In a low-carbon future, where does fusion fit in?

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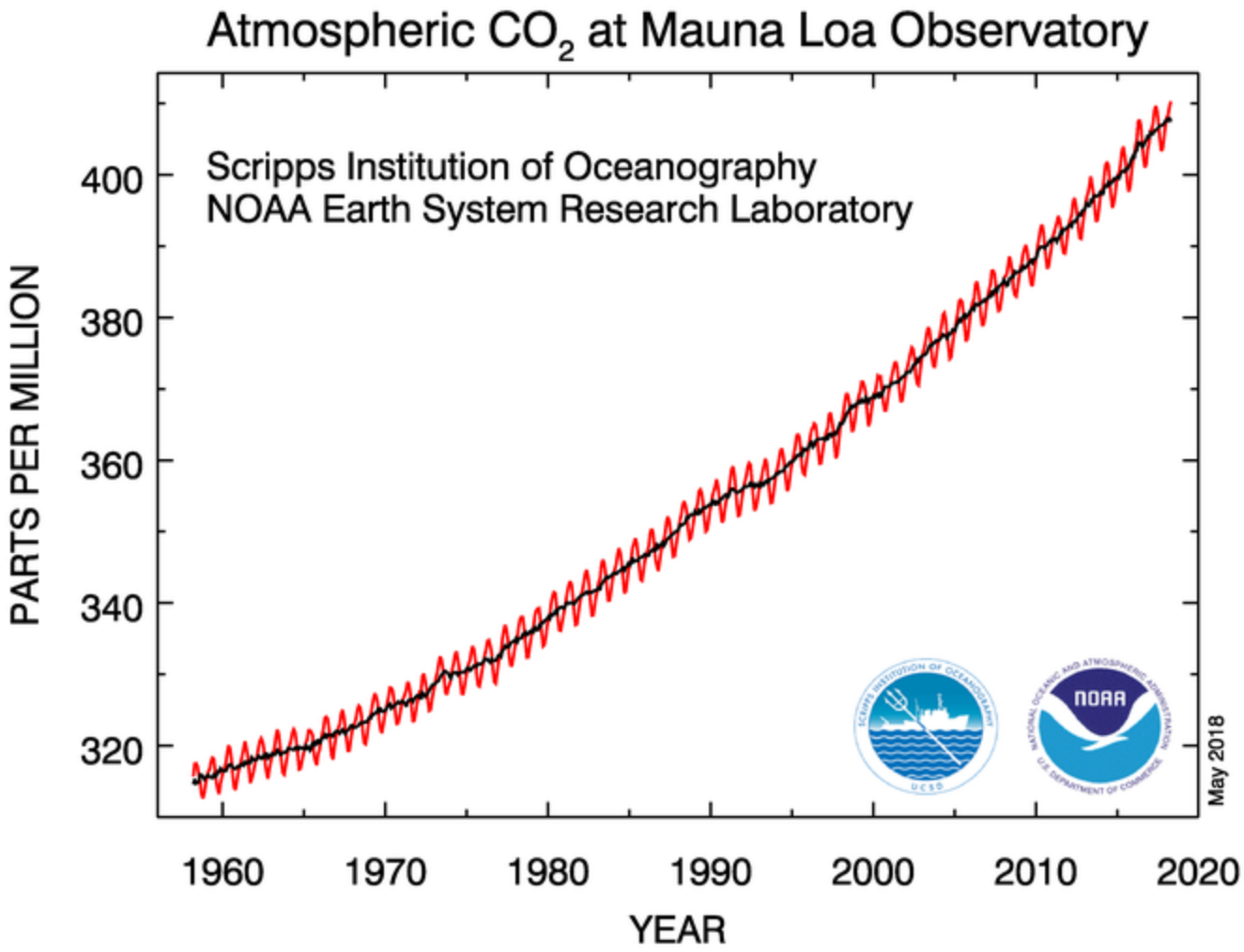
Introductory Address

International Conference on Plasma Surface Interactions in Controlled Fusion Devices

