THE CURC-EPRI ADVANCED COAL TECHNOLOGY ROADMAP

July 2015 UPDATE

Prepared by the Coal Utilization Research Council and the Electric Power Research Institute

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List of Acronyms

ARPA-E	DOE's Advanced Research Projects Agency-Energy
AUSC	Advanced ultra-supercritical combustion
BD-PC	Boundary Dam Pulverized Coal CCS repowering project, Saskatchewan, Canada
Btu	British thermal unit
CAFE	Corporate Average Fuel Economy
CAR	Center for Automotive Research
CLC	Chemical looping
CO_2	Carbon dioxide
CCPI	Clean Coal Power Initiative
CCS	Carbon capture and storage
CCUS	Carbon capture utilization and storage
CURC	Coal Utilization Research Council
DOE	U.S. Department of Energy
EIA	U.S. Energy Information Administration
EOR	Enhanced oil recovery
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
GHG	Greenhouse gas
GDP	Gross Domestic Product
GW	Gigawatt(s)
GWh	Gigawatt hour
IGCC	Integrated gasification combined cycle
H_2	Hydrogen
Hg	Mercury
FOAK	First of a kind
ITM	Ion transport membrane
KC-IGCC	Kemper County IGCC project, Kemper County, Mississippi
LCOE	Levelized cost of electricity
Mcf	Thousand cubic feet
Mpg	Miles per gallon
MM	Million Metric
MW	Megawatt
MWh	Megawatt hour
NCC	National Coal Council
NETL	National Energy Technology Laboratory
NGCC	Natural gas combined cycle
NOAK	Next of a kind
NOx	Nitrogen Oxide

O&M	Operating and Maintenance
O_2	Oxygen
P-Oxy	Pressurized oxygen combustion
PM	Particulate matter
RD&D	Research, development, and demonstration
SO_2	Sulfur Dioxide
SOAK	Second of a kind
ZLD	Zero liquid discharge

EXECUTIVE SUMMARY

The CURC-EPRI 2015 Advanced Coal Technology Roadmap Update

Background

Coal is a key element of the U.S. economy and provided the fuel for 18.5% of total U.S. energy consumption, and 43% of U.S. electric power generation in 2013. This energy resource plays a similar role in the global energy economy. Between 2002 and 2010, world coal consumption grew at nearly twice the rate of growth of all other fuels. Coal's wide use derives from its abundance, accessibility, transportability/storability and stable low cost compared to other fuels.

Despite these attributes, coal faces strong regulatory and economic challenges in today's marketplace. Compliance with recent environmental regulations has driven up the cost of coal-based power generation in the United States, and future regulations may increase costs further. These regulations are a key factor in early coal plant retirements, cancellations of planned new coal units and the drive to increase coal plant efficiency. Reduced demand for electricity due to the lingering effects of the 2008 recession and competition from natural gas-fueled generation also have limited the demand for new coal-based power plants.

Technology has enabled the historical environmental and economic challenges of coal use to be overcome in the past. The formula for successful technology development continues to rely on collaboration between the government and the private sector to cost-share in research, development, and demonstration (RD&D). These public and private sector RD&D collaborations have yielded a return of $13 for every dollar of federal funding spent for coal RD&D (per DOE calculations; see footnote 13).

This report identifies key research, development, and demonstration (RD&D) priorities for developing cost-effective, efficient, and environmentally compliant technologies that convert coal to electricity and other useful forms of energy and manufacturing feedstocks. This "Roadmap" is a joint effort between the Coal Utilization Research Council ("CURC", www.coal.org) and the Electric Power Research Institute ("EPRI", www.epri.com). Earlier Roadmaps were published by CURC and EPRI in 2003, 2008, and 2012. CURC led the development and publication of this report; recommendations and opinions regarding existing or future policies and regulations are solely those of CURC. EPRI provided detailed technical input and review relative to characteristics, capabilities and RD&D needs for existing, emerging, and potential technologies.

The 2015 Update

The 2015 Roadmap Update was undertaken amid several new market conditions that required a re-examination of the technology development needs for the new and existing fleet of coal plants. This re-examination took into account several factors, including fluctuations in the market for coal use in the United States today; the impact of recently proposed regulations to limit emissions of greenhouse gas (GHG) emissions from fossil-fueled power plants; the availability and growth of low-cost, domestic supplies of natural gas being used in both new and existing power generation, increasing levels of renewable electricity generation; and an electric power market that is experiencing and projecting low or no load growth over the next decade. Additionally, since 2012, two carbon capture utilization and storage (CCUS) projects have been completed or nearly completed their construction phase, which has provided a better understanding of the costs of carbon capture and storage (CCS)/CCUS. Lastly, amid growing concerns associated with an aging, existing coal fleet and anticipated coal fleet retirements, the 2015 Roadmap Update also examines the ability to accelerate the development of transformational technologies so that viable new coal-based technology options will exist in the 2025-2030 timeframe to replace retiring coal capacity. However, the availability of these transformational options will be strongly dependent on the level of federal funding available to implement the technology development recommendations included in this report.

The 2015 Roadmap Update examines three new technology development pathways:

(1) A new program that considers the value of the existing coal fleet, and describes a technology program necessary to support the existing coal fleet as it takes on new challenges in responding to new regulatory and dispatch requirements;

(2) A new "transformational" technology program that defines development needs for new technologies that will deliver significantly higher value in terms of cost, efficiency, flexibility and environmental performance relative to current coal-based electricity generation; and

(3) A new large-scale pilot program that anticipates federal support of evaluating new technologies under real operating conditions at a scale beyond laboratory and bench-scale and before testing technologies in a commercial-scale demonstration.

The 2015 Roadmap Update also reflects changes to the Gasification RD&D program, which identifies promising new technologies that offer lower cost and better performing gasification-based power systems in the future, and a more defined Advanced Combustion program that includes pathways for next generation and transformational carbon dioxide (CO_2) capture technologies.

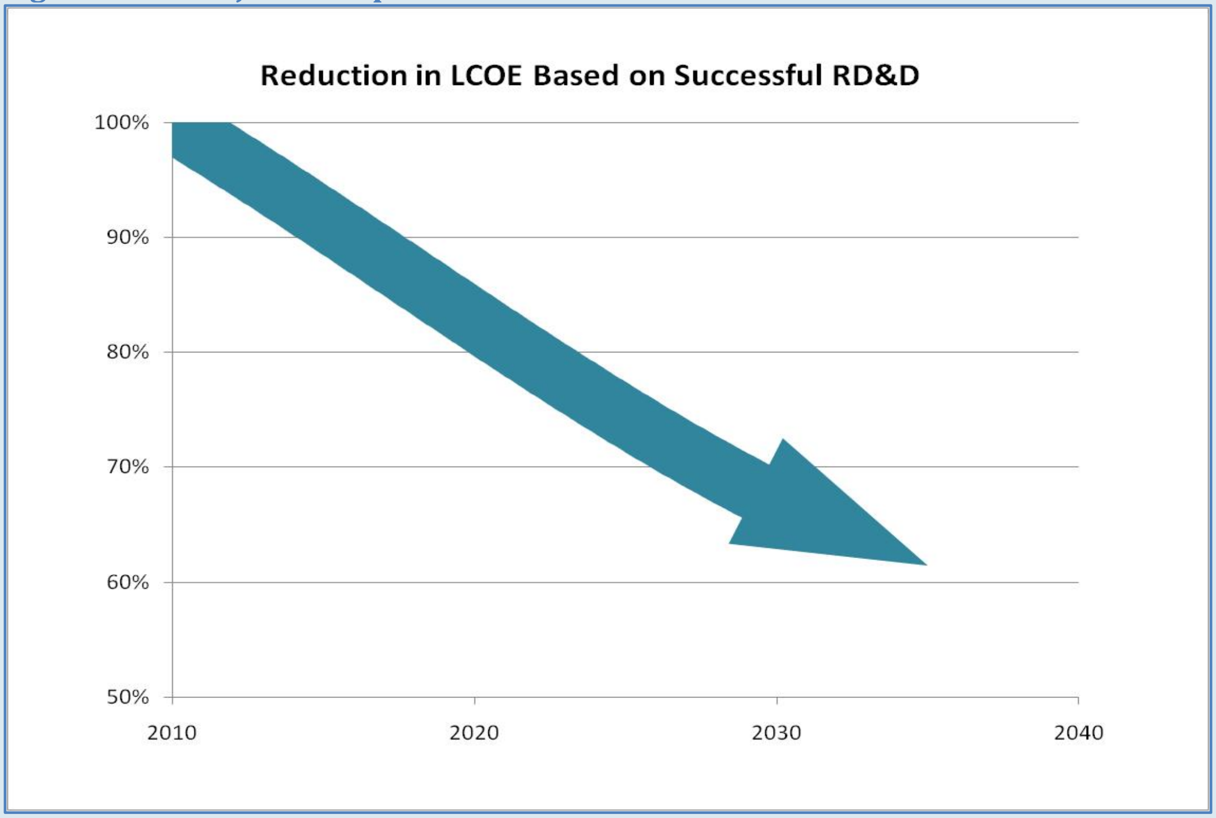
Other changes include updated descriptive statistical data on coal-based power – both the technology RD&D pathways and funding profiles – as a result of new and changed development activities in each program area, and a new cost-of-electricity analysis that reflects the benefits and impacts of the Roadmap development efforts if fully funded and successfully implemented by the private sector in partnership with the federal government.

Projected Benefits of Technology Development

The technology development plan outlined in this Roadmap offers the potential to deliver first-of-a-kind (FOAK), low-carbon coal technology options by the 2025-2030 timeframe, including small-scale transformational systems which would be compatible in size with capacity needs of the United States power market at that time. If proposals to regulate GHGs are promulgated in their proposed form, additional funding to support accelerated RD&D will be necessary to enable the availability of a coal technology option based on the proposed regulatory timeline.

Attachment 2 to this report identifies a significant number of commercial-scale demonstration projects that are currently in planning or underway. The majority of these projects will be fueled by coal and incorporate CO_2 capture and storage. They have received partial funding from the federal government through demonstration grants or other financial incentives. They are "first-generation" projects utilizing technologies developed through public and private cost-share programs. Continued, well-funded and successfully executed RD&D can reduce costs further and could produce the next generation of technologies in new demonstration plants. Figure ES-1 shows how the cost of electricity (relative to today's levels) from coal-based power plants equipped with CCS can be reduced through RD&D. Levelized costs of electricity (LCOE) could potentially be reduced by another 10-15% (absolute)[1] in 2025-2035 if the captured CO_2 is sold for use in Enhanced Oil and Gas Recovery (EOR).

Figure ES-1. Projected Improvements in Power Costs



These reductions can be achieved while further reducing the already well-controlled emissions of traditional pollutants. Figure ES-2 depicts the reductions of sulfur dioxide (SO_2), nitrogen dioxide (NO_x) and other traditional pollutants compared to a new coal-fueled power plant built with 2010 technology.

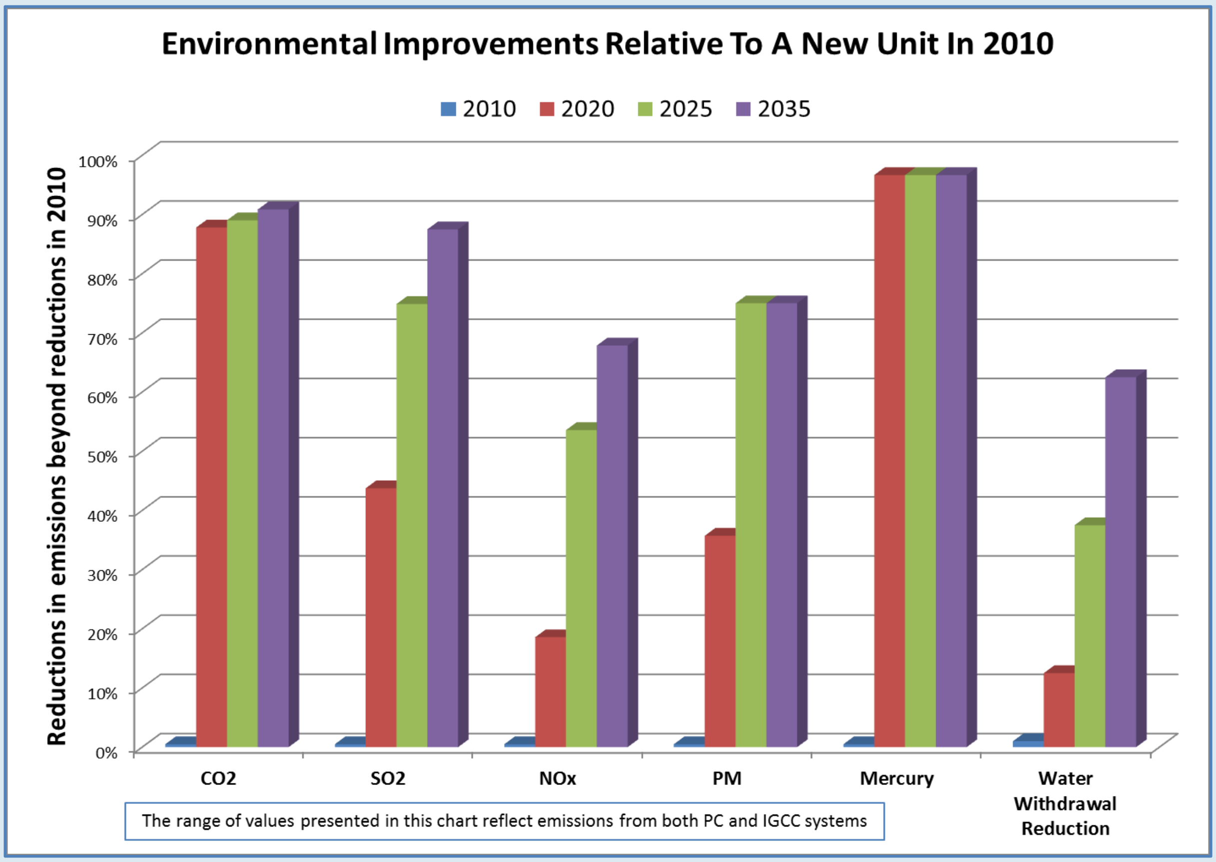
[1] For example, if saline storage-based LCOE has decreased by 35% in 2030, the decrease for an EOR-based power system could decrease by an additional 10-15%, or an overall decrease of 45-50%. The value of EOR revenues is uncertain because they vary regionally, and with the future price of crude oil.

In addition to these economic and environmental benefits, improved coal technologies can enhance the nation's energy security by reducing imports of crude oil through capturing CO_2 for use in producing domestic oil via EOR; converting coal to transportation fuels or coproducing both electricity and liquid fuels or chemicals; reducing exposure to increasing electricity costs through a diverse generation technology portfolio; and lowering the cost of electricity to facilitate greater market penetration by electric vehicles, thereby lowering the numbers of fossil fueled vehicles.

