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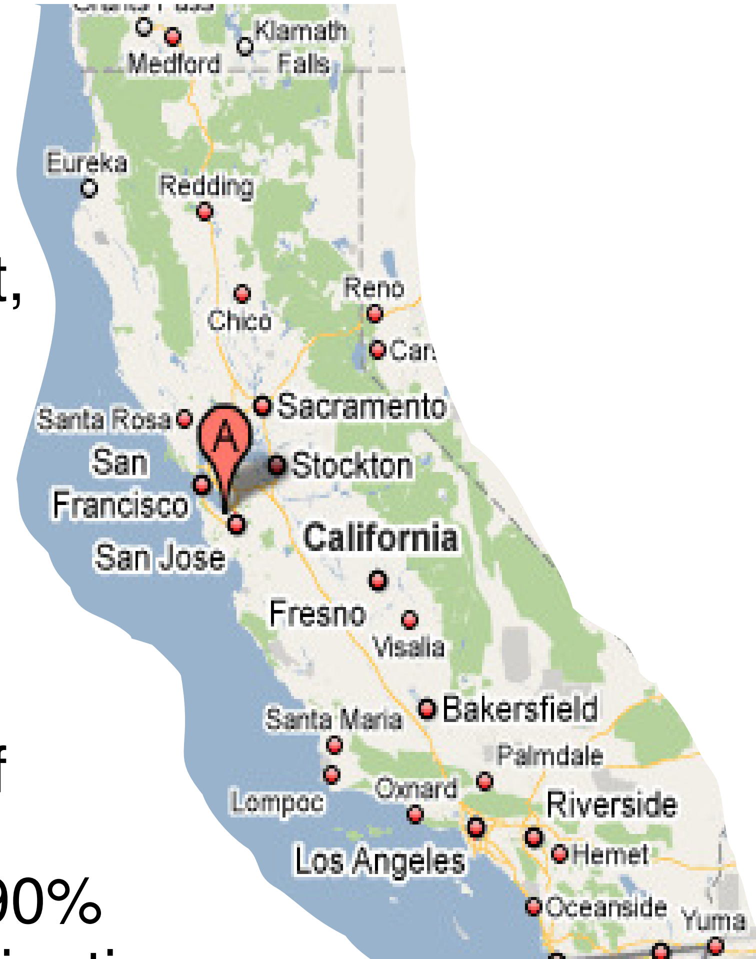
Status of Post-Combustion CO_2 Capture Technologies

Abhoyjit S. Bhown

DOE: Beyond 2020 CO_2 Capture Workshop
Gaithersburg, MD
March 3-4, 2010

About The Electric Power Research Institute

- Major locations in Palo Alto, CA; Charlotte, NC; Knoxville, TN
- Established 1973 as independent, not-for-profit research center
- Nearly every area of electricity generation, delivery, use, health, environment, efficiency
- $325 million/yr revenue; 650 staff
- EPRI's members generate over 90% US electricity. International participation represents approximately 15% of EPRI's total program



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What We'll Talk About

- Scope of CO_2 problem
- Why the problem is challenging
  - Energy
  - Scale
- What EPRI is doing
  - Approach and status
  - External collaborations and internal effort
- Conclude
  - Future roadmap
  - Closing comments

Old Discussion: Global Warming by CO_2

PHILOSOPHICAL MAGAZINE

AND

JOURNAL OF SCIENCE.

[FIFTH SERIES.]

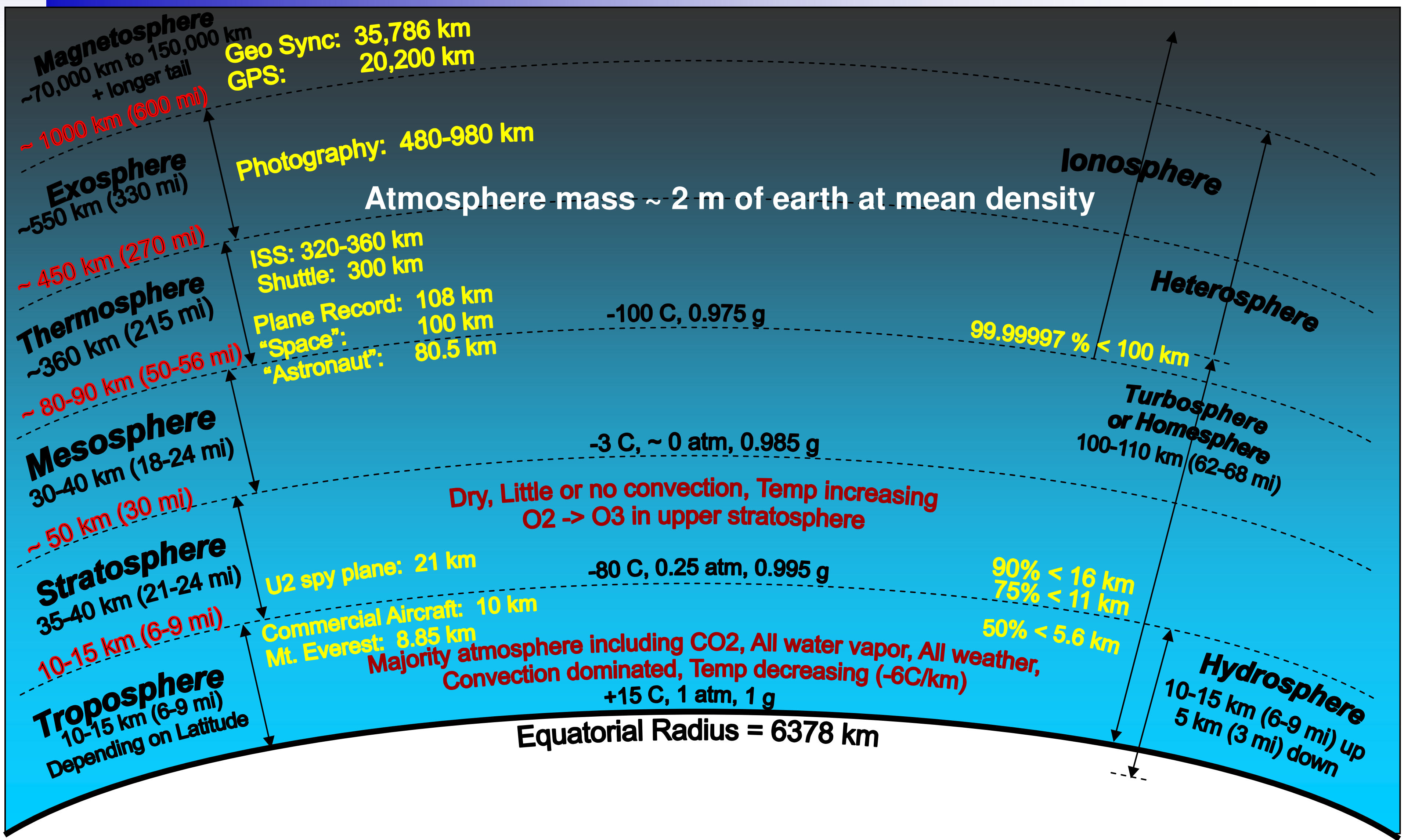
APRIL 1896.