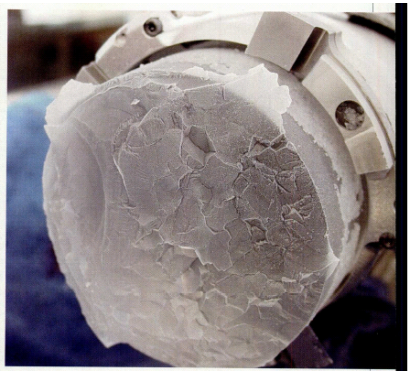
Richardson Auditorium

Princeton University, June 18, 2018

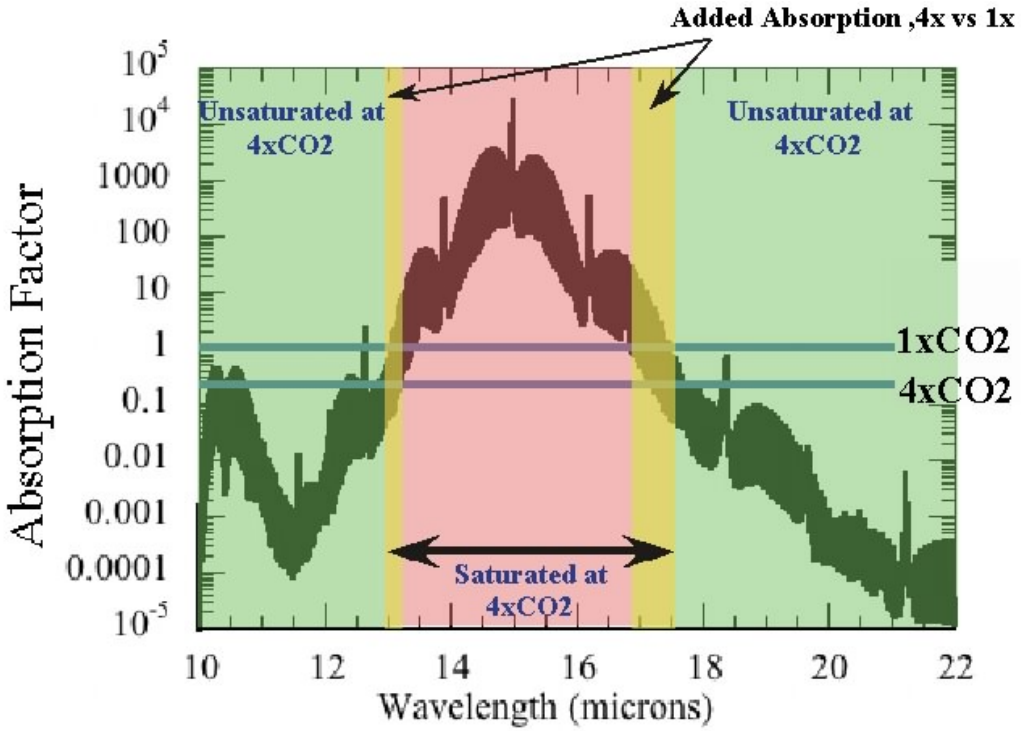
Above 410 for the first time last April

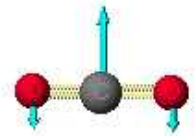


Antarctic CO_2 and temperature vary together



CO_2 absorption band





bond bending

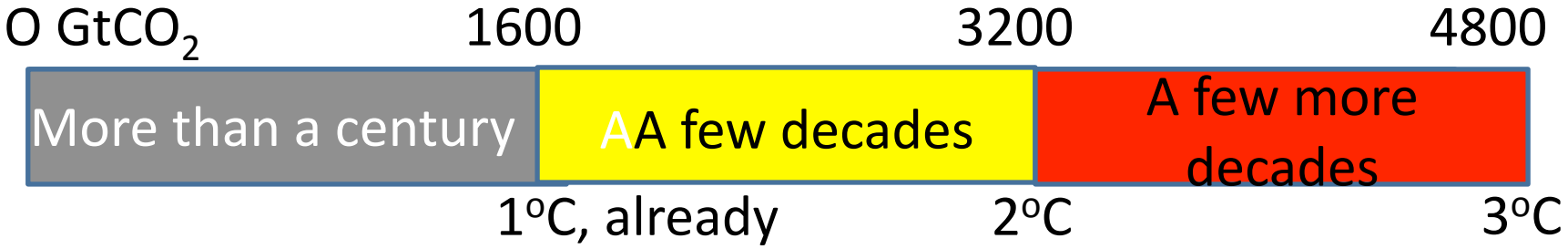
Climate science R&D is as urgent energy R&D, to learn how quickly serious trouble will arrive.

A single big idea

We are confronting one overarching, counterintuitive, new idea:
Human beings are able to change the planet at global scale.

This new idea is unwelcome. We wish we lived on a larger planet.