The Cost of the RD&D Effort

The RD&D and large-scale pilot efforts required to achieve these results are estimated to cost, on average, approximately $650 to $1,420 million per year in the early years of the program, and average $850 million per year through 2035 (see Table ES-1). The federal share of these requirements are estimated to average approximately $570 to $940 million per year in the early years, and $495 million per year from 2026-2035.

Figure ES-2. Projected Reductions in Air Emissions and Water Use from Coal RD&D



Notes to Figure ES-2: Percentages are relative to levels of reduction achieved as of 2010 for U.S. fossil fleet (NO_x and SO_2 = 90 - 99% reduction; Particulate Matter (PM) = 99.6% reduction; Mercury (H_g) = 90% reduction; and water withdrawal reduction (as a result of cooling towers) = 98%). For CO_2, percentages are relative to capture levels of 0%, as carbon controls were not required in 2010.

Table ES-1. Projected Cost of Recommended RD&D Effort

Funding ($M/year)		2016-2020	2021-2025	2026-2035
RD&D	Total (Industry and Federal)	346	241	97
	Federal (80%)	277	192	77
Pilots	Total (Industry and Federal)	279	322	89
	Federal	279	322	89
Demos	Total (Industry and Federal)	28	854	654
	Federal (50%)	14	427	327
Total (Public/Private) Annual Funding		**653**	**1,416**	**850**
Annual Federal Budget		**570**	**941**	**493**

Details on the specific types of technologies needed, and cost of RD&D over time, by major technology category, are included in the body of this report.

The CURC-EPRI 2015 Advanced Coal Technology Roadmap

Introduction

This report presents a RD&D plan for developing technologies that convert coal to electricity and other useful forms of energy and manufacturing feedstocks. The plan, or "Roadmap," was a joint effort between the Coal Utilization Research Council (CURC, www.coal.org) and the Electric Power Research Institute (EPRI, www.epri.com).

Earlier Roadmaps were published by CURC and EPRI in 2003, 2008, and 2012. This update includes new data on recent advances in technology; addresses the increased stress on the U.S. economy which has diminished support for technology development; accounts for low-cost, increased domestic supplies of natural gas; and recognizes regulations to control both hazardous and criteria air pollutants from coal use as well as new, proposed policies for controlling emissions of CO_2.

Reflecting on these changed conditions, the 2015 Roadmap update includes pathways for pilot-scale demonstration activities; reflects the need to replace existing capacity with smaller scale, more modular commercial systems that may be needed in the 2025-2030 timeframe to account for slower load growth and to serve as replacement options for aging coal units; takes into account market constraints likely to result in slower penetration of emerging integrated gasification combined cycle (IGCC) technologies; and provides a more detailed analysis of transformational technologies that can introduce new methods of converting coal to useful energy. This Roadmap Update also includes an examination of the technology needs to ensure the economic and energy security benefits provided by the existing coal fleet can be maintained well into the future.

The Roadmap identifies coal technology advancements that can achieve specific cost, performance and environmental goals, and identifies pathways for developing the technologies needed to achieve those goals through collaborative efforts between the public and private sectors. Specific benefits which can be achieved through successful implementation of the Roadmap are discussed below, and can generally be categorized as:

1. Aggressive reduction of water use and air pollutants, including NO_x, SO_2, H_g and PM;
2. Reduction of CO_2 emissions;
3. Production and preservation of affordable electricity essential for U.S. competitiveness through a diverse generation technology portfolio;
4. Improved energy security by –
    a. Using captured CO_2 as a commodity to recover crude oil, thereby increasing domestic oil production;

b. Deploying technologies for the production of liquid fuels and other marketable products;

c. Generating affordable power for electricity consumers including increased industrial and advanced manufacturing customers and to fuel electric vehicles; and

d. Improving the operational flexibility of the existing and future coal plants to ensure continued electricity grid reliability and stability.

5. Ensuring significantly improved technologies are tested at large pilot-scale to assure availability of coal generation options by the 2025-2030 timeframe when a significant portion of the existing fleet of coal plants may be candidates for retirement.

Value of Coal and Coal Technology Development

Coal plays a significant role in the global and domestic energy economy. Globally, consumption of coal increased at a rate of 4.2% per year between 2002 and 2012.[1] Growth in global coal use outpaced the 2.5% annual growth rate of all energy forms (including coal).[2] Most of this growth in coal use was in China and India where annual growth rates were 9% and 6% per year, respectively, over this time period.[3] In contrast, U.S. coal consumption declined by 2.3% per year over this period.[4] Coal comprised 18% of total U.S. energy consumed in 2014.[5]

In 2014, the U.S. coal electricity generation fleet totaled 300 gigawatt (GW) of capacity and 1,586 million megawatt hour (MWh) of generation, which constituted 28% and 39% of total U.S. electric capacity and generation, respectively.[6] Over the past six decades, coal-based power generation has exceeded that of any other generation source in the United States. Because coal-fired generation is among the least-cost approaches in the United States to generate electricity (see Figure 1 below), this reliance on coal for electric power has resulted in large benefits to society. These include the ability to use a domestic resource to supply energy needs, the energy security of a "storable" fuel source for electricity, and the macro-economic stimulus of low-cost electric power. Table 1 shows that U.S. electricity typically costs consumers and industry about one-third to one-half the cost of electricity in Europe. Low-cost electricity, provided in large part by coal, provides an advantage to U.S. manufactured goods competing in the global marketplace.

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[1] International Energy Statistics, U.S. Department of Energy (DOE)/U.S. Energy Information Administration (EIA), coal, http://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid=1&pid=1&aid=2&cid=regions&syid=2002&eyid=2012&unit=TST.

[2] International Energy Statistics, U.S. DOE/EIA, total, http://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid=44&pid=44&aid=2&cid=regions&syid=2002&eyid=2012&unit=QBTU.

[3] Op. Cit., International Energy Statistics, coal.

[4] Ibid.

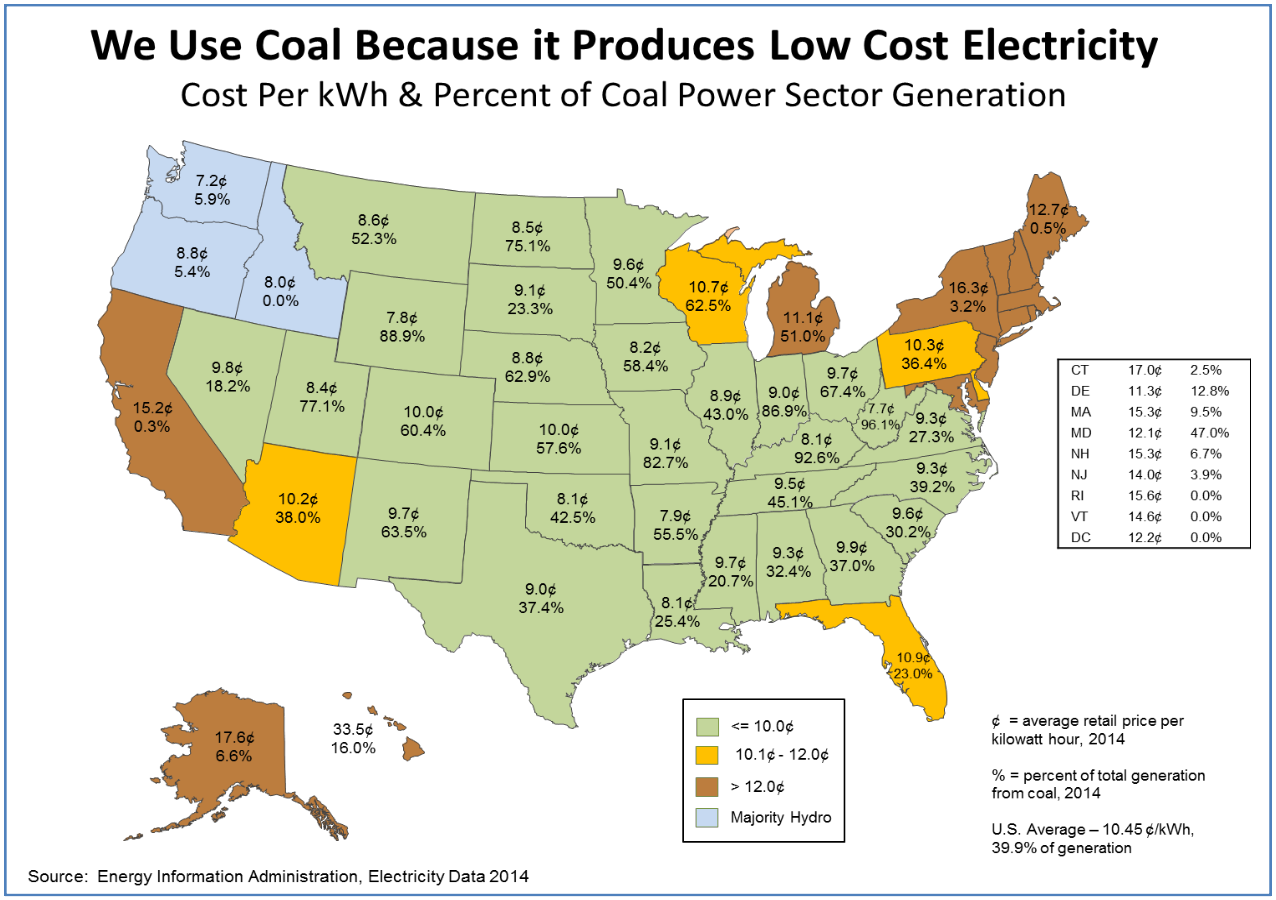
[5] Monthly Energy Review – April 2015, U.S. EIA, April 28, 2015, Table 1.3, http://www.eia.gov/totalenergy/data/monthly/archive/00351504.pdf.

[6] Electric Power Monthly – February 2015, U.S. EIA, February 2015, http://www.eia.gov/electricity/monthly/current_year/february2015.pdf. Capacity data are for December 2014. Generation data are for the entire year.

Table 1. Cost of Electricity in the United States vs. Cost of Electricity in Europe[7]

Consumer Class	Electricity Price in 2013, Cents/kWh						
	U.S.	Denmark	France	Germany	Italy	Spain	UK
Residential	12	42	20	41	32	31	24
Industrial	7	15	13	20	23	17	16

Figure 1. Coal Use in the United States



Challenges to Continued Coal Use in the United States

Despite its strong historic, current and projected future role as a primary energy resource in the United States, the utilization of coal in this country faces multiple challenges. These include regulatory challenges such as case-by-case determinations of CO_2 limitations for new coal-based power plants as required by the U.S. Environmental Protection Agency (EPA); recent regulations that significantly tighten emission limits on criteria pollutants (the Cross-State Air Pollution Rule); and the February 2012 regulation of hazardous air pollutant emissions from electric utilities, as modified following a reconsideration process by EPA (the "MATS" rule).[8] The

[7] Reliable & Resilient – The Value of Our Existing Coal Fleet, Table B.1, National Coal Council, May 2014.

[8] The final regulations reflect a combination of requirements in an initial "final" rule. National Emission Standards for Hazardous Air Pollutants From Coal and Oil-Fired Electric Utility Steam Generating Units and Standards of Performance for Fossil-Fuel-Fired Electric Utility, Industrial-Commercial-Institutional, and Small Industrial-

U.S. Energy Information Agency (EIA) projects that there will be approximately 50 gigawatts (GW) of coal capacity retirements by 2020, or 16% of the total coal capacity in 2013, due in part to the cost of compliance with these regulations.[9]

Complicating the compliance decision process is the continuing uncertainty regarding regulations to limit the emissions of CO_2 for both new and existing power plants. EPA has issued a proposed rule for new coal-fired power plants that would require new coal-fueled power plants to comply through the installation of CO_2 capture equipment so as to meet CO_2 emissions levels equivalent to an uncontrolled natural gas combined cycle unit. This new plant rule is expected to be issued in final form at the end of Summer 2015. Another rule has been proposed for electric generators to reduce fleet-wide GHG emissions from existing coal plants. Although the existing plant rule, as proposed, would not require existing units to retrofit CO_2 capture technology, the net effect of the rule is to require reduced coal use, and the EPA projects that it will result in an additional 50 GW of coal capacity retirements by 2020.[10] Coal is clearly facing significant economic challenges with the requirements to install expensive control technologies for compliance with new EPA environmental regulations while also competing with currently low-priced natural gas as a power sector fuel.[11] These factors also adversely impact development of cost-competitive technologies to improve the utilization of coal.

Another challenge to coal use by power plants is the uncertain growth rate in electricity demand, combined with the fact that new plants typically require seven years to design, permit, and construct. Increases in power demand will be heavily influenced by economic growth, the future role of electricity-intensive manufacturing in the U.S. economy, demand response, end-use efficiency technologies and policies, and potential shifts in end-use technologies from liquid fuels to electricity. For example, the transportation industry of the future may place significant new demands on power generation to supply electric vehicles.

Benefits to Society from Improved Coal Technologies

Environmental Benefits

Over the last 40 years, technology advances have led to impressive improvements in coal's environmental "footprint." Figure 2 shows the sharp decrease in emissions of SO_2 from the fleet of existing coal-fired power plants, as new technologies were applied. Dramatic reductions have also been realized in NO_x emissions from coal-fired power plants, 93% of coal-fired power

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Commercial-Institutional Steam Generating Units, 77 Fed. Reg. 9,304 (Feb. 16, 2012), on reconsideration, Reconsideration of Certain New Source Issues, 78 Fed. Reg. 24,073 (Apr. 24, 2013).

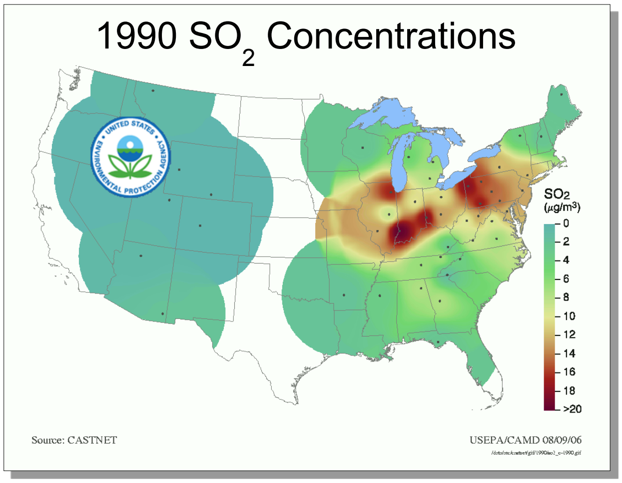
[9] Annual Energy Outlook, 2014 with Projections to 2040, April 28, 2014, at IF-34 http://www.eia.gov/forecasts/aeo/power_plant.cfm.

