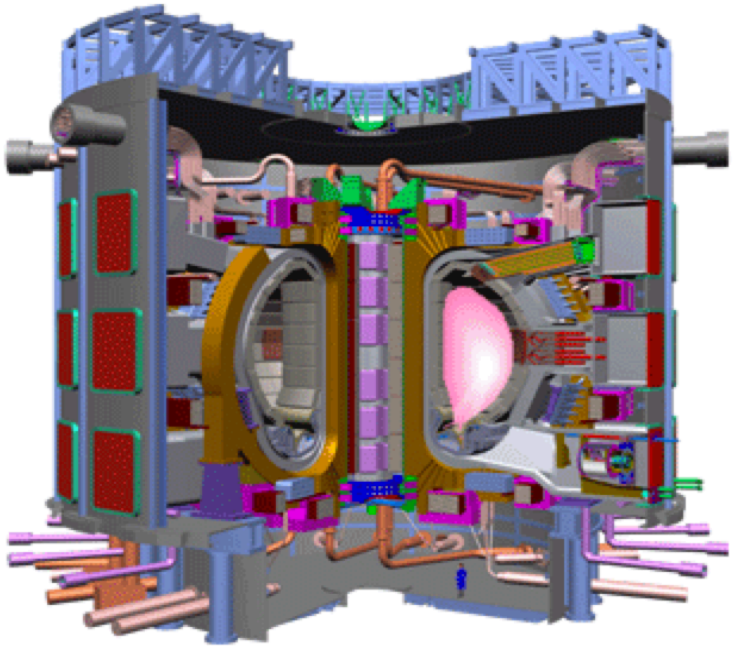
ITER is a very large international tokamak experiment, coming online in the late 2020s.

BASIC PARAMETERS.
Plasma Major Radius 6.2m
Plasma Minor Radius 2.0m
Plasma Current 15.0MA
Toroidal Field on Axis 5.3T
Fusion Power 500MW
Burn Flat Top >400s
Power Amplification Q>10

Cost is > 12 Billion Euro.