Our small planet

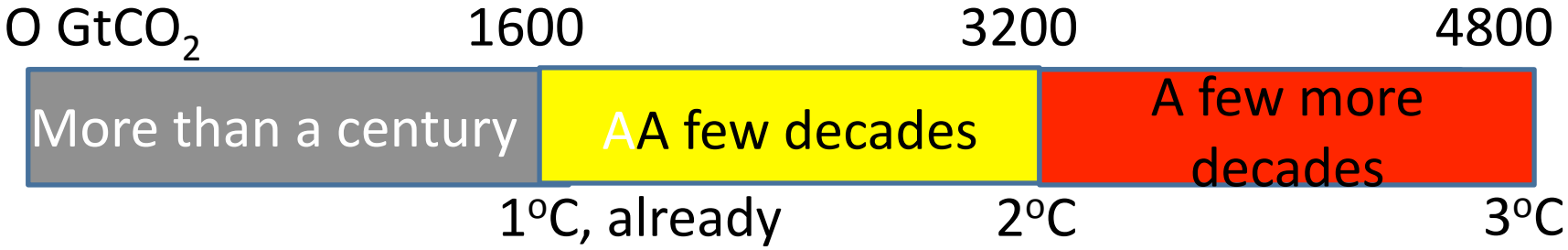


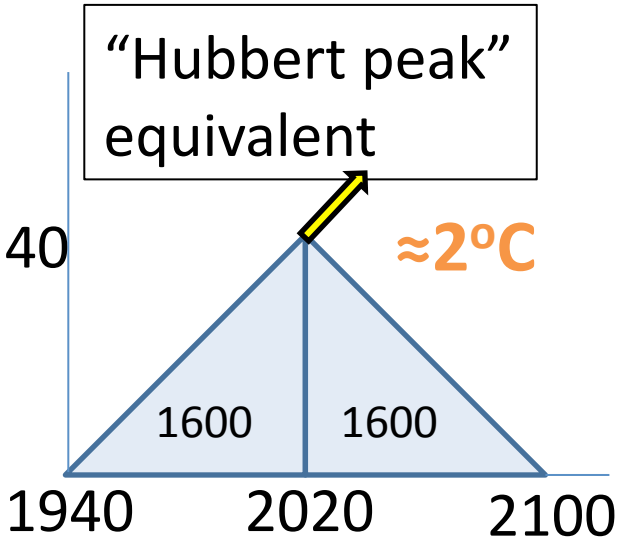
A useful approximation: The long-term average temperature rise on the Earth's surface is proportional to the cumulative global emissions of CO_2.

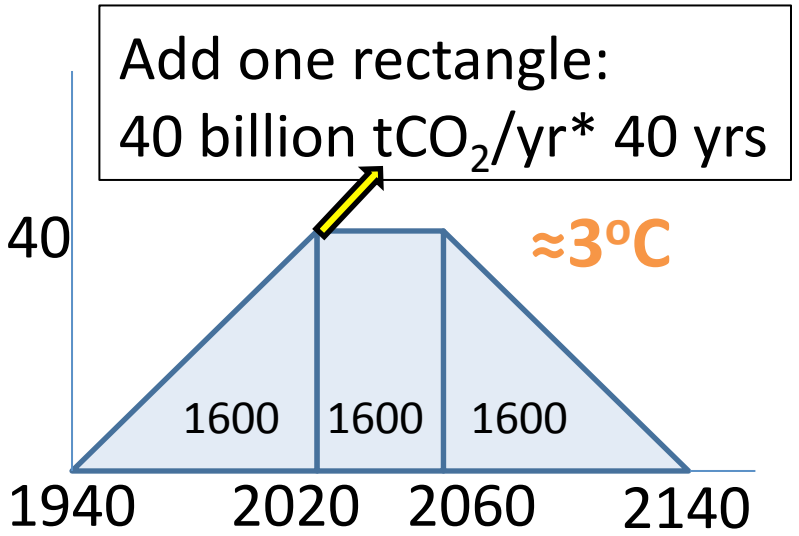
2^oC is the most discussed target.

The multiplier from emissions to temperature rise reveals that our planet is small.

Carbon budgets







If we were not confronting climate change, the era of fossil fuels (coal, oil, and gas) could last hundreds of years.

Four ways to emit 5 ton CO_2/year

Activity	**Amount producing 5 ton CO_2/year emissions**
a) Drive	30,000 km/yr, 5 liters/100km (45 mpg)
b) Fly	30,000 km/yr
c) Heat home	Natural gas, average house, average climate
d) Use electricity	400 kWh/month if all coal-power (1000 gCO_2/kWh) 800 kWh/month, natural-gas-power (500 gCO_2/kWh)

When we as a species do ordinary things globally with the technologies we have, we harm ourselves.*

***Examples of ordinary things*: eating hamburgers, commuting to work, building with concrete, going skiing.**

Budgets demand choices

The budget concept leads inexorably to choices about which fossil fuels to extract and which to consider “unburnable”:

When?	Better options someday?
Whose?	Geopolitical stability
Used where?	“Fairness”
For what purpose?	Who judges?
Which fossil fuels?	Those with the highest H/C ratio?

Judgments about which fossil fuels are “unburnable” have no precedents.

“Stabilization wedges”… in 2004

2011 Kentucky Derby, AP Photo/Matt Slocum. https://www.cbsnews.com/pictures/2011-kentucky-derby/7

Slide pair: courtesy of Greta Shum, Andlinger Center, Princeton University

“Stabilization wedges”… in 2018

Melbourne Cup, The Foreign Correspondents‘ Club, Hong Kong. https://www.fcchk.org/event/melbourne-cup

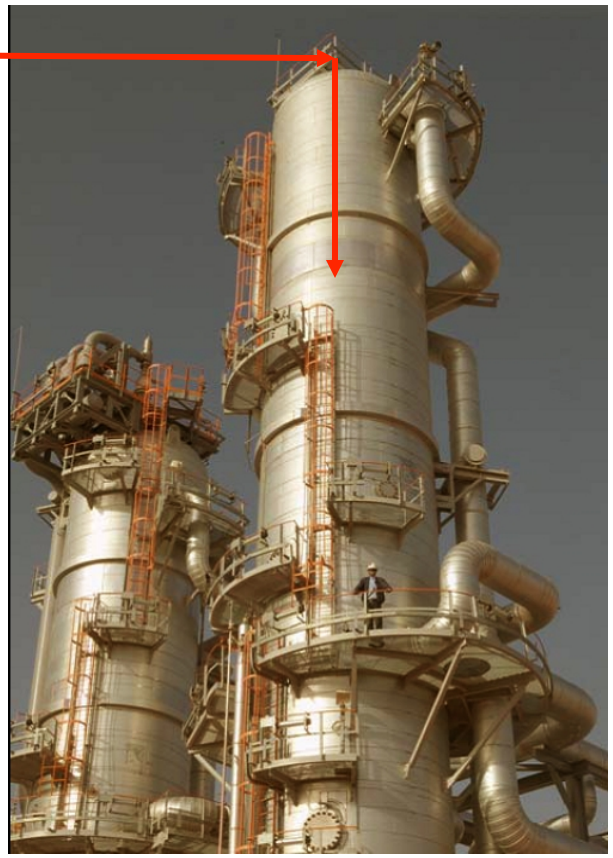
Four potential low-carbon replacements of the current fossil energy system

