Reducing CCS Costs: Learning Curves, Learning through Research & Development, and Learning by Doing

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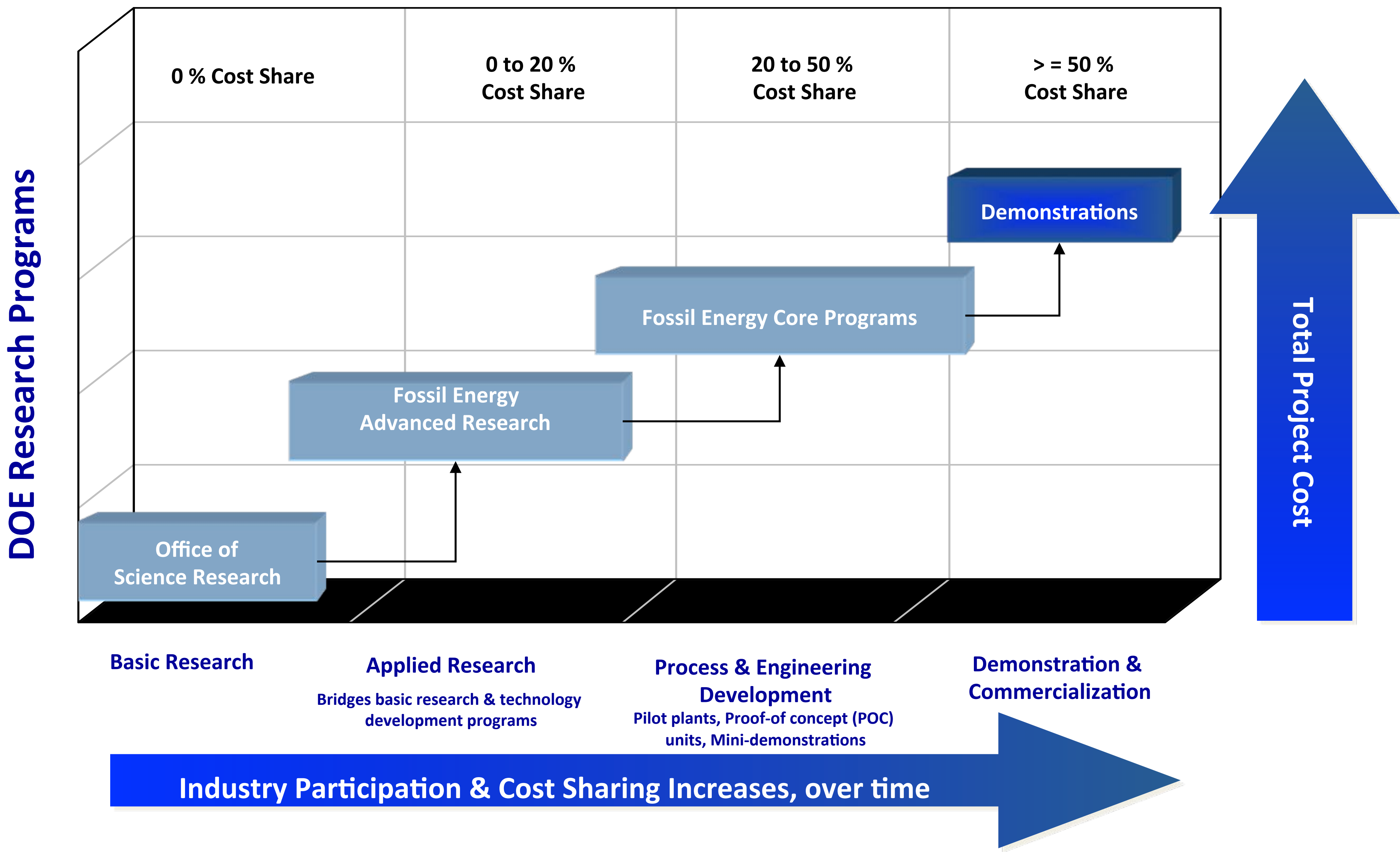
U.S. DEPARTMENT OF ENERGY | National Energy Technology Laboratory