This is JET (1985-present)
Q = 0.65 record performance



This is ITER, predicted Q > 10

A typical road map to fusion: Big machines, many decades

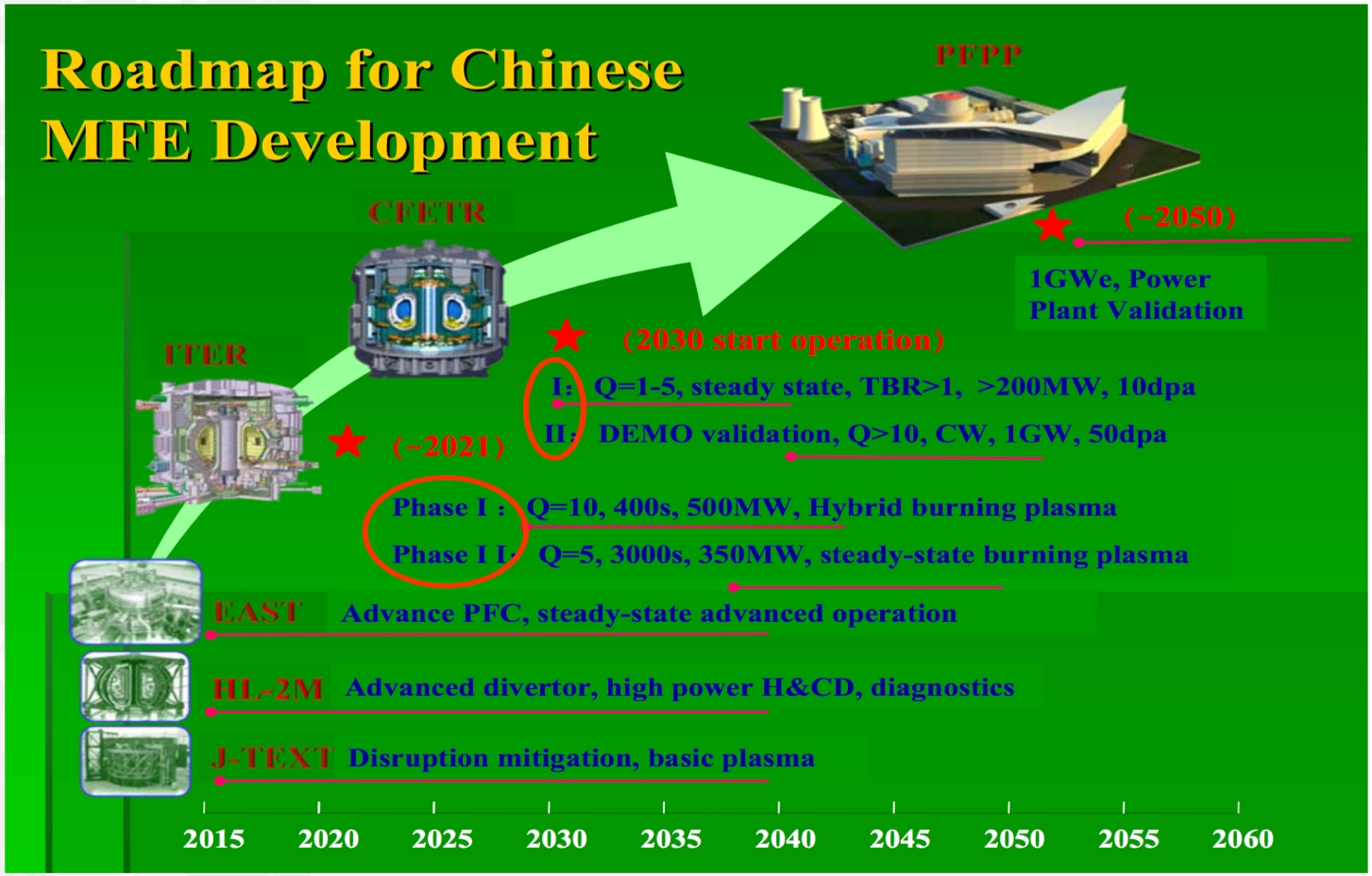
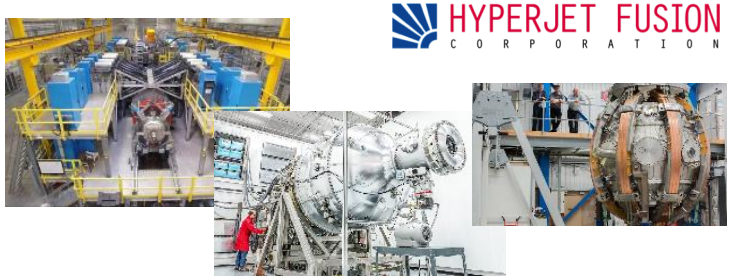


Image from Yuanxi Wan, FPA presentation, December 16-17, 2014 35 th FPA , Washington USA