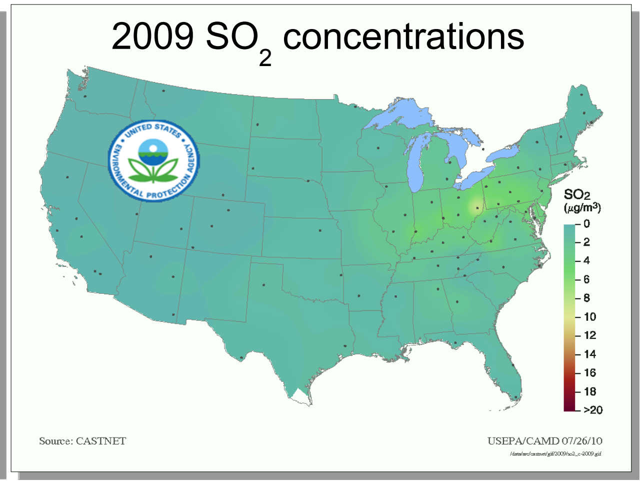
[10] See Regulatory Impact Analysis for the Proposed Carbon Pollution Guidelines for Existing Power Plants and Emission Standards for Modified and Reconstructed Power Plants, U.S. EPA, June 2014, at Table 3-12, http://www.epa.gov/ttnecas1/regdata/RIAs/111dproposalRIAfinal0602.pdf.

[11] Natural gas prices historically have been much more volatile than coal prices. Annual wellhead prices averaged less than $0.25 per thousand cubic feet (mcf) prior to 1974, and less than $1.00/mcf through 1978. Since then, they have increased to $2.51/mcf in 1985, dropped to $1.55/mcf in 1995, increased to $7.97/mcf in 2008, and decreased to $2.70/mcf in February 2012. See http://www.bloomberg.com/energy/ and U.S. EIA, Natural Gas (release date June 30, 2015), at http://www.eia.gov/dnav/ng/hist/n9190us3a.htm.

plants in the United States that have installed, or are now in the process of installing, low-NO_x burners, and other technologies which reduce power plant emission of NO_x.

Figure 2. Improvements in SO_2 Concentrations in the United States 1990-2009





The cumulative benefit resulting from collaborative RD&D programs led by the DOE and its industrial partners for the period 2000 through 2020 is estimated at $111 billion at a cost to the federal budget of less than $8.5 billion ($2008).[12]

New coal-fueled power plants being built show even more dramatic reductions in emissions. Compared to power plants built in 1970, today's new plants emit 95% less SO_2 and NO_x, and 90% less H_g (see Figure 3). The addition of CO_2 emissions control technologies can reduce these criteria air emissions to near zero emission levels. Significant advances also have been achieved in managing solid wastes from coal combustion.

Today's modern coal-fueled power plants can achieve conversion efficiencies of 39% higher heating value and more compared to efficiencies of 33% or less in coal plants constructed in the 1970's. These increases in efficiency alone result in more than a 15% reduction in potential CO_2 emissions.[13] Further reductions in CO_2 emissions will require RD&D as described in this Roadmap. The public/private collaborative research, development and demonstration efforts now underway in the United States to address CO_2 emissions from coal-fired power plants are significant, and with continued support, can achieve targets for cost and performance that are highly competitive with other forms of clean energy generation.

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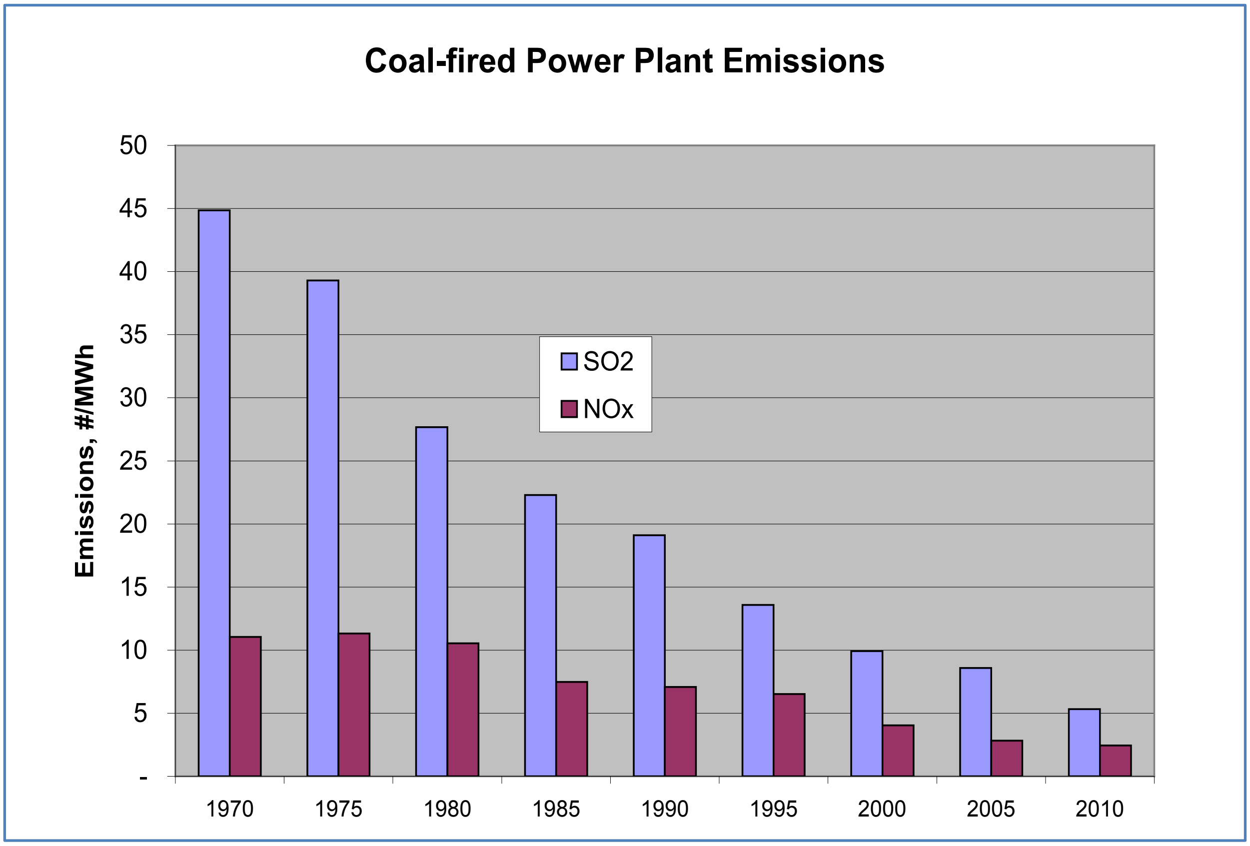
[12] Benefits of Investments in Clean Coal Technology, Management Information Services, Inc., October 2009 (revised Oct. 29, 2009), at Ii, http://www.americaspower.org/sites/all/themes/americaspower/images/pdf/Benefits-of-Investment-in-Clean-Coal-Technology.pdf; and U.S. DOE/National Energy Technology Laboratory (NETL), at 4, http://www.engineeringx.pitt.edu/uploadedFiles/Coal_Conference/Pl3-1%20-%20Anthony%20Cugini.pdf.

[13] Calculation by CURC, assuming use of the same rank coal. A 33% efficiency means that each kilowatt-hour of power requires 10,339 British thermal units (Btus). A 39% efficiency reduces that energy requirement to 8,749 Btus. For the same rank coal, CO_2 emissions are directly proportional to these energy requirements.

Figure 3. Historic Improvements in Coal Plant Emission Reductions

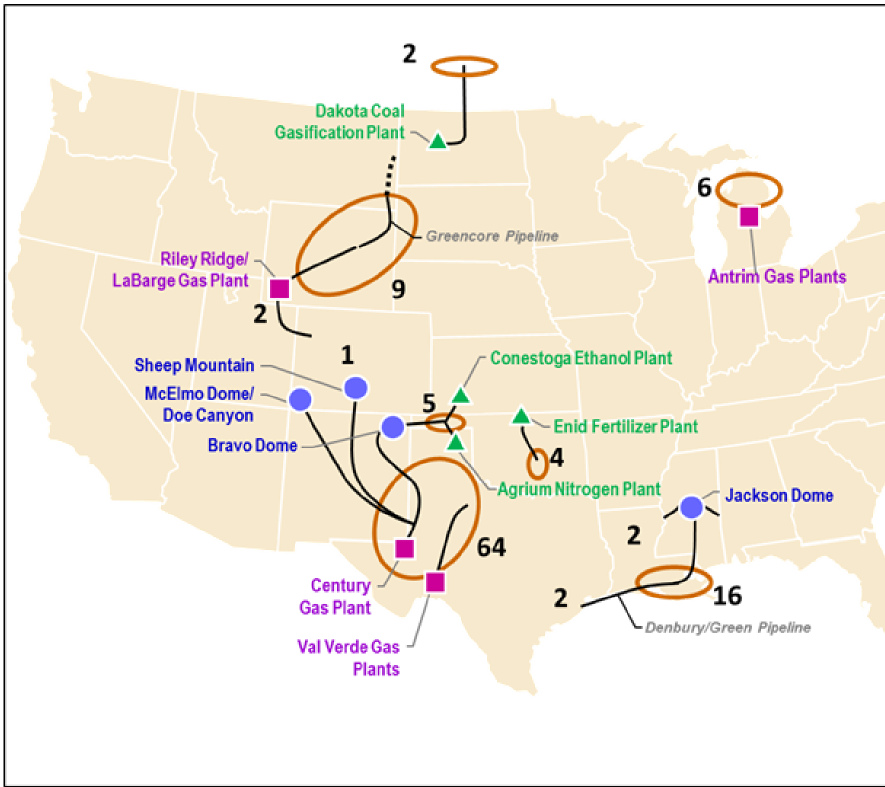


Looking to the future, many of the environmental benefits expected from implementation of the proposed technology Roadmap derive from the reduction in CO_2 emissions. Just as today's new coal plants achieve much lower levels of emissions than those of two decades ago, tomorrow's new coal plants are projected to achieve near zero levels of emissions. By combining successful implementation of technology advances identified in the Roadmap with opportunities for beneficial use of captured CO_2 (see Figure 4), coal-based power plants could achieve lower CO_2 emissions at a cost of electricity competitive with other low-carbon generation alternatives.

> "We need to invest heavily in energy efficiency and in renewable energy sources, but the only way we can hope to limit global warming to less than two degrees is to combine it with a significant expansion of the use of carbon capture and storage (CCS). … We must capture the carbon dioxide emitted from burning fossil fuels."
>
> *~ Dr. Christian Friis Bach, Executive Secretary and Under-Secretary General, UN Economic Commission*

The central goal of the Roadmap is to reduce the cost and improve the environmental performance of both existing and new coal conversion systems, including reducing the costs to install CO_2 capture systems and reducing the consumption of energy from the power plant needed to operate those systems. Even though first-generation technologies capable of capturing CO_2 from power plants exist today, they are not commercially viable, are very expensive to implement, and have not yet been demonstrated in electric power generation systems at scale. Additionally, there is very limited experience with storing large volumes of CO_2 in saline geologic formations. One important strategy to overcome the cost challenges is to use captured CO_2 for beneficial purposes. Consequently, this research area is sometimes referred to as "Carbon Capture, Utilization and Storage," or CCUS. For example, there appears to be a significant domestic market for CO_2 use in EOR today (see Figure 4). With increased volumes of CO_2 supplies, the completion of major CO_2 pipelines, and new EOR projects announced by industry, NETL estimates that EOR production using anthropogenic sources of CO_2 will grow significantly (see Figure 5).

Figure 4. Current EOR Projects, CO_2 Sources and Pipelines (2012) [14]

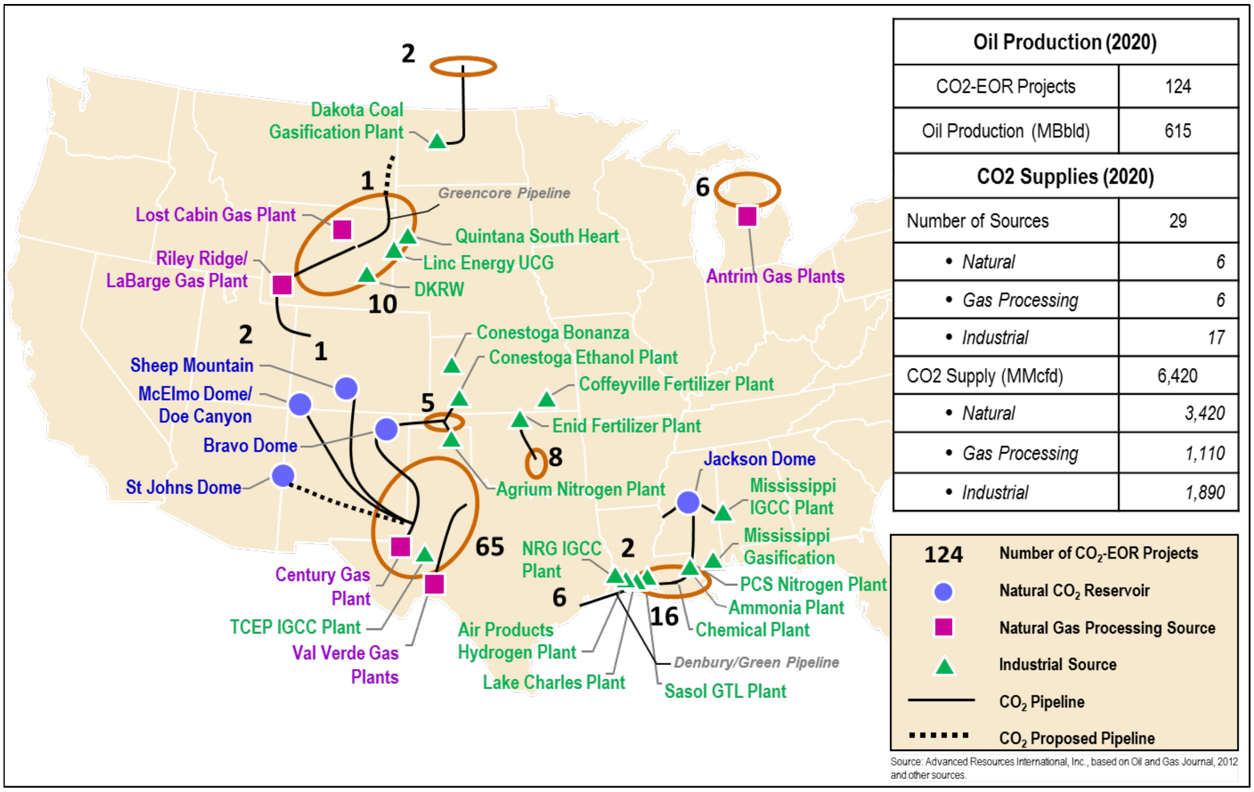


Oil Production (2012)	
CO2-EOR Projects	113
Oil Production (MBbld)	282
CO2 Supplies (2012)	
Number of Sources	13
• *Natural*	*5*
• *Gas Processing*	*4*
• *Industrial*	*4*
CO2 Supply (MMcfd)	3,000
• *Natural*	*2,570*
• *Gas Processing*	*380*
• *Industrial*	*50*

Source: Advanced Resources International, Inc., based on Oil and Gas Journal, 2012 and other sources.