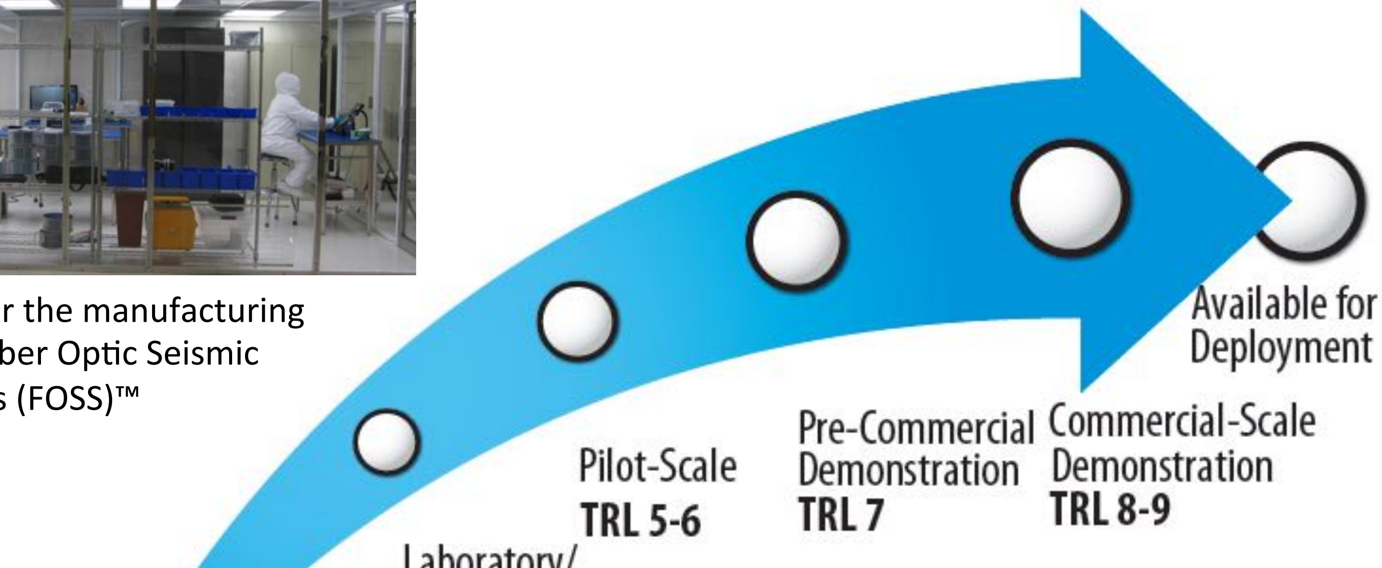
Cost Share Ensures Commercial Relevance



Carbon Storage Program

Technology Readiness Levels (TRLs)

The clean room for the manufacturing of the 300ºC Fiber Optic Seismic Sensors (FOSS)™



Field deployment and testing of the 5 level 3C array prototype at an industrial well in California

Advanced Coal Power Technologies

Aspects Applicable to Natural Gas

State-of-the-Art

Today's IGCC

Today's Supercritical PC

2nd-Generation

Advanced H_2 Turbines

Syngas Cleanup

Advanced Pre-combustion Capture

Advanced Ultra-Supercritical (AUSC) PC

Advanced Post-combustion Capture

AUSC Oxycombustion

Transformational

Integrated Gasification Fuel Cells (IGFC)