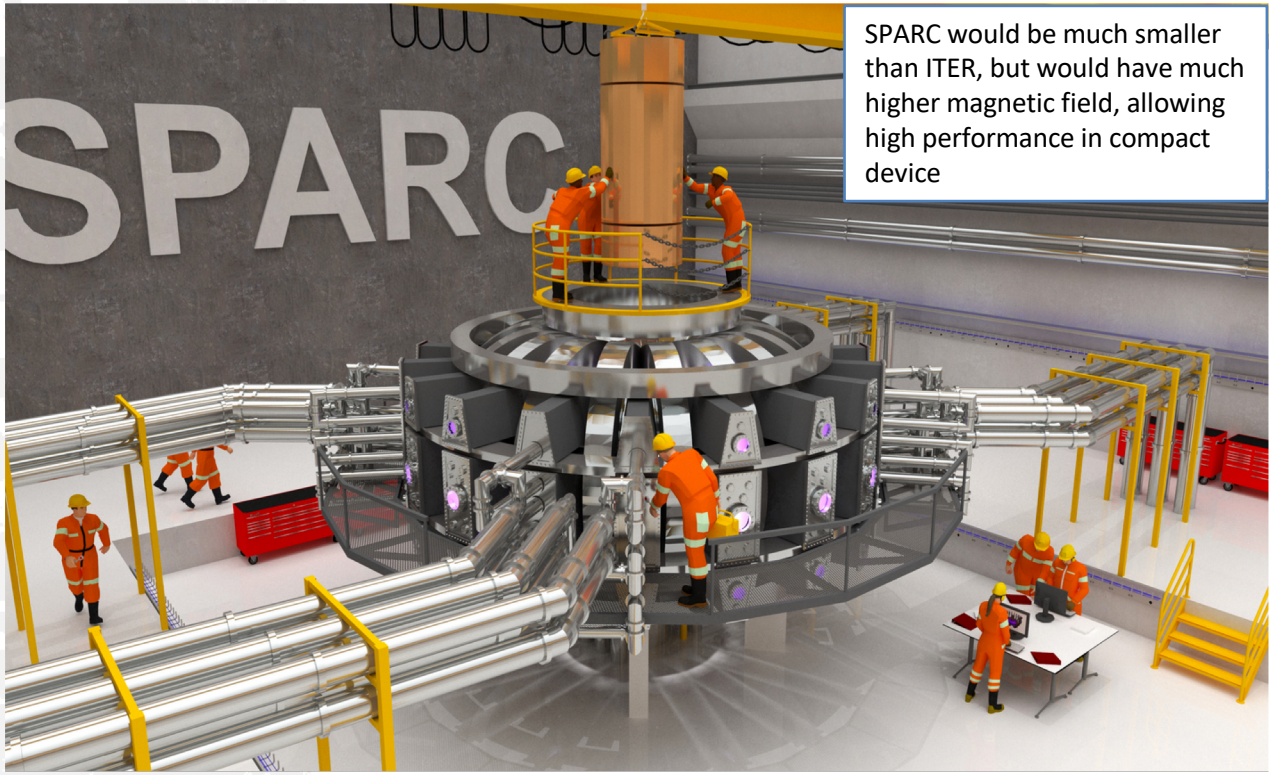
A faster path to fusion energy based on smaller tokamaks and other technologies is gaining momentum around the world

- There is a nascent fusion industry – a growing number of companies
- They are optimizing for things beyond physics
- Moving faster than government programs
  - Tight focus on deliverables and milestones
  - With less $ (now) and different resources than gov't
  - High-growth potential

Commonwealth Fusion Systems
tokamak energy
generalfusion
LOCKHEED MARTIN SKUNK WORKS
tae TECHNOLOGIES
Helion Energy
MIFTI
PHOENIX
HYPERJET FUSION CORPORATION



SPARC is a compact high-field tokamak proposed at MIT that could come online in less than a decade



SPARC would be much smaller than ITER, but would have much higher magnetic field, allowing high performance in compact device

http://news.mit.edu/2018/mit-newly-formed-company-launch-novel-approach-fusion-power-0309