1. Stop CO_2 from reaching the atmosphere
2. Greatly expand wind and solar (*the most credible today*)
3. Expand fission power
4. Develop fusion power

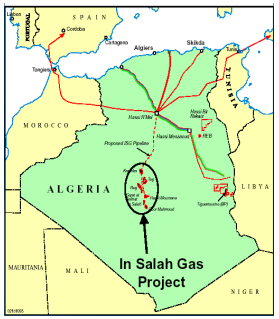
In all four cases, the replacements will require:

- **aggressive energy efficiency**
- **deep electrification**
- **prolonged R&D**
- **strong policy support**

Stop CO_2 from reaching the atmosphere



Natural gas purification by CO_2 removal, then CO_2 pressurization for nearby injection



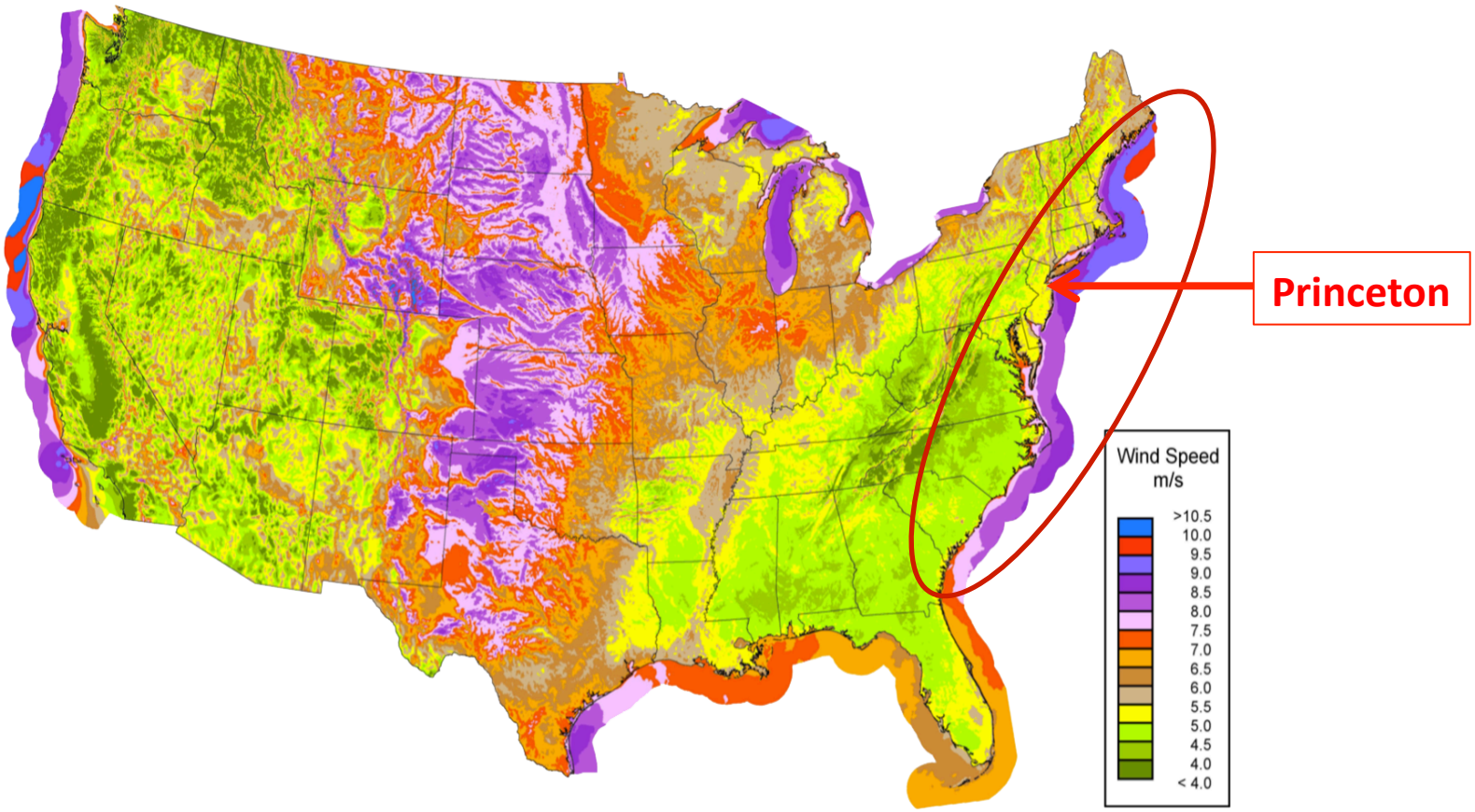
Amine contactor towers

U.S. CO_2 pipelines already in place