[14] Near-Term Projections of CO2 Utilization for Enhanced Oil Recovery, April 7, 2014, DOE/NETL-2014/1648, http://www.netl.doe.gov/File%20Library/Research/Energy%20Analysis/Publications/Near-Term-Projections-CO2-EOR_april_10_2014.pdf

Figure 5. Projected EOR Projects, CO_2 Sources and Pipelines (2020)[15]



Attachment 2 provides a map of the first-of-a-kind commercial-scale CCS and CCUS demonstration facilities which are being planned or are under construction (with the exception of Canada's 110 MWe Boundary Dam repowering project which is not a U.S. demonstration project). Five of these six facilities plan to employ EOR to improve the project's economics. It is important to note that these units would not be commercially competitive without significant government subsidies. Improved technologies, as well as the "learn by doing" strategy represented by on-going CCS and CCUS demonstrations, can help to reduce costs of CCUS over time and eventually eliminate the need for public incentives. The Roadmap identifies the types of RD&D that can reduce the costs of CCS by as much as 40% on a LCOE below current costs (see Figure 8). If the Roadmap is implemented in a timely manner, these technologies are expected to be ready for commercial deployment by 2025-2035.

Capturing CO_2 also can lead to additional reduction of criteria pollutants as a "co-benefit." Moreover, the development of these technologies for coal-based power generation also can make carbon reductions from the use of other fossil fuels, including natural gas and petroleum coke, technically and economically feasible.

One of the most significant benefits from the proposed technology improvements identified in the Roadmap is the increase in efficiency of power generation. This improvement reduces all emissions, including CO_2, due to less fuel being required for a given amount of electrical generation. Higher efficiency also increases the economic feasibility of CO_2 capture. The

[15] Ibid.

technologies identified in the Roadmap are projected to provide 20 to 40% improvements in heat rate in 2025-2035, compared to current estimates for coal power plants with CCS. New technologies currently under development and identified in the Roadmap would provide alternatives to traditional steam cycles, with significantly higher generation efficiencies and improved pathways for CO_2 capture.

A less obvious, but critical benefit of improved coal technology is assuring the availability of lower-cost electricity to accelerate the trend toward greater electrification.[16] A key area of potential electrification in the United States is plug-in electric vehicles. In 2013 the United States consumed more than 25 quadrillion Btu's of petroleum (about 26% of total U.S. energy use) for transportation.[17] Analysts considering pathways to reduce use of imported oil, or reduce GHG emissions from the transportation sector, have concluded that a large portion of those reductions could be achieved by operating passenger vehicles using electricity. In terms of reducing net carbon impact, coal with CCS offers an attractive resource if a large increase in electricity supply is needed to power motor vehicles. Electric vehicles would eliminate ground-level urban emissions of a broad spectrum of air pollutants. The electricity would be provided by low-emission power plants, typically remote from densely populated urban centers. According to the Center for Automotive Research (CAR), a 20% market penetration of plug-in electric vehicles will be required in 2025 to meet a 56 miles-per-gallon (mpg) Corporate Average Fuel Economy (CAFE) standard,[18] a target similar to the recent mandate to increase CAFE mileage from 35.5 mpg in 2016 to 54.5 mpg in 2025. This level of demand would require a significant increase in base-load power generation by as much as 80,000 GWh per year, or the equivalent of 18 modern 600 MW-net power plants.[19]

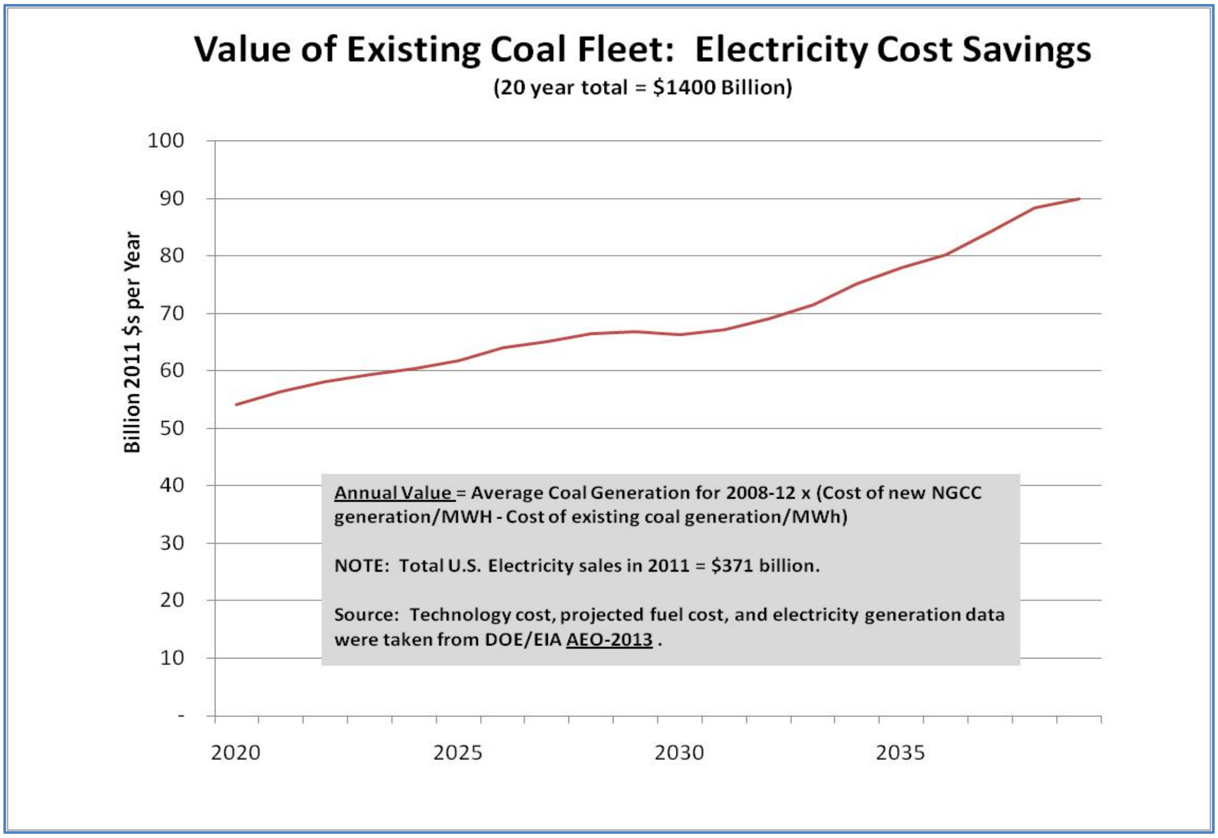
In addition to benefits in air quality and solid waste management, the Roadmap identifies potential reductions in the use and consumption of water in power plants. This could be an enormously important benefit as the nation's population increases and as geographic shifts continue, particularly in the arid West. Thermal power generation – not just coal – uses a significant amount of water. New technologies to reduce waste heat via more efficient operation, combined with novel approaches to re-using waste water and recovering waste water that would otherwise be exhausted, can reduce the volume of water required by new power plants. Improved technologies also are needed to reduce and eventually eliminate power plant effluents discharged to receiving waters.

[16] Electrification is the substitution of electrical energy for direct combustion of other fuels, similar to replacing oil lamps with electric lighting.
[17] Monthly Energy Review, December 2014, U.S. DOE/EIA, December 2014, http://www.eia.gov/totalenergy/data/monthly/archive/00351412.pdf.
[18] See generally The U.S. Automotive Market and Industry in 2025, Center for Automotive Research, June 2011, http://www.cargroup.org/?module=Publications&event=View&pubID=10.
[19] While there is much more that would go into a detailed projection of real-world power plant demand, this single example demonstrates that there may be a strong and growing necessity for reliable and affordable base-load power generation into the future.

Economic Benefits

One way of viewing the economic benefit of the existing coal fleet is to estimate the cost of replacing it with another source of power. A recent report by the National Coal Council (NCC) postulated that if all coal units were replaced by new natural gas-fired power plants, the resulting cost impact on electricity would be more than $50 billion per year, or an increase in power costs of about 15% (see Figure 6 below). Using an established relationship between electricity price and Gross Domestic Product (GDP), the NCC report concluded that such an increase in power costs would reduce GDP by $240 billion per year, and eliminate 2 million U.S. jobs.[20]

Figure 6. Value of Existing Coal Fleet: Electricity Cost Savings



Significant economic benefits have resulted from past coal technology development programs. For example, in a recent analysis of overall benefits of the program, the DOE concluded that taxpayers received $13 of benefits for every dollar invested in this RD&D program.[21] In a "lessons learned" review of the DOE Clean Coal Technology Program, the General Accounting Office concluded that: "[T]his program serves as an example to other cost-share programs in

[20] Op. cit., National Coal Council, 2014.
[21] Op cit., Emerging Fossil Energy Technologies at 4.

demonstrating how the government and private sector can work effectively together to develop and demonstrate new technologies."[22]

CURC has identified several sources of economic benefits attributable to future improvements in coal utilization technology, including:

- Lower-cost electricity, compared to what those costs would be but for successful development and application of technology, and the impact of lower costs on the macro-economy;
- Capture of CO_2 at a cost that makes it attractive for use in domestic EOR; and
- Flexible merchant polygeneration plants that combine electricity generation with co-production of energy for industrial processes (e.g. desalination), transportation fuels, fertilizer, or other chemicals from coal gasification systems.

Lower-cost electricity can result from application of improved technologies to power plants. In the case of existing power plants, improved technology reduces capital expenditures for emissions control systems, resulting in lower-cost electricity rather than replacing the existing plant with a new, more expensive power plant equipped with emissions controls.[23] For new power plants, lower-cost electricity can result from improved technologies to reduce the capital and operating cost of the power plant, such as advanced materials enabling higher-efficiency plants operating at higher temperatures and pressures. Numerous studies have concluded that lower-priced electricity can have a stimulating effect on the general economy and improve employment.[24]

A major component of the total cost of electricity is the cost of fuel used in generation. Figure 7 shows historic prices for coal and natural gas delivered to U.S. electric utilities.[25] Historically, coal has been not only a much less costly fuel, but also exhibited much less price volatility than natural gas. Natural gas prices can be even more volatile on a regional basis, due in part to limited infrastructure and seasonal variation in demand for natural gas. For example, during the months of January and February 2014, New England electric utilities paid more than $17 per million Btu for gas, while the average for the United States was $7.44 per million Btu (and coal averaged $2.32 per million Btu).[26]

[22] Statement of Jim Wells at 2, Director, Natural Resources and Environment, U.S. General Accounting Office, Before the Subcommittee on Energy, Committee on Science, House of Representatives, GAO-01-854T, June 12, 2001, http://www.gao.gov/assets/110/108872.pdf.

[23] This assumes that the existing power plant would not be required to retrofit carbon capture equipment, which is much more costly than conventional pollution controls.

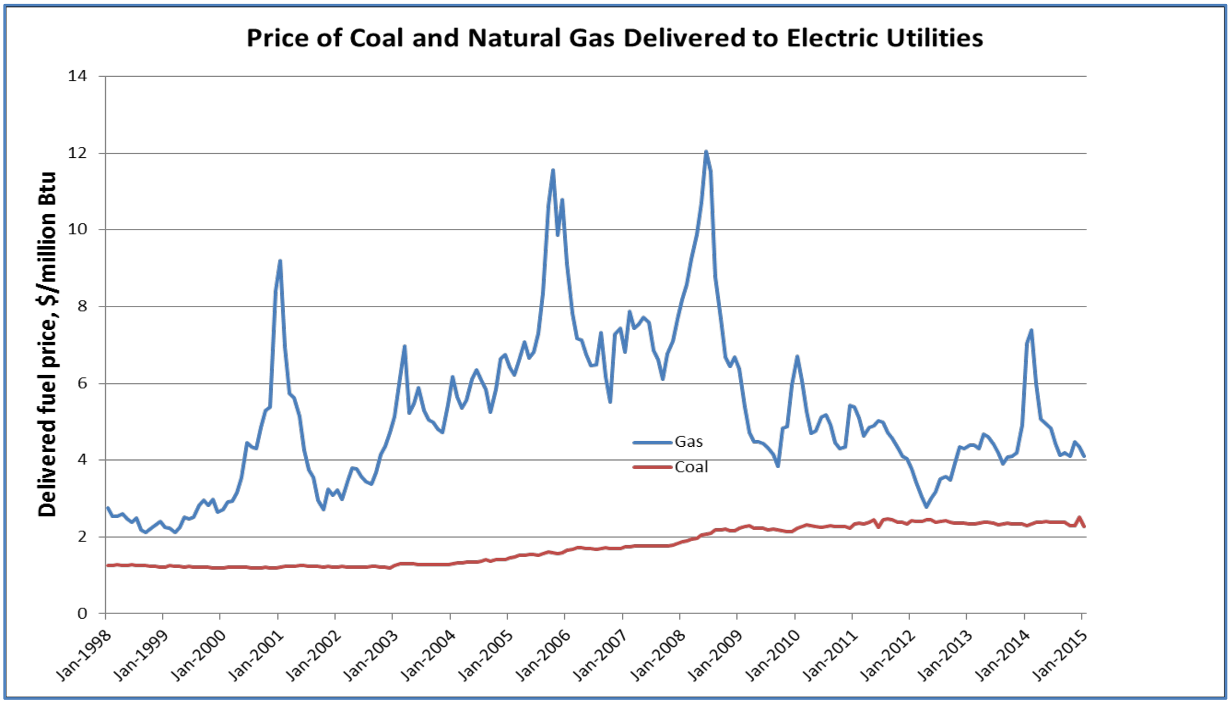
[23] Climate Policy and Labor Markets, O. Deschenes, Working Paper 16111, National Bureau of Economic Research, June 2010, http://www.nber.org/papers/w16111.

[24] See ibid.

[25] U.S. EIA Electric Power Monthly (1998-2015).

[26] For example, if saline storage-based LCOE has decreased by 35% in 2030, the decrease for an EOR-based power system could decrease by an additional 10-15%, or an overall decrease of 45-50%.The value of EOR revenues is uncertain because they vary regionally, and with the future price of crude oil.