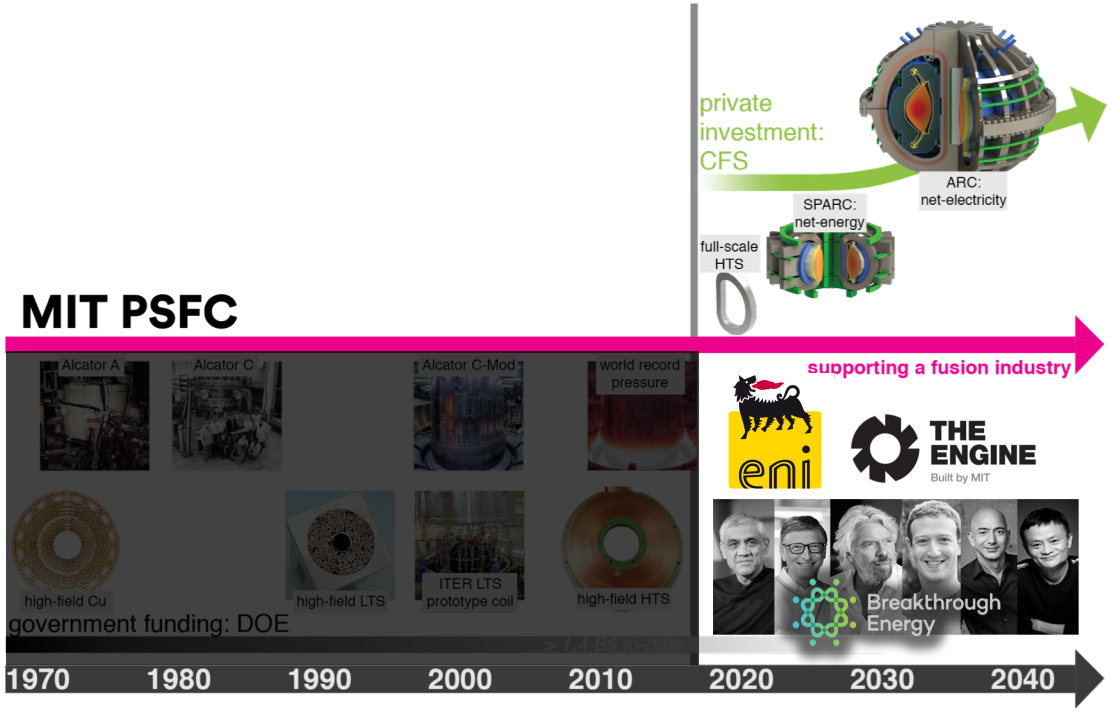
SPARC would achieve mQ > 2 [Greenwald, NAS paper]

New Technology