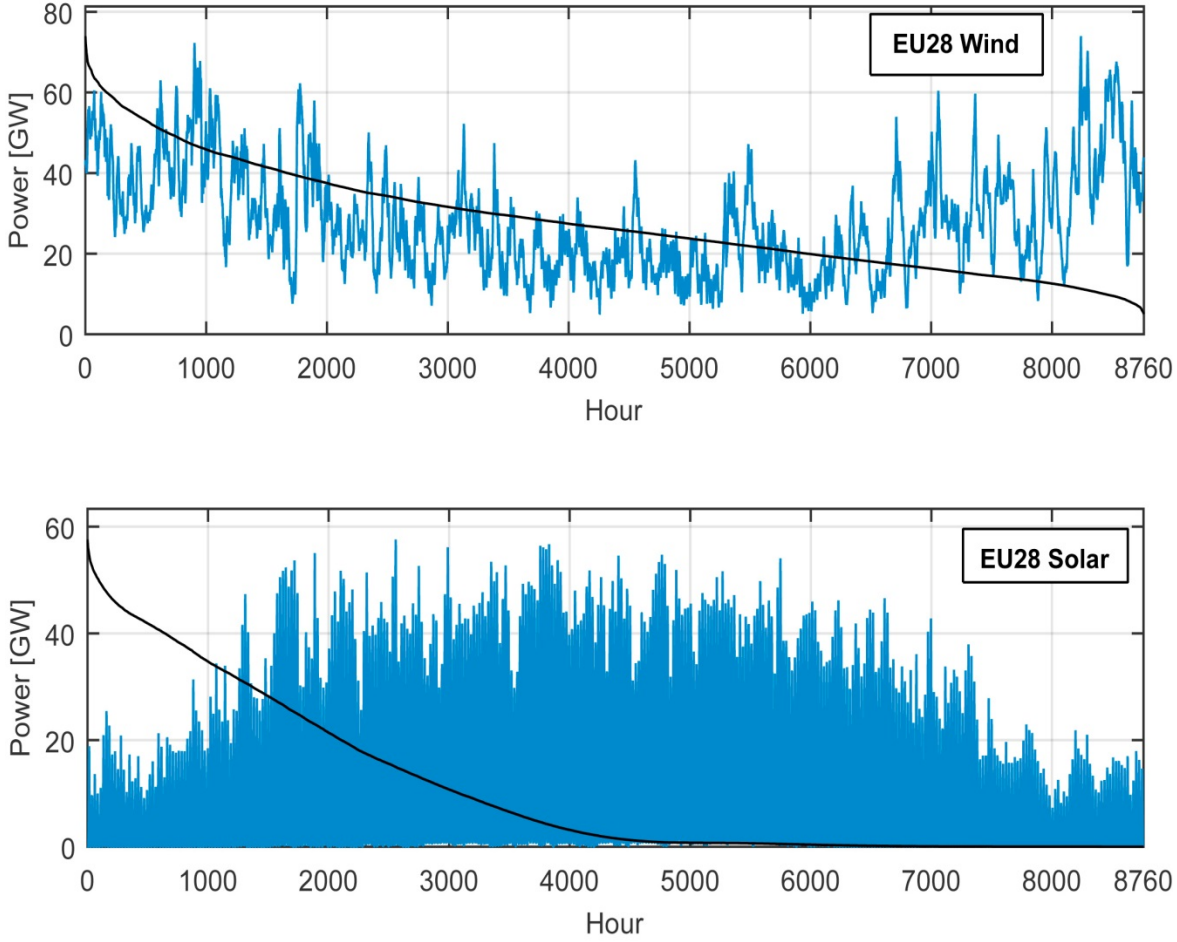
http://www.nicholas.duke.edu/thegreengrok/co2pipeline, from *CO2 Pipelines and EOR in the US - Regulatory Issues and Opportunities,* Lawrence J. Wolfe, lwolfe@hollandhart.com. Slide 11.

Greatly expand wind and solar

Off the Atlantic shore



Seasonal baseload power to complement renewables: an opportunity for fusion.



Alexander Buttler, Felix Dinkel, Simon Franz, Hartmut Spliethoff , "Variability of wind and solar power: An assessment of the current situation in the European Union based on the year 2014." *Energy* 106 (2016), 147-161, Figure 4.