Pulse Combustion

3100°F H_2 Turbine

Chemical Looping Gasification

Transformational H2 Production

Transformational CO_2 Separation

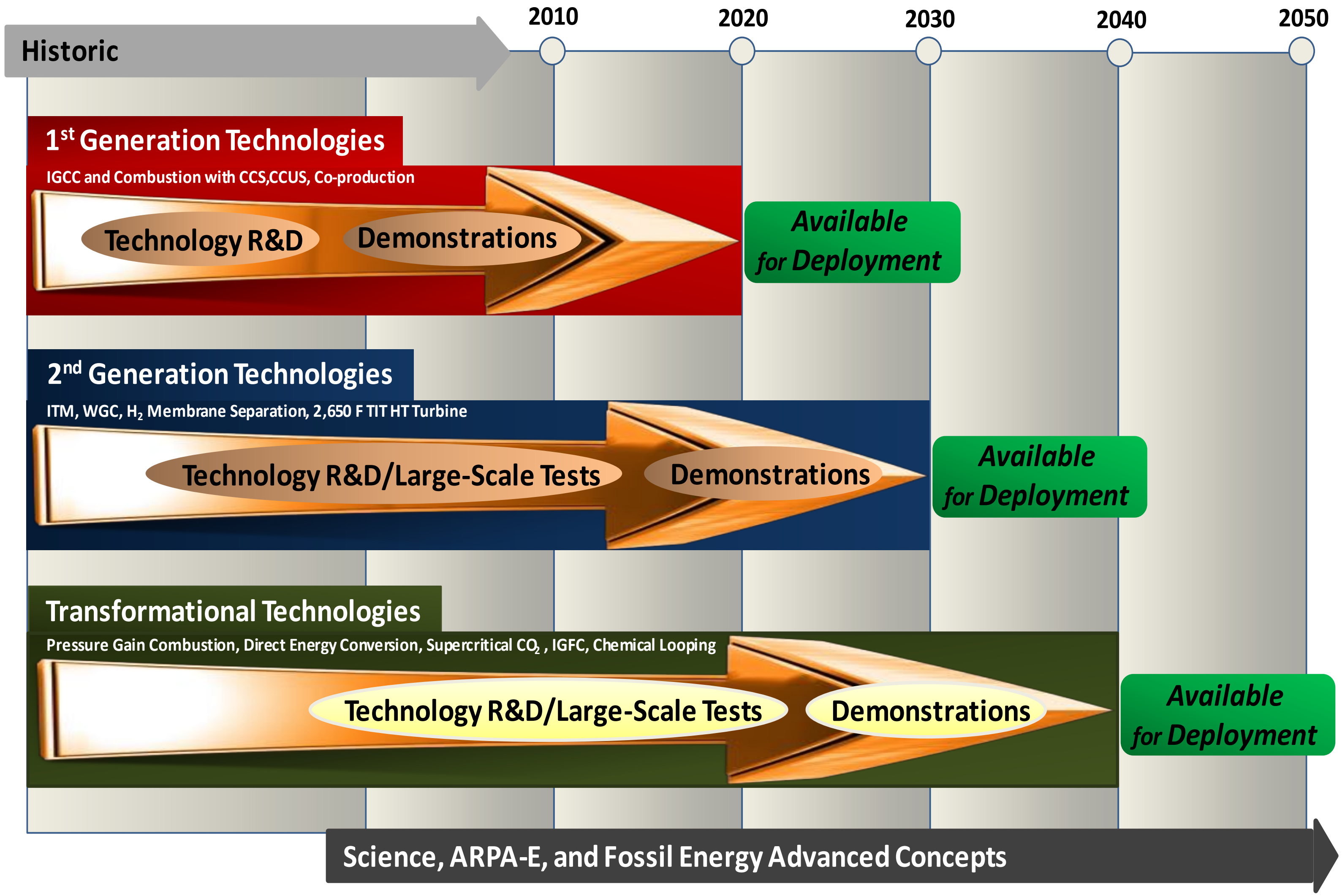
Chemical Looping Combustion

Direct Power Extraction

Supercritical CO_2 Cycles

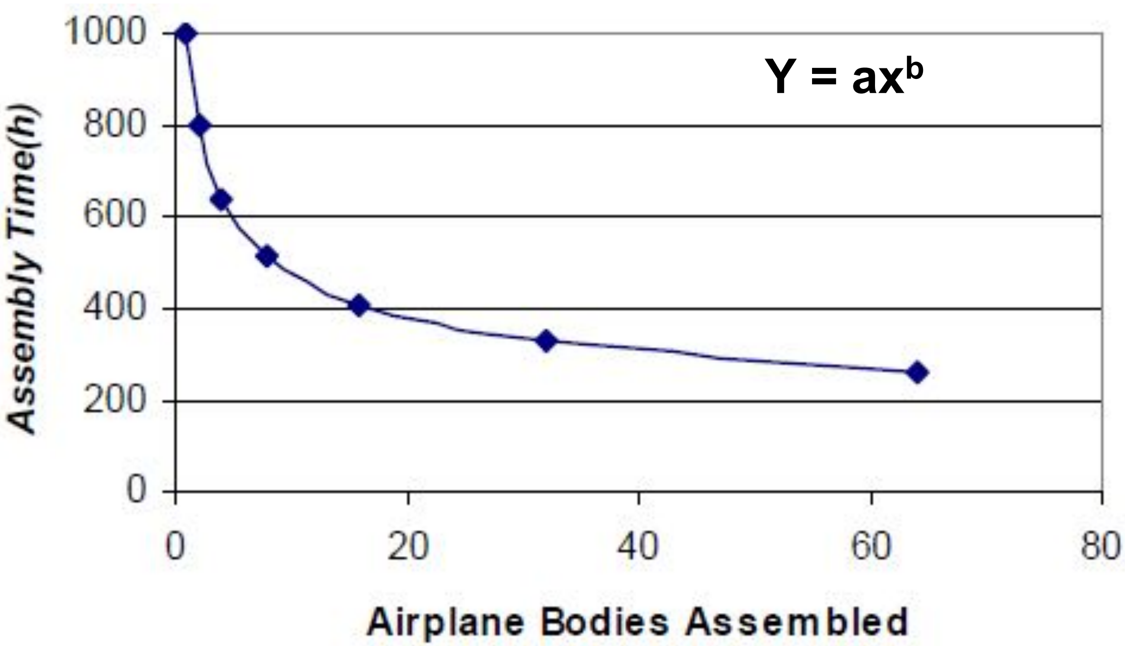
Pressurized Oxycombustion

CCRP Technology Development Timeline



Background – Learning Curves

Sample Learning Curve Function



a = Cost of first unit

x = Number of units produced

b = Learning rate exponent

$1 - 2^{-b}$ = Learning Rate, reduction in capital cost for doubling of capacity

- Developed by T.P. Wright in 1936 after observing labor time reductions to assemble airplanes.
- In 1998 Mackay & Probert showed that a similar rule could be applied to capital cost reductions in renewable energy.
- Models including NEMS rely on this curve to predict future capital costs.

Source: "Learning and Cost Reductions for Generating Technologies in the National Energy Modeling System (NEMS)" E.Gumerman & C.Marnay. Lawrence Berkeley National Laboratory, University of California

Background - Large Variation in Learning Curves for Energy Technology

Technology	Region of Study	Time Period of Study	Estimated Learning Rate	Reference
Coal Power Plants	USA	1960 – 1980	1.0% – 6.4%	Joskow & Rose (1985)
Coal for Electric Utilities	USA	1948 – 1969	25%	Fisher (1974)
Crude Oil at the Well	USA	1869 – 1971	5%	Fisher (1974)
Solar PV Modules	World	1976 – 1992	18%	IEA (2000)
Wind Power	USA	1985 - 1994	32%	IEA (2000)
Wind Power	EU	1980 – 1995	18%	IEA (2000)

Data Source: McDonald & Schrattenholzer, 2001.