XXXI. *On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground.* *By* Prof. SVANTE ARRHENIUS *.

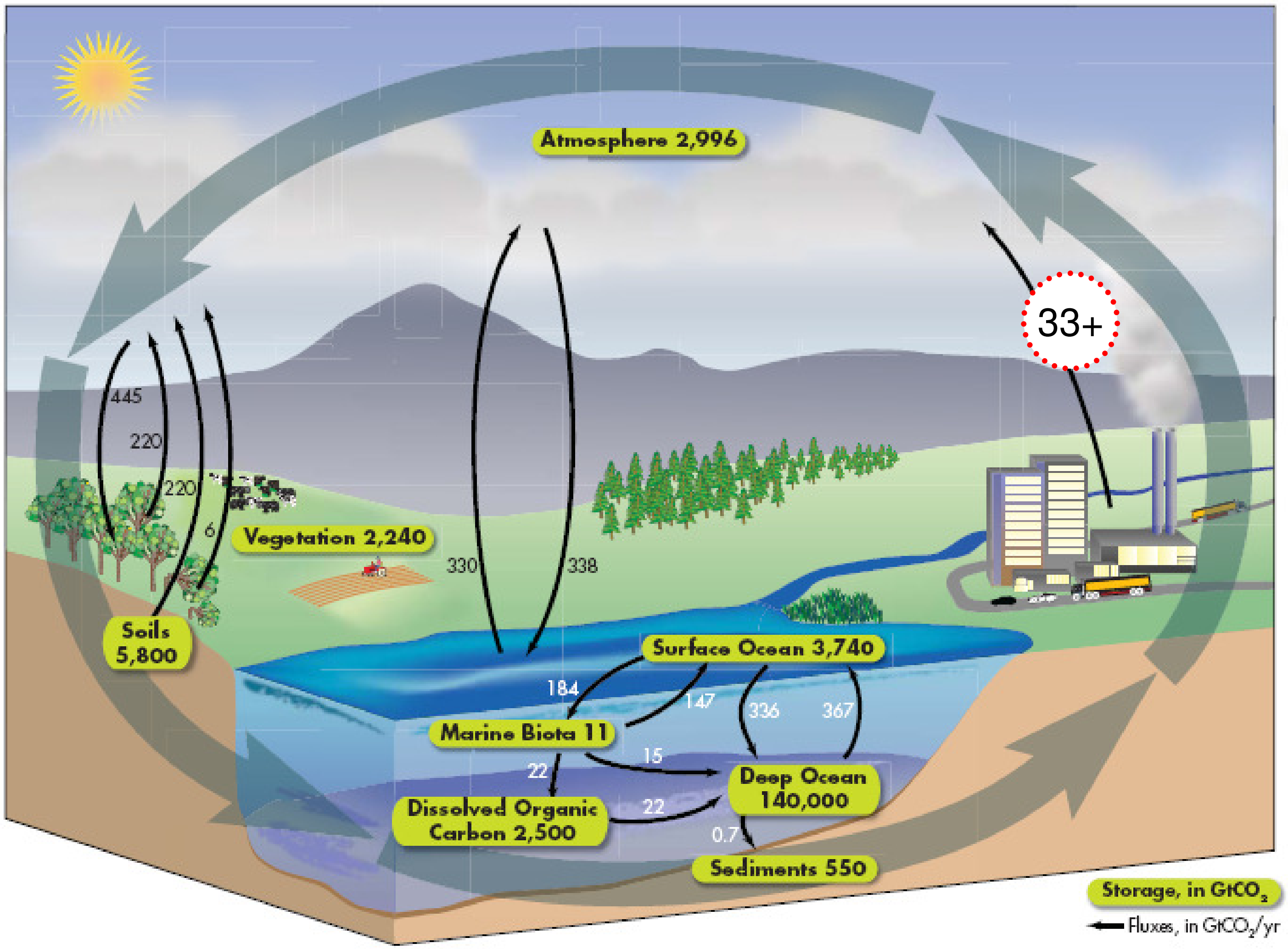
I. *Introduction: Observations of* Langley *on Atmospherical Absorption.*

A GREAT deal has been written on the influence of the absorption of the atmosphere upon the climate. Tyndall † in particular has pointed out the enormous importance of this question. To him it was chiefly the diurnal and annual variations of the temperature that were lessened by this circumstance. Another side of the question, that has long attracted the attention of physicists, is this: Is the mean temperature of the ground in any way influenced by the presence of heat-absorbing gases in the atmosphere? Fourier‡ maintained that the atmosphere acts like the glass of a hothouse, because it lets through the light rays of the sun but

Earth's Atmosphere is Thin…



Global Carbon Cycle



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U.S. Electricity Generation

Global Emissions

- **33+ Gt CO_2/year**

U.S. Emissions

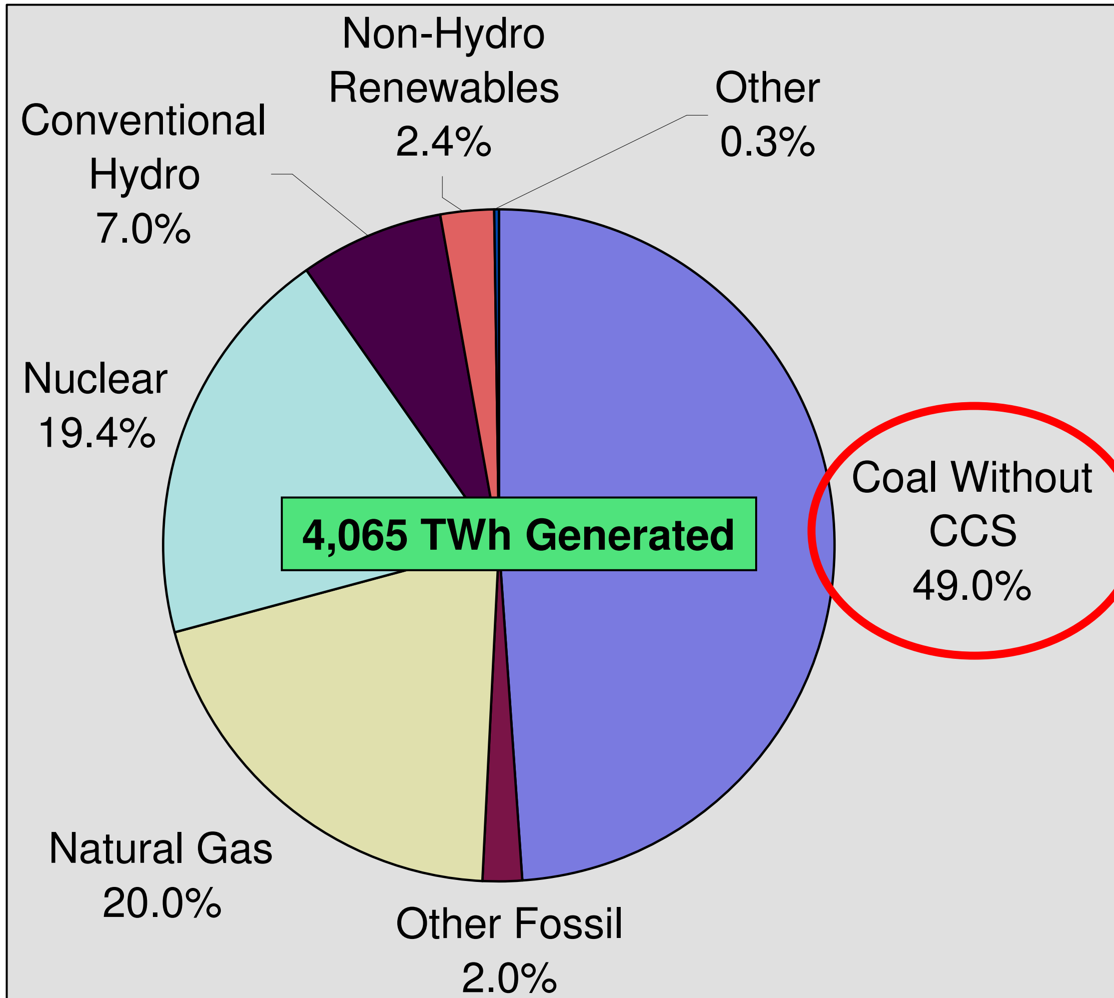
- **6.0 Gt CO_2**
- **~20% of global CO_2**