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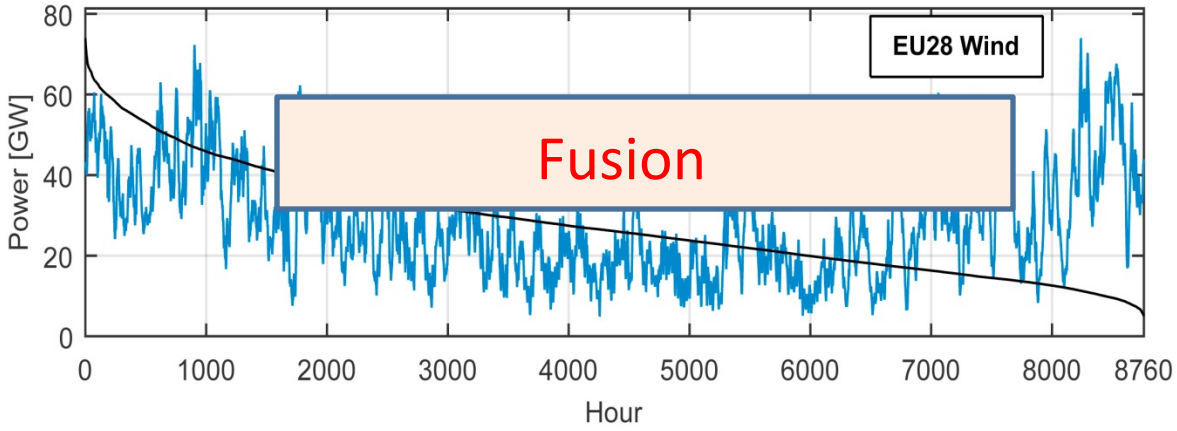
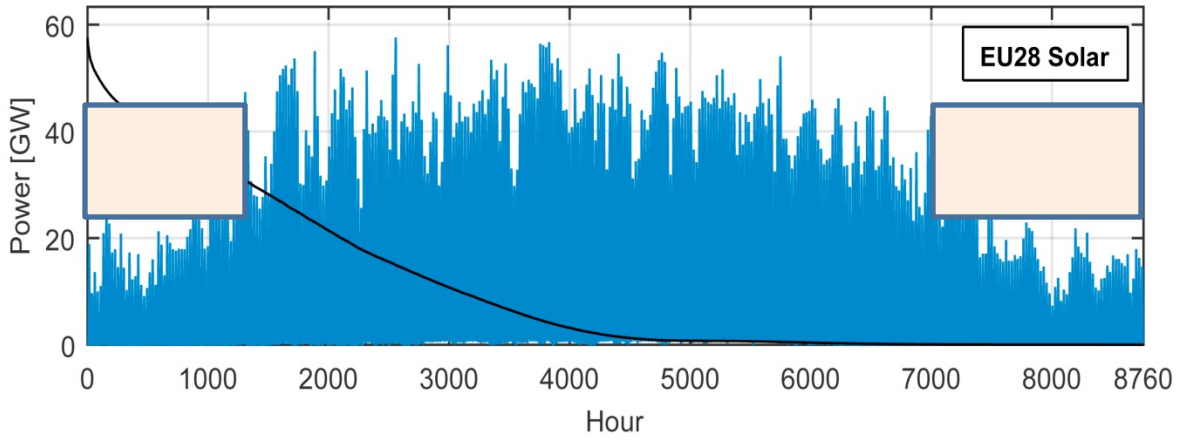