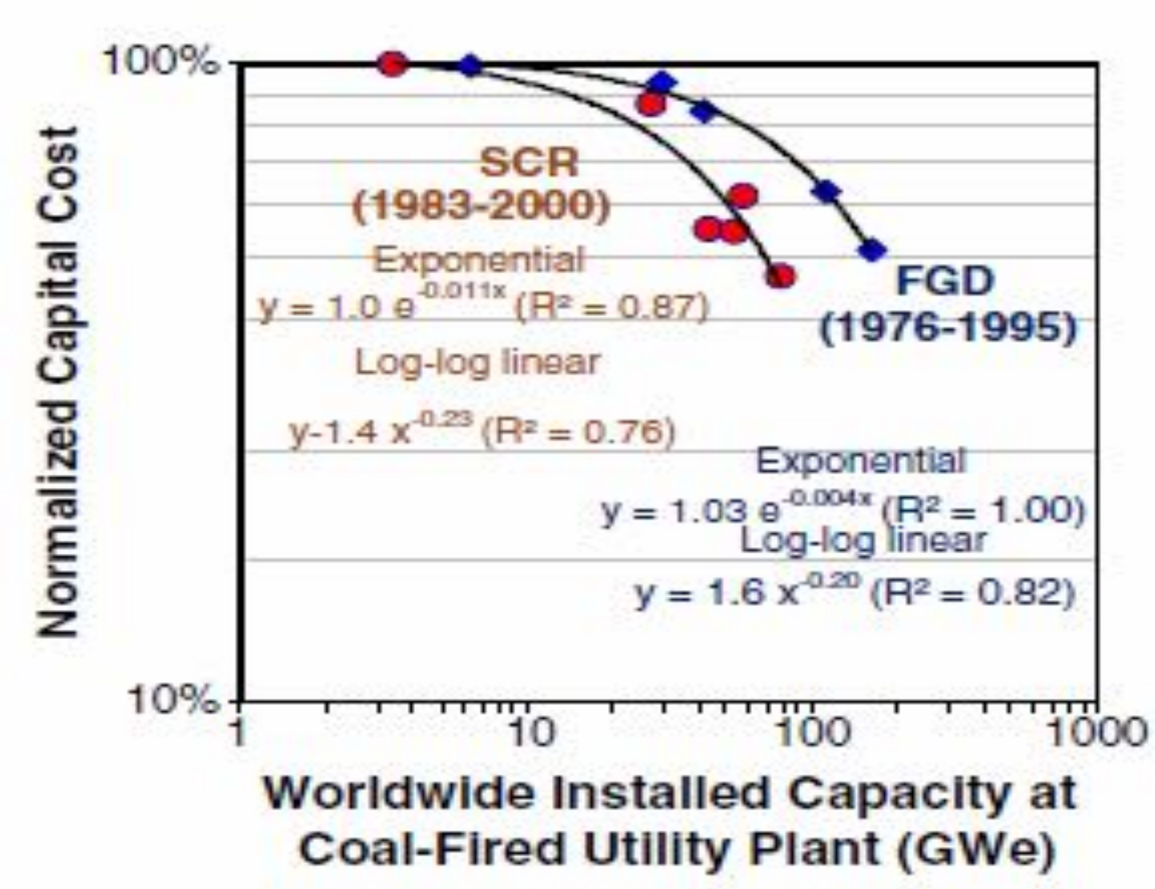
Background - Explanations for Variability

- Experience depreciation
- Short-term pricing behavior
- Differences in performance measures
- Definitional differences
- Varying intensities of R&D
- Economies of scale
- Cost variability for factors such as land costs, wages, and interest payments

Source: Alan McDonald & Leo Schrattenholzer (2000). Learning Rates for Energy Technologies. Energy Policy 29, 255-261.

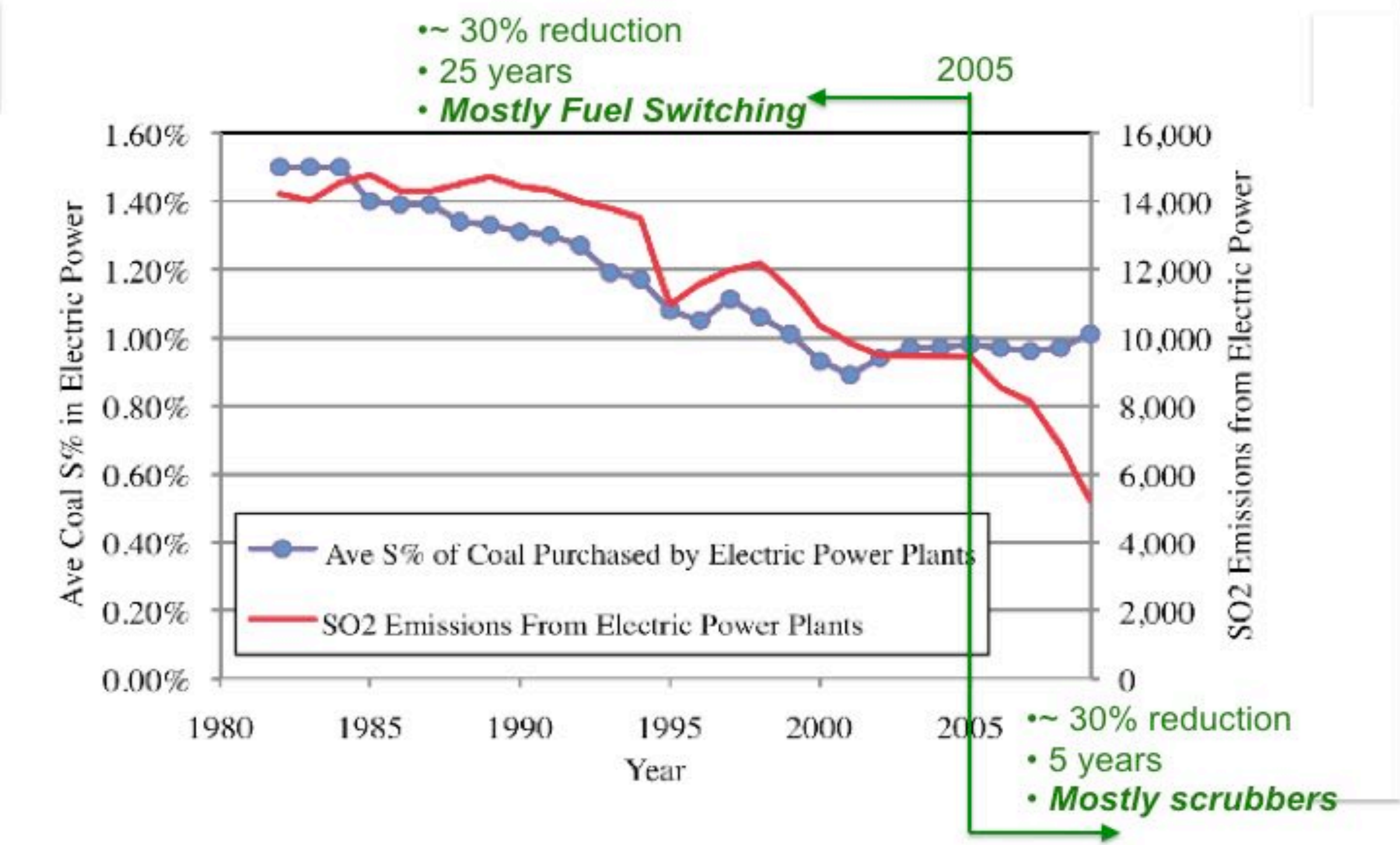
SO_2 & NO_x Control Learning Curves

Non-linear learning curves are prevalent in power plant emission control technologies.