Figure 7. Price of Coal and Natural Gas Delivered to Electric Utilities[27]



Even with projected low-cost natural gas over the next decade, natural gas has historically been subject to significant price fluctuations, such as during cold weather events in recent years. Uncertainty in natural gas prices is driven by several factors:

- there is significant pressure to export natural gas to overseas markets where natural gas prices are significantly higher than in North America;
- there is pressure to reduce emissions associated with new natural gas production wells as well as the infrastructure to transport the gas throughout the country;[28]
- significant new gas transportation infrastructure is needed along with increased pipeline safety measures; and
- substantially increased demand for natural gas use in power generation along with growth in industrial, commercial and residential demand could potentially drive up natural gas prices in the United States.

As shown in Figure 7, and in contrast to natural gas, coal has maintained a low and non-volatile cost profile since the 1970s. Coal provides a secure and stable fuel supply for power generators, and it is not subject by regulation to be prioritized for other uses, unlike gas. The need for fuel diversity is cited by electric power generators as a top priority. Generation portfolio diversity

[27] Op. cit., Electric Power Monthly (1998-2015).
[28] New Actions to Reduce Methane Emissions will Curb Climate Change, Cut Down on Wasted Energy, J. Podesta, Counselor to the President, January 14, 2015, http://www.whitehouse.gov/blog/2015/01/14/new-actions-reduce-methane-emissions-will-curb-climate-change-cut-down-wasted-energy.

thus depends in part on the option to replace retiring base-load coal capacity with new coal-based technologies that are affordable and meet all regulatory requirements.

Another economic benefit of coal research can come from the sale of captured CO_2 to enhanced oil and gas recovery, or EOR. The United States currently produces about 4% of its oil by use of CO_2 for EOR.[29] In addition to conventional oil plays where EOR is occurring (see Figure 4), the United States has a wealth of oil and gas reserves in the unconventional (shale) oil reservoirs in the United States. Thanks to recovery technologies such as horizontal drilling developed by the DOE's Fossil Energy program, the United States has begun to access those reserves. However, those fields are experiencing low recovery levels with these extraction techniques. Additionally, there are pilot projects underway targeting the Residual Oil Zone to access those fields. Using CO_2 to access the large amount of oil trapped in those reservoirs is another source of domestic oil production. Most of this oil production uses relatively inexpensive "natural" CO_2 extracted from the ground in a manner similar to natural gas extraction. But future supplies of this inexpensive CO_2 are projected to be limited.[30] RD&D that sharply reduces the cost of captured CO_2 can create a means to enable the production of tens of billions of barrels of domestic oil.[31] In addition to the economic value of the oil, the associated economic activity related to its production could have a measurable impact on jobs and the U.S. economy.[32] Moreover, increased domestic production of oil using CO_2 for EOR could directly displace oil imports, reducing the U.S. trade deficit, and enhance energy security.

The co-production of electricity and other products, sometimes cited as "polygeneration," has been the subject of prior research, but is generally not practiced commercially. Based in large part on previous RD&D by DOE and its collaborating private sector partners, and with the support of federal cost-sharing measures, polygeneration projects now are under construction or in the late stages of design. Two of the demonstration projects included in Attachment 2 employ polygeneration. These facilities are commercial-scale operations which will produce electricity, CO_2 for sale and use in EOR, and urea, a high-value fertilizer for agricultural use. Continued successful RD&D that is targeted at reducing costs could better enable the investment in, and operation of, these polygeneration systems without any reliance on public support or incentives.

[29] U.S. EOR production using miscible CO_2 is estimated to be 293,000 BPD. Oil & Gas Journal, April 2014, http://www.ogj.com/articles/print/volume-112/issue-4/special-report-eor-heavy-oil-survey/survey-miscible-co-sub-2-sub-continues-to-eclipse-steam-in-us-eor-production.html (subscription required).
2013 U.S. petroleum production was 7.44 million BPD. Monthly Energy Review, December 2014, U.S. DOE/EIA, http://www.eia.gov/beta/MER/index.cfm?tbl=T03.01#/?f=A&start=1949&end=2013&charted=6-12-15.

[30] See, for example, Storing CO_2 with Enhanced Oil Recovery, DOE/NETL-402/1312/02-07-08, February 7, 2008, http://www.netl.doe.gov/kmd/cds/disk44/D-CO2%20Injection/NETL-402-1312.pdf.

[31] See ibid., Table 7.

[32] Enhanced Oil Recovery & CCS, L.D. Carter, U.S. Carbon Sequestration Council, January 2011, http://www.uscsc.org/Files/Admin/Educational_Papers/Enhanced%20Oil%20Recovery%20and%20CCS-Jan%202011.pdf .

Energy Security Benefits

For several decades, the United States has relied on coal to reduce its consumption of oil for power generation. In the mid-1970s, oil-fired generation provided 17% of U.S. electricity; today, oil generates only 1% of our power.

Three of the systems cited above for their economic benefits can also provide energy security benefits by backing out imported oil. These are: low-cost CO_2 capture systems linked to domestic EOR production; polygeneration systems that produce transportation fuels or other commodities traditionally made from oil; and low-cost electricity supply for a large fleet of plug-in electric vehicles.

Utilities rely on coal as a reliable, low-cost option that provides balance among their fleet of generating sources. Coal has enabled utilities to provide low-cost power to their customers during periods of fuel supply disruption or other events. In fact, unlike natural gas or renewables, coal reserves can be stockpiled onsite at generating units for many days, so in periods of disruption to delivery, backup reserves are available to continue generating electricity.

The value of the existing coal fleet was particularly apparent during the 2014 winter weather event often characterized as the "Polar Vortex." During the months of January and February, coal-fueled generation met 92% of the increase in electricity demand (versus January and February 2013).[33] American Electric Power reported that 89% of the coal capacity scheduled for retirement in 2015 was up and running to meet demand. The comparable figure for Southern Company was 75%.[34]

The Structure of the Roadmap

There are two distinct platforms for technology development identified in the Roadmap: Existing Plants and New Plants.

Existing Plants

Coal-fired power plants, which traditionally have operated as "base load" (or continuously operated) units, will increasingly be called upon to operate more flexibly in a range of "cycling modes" as utilities expand their use of natural gas and intermittent renewable energy generation. Flexible operations require more frequent startups and shutdowns, operation at partial and minimum load, and a much higher degree of ramping unit output from one operating condition to another. The consequences of such flexible operations are much greater wear and tear on the generating unit being cycled, and much greater complexity in managing the numerous sub-systems within the power plant in order to assure safe and reliable operation under a wide range of operating conditions.

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[33] Reliable & Resilient: The Value of Our Existing Coal Fleet, National Coal Council, May 2014, at 12, http://www.nationalcoalcouncil.org/page-NCC-Studies.html.
[34] Ibid. at 14.

The CURC-EPRI Roadmap recommends research targeted specifically to support the existing fleet. This includes RD&D to provide:

- Improved technologies to reduce the cooling water consumption by coal-fired power plants;
- Improved approaches to treat power plant water effluent;
- Improved hazardous air pollutant control systems, capable of performing well on units flexible modes of operations;
- Improved ability to operate with different fuels, such as alternative coals and coal pretreatment, biomass co-firing, and natural gas co-firing;
- More reliable operation for units operating in "cycle mode" by developing improvements in welding component fabrication using new materials; providing improved diagnostic techniques, including better sensors and controls for early identification of "wear and tear" problems; and
- Developing advanced (high-temperature-tolerant) materials for units undergoing replacement of major subsystems.

The Roadmap does not specifically recommend CCS technology development tailored for existing units, but notes that many types of CCS designed for new post-combustion systems would also be practical for existing coal-fired power plants if RD&D can sufficiently reduce costs. Consideration of CCS on existing units not only must take into consideration costs, but other site-specific issues such as access to EOR or other geologic storage options and the amount of space available onsite to accommodate the equipment to capture CO_2.

New Plants

In developing the Roadmap for new coal plants, CURC and EPRI based the analysis on a set of expected environmental performance targets using 2010 as the baseline. Prior to the 2015 Roadmap Update, in the absence of any commercial-scale power plants with CCS technologies, it was necessary to base cost estimates on engineering studies. However, during the past year a pulverized coal power plant equipped with a 90% CCS system commenced operation under a technology demonstration program subsidized by the Canadian government.[35] Construction of a second commercial-scale CCS demonstration project, this one involving an IGCC power plant capturing 65% of the CO_2 it produces, and subsidized by the U.S. government, is nearing completion in the United States.[36] CURC used the published capital costs[37] for these two units, adjusted for a number of factors to make them consistent with the costing methodology used in this Roadmap, to establish a cost baseline for existing CCS technology.[38] These targets serve

[35] Boundary Dam Carbon Capture Project, SaskPower CCS, http://www.saskpowerccs.com/ccs-projects/boundary-dam-carbon-capture-project/.

[36] Gasification and TRIG, Mississippi Power / Southern Company, http://www.mississippipower.com/about-energy/plants/kemper-county-energy-facility/gasification-and-trig.

[37] "Published Capital Costs" include owners' costs, interest during construction, and escalation, and should not be confused with total plant cost or engineering, procurement and construction cost.

[38] CURC believes that basing existing costs on actual plants and adjusting for their FOAK status is more valid than previous cost approaches that, by necessity, were based on paper studies.

as "guide posts" to help measure progress in achieving the cost and environmental performance goals we established in this Roadmap between today through 2035. The Roadmap incorporates the philosophy that a variety of technology options should be developed and pursued in order to ensure we have options in the marketplace for achieving the goals, and includes a comprehensive suite of technology pathways for both combustion- and gasification-based generation platforms, as well as options for pursuing CO_2 storage in EOR and saline reservoirs.

Timing

The Roadmap identifies three time periods against which progress in technology development should be measured: 2020, 2025, and 2035. For each of these years, the Roadmap identifies the cost and performance of technologies that will have been demonstrated at FOAK commercial scale if the Roadmap is implemented.[39] It is important to recognize that this approach differs from that typically used by the DOE, which sets its timing goals for when technologies will be ready for commercial demonstration. Readers wishing to compare the CURC-EPRI Roadmap projections to DOE projections should add 5-7 years to the DOE projections. This adjustment will account for the time needed to design, permit, and construct a demonstration unit and then will roughly equate to the time convention used in this Roadmap. Further, the 2020 goals are reflective of first generation technology cost and performance targets, i.e., for those technologies that will be demonstrated in the projects identified in Attachment 2. The 2025 and 2035 targets reflect a combination of cost and performance targets for second generation and transformational technologies contemplated in the gasification, combustion and transformational technology Roadmap programs.

Technology Groupings

The Roadmap analysis for new plants was divided into several distinct technology areas: advanced combustion, including post combustion capture; gasification; transformational; cross-cutting; and existing units. These areas include a comprehensive suite of technology options which, if pursued, can lead to the benefits described in this report.

Most of the analysis supporting the earlier 2012 Roadmap was based on consideration of conventional power generation units, such as pulverized coal systems with CCS and coal gasification systems with CCS. The 2015 Roadmap Update considers new energy conversion platforms and new gasification technologies with CCS and CCUS that are projected to have improved benefits over those described in the last Roadmap. CURC recognizes that during the near-term and medium-term industry may pursue CCUS, rather than CCS, and production of other products in addition to electricity (polygeneration). The prospect of using CO_2 for beneficial purposes – e.g., to augment domestic oil production via EOR – was incorporated in the Roadmap by a simplifying assumption regarding the value of CO_2 for EOR. As a practical matter, EOR has the potential to significantly reduce the cost of generation by units equipped with CCS.[40] However, generating units employing EOR for storage also may use storage in

[39] Hence, the projected technology costs are for SOAK units.

[40] The value for CO_2 used in EOR varies both regionally, and with the price of crude oil. This Roadmap Update assumed oil prices would return to approximately \$100/barrel in the Roadmap's projection period (2025-2035),

geologic brine reservoirs, either as a backup system or to accommodate temporary upsets at the power plant or the EOR facility. The benefits of polygeneration are discussed in general terms elsewhere in this report, but polygeneration was deemed to be too site- and market-specific to allow quantitative projections about cost improvements in this technology 15-25 years in the future.

Although IGCC was used as the primary platform for gasification and advanced hydrogen (H_2) turbines, many of the targeted technologies would also benefit industrial gasification such as coal-to-liquids and coal-to-substitute natural gas, either in stand-alone industrial configurations or as part of a polygeneration facility.

Certain cross-cutting technology RD&D, such as the evaluation of geologic CO_2 storage reservoirs, is necessary to ensure that there will be readily accessible storage facilities for the advanced power systems developed under the Roadmap.

The Roadmap also considers additional cross-cutting technology improvements for reducing the consumption and discharge of water by coal-based power generators. Water always has been a critical resource in many of the Western states, but is becoming a significant issue in numerous Eastern areas as well.[41] The U.S. Geological Survey reports that in 2000, thermoelectric power (which includes fossil energy and nuclear power plants) was responsible for about 39% of total fresh water withdrawals in the United States.[42] Reducing water use and discharge not only preserves the water resource, but also reduces environmental impacts on biota entrained in water used for cooling purposes and impacts from the discharged water. Power plants also consume significant amounts of process water and must reduce or eliminate contaminants in subsequent discharges of this process water. EPA has proposed revised effluent guidelines (regulations) for the power sector, including a greater focus on discharges from coal ash ponds and flue gas desulfurization system.[43] The Roadmap includes research on general water management practices, as well for development of zero liquid discharge (ZLD) technologies.

CURC and EPRI examined a suite of transformational technologies that contemplate new reactions and processes that can make energy conversion more thermodynamically advantageous. Transformational technologies are game changing power generation

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and that EOR producers would pay $26/tonne of delivered CO_2 (versus transportation and storage costs in saline formations of $10/tonne CO_2. The net impact on the LCOE from advanced coal systems with CCS was to increase the cost reduction of Roadmap technologies in 2025-2035 from about 30-50% (without EOR payments) to 45-65% (with EOR payments) – relative to baseline coal systems with CCS and not receiving EOR payments.

[41] Note, for example, that the U.S. Department of Agriculture designated 150 of Georgia's 159 counties as federal disaster areas due to extensive crop damage from drought in 2011. News Release: USDA Designates 150 Counties in Georgia as Primary Natural Disaster Areas, U.S. Department of Agriculture, Farm Service Agency (Sept. 8, 2011), http://www.fsa.usda.gov/FSA/newsReleases?area=newsroom&subject=landing&topic=edn&newstype=ednewsrel&type=detail&item=ed_20110908_rel_0115.html.

[42] Estimated Use of Water in the United States in 2000, U.S. Geological Survey Circular 1268, March 2004, http://pubs.usgs.gov/circ/2004/circ1268/. Note that much of the water "withdrawn" for purposes of once-through cooling at power plants (91% of total power plant withdrawals) is returned to the contributing water body.