U.S. Electric Utility

- **2.4 Gt CO_2**
- **41% of U.S. CO_2**
- **33% of U.S. GHGs**

TWh = Terawatt-hour = 10^{12} Watt-hour

Gt = Gigatonne = 10^9 tonne = 10^{15} kg



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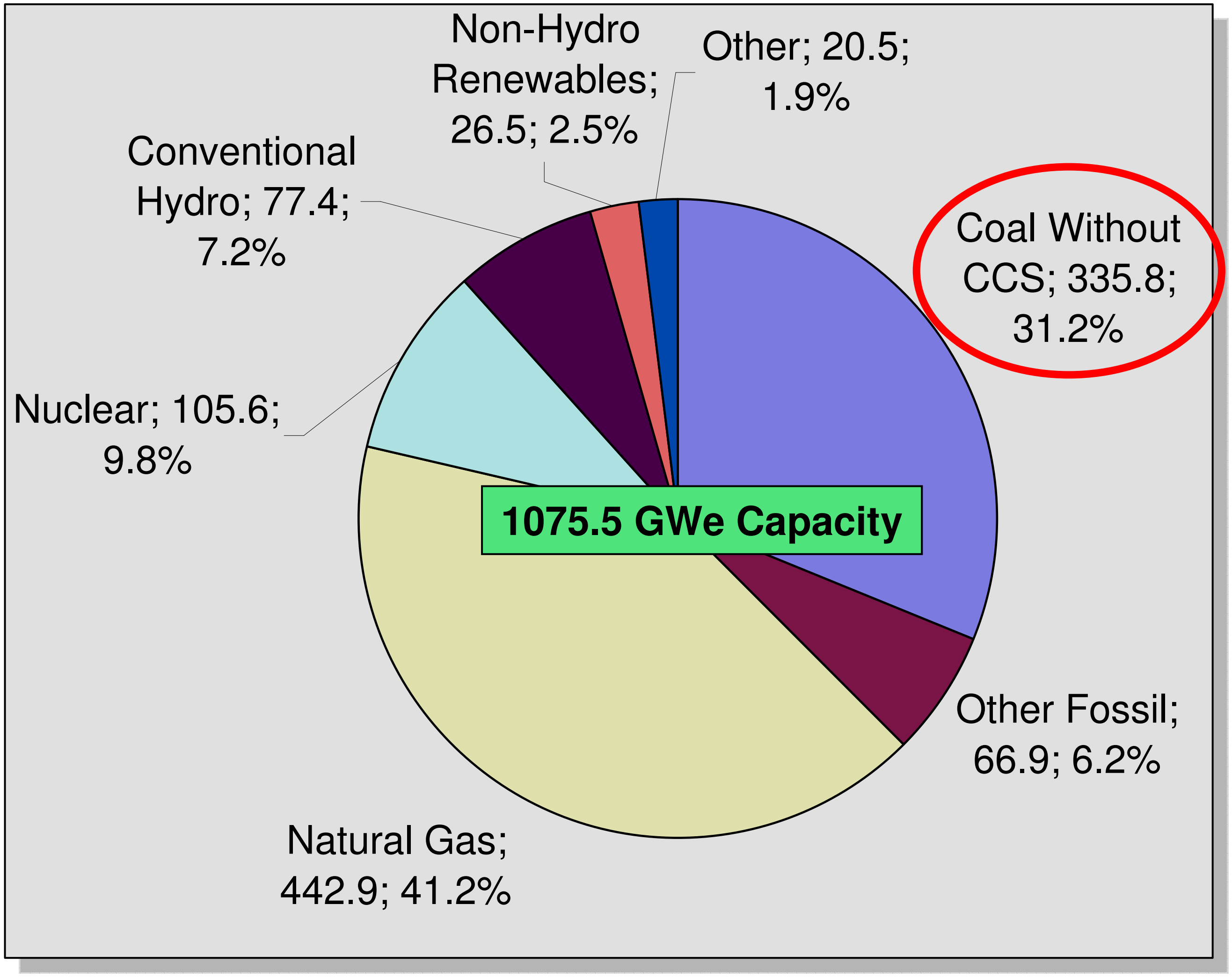
U.S. Installed Capacity