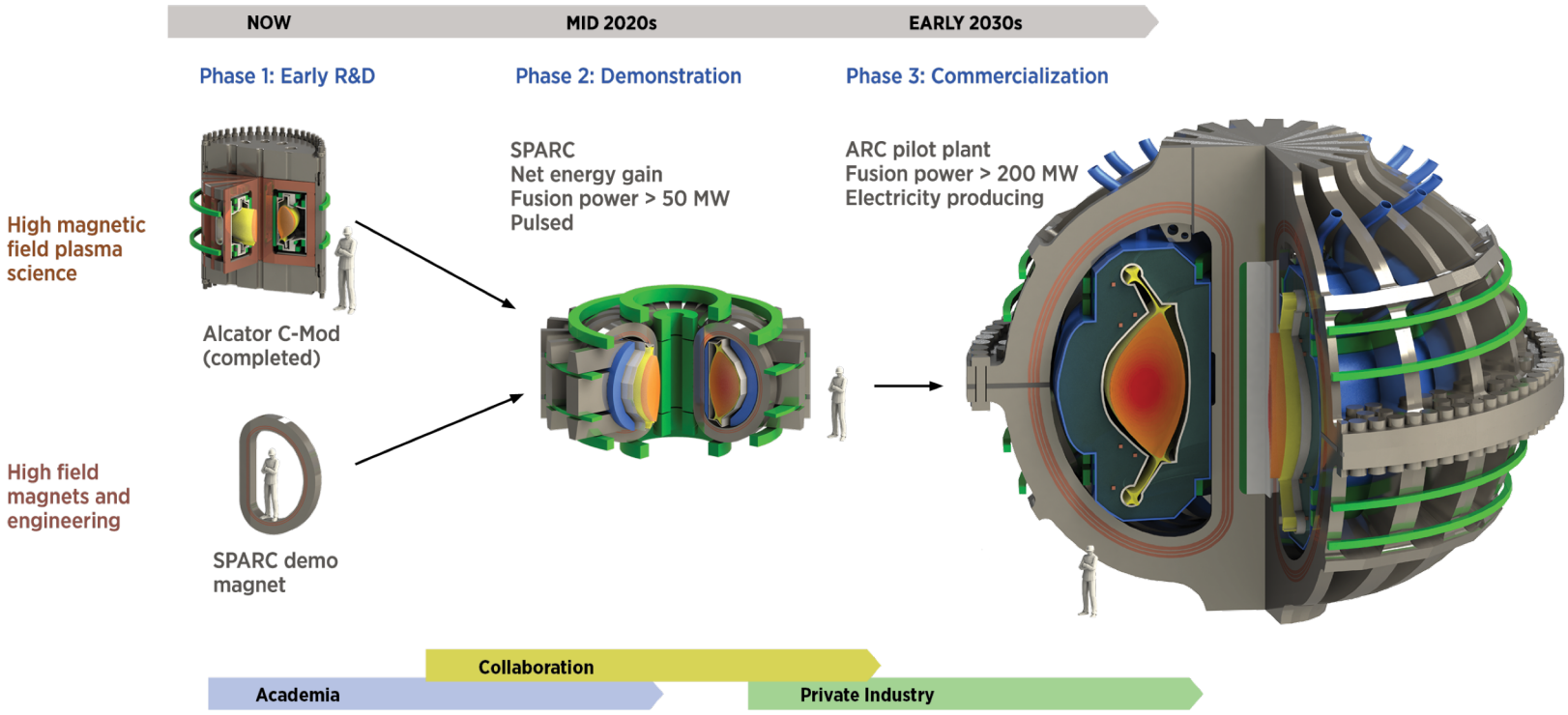
- HTS magnets make fusion **10x** smaller, faster, and cheaper