Yeh, S., Rubin, E.S., Hounshell, D.A., and Taylor, M.R. (2009) Uncertainties in Technology Experience Curves, for Integrated Assessment Models, Environmental Science & Technology, **43** (18), 6907-14.

CO_2 Analogous to US Power SO_2 Emissions



Source: "CCS Theory of Change" by John Thompson, Clean Air Task Force, Nov. 21, 2013; adapted from "Anthropogenic Sulfur Dioxide Emissions: 1850-2005 Supplementary Material" S.J. Smith et. Al.

Background - Key Findings from Literature

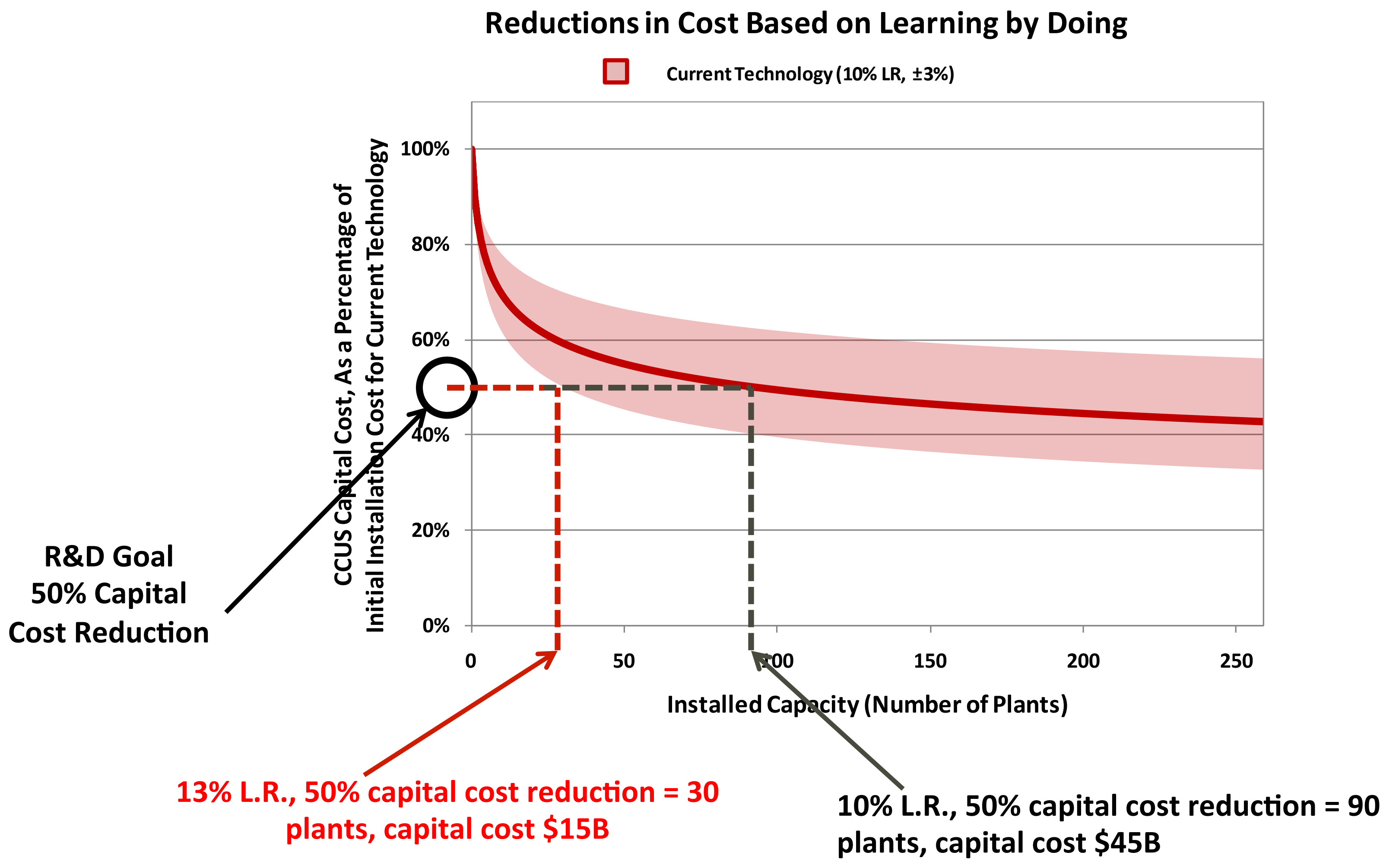
- **Both Research and Development (R&D) and learning-by-doing play an important role in innovation and the cost of energy technologies in the marketplace[1]**
- **Caution should be taken when using this approach due to the following issues:**
  - Wide variation in learning curve rates and behavior
  - Cannot separate effects of R&D from learning-by-doing

[1]For more details on the models, see Alan McDonald & Leo Schrattenholzer, "Learning Rates for Energy Technologies." Energy Policy, 29 (2001), 255-261; and Sonia Yeh and Edward Rubin, "A Review of Uncertainties in Technology Experience Curves." Energy Economics 34 (3) (2012), 762-771.