Coal Plants

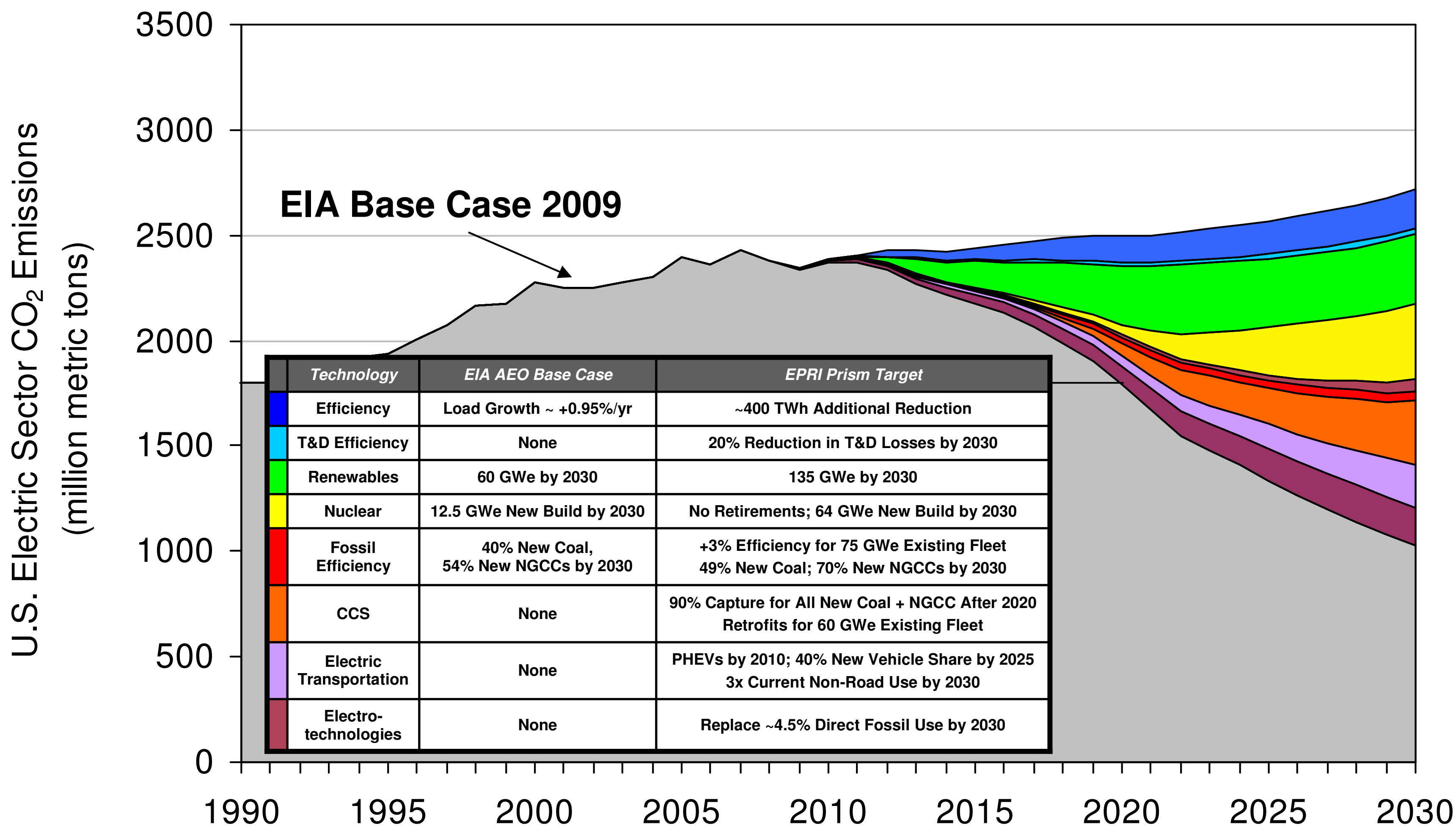
- **20.7 tCO_2/day/MWe**
- **Cheap**

Natural Gas

- **½ CO_2 emissions**
- **More expensive**

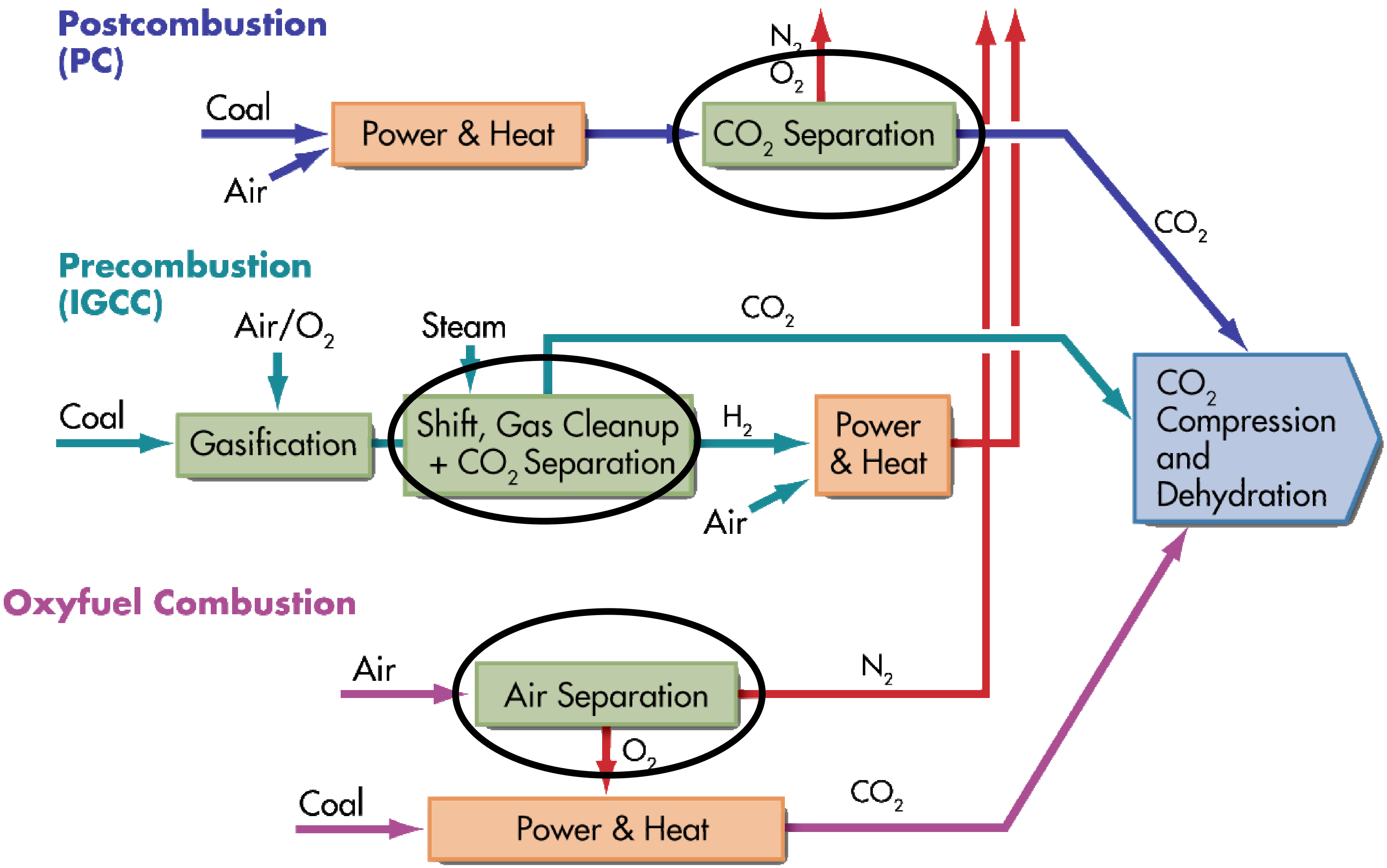


Reducing CO_2 Emissions



	Technology	EIA AEO Base Case	EPRI Prism Target
	Efficiency	Load Growth ~ +0.95%/yr	~400 TWh Additional Reduction
	T&D Efficiency	None	20% Reduction in T&D Losses by 2030
	Renewables	60 GWe by 2030	135 GWe by 2030
	Nuclear	12.5 GWe New Build by 2030	No Retirements; 64 GWe New Build by 2030
	Fossil Efficiency	40% New Coal, 54% New NGCCs by 2030	+3% Efficiency for 75 GWe Existing Fleet 49% New Coal; 70% New NGCCs by 2030
	CCS	None	90% Capture for All New Coal + NGCC After 2020 Retrofits for 60 GWe Existing Fleet
	Electric Transportation	None	PHEVs by 2010; 40% New Vehicle Share by 2025 3x Current Non-Road Use by 2030
	Electro-technologies	None	Replace ~4.5% Direct Fossil Use by 2030

CO_2 Capture in Coal Power Systems



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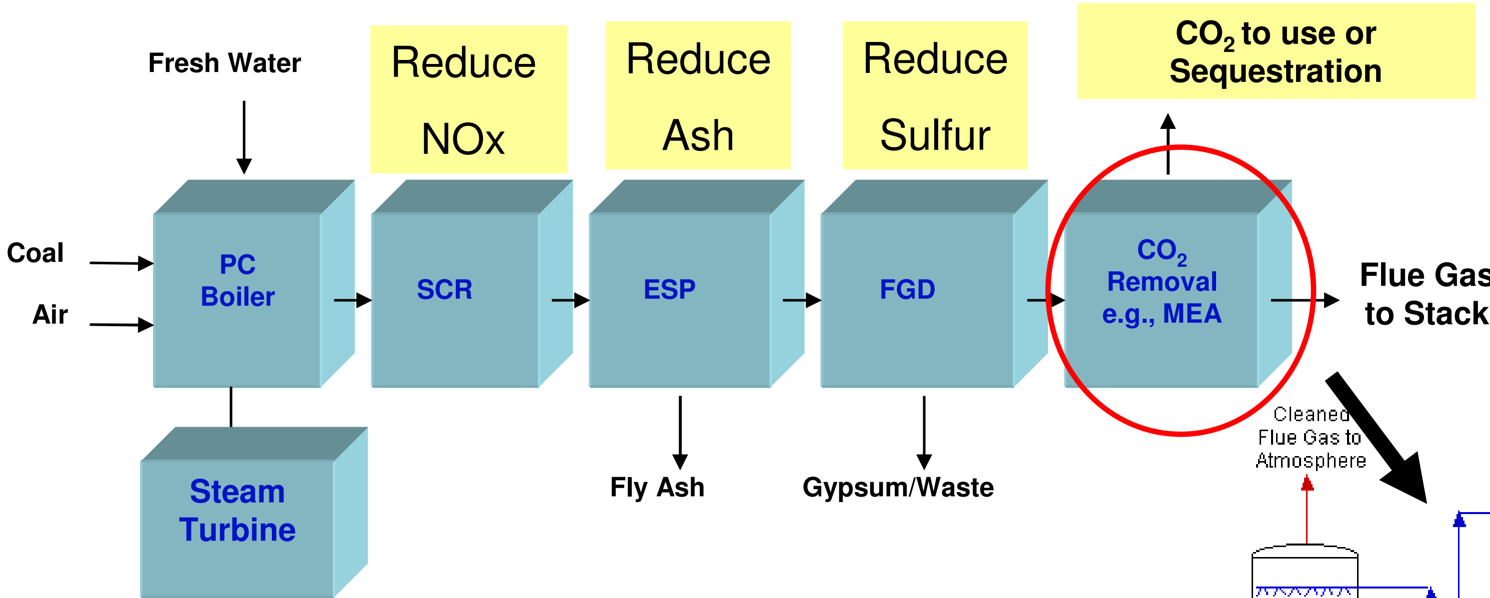
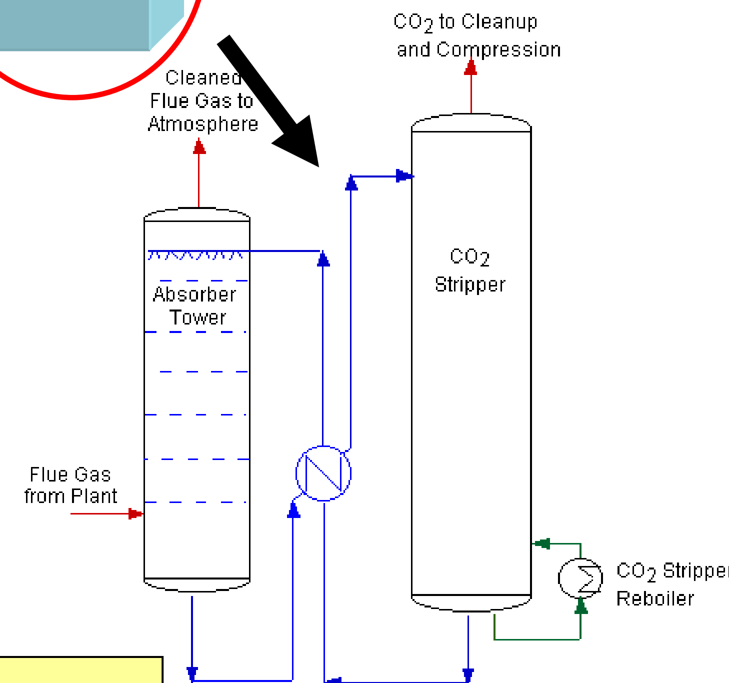
Pulverized Coal with CO_2 Capture "Today"