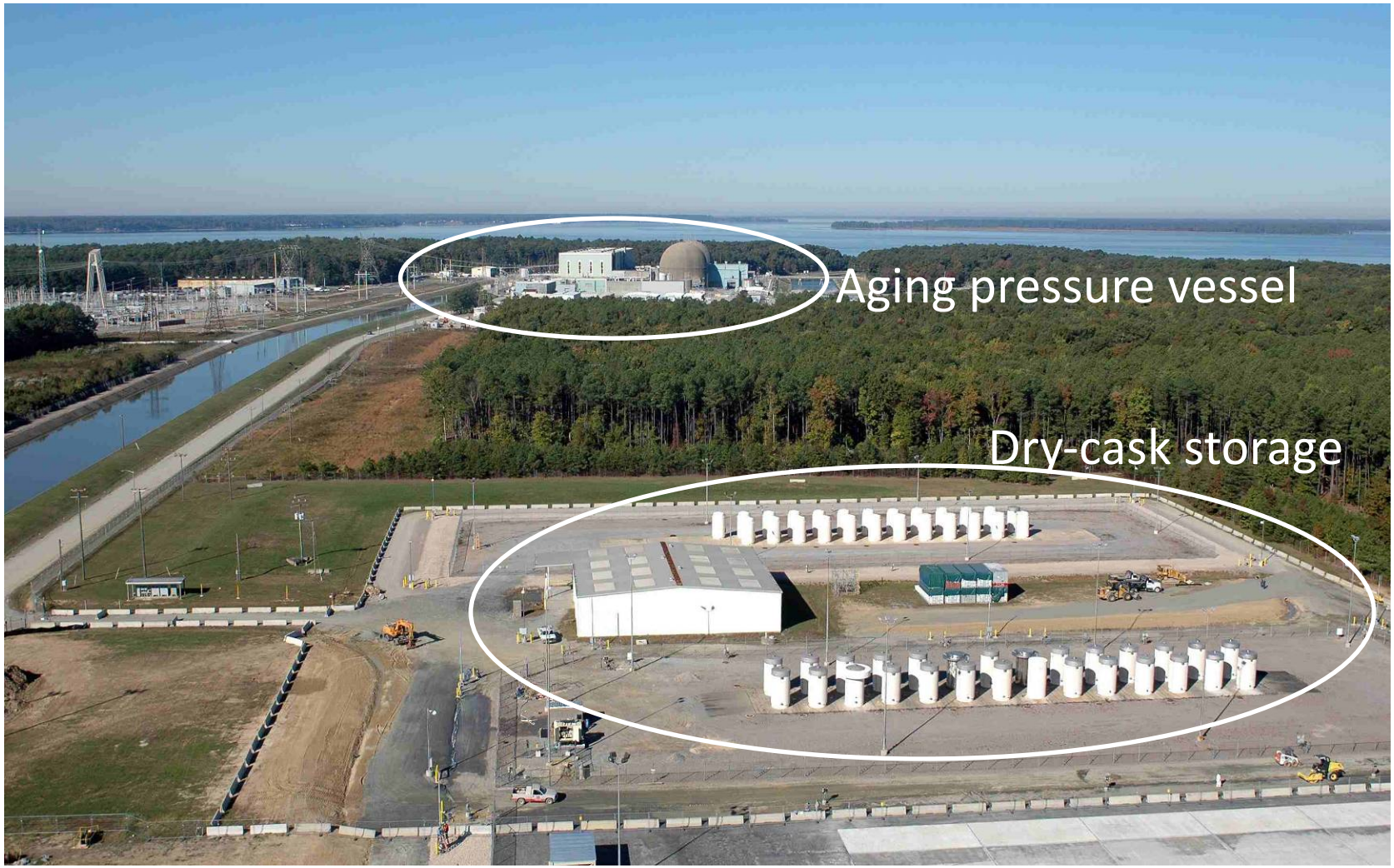


Here, wind and solar are complementary.

Competition is hydropower, stored chemicals, thermal ponds.

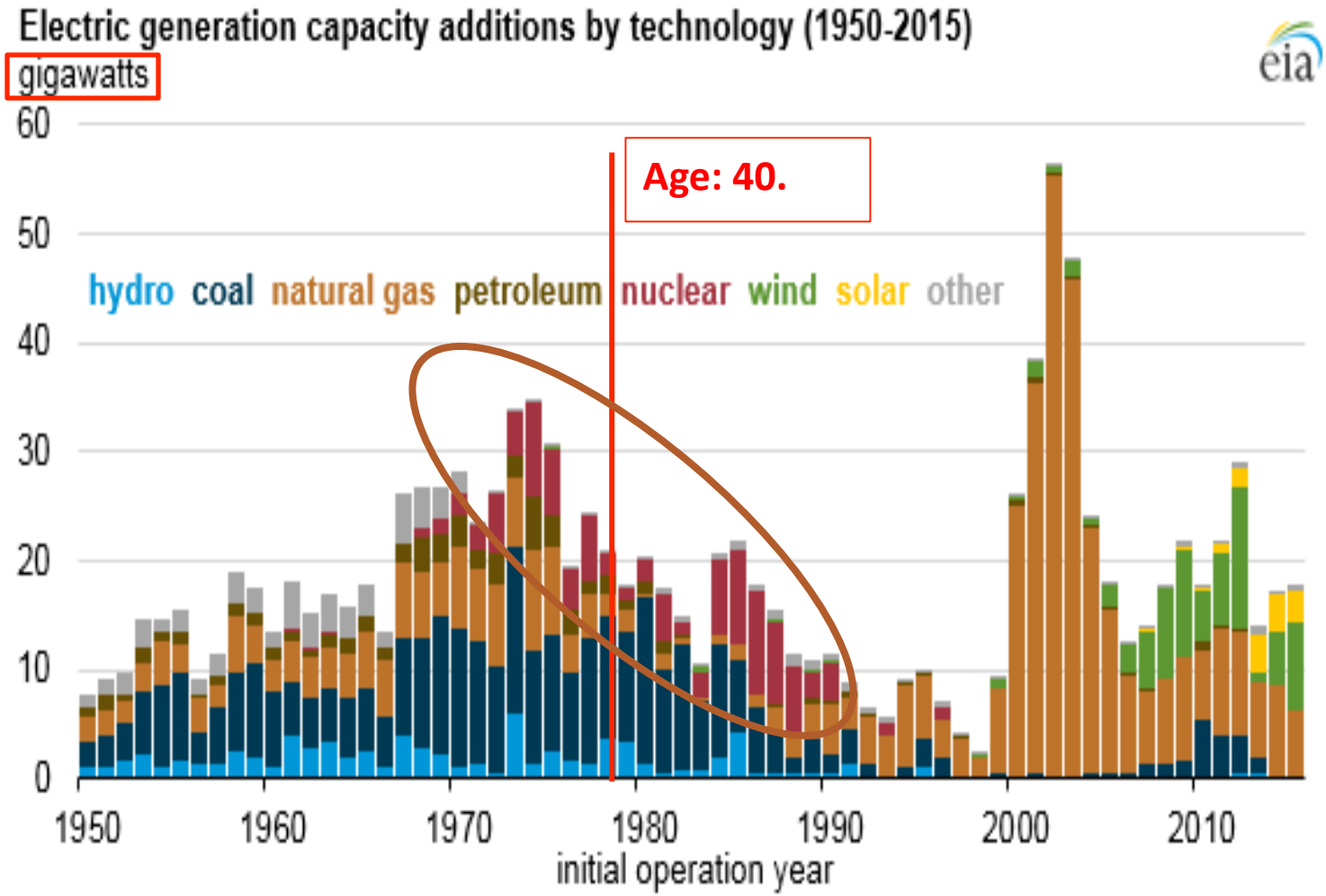
Alexander Buttler, Felix Dinkel, Simon Franz, Hartmut Spliethoff , "Variability of wind and solar power: An assessment of the current situation in the European Union based on the year 2014." *Energy* 106 (2016), 147-161, Figure 4.