Choice of Learning Rate

- Rubin et al (2007), identified historic learning rates from similar power plant technologies:
  - 11% FGD
  - 12% SCR
  - 10% GTCC
  - 5% PC Boilers
- Riahi et al (2004), estimated a 13% learning rate for CCUS technologies.
- Assume a 10% learning rate representing the average of the above learning rates and a 3% error band to reflect inherent uncertainty.

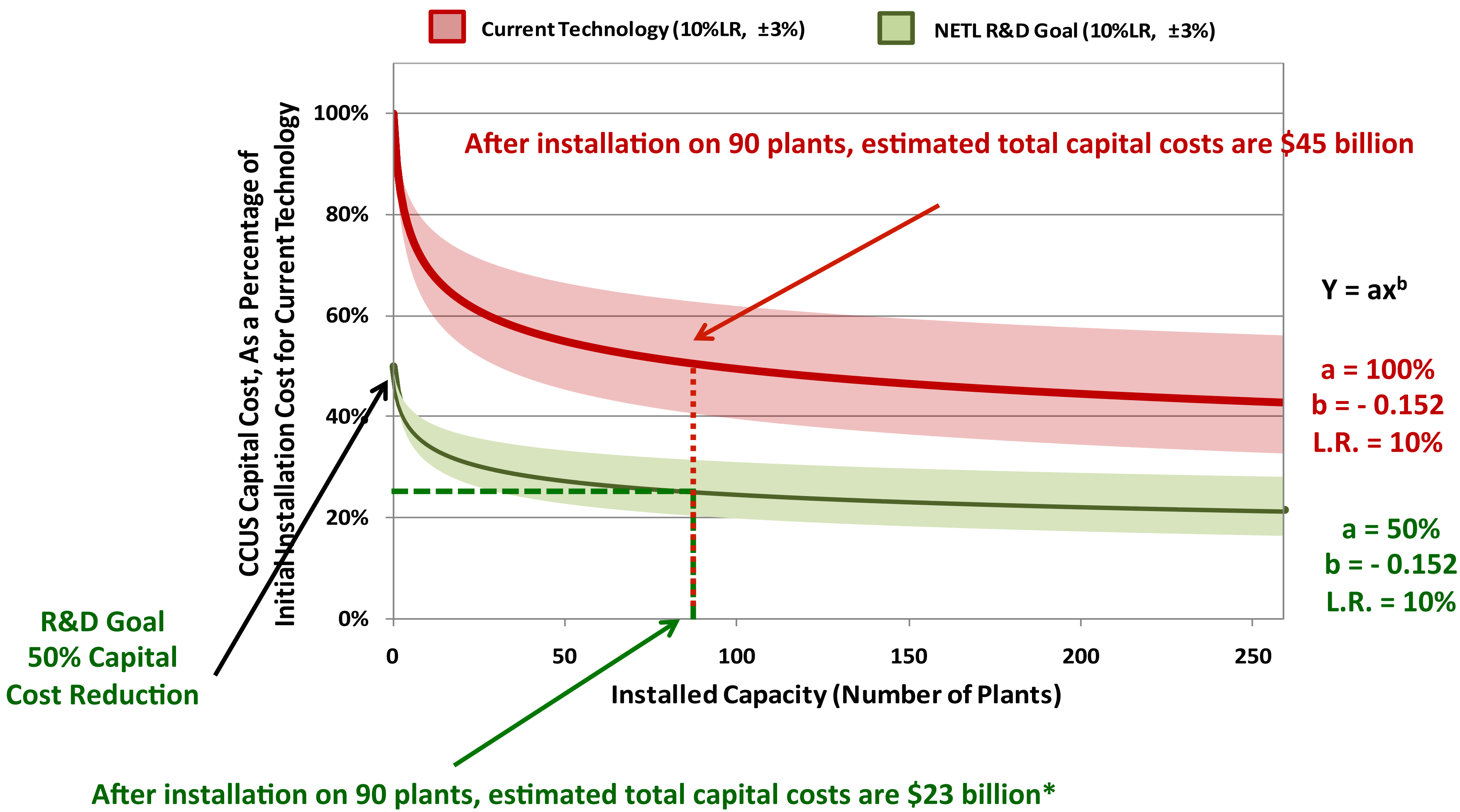
How Many Learning-By-Doing Plants = R&D Goal?



$Y = ax^b$

a = 100%
b = -0.152
L.R. = 10%

Learning Occurs With R&D, Too



*R&D case includes capital costs but not R&D costs.

Net Present Value Tool

- **Question: How many plants would install CCUS if there were a price for CO_2?**