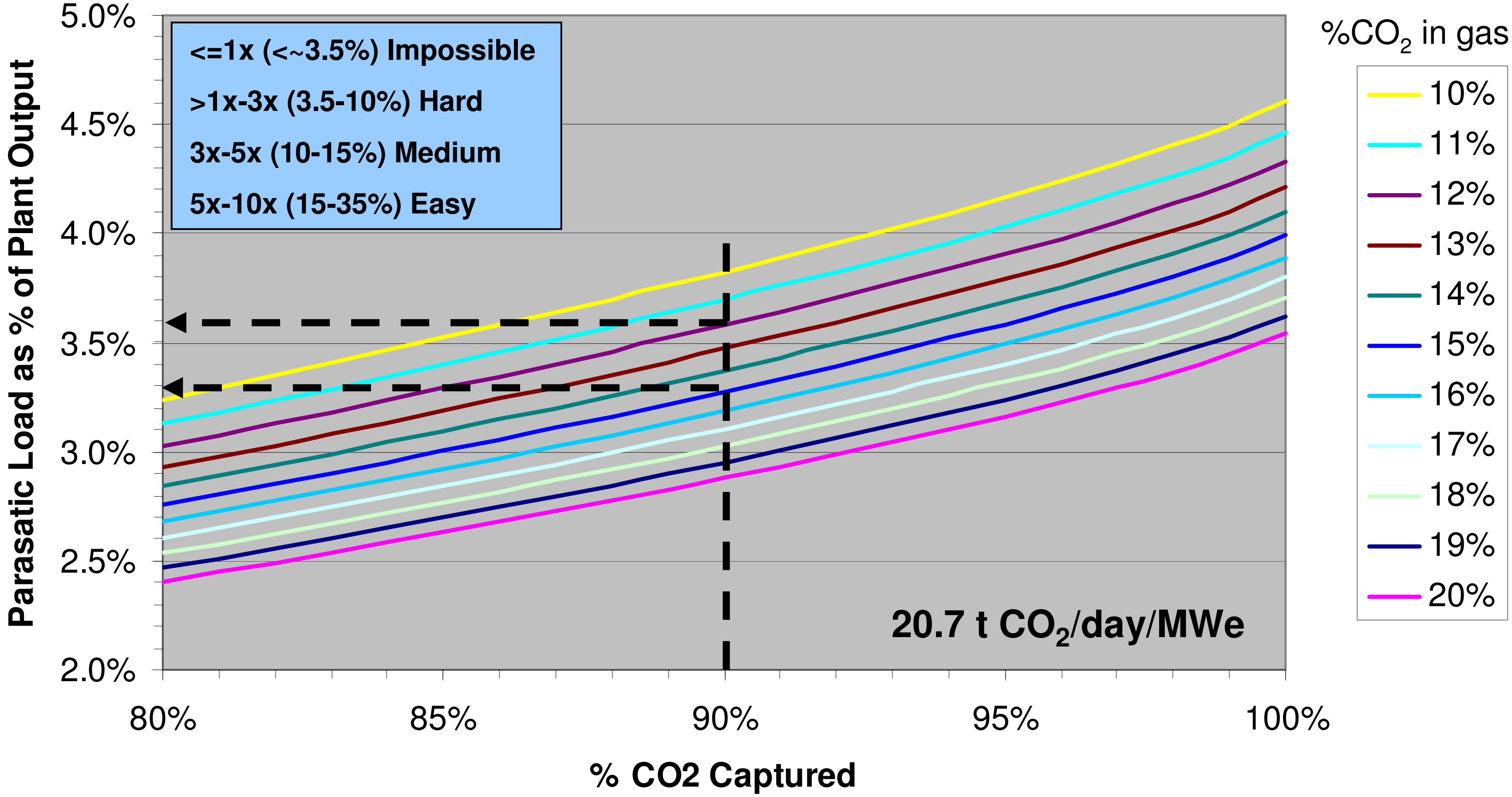




- Pre-condition Flue Gas (Clean)
- Absorb and Strip CO_2
- Mostly amine/ammonia chemistry today

Needs Space, Integration & Energy

Thermodynamic Minimum Parasitic Load for Capturing CO_2 at 40°C from PC Plants



If all capture energy comes from net power output, then thermodynamic minimum parasitic load is ~3.5% to capture 90% CO_2

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Minimum Energy for CO_2 Capture

- Need a thermodynamic minimum of about 3.5% of energy from power plant to capture 90% CO_2
  - Minimum energy is equivalent to 0.165 GJ/t CO_2
  - Does not include compression
  - Assumes all energy comes from net electrical output
  - 40^{o}C flue gas
  - 20.7 t CO_2/day/MWe
- Minimum energy for capturing 385 ppm CO_2 from air
  - 0.524 GJ/t CO_2 (100% capture)
  - 0.465 GJ/t CO2 (near 0% capture)
  - About 3x the minimum energy from flue gas

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Increase in Power Costs with "Today's Technology"

Power plant performance and cost parameters[a]	Pulverized coal power plant	Natural gas combined cycle power plant	Integrated coal gasification combined cycle power plant
Reference plant without CCS			
Cost of electricity (US$/kWh)	0.043-0.052	0.031-0.050	0.041-0.061
Power plant with capture			
Increased fuel requirement (%)	24-40	11-22	14-25
CO_2 captured (kg/kWh)	0.82-0.97	0.36-0.41	0.67-0.94
CO_2 avoided (kg/kWh)	0.62-0.70	0.30-0.32	0.59-0.73
% CO_2 avoided	81-88	83-88	81-91
Power plant with capture and geological storage[b]			
Cost of electricity (US$/kWh)	0.063-0.099	0.043-0.077	0.055-0.091
Cost of CCS (US$/kWh)	0.019-0.047	0.012-0.029	0.010-0.032
% increase in cost of electricity	43-91	37-85	21-78
Mitigation cost (US$/t$CO_2$ avoided)	30-71	38-91	14-53
(US$/tC avoided)	110-260	140-330	51-200

CCS: ~30% rise in fuel requirement and ~65% rise in cost of electricity

Source: IPCC, CCS

CCS Costs with Today's Technology

CCS system components	Cost range
Capture from a coal- or gas-fired power plant	15-75 US$/t$CO_2$ net captured
Capture from hydrogen and ammonia production or gas processing	5-55 US$/t$CO_2$ net captured
Capture from other industrial sources	25-115 US$/t$CO_2$ net captured
Transportation	1-8 US$/t$CO_2$ transported
Geological storage[a]	0.5-8 US$/t$CO_2$ net injected
Geological storage: monitoring and verification	0.1-0.3 US$/t$CO_2$ injected
Ocean storage	5-30 US$/t$CO_2$ net injected
Mineral carbonation	50-100 US$/t$CO_2$ net mineralized