[43] See Effluent Limitations Guidelines and Standards for the Steam Electric Power Generating Point Source Category; Proposed Rule, 78 Fed. Reg. 34,432 (June 7, 2013), http://water.epa.gov/scitech/wastetech/guide/steam-electric/proposed.cfm.

technologies that represent an entirely new way of energy conversion and will enable a step change in performance, efficiency and cost of electricity compared to today's state-of-the-art technologies. Transformational technologies represent more than an evolutionary, incremental improvement to today's state-of-the–art technologies:

- Transformational technologies have the potential to generate a new learning curve with projected cost/performance/environmental characteristics that are significantly improved compared to current technologies.
- Transformational technologies use new approaches for power generation and/or carbon capture that enable substantial, breakthrough performance improvements and cost reductions relative to current state-of-the-art technology.
- Transformational technologies encompass a broad range of technology improvements. Examples include thermodynamic improvements in energy conversion and heat transfer, turbine technology, and CO_2 capture systems that all drive cost reductions in the CO_2 capture system as well as reduce the consumption of energy that is needed to operate the CO_2 capture system.

The transformational technologies examined in the Roadmap include pressurized oxygen combustion, chemical looping, and supercritical CO_2 cycles which would replace steam with supercritical CO_2 as the working fluid, each of which result in more compact and high-efficiency energy production systems that capture CO_2. New turbines to support the higher temperatures and pressures of these systems, particularly the supercritical CO_2 cycles, are also considered. Each of these technologies produces a concentrated stream of CO_2 as a consequence of their conversion platforms, resulting in lower costs and energy penalty associated with the capture of CO_2.

In addition to looking at transformational technologies, the CURC membership and EPRI agreed that it would be productive and appropriate to prioritize funding to conduct research on so-called "breakthrough" technologies. The Roadmap defines these as technologies which reflect "out-of-the-box" thinking, or fundamentally new approaches to solving coal's challenges. Examples of breakthrough technologies for coal might include the substitution of biosystems for current chemical processes[44] and CO_2 sorbents based on new man-made compounds. Funding for this kind of activity are consistent with RD&D supported through the DOE's Advanced Research Projects Agency-Energy (ARPA-E) program or the fundamental research conducted in the applied energy programs at DOE.

Large Pilot Projects Supported in the Roadmap

New commercial-scale power plants with CCS technology will cost in excess of $1 billion each. Such technologies, given their inherent financial and FOAK technical risk, cannot leap from a conceptual stage to commercial deployment in a single step. Rather, development of these advanced technologies follows an established, reasoned process.

[44] For example, a genetically engineered microbe could be used to convert coal to methane or H_2, eliminating many sources of pollution and creating a physically more convenient energy form.

The 2015 Roadmap Update places increased emphasis on large-scale pilot testing of technologies, compared to previous CURC-EPRI Roadmaps. Large pilots are necessary to bridge the gap between lab scale testing of new technologies and FOAK, commercial sized demonstration. Large-scale pilot activities reflect technology development which is beyond laboratory development and bench-scale testing, but not yet advanced to the point of being tested under real operational conditions at commercial scale. Large pilots provide the operational data needed to better understand the technical and performance risks of new technologies before the application of such technology at a commercial-scale or in advancing to a commercial-scale demonstration project, requiring significantly more investment and guarantees on the performance of the technology intended to be demonstrated through such a FOAK demonstration. Large-scale pilots need to be large enough to validate scaling factors and demonstrate the interaction between major components so that control philosophies for a new process can be developed and enable the technology to advance from large-scale pilot plant to commercial-scale demonstration technology or application.

While large-scale pilots are important for all technologies in the coal RD&D portfolio, this step is particularly important for transformational technologies as step-change technologies have a completely different process for extracting chemical energy from coal, which means the technical risk is greater than simple process improvements that are in practice today. Given progress in the development of transformational technologies, this Roadmap recommends a series of large-scale pilot projects for transformational technologies in the 2016-2022 period, in addition to component testing pilots, as well as both component and commercial-scale demonstration projects to integrate the technologies contemplated in the Roadmap into complete operational systems.

Quantitative Approach

Most of the quantitative analysis of cost and performance conducted for the Roadmap was based on a typical large generating unit – e.g., 500 to 800 MW of capacity. However, it should be noted that market forces such as very low growth rates in electricity demand are leading the power sector to focus on smaller-sized commercial capacity additions.[45] The ultimate penetration of these technologies into the marketplace will depend on a range of factors, including future electricity demand (which may in turn depend on new consumption technologies such as electric vehicles, and continuing trends for electrification), the cost of competing technologies and their fuels, and future environmental regulations. While projecting such factors is beyond the scope of this report, these factors are weighed considerably by corporations as they make decisions about investing in CCS technology.

The quantitative analysis of advanced technologies considered in this Roadmap was conducted by EPRI, using EPRI's economic models. Assumptions used in the models were agreed upon by EPRI and CURC members. Input assumptions included a power system's capital cost, fixed operations & maintenance (O&M) costs, variable O&M, heat rate (efficiency), cost of capital, and fuel cost. These inputs are for a SOAK commercial unit, with the FOAK being the completed

[45] See Technical Workshop Report – An Industry View: Advancing the Next Generation of Coal Conversion Technologies, Convened by CURC, November 18-19, 2014.

commercial demonstration unit which is included in the Roadmap and assumed to be co-funded with both public and private funds. Cost results were calculated as the LCOE, which is the average cost of electricity produced by the unit over its economic life, expressed in 2011 (constant) dollars per MW-hour. Reported costs in Figure 8 are stated as a percentage reduction in LCOE from costs estimated for a new coal unit with CCS technology available in 2010.

Estimating Costs in 2015 Roadmap Update

Part of the progress in CCS technology development since publication of the 2012 CURC-EPRI Roadmap has been the construction of two commercial-scale CCS systems: the Boundary Dam Pulverized Coal CCS repowering project (BD-PC) in Saskatchewan, Canada; and the Kemper County IGCC project (KC-IGCC) in Kemper County, Mississippi. The BD-PC project officially started up in September 2014 and the KC-IGCC project is very near completion of construction, so their capital costs are well established. Hence, the accuracy of estimating the cost of currently available CCS technologies can be improved over 2012 estimates by beginning with data from these "real world" projects (although these are FOAK projects that have experienced some unique costs), and making adjustments for any differing design criteria and cost conventions used in the Roadmap. Capital cost data for these projects available in October 2014 were adjusted to reflect a 90% capture rate rather than the actual design rate of 65% at KC-IGCC. This adjusted average cost represents "as spent" capital costs for a FOAK demonstration project. The Roadmap cost conventions call for a "total plant cost" characterization of capital cost, which excludes certain components of "as spent" costs, such as financing costs during construction. Additionally, the Roadmap is based on costs for SOAK projects, which do not include features unique to demonstration projects, and which tend to benefit from a small, additional "learning curve" cost reduction. Each of these factors are estimated to reduce the capital cost from reported demonstration project capital costs by about 20%, for a theoretically constructed SOAK CCS project.

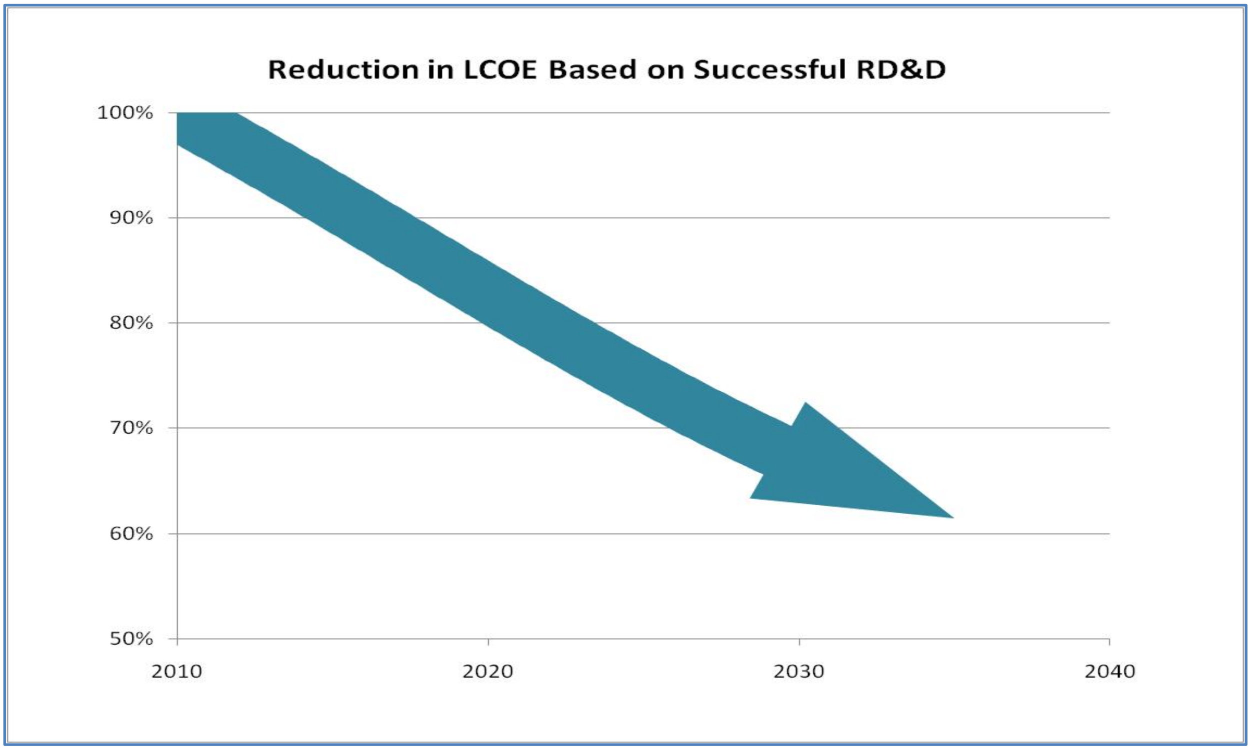
Combining this reduced capital cost with published National Energy Technology Laboratory (NETL) estimates for O&M and heat rate for more generic CCS designs yields an approximate estimate of the current cost for electricity generated by coal-fueled units equipped with CCS that is consistent with the conventions used in the Roadmap to project future CCS technology costs. CURC compared this current cost with projected costs from more advanced designs that are expected to evolve, if the research program advocated by this report is implemented and is successful. The projected reduction in power cost from a new unit is portrayed by the broad arrow in Figure 8. The width of this arrow is intended to convey the fact that these projected cost reductions have a significant amount of uncertainty. Nevertheless, projected cost improvements are believed sufficient to meet both the 20% cost reduction goal set by DOE/NETL in that organization's program planning report for CCS ready to be deployed by 2025, as well as longer-term goals previously published by NETL. These results are robust over a range of CCS technologies, including relatively traditional approaches to capture systems for both pulverized coal and gasification-based power systems. Moreover, if RD&D is successful on emerging "transformational" power concepts such as pressurized oxycombustion, chemical looping systems, and power plants that use CO_2 as a working fluid instead of water, then CURC estimates that slightly larger cost reductions are possible by 2035. In short, with an appropriate level of RD&D, coal-based power generation with CCS technology could overcome technical and cost barriers that challenge today's industry, and could thereby allow coal to continue to make a major contribution to the U.S. economy and energy security for the foreseeable future.

Results

New Electric Generators

With the implementation of the recommended Roadmap technology development program, coal-based power generation equipped with CCS could advance significantly in terms of environmental performance, while reducing the cost of electricity by approximately 40%, compared to a new coal-fired power plant built with current CCS technology. Figure 8 shows the relative improvement in technology and cost over time. The bandwidth in the arrow represents the range of estimates in the Roadmap cost analysis, and reflects both combustion-based and gasification-based technology cost improvements.

Figure 8. Improvement in Cost of Electricity Due to RD&D[46]



The cost of electricity results presented in Figure 8 include the estimated cost for permanent storage of captured CO_2 in a geological saline reservoir. If, on the other hand, the power facility was reasonably close to an EOR opportunity, the CO_2 could become a valued commodity. In this

[46] This figure was developed using EPRI's revenue requirements methodology to calculate levelized costs in constant dollars over a 30-year period.

instance, the LCOE from such an advanced power plant equipped with CO_2 capture and selling the CO_2 for EOR could decrease significantly.[47]

Key technological changes, their impacts on power plant performance over time, and the cost of the recommended RD&D program are presented in Tables 2, 3 and 4.

Table 2. Goals for Performance Improvements for Units with CCS

Performance area	2010 (base)	2020	2025	2035
- General (Size, MW)	540	570-600	580-630	650-750
- Efficiency - Efficiency, no CCS	28-31% 39%	32-33% 39%	37-38% 45%	43-44% 48%
- Emissions -- CO_2 (% cap) -- CO_2 (T/MWh) -- SO_2 (#/MWh) -- NO_x (#/MWh) -- PM (#/MWh) -- Hg (#/GWh)	 -- -- 0.05-0.4 0.44-0.70 0.14 0.006	 90% 0.10 0.05-0.4 0.44-0.70 0.09 0.0002 – 0.003	 90% 0.09 0.001-0.2 0.40-0.25 0.02-0.05 0.0002 – 0.002	 90% 0.07-0.08 0.0001-0.1 0.35-0.10 0.02-0.05 0.0002 – 0.001
- Other -- Water Gal/MWh --- Consumption --- Withdrawals -- Water Discharge	 600 800 Treatment	 500 700 Treatment	 400 500 ZLD	 200 300 ZLD
NOTE: The values in this table reflect RD&D goals only and should not be used for establishing emission standards. The 90% CO_2 emissions target identified in 2020 is dependent on the success of the first generation CCS and CCUS demonstration projects currently in design and development. While we believe the targets are technically achievable, CO_2 capture and geologic storage technologies are not yet demonstrated at commercial scale, nor are they currently economically viable. Successful implementation of the Roadmap is expected to deliver proven, cost-competitive technologies in the future.				

Table 3. Example Technologies by Technology Group[48]

Technology Type	2020	2025	2035
Existing Plants	Water		
	- Reduced water consumption - Advanced membrane treatment - Flue gas moisture recovery - Advanced hybrid cooling	Pilot project testing for advanced cooling, flue gas moisture recovery technologies	
	Materials		
	- Improved fabrication/repair - Advanced materials		

[47] Assuming oil prices return to about $100/barrel, and depending on regional variations in the value of CO_2 for EOR, the impact of selling CO_2 for EOR instead of paying transport and storage costs in a saline reservoir could reduce LCOE by an additional 15% (e.g., to less than 50% of 2010 LCOE without EOR).

[48] Dates reflect the timing by which the technology would complete the development at the scale described in the Table.