- **Compared:**

  Current technology costs

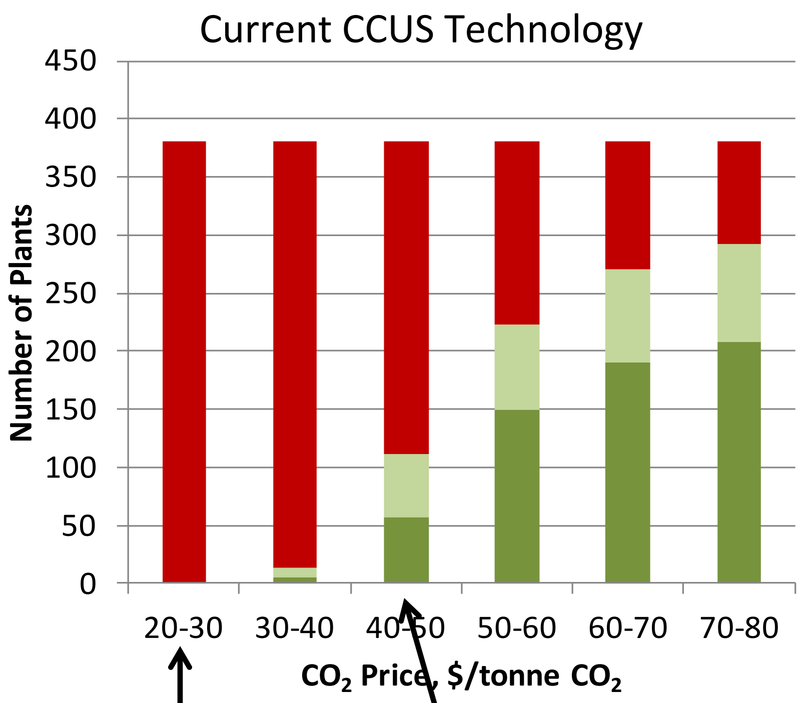
  EPEC R&D Goals = 50% reduction in CCUS retrofit costs

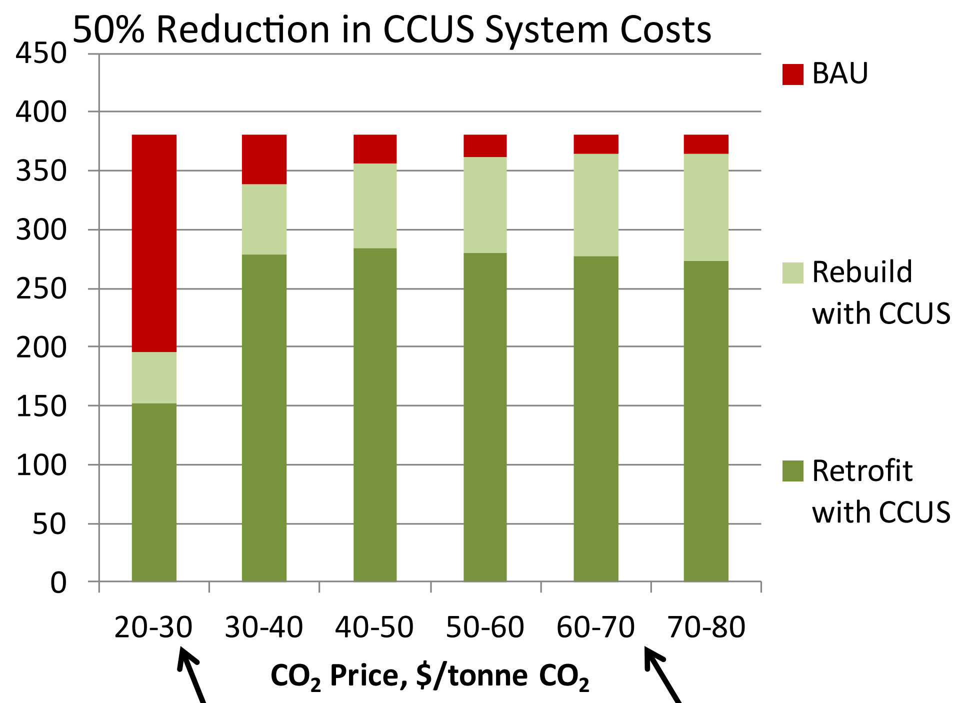
  EPEC R&D Goals Lite = 25% reduction in CCUS retrofit costs

- **Examined how many plants retrofit with CCUS, how many rebuild with CCUS, and how many continue running business as usual (BAU).**

There Can be No Learning-by-Doing if There is No Doing

If R&D is not performed, the cost is too high for most plants to install technology or replace with new CCUS facilities; learning-by-doing never gets off the ground.





Low CO_2 market price, no plants retrofit, thus no learning occurs.