Capture is ~70-80% of the cost of CCS

Source: IPCC, CCS

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Post-Combustion CCS Goals

- Old Goal
  - 10% parasitic load
  - 20% cost of electricity increase
- New Goal
  - 35% cost of electricity increase (including capture, compression, transportation, injection, MMV…)
  - Widely deployed by 2020
- “Current” technologies
  - ~25-30% parasitic load
  - ~60-90% rise in cost of electricity
  - None commercial on post-combustion coal for power

Largest 10 US Power Plant CO_2 Emitters

	Plant	Company	Parent	Location	CO2, Mt/yr	GWe
1	Scherer	Georgia Power	Southern Company	Juliette, GA	24.1	3.56
2	Bowen	Georgia Power	Southern Company	Cartersville, GA	20.1	3.50
3	Miller	Alabama Power	Southern Company	Quinton, AL	19.9	2.82
4	Martin Lake	Luminant	Energy Future Holdings	Tatum, TX	19.1	2.38
5	Gibson	Duke Energy Indiana	Duke Energy	Owensville, IN	18.7	3.34
6	WA Parish	NRG Texas	NRG Energy	Thompsons, TX	18.7	2.70
7	Navajo	Salt River Project		Page, AZ	18.5	2.41
8	Gavin	Ohio Power	Amercian Electric Power	Chesire, OH	17.9	2.60
9	Monroe	Detroit Edison	DTE Energy	Monroe, MI	17.6	3.28
10	Colstrip	PPL Montana	PPL Corp	Colstrip, MT	17.4	2.27
				AVERAGE	19.2	2.89

Sources: EPA, IEA

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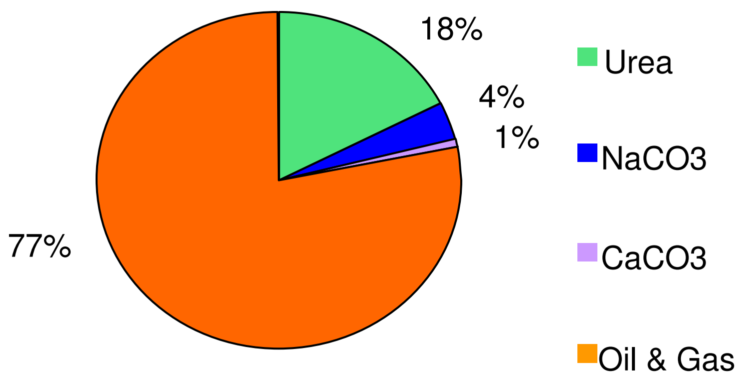
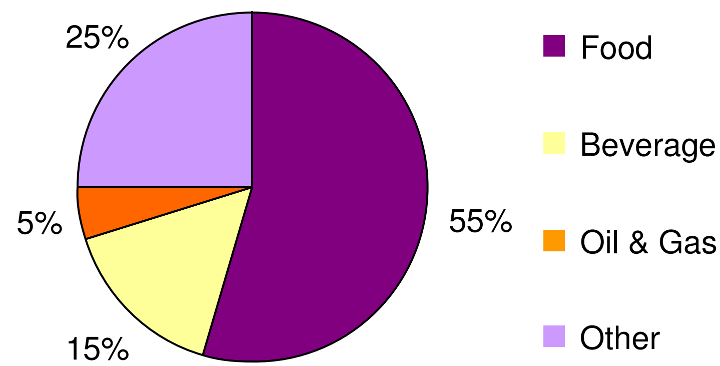
Current US Annual CO_2 Utilization

Gaseous Consumption = 30.9 million metric tons



Mainly EOR

Liquid/Solid Consumption = 7.1 million metric tons



Mainly Food

~40Mt use vs. 2.4 Bt emissions from utility and 6Bt from US
<u>All</u> of EOR in US is ~24Mt, about that from <u>one</u> large power plant

Source: Howard Herzog / MIT Laboratory for Energy and the Environment

Challenges for CO_2 Capture – Scale

	US Production, Estimated 2008			Global Production, Estimated 2008		
	Mt/yr	Gmol/yr	GWe at 90% capture	Mt/yr	Gmol/yr	GWe at 90% capture
1 Sulfuric Acid	37.7	384.7	2.5	199.9	1826.1	11.8
2 Nitrogen	31.7	1130.4	7.3	139.6	4465.2	28.9
3 Ethylene	24.4	761.5	4.9	112.6	3151.9	20.4
4 Oxygen	22.7	808.6	5.2	100.0	3193.8	20.7
5 Lime	19.0	338.1	2.2	283.0	4521.8	29.3
6 Polyethylene(HDPE, LDPE, LLDPE, etc.)	16.5	516.7	3.3	60.0	1680.1	10.9
7 Propylene	14.9	345.4	2.2	53.0	1102.1	7.1
8 Ammonla, Synthetic Anhydrous	13.6	797.9	5.2	153.9	8097.1	52.4
9 Chlorine	11.7	165.3	1.1	61.2	772.9	5.0
10 Phosphoric Acid	11.1	113.6	0.7	22.0	201.2	1.3
45 Acetic Acid	2.2	37.4	0.2	8.0	119.4	0.8
46 Propylene Oxide	2.1	36.0	0.2	6.3	97.4	0.6
47 Phenolic Resins	2.1	20.8	0.1	6.8	61.0	0.4
48 Calcium Carbonate (Precipitated)	2.0	19.7	0.1	13.0	116.4	0.8
49 Butadiene (1.3)	1.9	35.5	0.2	10.3	170.0	1.1
50 Nylon Resins & Fibers	1.9	7.5	0.0	2.3	8.2	0.1
TOTAL	**409**	**8,467**	**55**	**2,412**	**47,020**	**304**
Coal-fired Capacity			**335**			**>1000+**
CO2 from Electricity	**2,400**	**54,545**		**9,600**	**218,182**	
CO2 from All Sources	**6,000**	**136,364**		**33,000**	**750,000**	

A + CO_2 → ACO_2
Limited supplies of A & limited sales of ACO_2
Must regenerate A or produce A with CO_2 constraints

Source: American Chemistry Council and Public Websites

Challenges for CO_2 Capture

- Broad Challenges
  - Energy penalties
  - Capture large amounts of CO_2 (multiples of chemical industry)
- Additional Constraints
  - Limited water availability (cooling)
  - Limited land availability
  - Tolerate other flue gas constituents
  - Existing balance of plant
  - Features that limit to only certain regions
  - Once-through capture processes
  - Saleable products

What We'll Talk About

- Scope of CO_2 problem
- Why the problem is challenging
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Integrated CO_2 Storage Demonstrations and Accelerated Postcombustion Capture Development at EPRI

Find Improved CO_2 Capture Processes

- Proactively mine universities, conferences; announce interest
- Develop conceptual system design
- Evaluate & select for industry support

Scale-Up (0.25–5 MW)
(follow-on initiative)

Verify operability, energy consumption, CO_2 capture rates

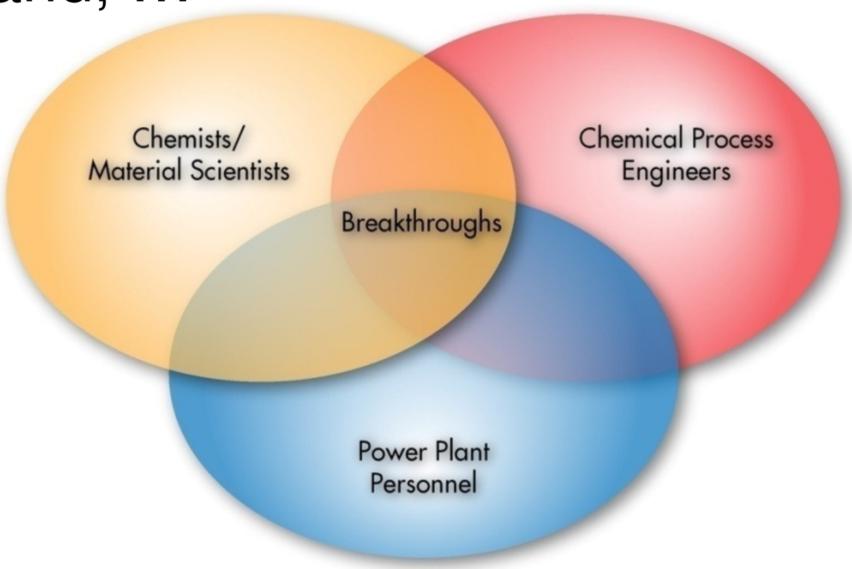
Capture and Storage Demo (~20 MW)