Technology Type	2020	2025	2035
	Engineering, O&M		
	- Integrated instrumentation and control approaches - Flexible operations simulator - Improved pollutant control systems capable of flexible operations - Operations with different fuel blends	- Large pilot using advanced flexible operation technology - Engineering, design for integration into advanced ultra-supercritical combustion (AUSC) retrofit pilot demonstration	Demonstration of AUSC components for possible retrofit to improve efficiency and reliability of existing power plants
Gasification	FOAK contingency and margin reduction	Dry feed pump	Advanced H_2 turbines, gasifiers & acid gas removal.
	Optimized & shortened construction	Cryo/ion transport membrane (ITM) air separation unit	Full ITM integration
		Warm acid gas cleanup	Temp swing CO_2 sorbents & high-T/low-cost CO_2 sorbents
		Foul resistant & fouling mitigation heat exchangers	Pressure swing adsorption integrated high-efficiency cleanup and high-T/low-cost sour syngas purification
			Improved shift catalysts for syngas
			Membrane H_2 separation
		Compact gasifier	Integrated IGCC with compact gasifier and H_2 turbines
Advanced Combustion & Post-Combustion Capture	Improved solvent chemistry and performance for lower energy penalty of CO_2 capture systems	Reduced energy penalty through advanced solvent and membrane large pilots	Solvent chemistry and membranes that supports high pressure CO_2 regeneration
	Improved heat integration	Improved heat integration, waste heat recovery	Alternative working fluid such as supercritical CO_2
	- AUSC Component Test Facility - AUSC plant materials development to 1300^{o}F steam cycle	AUSC plant materials development to 1400^{o}F steam cycle	Demonstration of AUSC facility
Transformational Technologies	Lab and bench scale testing of chemical looping (CLC) and pressurized oxycombustion (P-Oxy) systems	Large pilot-scale operations of CLC and P-Oxy	Large-scale demonstration and commercial application of CLC and P-Oxy
		Supercritical CO_2 turbomachinery	Large-scale demonstration of an integrated CO_2 system
CO_2 Storage	Completion of Regional Carbon Sequestration Partnership projects	5 diverse sites qualified to accept 50 million metric (MM) tonnes of CO_2 at a rate of 5 MM tonne/y	3-5 completed demos of 4 MM tonne CO_2 stored at rate of 1 MM tonne/y
Cross Cutting	Improved cooling and water management practices	Hybrid cooling on most plants.	

Technology Type	2020	2025	2035
		Advanced sensors and controls	
		Next generation oxygen (O_2) production technology deployed and in full integration with power plant	

This table focuses on the availability of new technologies (e.g., technologies demonstrated at commercial-scale), but it also includes some emerging technologies that have completed pilot-scale projects.

Table 4. Technology Development Cost (Total Public/Private), in $ Million/Year[49]

Technology type	Type of Funding $M/yr	2016-2200	2021-2025	2026-2035
Existing Plants	RD&D	9	8	0
	Large Pilots	0	3	0
	Demonstrations	0	3	1
Gasification*	RD&D	38	36	28
	Large Pilots	100	39	40
	Demonstrations	25	282	336
Advanced Combustion & Post Combustion Capture	RD&D	66	52	0
	Large Pilots	80	58	9
	Demonstrations	0	180	159
Transformational	RD&D	69	40	26
	Large Pilots	99	222	40
	Demonstrations	3	389	157
CO_2 Storage	RD&D	76	68	36
Cross Cutting	RD&D	68	17	3
Breakthrough	RD&D	20	20	4
Totals	**RD&D**	**346**	**241**	**97**
	Large Pilots	**279**	**322**	**89**
	Demonstrations	**28**	**854**	**654**
Total Annual Roadmap Costs		**653**	**1417**	**840**

Notes: *Alternate O_2 supply, including ITM, is included in the gasification program budget

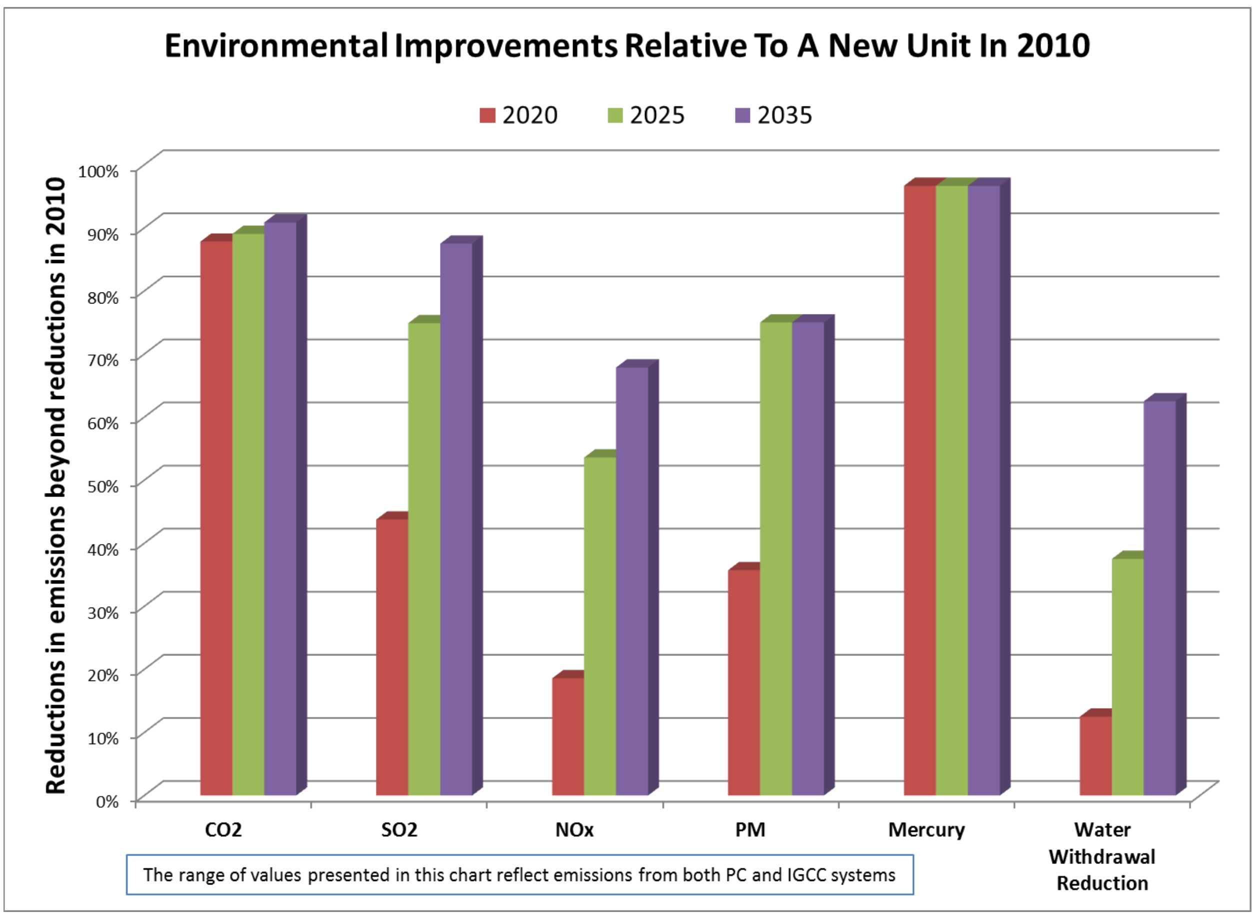
[49] These costs reflect the total expenditure needed for RD&D, including both federal and private sector contributions. Note that the RD&D figures are expressed as an **annual** amount, averaged over the multi-year period. Commercial-scale demonstration project costs tend to be significantly higher than development and pilot costs; multiyear funding may need to be accumulated for certain demonstrations (for example, projects that are new energy platforms or entirely new systems) in order to support the higher costs and resulting cost-share associated with scale of the demonstration project.

The RD&D program for the gasification and combustion programs incorporate a strategy to reduce the number and risk of commercial-scale demonstration projects by evaluating advanced components at an industrial pilot-scale facility within the RD&D program. Commercial-scale demonstrations of integrated systems will follow such pilot-scale component testing. The transformational program contemplates the development of several large-scale pilots to test new energy conversion platforms.

A large-scale pilot program could contribute substantial cost savings to the overall RD&D program. Large pilots are a cost-effective way to advance new technologies because they enable the testing and demonstration of the key elements of a new technology – and reduce the risk of failure – at a small fraction of the cost required for a commercial-scale demonstration.

Figure 9 displays the percent reduction in emissions at a new coal-based power plant, compared to current technology, assuming the technologies identified in the Roadmap are fully funded as well as successfully developed and deployed.

Figure 9. Projected Emission Reductions versus 2010 Technology



Notes for Figure 9 - Percentages are relative to 2010 levels for U.S. fossil fleet (NO_x and SO_2 = 90 - 99% reduction; PM = 99.6% reduction; H_g = 90% reduction; and Water Withdrawal Reduction (as a result of cooling towers) = 98%). For CO_2, percentages are relative to capture levels of 0%, since carbon controls were not required in 2010.

Figures 10 and 11 present the array of gasification-related and combustion-related technologies which are expected to be developed under the Roadmap over time, in the context of programmatic objectives.

Figure 10. Key Gasification-related Technologies Including Cost and Performance Improvements

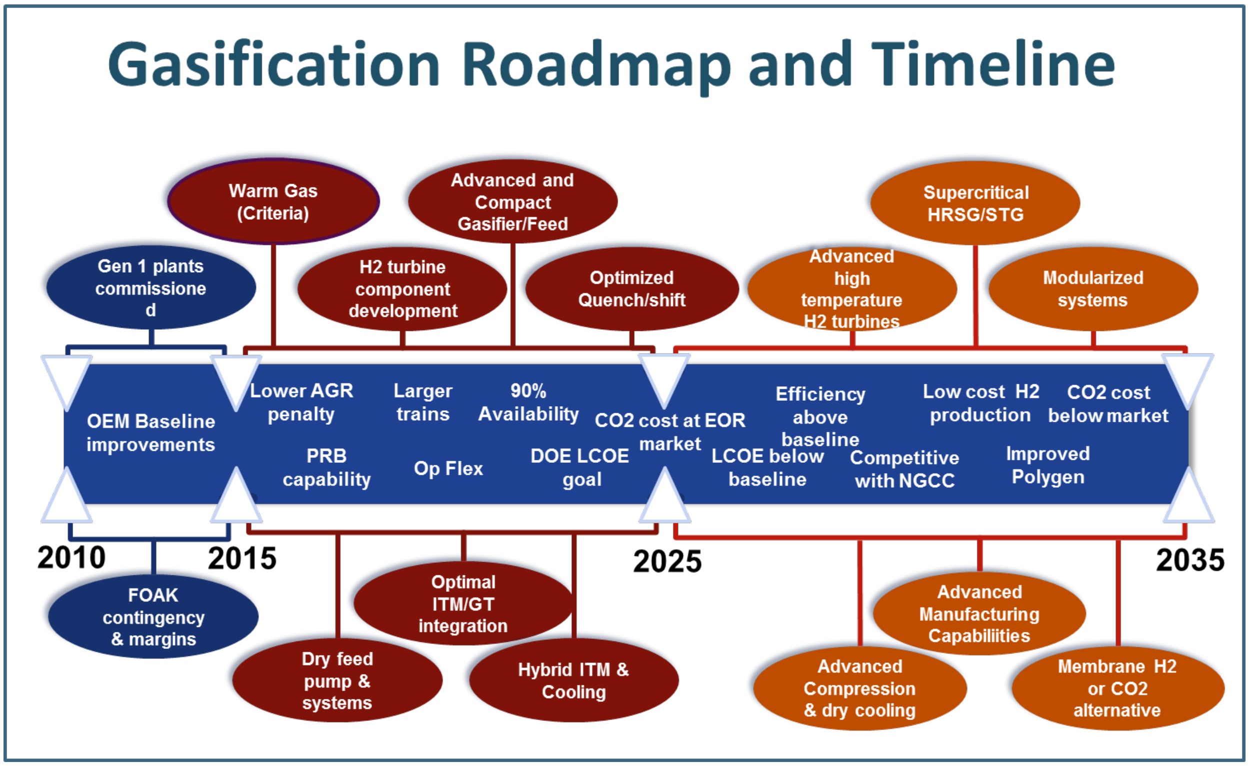
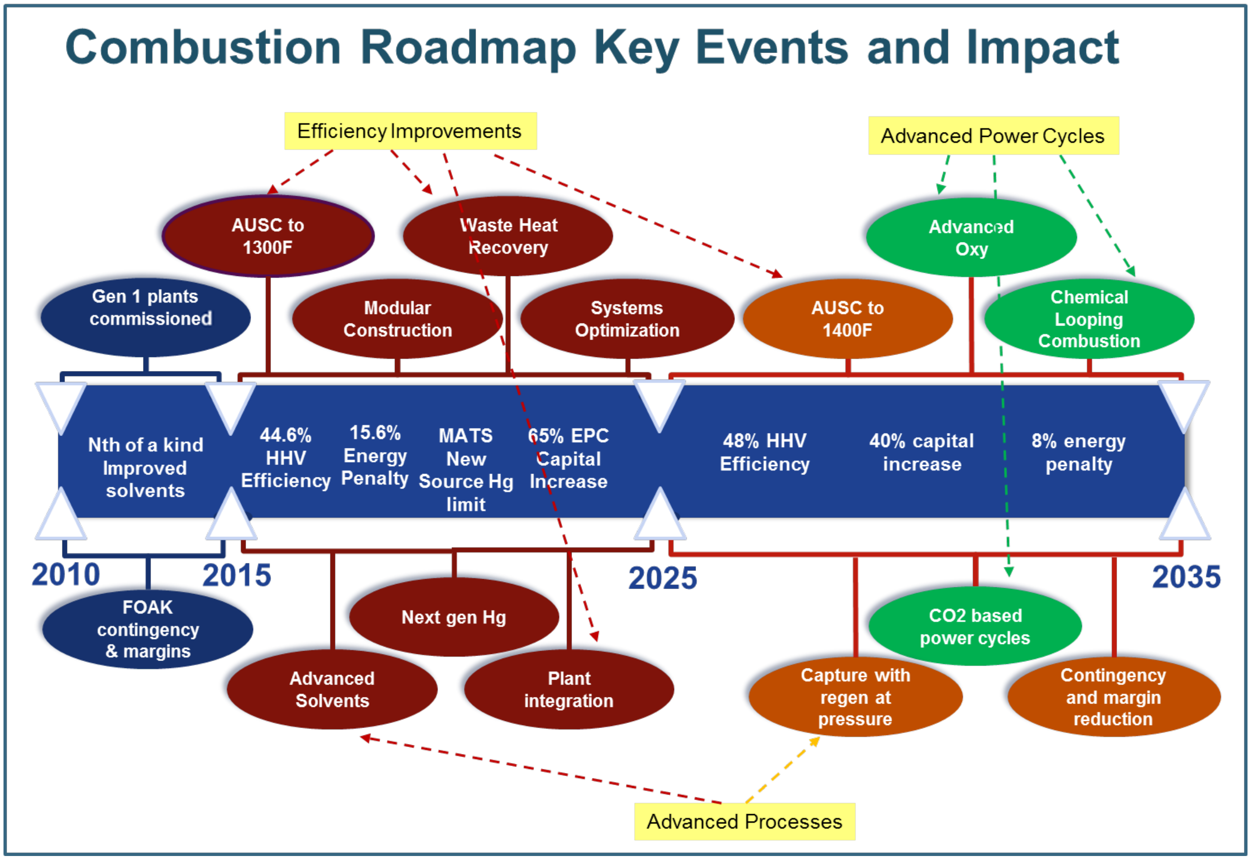