New Organizational + Funding Model

- ‘Born at scale’

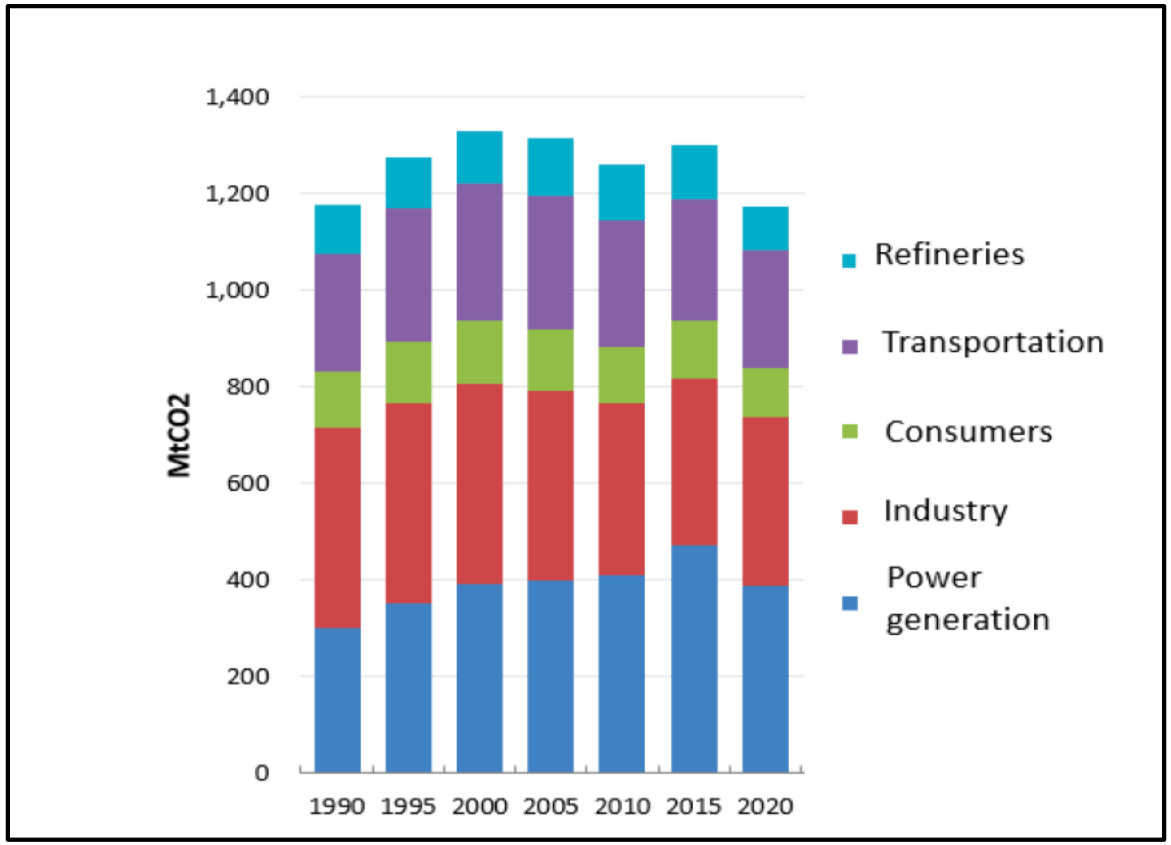


A New Path


NOW
MID 2020s
EARLY 2030s
Phase 1: Early R&D
Phase 2: Demonstration
Phase 3: Commercialization
High magnetic field plasma science
Alcator C-Mod (completed)
SPARC
Net energy gain
Fusion power > 50 MW
Pulsed
ARC pilot plant
Fusion power > 200 MW
Electricity producing
High field magnets and engineering
SPARC demo magnet
Collaboration
Academia
Private Industry

What should Japan do?

Japan's carbon emissions



1. New missions and new markets for nuclear energy in Japan's energy mix.

FINAL REPORT

Japan's Next Nuclear Energy System (JNext)

Principal Investigator:
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TEPCO Professor, Nuclear Science and Engineering (NSE)
Director, Center for Advanced Nuclear Energy Systems (CANES)
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Prof. Emilio Baglietto (NSE)
Dr. Charles Forsberg (NSE)
Prof. Michael Driscoll (NSE)
Prof. Herbert Einstein (Civil & Environmental Engineering)
Iain Macdonald (ArtEZ, Netherlands)
W. Robb Stewart (graduate student, NSE)
Enrique Velez-Lopez (graduate student, Civil & Environmental Engineering)
Kennard Johnston (visting student, Morgan State Univ.)
Go Hashimoto (visiting student, Univ. of Tokyo)

(Rev. 1)

November 2, 2019

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Three new missions for nuclear energy in Japan

1)	Flexible electricity generation at existing power plant sites, to replace retiring coal/natural gas capacity, and to complement variable generation from solar and wind.
2)	Flexible co-generation of electricity and heat at industrial sites, to support the production of valuable products, including hydrogen for transportation.
3)	Generation of power and heat for niche markets such as remote communities/islands, military bases, mining sites, disaster relief, district heating, data centers, and freight ship propulsion.

Source: Buongiorno et al, *Japan's Next Nuclear Energy System*, MIT, November 2019 (in process)

Three new missions for nuclear energy in Japan

1) Flexible electricity generation at existing power plant sites, to replace retiring coal/natural gas capacity, and to complement variable generation from solar and wind.	**Small modular BWR**
2) Flexible co-generation of electricity and heat at industrial sites, to support the production of valuable products, including hydrogen for transportation.	**HTGR**
3) Generation of power and heat for niche markets such as remote communities/islands, military bases, mining sites, disaster relief, district heating, data centers, and freight ship propulsion.	**Heat-pipe micro- reactor**

Source: Buongiorno et al, *Japan's Next Nuclear Energy System*, MIT, November 2019 (in process)

1. New missions and new markets for nuclear energy in Japan's energy mix.

2. Participate in international capital pools dedicated to commercialization of advanced nuclear technologies.