- Site 1 with current capture technology
- Sites 2–5 with advanced capture technology from screening project

- Storage uncertainty = RISK; need long-term demo, start now
- Use advanced capture processes as become available
- Leverage DOE, others

Summary of Effort

- Identify, vet, and appropriately accelerate promising post-combustion CO_2 capture process globally.
- Examined 110+ post-comb CO_2 capture processes so far
- No proven breakthrough technologies yet (~10% parasitic)
- Additional constraints: water, land, …
- Synthesis chemists, process developers, and power plant personnel are not working synergistically
- Breakthroughs will require collaboration



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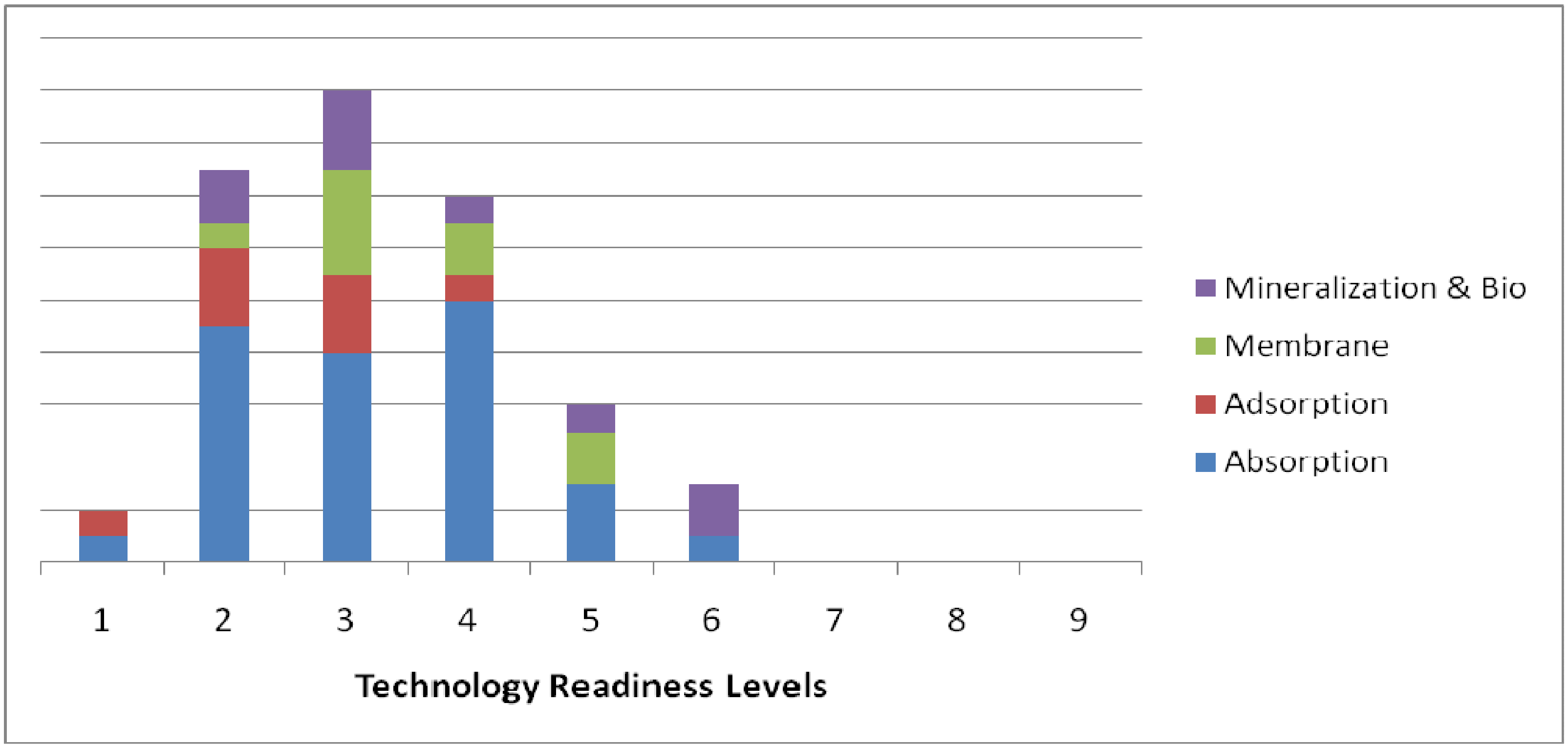
State of Capture Development

	Absorbent (solvents)	Adsorbent (solid)	Membrane
Commercial Usage in CPI*	*High*	*Moderate*	*Low/Niche*
Operational Confidence	*High*	*High, but complex*	*Low to moderate*
Energy Penalty No Compression	*<18% to 25%*	*~14% to 20%*	*~12%-15%*
Source of Energy Penalty	*Solvent Regen thermal*	*Sorbent Regen thermal/vac*	*Vacuum on permeate*
Trends	*New chemistry, thermal integrat.*	*New chemistry, process config*	*New membrane, process config*

*Chemical Process Industries

Capture Technologies: TRL Ranking

- Majority of processes are absorption based
- Most are at TRL 2 -4 (preliminary design to laboratory validation)



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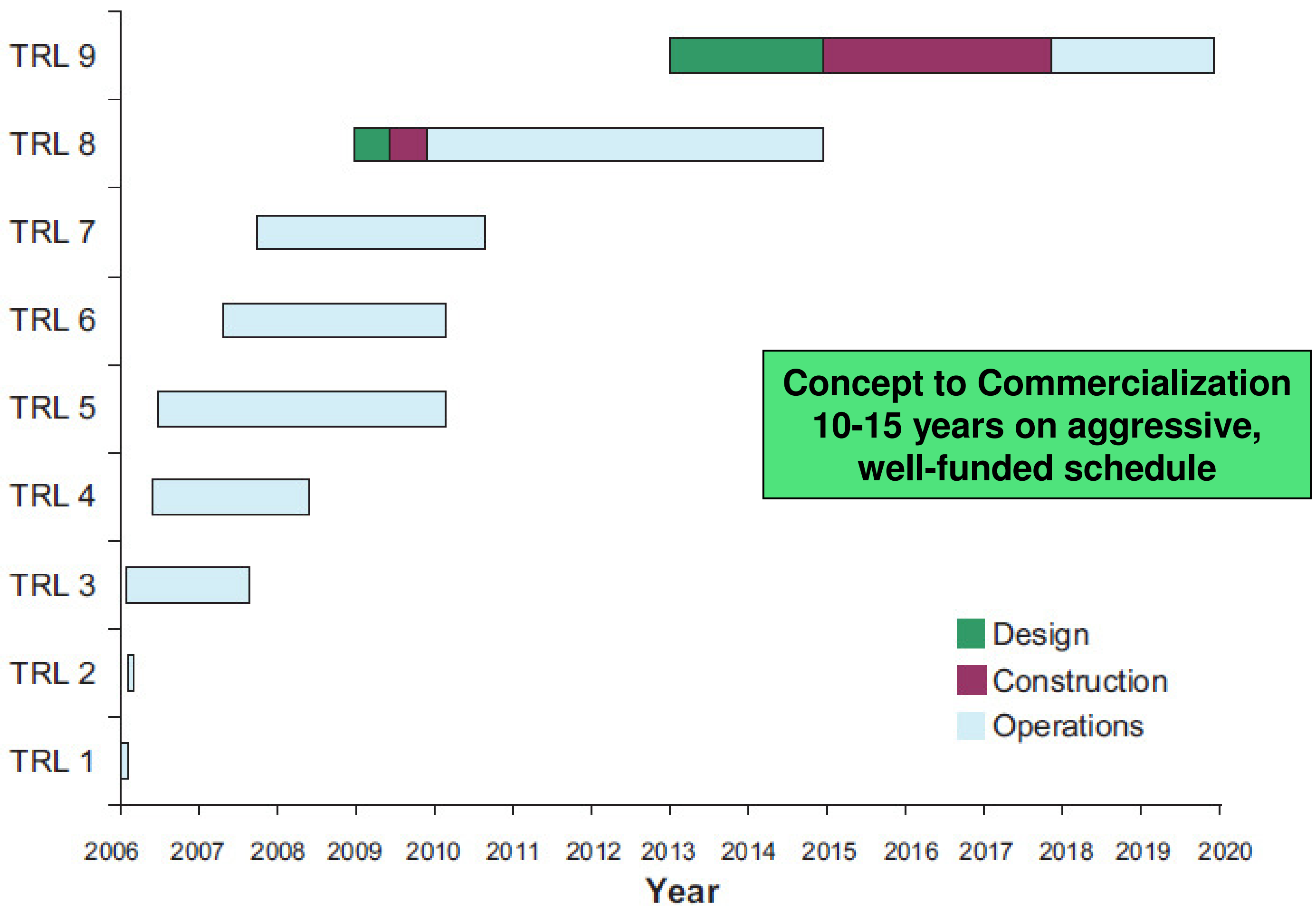
Timescale for Capture Process Development