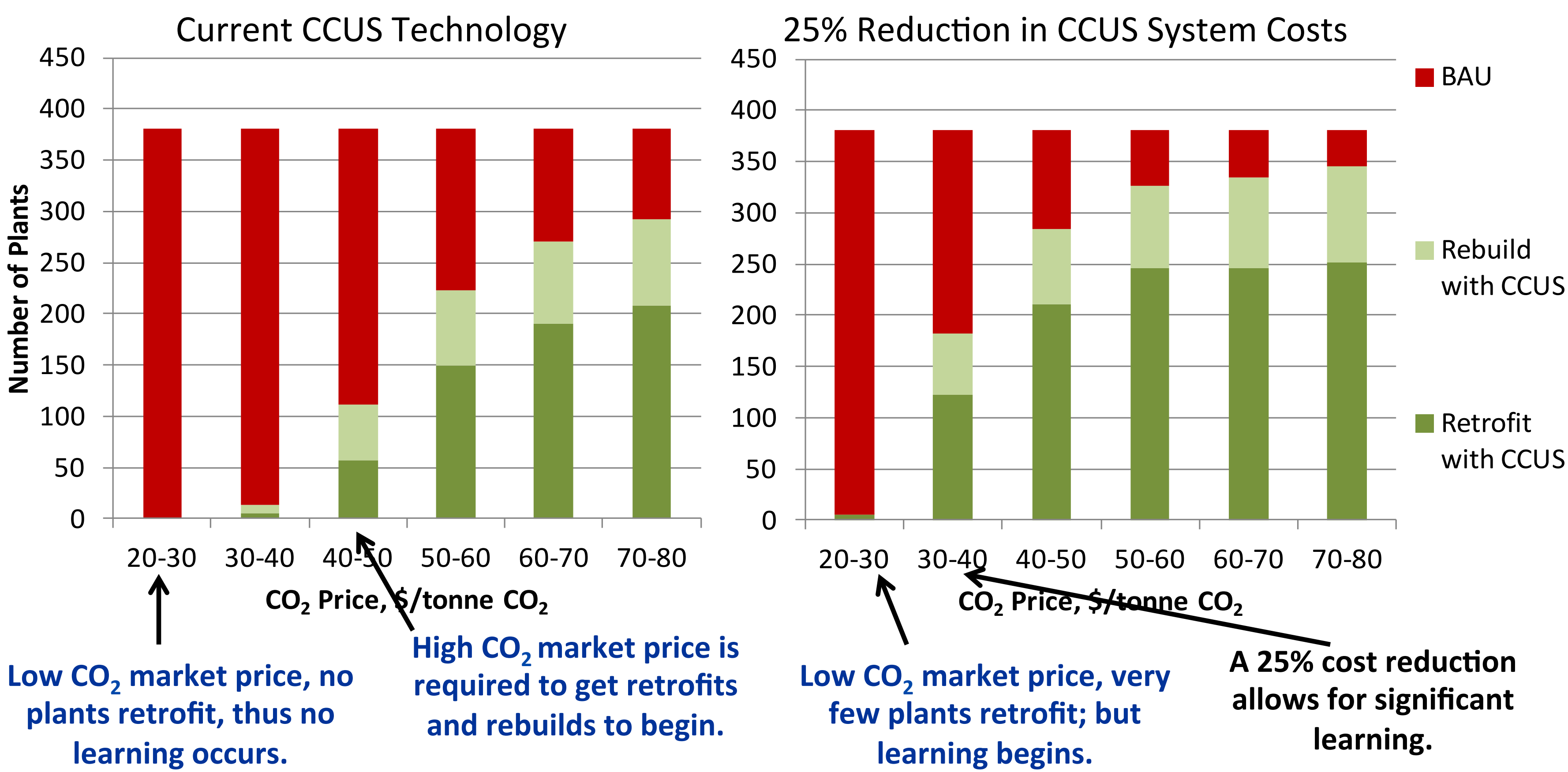
High CO_2 market price is required to get retrofits and rebuilds to begin.

Low CO_2 market price, some plants retrofit; learning begins.

High CO_2 market price, substantially more retrofits

What if R&D Only Achieves a 25% CCUS System Cost Reduction?

Even if the NETL R&D program falls short of its goals, there is still value in the form of reduced CCUS system costs, increased deployment, & earlier learning-by-doing.



References

"CCS Theory of Change" by John Thompson, Nov. 21, 2013.

"Climate Change, Technology Innovation, and the Future of Coal" by Edward Rubin, in Cornerstone, Vol. 1, Issue 1, Spring 2013.
http://cornerstonemag.net/climate-change-technology-innovation-and-the-future-of-coal/

"Evaluating the Impact of R&D and Learning by Doing on Fossil Energy Cost Reductions: There Can be No Learning if There is No Doing" by Katrina Krulla, DOE/NETL-342/020613, Feb. 2013.
http://netl.doe.gov/File%20Library/Research/Energy%20Analysis/Publications/Learning-Curve-Analysis-Report.pdf

"Moore's Law vs. Wright's Law", Forbes, March 25, 2013.
http://www.forbes.com/sites/jimhandy/2013/03/25/moores-law-vs-wrights-law/

Statistical Basis for Predicting Technological Progress" by Bela Nagy, et al., Feb. 28, 2013.
http://www.plosone.org/article/fetchObject.action?uri=info%3Adoi%2F10.1371%2Fjournal.pone.0052669&representation=PDF

For Additional Information

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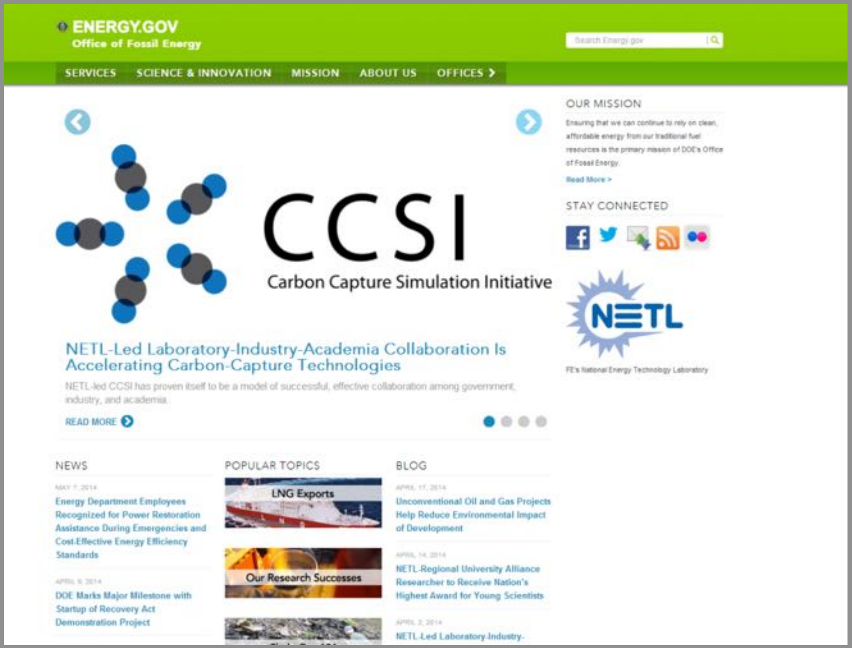

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