Expand fission power



Site: Surry station, James River, VA; 1625 MW since 1972-73,. *Credit*: Dominion.

In the U.S. and much of the world, nuclear fission power is in retreat.

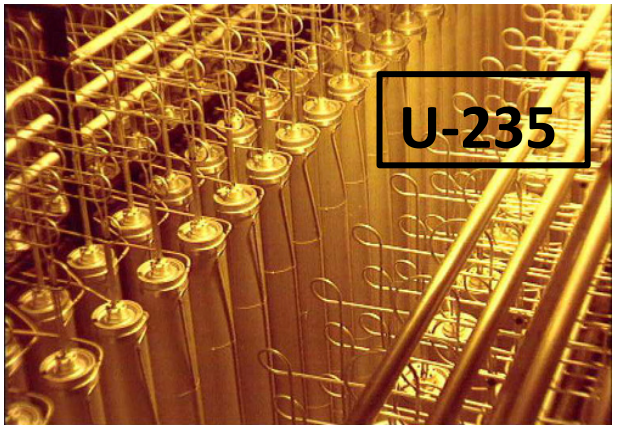


U.S. power plants

Nuclear power: fuel cycle -X> nuclear war

Uranium isotope enrichment and spent-fuel reprocessing to recover plutonium are both routes to nuclear weapons.

The global development of nuclear power must not abet national nuclear weapons programs. Instead, it must be based on much strengthened international institutions that govern the nuclear power fuel cycle in all countries.



Gas-centrifuges for enrichment

Reprocessing plant, La Hague, France

What will determine fusion's future? (1 of 2)

1. *Open questions for fusion technology*
    a. Can the divertor and first wall be made durable enough to avoid large replacement costs [*your meeting this week*]?

    b. Where will the tritium come from for the first commercial plants?

    c. How will the stellarator compete with the tokamak?

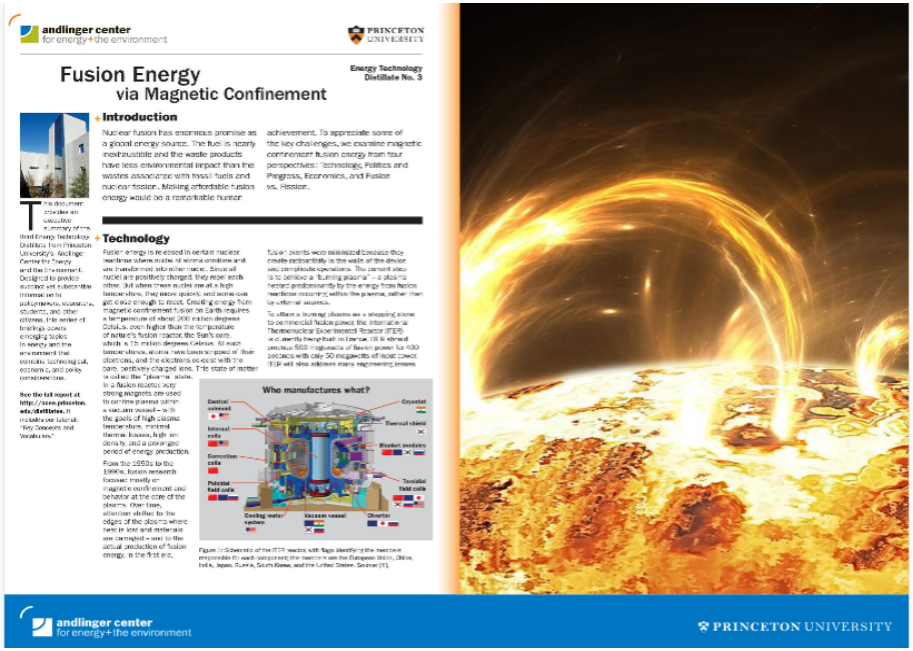
2. *Fusion in balance with renewable energy*
    a. Where there are large winter-summer differences in solar and wind resources, can fusion provide complementary seasonal base-load energy competitively (e.g., six months on, six months off) ?

What will determine fusion's future? (2 of 2)

3. *Can fusion power be governed in ways that prohibit the production of plutonium from fusion's abundant neutrons?*
    i. No uranium at fusion-only reactors.
    ii. No fission-fusion hybrids.

Well-governed global fusion power is less likely to lead to nuclear war than global fission power.

The Nuclear Fusion Distillate



The fusion “distillate” is written for the reader who has an appetite for technological argument but has no background and no comfort even with algebra. It treats both technology and policy and seeks be evenhanded.

https://acee.princeton.edu/wp-content/uploads/2016/05/ACEE-Fusion-Distillate.pdf