CO_2 to Carbon or Fuels

- "Convert" CO_2 to carbon
  - $C + O_2 \rightarrow CO_2$; $\Delta H \sim -393.5$ kJ/mol
  - About 1/3 ΔH converted to electricity in power plant (-131 kJ/mol)
  - The same ΔH (393.5 kJ/mol) energy input is needed to reverse reaction and make carbon, i.e., minimum 3x power plant output
  - Practically, need far more than 3x power plant output
- "Convert" CO_2 to fuels
  - Identical issue as with carbon
  - All fuels are combusted to produce CO_2 and H_2O to generate ΔH
  - Reversing reaction will consume far more energy than available from combusting fossil fuels
- If such usable energy is available, then it may likely be better to use that energy to make electricity instead, and avoid generating CO_2 from fossil fuel combustion in the first place.

Sun as Energy Source for CO_2 Conversion

- Organisms use sun as energy source to convert CO_2 to fuels
- Process is slow and with poor use of sun's incident energy for purposes of CO_2 capture
- Fastest algae capture ~24 g $C/m^2/day$ (~1.5x of switch grass)
- About 45 mi^2 for 500 MWe coal-fired power plant under ideal conditions. Amine scrubbing is estimated at 12 acres, already viewed as a "very large" area
- For non-biological processes that use solar energy to drive CO_2 conversion, it may likely be better to convert the solar energy directly to electricity and avoid generating CO_2 from fossil fuel combustion in the first place

Limits on CO_2 Capture Technologies

- Second law violators
  - CO_2 to fuels need energy source, and energy comes from fuels
  - Sometimes do not account for overall total CO_2 footprint
- Real Estate Moguls
  - Biological processes use solar energy for CO_2 conversion, but need substantial land (~45 mi^2 for 500 MWe under ideal case)
  - Solar energy like better used to make electricity directly instead of converting CO_2 in non-biological processes?
- Massive Material Mismatch (once-through capture)
  - Limited use of CO_2 directly
  - Limited global supply of chemicals to capture CO_2 or make saleable products
- CO_2 gold mine ≠ CO_2 solution
- Control volume = Earth's atmosphere

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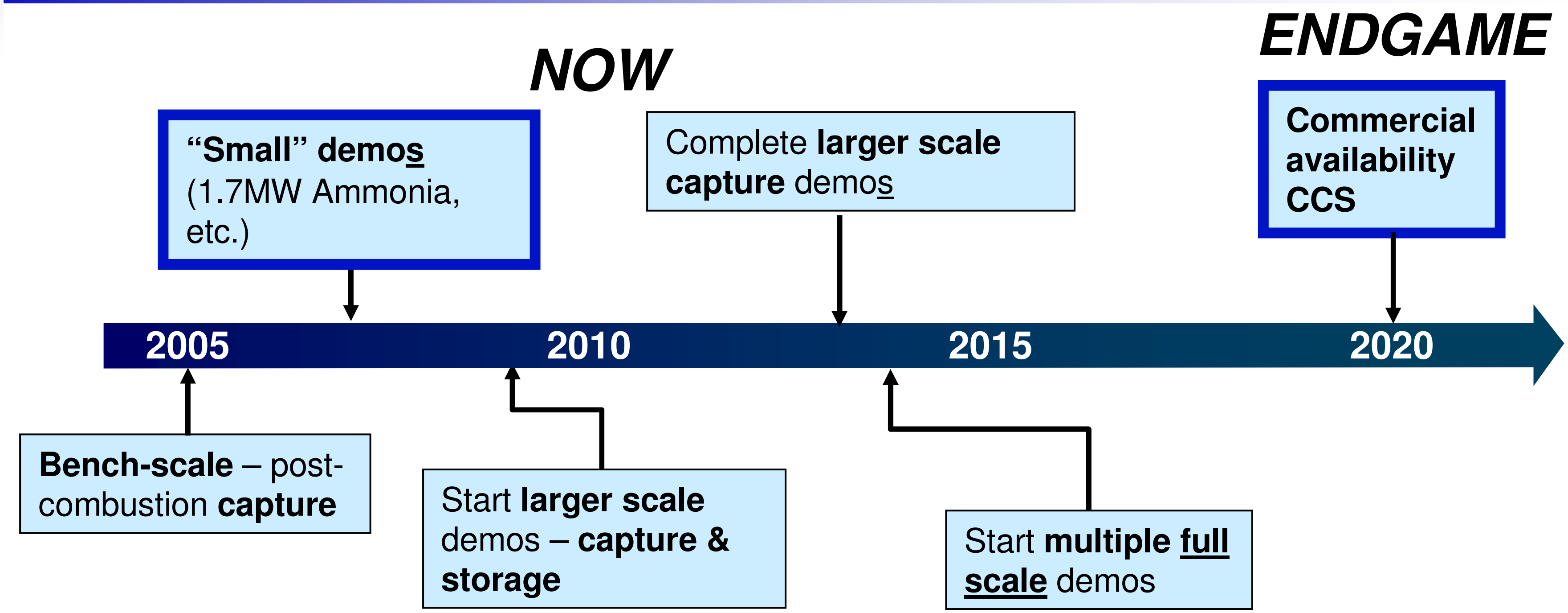
EPRI's Approach to Bridging the Disconnect

- Experimental Testing
  - Collaborations on several novel experimental approaches and processes
  - From early-stage concepts to 25 MWe pilots thus far
- Process Model Development
  - Develop process models for CO_2 capture processes applied to power plants
  - Conduct parametric studies to quantify desired separating material properties
  - Share results with chemists and material scientists to develop new separation chemistries

A Roadmap for Post-combustion Capture and Storage



Needs: Multiple large-scale CAPTURE & STORAGE demos

Timing: 2020 endgame ➔ start today, parallel paths

Realistic? A challenge – technical, policy, funding

Source: DOE-NETL Carbon Sequestration R&D Roadmap
Modified to add Chilled Ammonia example

Closing Comments

- Encourage and even demand innovation, but recognize that a commercial solution is needed very soon
- At the same time, allow creativity and flexibility because approaches that are not practical today may turn out to be synergistic with another one tomorrow
- Increase understanding not only in one's own research area, but also understand the challenges and issues of other key players in the entire solution chain
- Collaborative work, not just horizontally across disciplines, but more importantly vertically across application levels is critical to developing breakthrough technologies

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Questions?