Figure 11. Key Transformational Combustion-based Technologies Including Cost and Performance Improvements

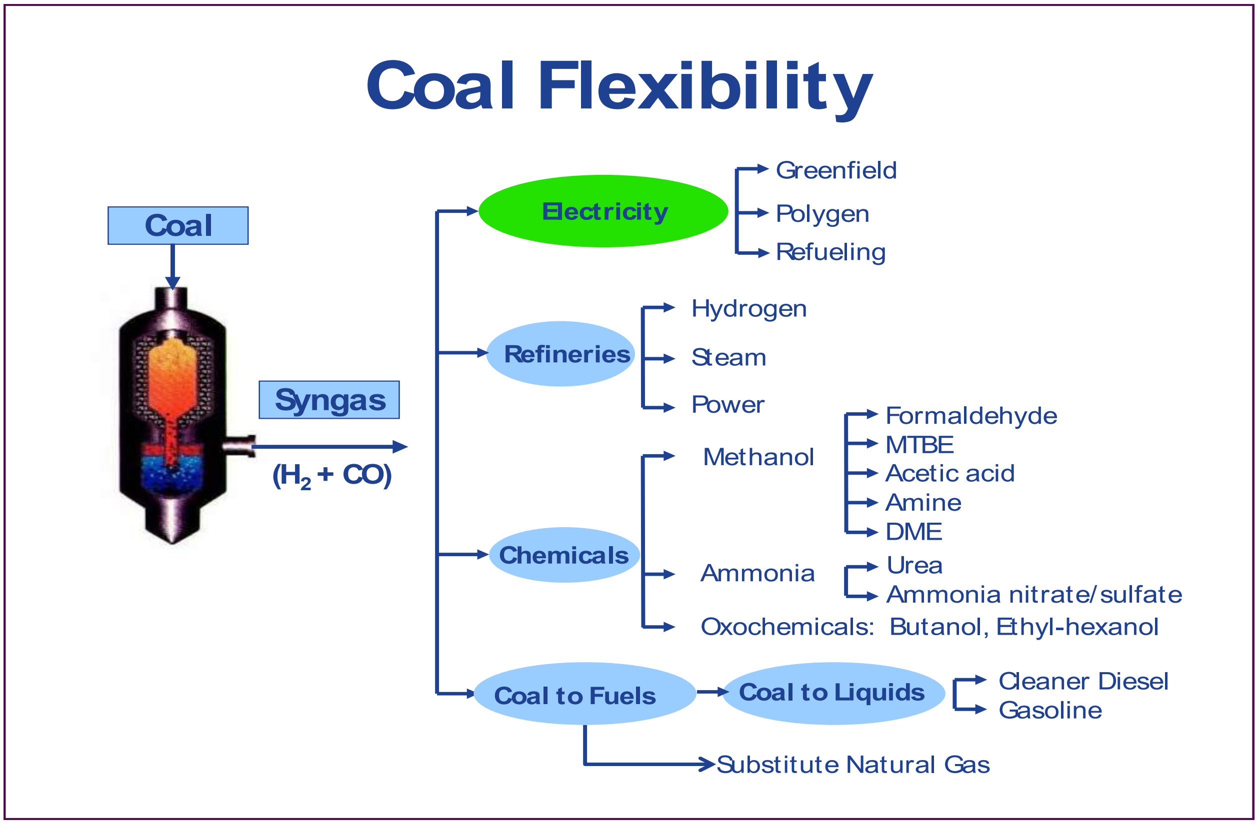


In addition to the RD&D related to efficiency improvements for new coal-based power systems, there is a need for additional technologies to improve the efficiency of existing power plants. In the past, such efficiency improvements were problematic given the potential for causing application of new source review standards, which frequently present a significant financial dis-incentive to implement any improvement. However, given reliance of proposed regulations to reduce CO_2 emissions from the existing coal fleet on substantial increases in fleet-wide unit efficiency, at a minimum, the DOE should conduct workshops and research to identify and pursue new technologies that could substantially improve the efficiency of existing coal-fired power plants. The benefits of such efficiency improvements result in the consumption of less coal/MWh and lower emissions/MWh.

Other Products from Coal

The co-benefits delivered by the Roadmap for coal-based products fully resonate with the current focus of the administration and congress on revitalizing manufacturing in the United States. Through gasification and direct conversion (e.g., liquefaction), coal can produce both intermediate and final feedstocks for a growing industrial base (see Figure 12). The wide variety of products can be tailored to local industrial needs. Most of the ongoing demonstration projects identified in Attachment 2 sell captured CO_2 for EOR or coproduce other commercial products in addition to electricity.

Figure 12. Potential Products from Coal Gasification



Cost of the Needed RD&D, Pilots and Demonstrations

To achieve the RD&D objectives of the Roadmap will require a commitment for public and private sector funding ranging from approximately $650 to $1420 million per year in the early years of the program, to $840 million per year after 2025 (see Table 5 below).[50] The federal share of these requirements is $570 to 940 million per year in the early years, and $495 million per year from 2026-2035.

[50] This funding does not reflect the additional cost to be borne by the private sector to build the SOAK plant, estimated at approximately $400 million per year before 2025, and $1.5 billion per year between 2026-2035.

Table 5. Public-Private Sector Cost Share to Implement the Roadmap

Funding ($M/year)		2016-2020	2021-2025	2026-2035
RD&D	Total (Industry and Federal)	346	241	97
	Federal (80%)	277	192	77
Pilots	Total (Industry and Federal)	279	322	89
	Federal	279	322	89
Demos	Total (Industry and Federal)	28	854	654
	Federal (50%)	14	427	327
Total (Public/Private) Annual Funding		**653**	**1,416**	**850**
Annual Federal Budget		**570**	**941**	**493**

CURC recommends continuation of the current RD&D policy of 80% federal and 20% private or other funding for research and development activities. For commercial-scale demonstrations, existing authorities require industry to contribute up to one half of the demonstration funds required by the project. Despite this, nearly all of the clean coal power initiative projects identified in Attachment 2 have not received a full 50% federal cost-share contribution to the project. The Roadmap contemplates full 50% federal cost-share towards the stated demonstration projects which will be necessary to achieve the projected cost and performance goals of the Roadmap. With respect to large pilots, CURC views the financing difficulties for any amount of industry cost share in today's market for large-scale pilots as an impediment to advancing these technologies and recommends 100% federal financial support for such a program,[51] with industry taking the lead in providing the intellectual and human capital necessary to advance the technologies.

Pilots provide the necessary information needed to determine if the risk of further investments in commercial-scale demonstrations are justified. However, large-scale pilot projects are still early enough in the technology development timeline that the time to commercialization and the risk that the process might not work at scale makes both commercial and internal financing difficult to justify. Given this and the timing of commercialization to achieve return on investment, funding for pilots are often more challenging than either basic research or full-scale commercial-scale demonstrations. The success of technologies at pilot-scale will help to understand and overcome the risks inherent in early phase technology development and if successful, encourage industry to make investments to advance the technologies to commercial implementation. Figure 13 illustrates the various phases of technology development to understand the need for federal government support through each phase.

[51] A bill was introduced recently in Congress that proposes eliminating past cost share requirements for pilot-scale projects. 114th Cong. § 2(b), https://www.congress.gov/bill/114th-congress/senate-bill/1283/text.

Figure 13. Technology Development Timeline[52]

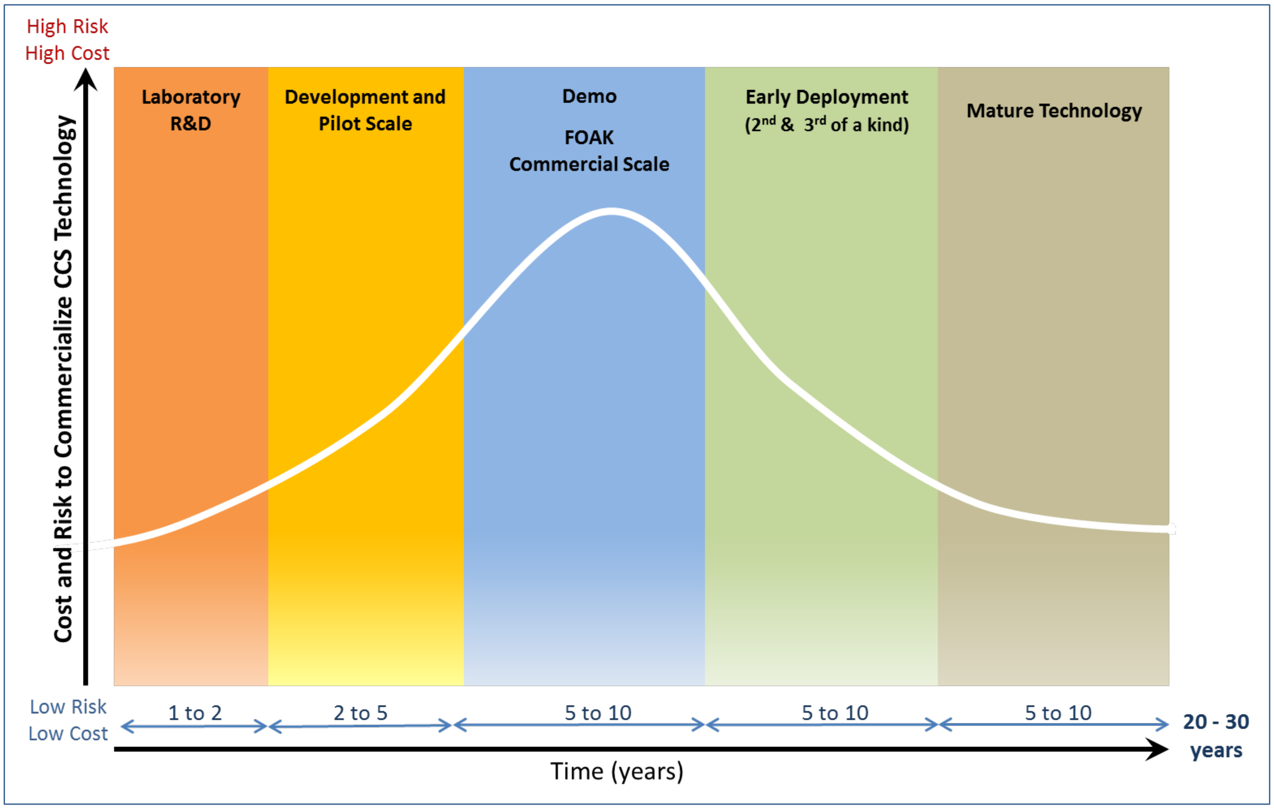


Figure 13 provides a graphical representation of how the cost and risk of failure evolve as technology progresses from a laboratory concept to commercialization. Pilot-scale projects, an area of increased focus in this updated Roadmap, provide a critical need to bridge between early technology development and commercial-scale demonstration while development costs and risks remain low to moderate. The graphic also shows why the ultimate value of a new technology is generally not realized until several commercial-scale replications have occurred. This final aspect of technology development is typically addressed with financial incentives for early deployment of new technologies – an area not within the scope of this Roadmap.

Figure 13 also shows the long lead times as well as the capital- and risk-intensive nature of advancing energy technologies from concept to demonstration and FOAK, all the way through to commercialization. For many energy technologies, including advanced coal and CCS/CCUS, the return on investment is a long-term proposition, and each phase of development carries significant technical and cost risk that must be addressed. The American Energy Innovation Council released a report in February of 2015[53] addressing the need for significantly more federal support for new energy technologies, stating:

[52] CURC adaptation from EPRI TAG.
[53] Restoring American Energy Innovation Leadership: Report Card, Challenges, and Opportunities American Energy Innovation Council, February 2015, http://americanenergyinnovation.org/restoring-american-energy-innovation-leadership/.

> *Such a risk-reward profile will rarely attract necessary investment from the private sector, and therefore many disruptive new technologies won't be brought to demonstration-scale. Not only is public investment critical to move new technologies through demonstration, but also such investment must come in large tranches due to the capital-intensive nature of new energy technologies. The large magnitude of viable energy technology investment is unlike most other industries.*[54]

Bill Gates further emphasized this point when he spoke at the 2012 ARPA-e conference, stating:

> *The IT revolution is the exception that has warped people's minds in how quickly things work. It's very different than having a software company, or even a chip factory, where your innovation cycles are two or three years, and your dependence on government policy is very low.*

BILL GATES ON FUNDING ENERGY INNOVATION, INCLUDING CCS:

"It's crazy how little we are funding this energy stuff. People underestimate how far away we are. That's partly why we can end up under-funding the innovative work that needs to go on."

Bill Gates, speaking at ARPA-E Summit, February 28, 2012.

As the figure in Attachment 2 shows, several commercial-scale projects under development represent the "first generation" CCS and CCUS technologies that need to be demonstrated. The fate of the "second generation" technologies is tied to the successful development of these initial projects. However, there currently is no formal plan within the DOE for demonstrating "second generation" CCS technologies, or for demonstrating other non-CO_2 cross-cutting technologies identified in the Roadmap. The Roadmap schedules demonstration projects to be completed by 2025 and 2035. For the 2025 goal to be achieved, it will be necessary to commence construction of these demonstration facilities by no later than 2020.

The Roadmap-recommended funding levels would ensure that a mixture of technologies are demonstrated that result in both well-defined improvements from existing technology as well as transformational technologies which are characterized in the Roadmap by the problems they solve, not in terms of specific hardware.[55]

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[54] Ibid. at 17.

[55] For example, the energy penalty associated with the compression of CO_2 is one major technology challenge that must be overcome. The Roadmap projects that additional RD&D on CO_2 compression would lead to large reductions in cost of electricity from some coal-based power technologies, and while a process concept need has

Resulting Benefits

A major benefit resulting from the proposed RD&D program is a reduction in the cost of producing low-emission power from coal. If the technology program recommended by the Roadmap is pursued and successful, the cost of power from new CCS-equipped systems beginning construction in 2030 will be about 40% less than currently available coal technologies, which is competitive with estimated costs of other low-carbon generating sources including wind, solar, and nuclear.[56] In addition, implementing the Roadmap will ensure advanced coal-based generating options with CCS are available when existing baseload generating units are retired, ensuring a balanced approach to a diverse portfolio of options for U.S. power generators.

Based on experience to date with initial commercial demonstration projects, it seems likely that most of the next generation of carbon capture-equipped coal-based generators will store CO_2 in conjunction with EOR projects, although some facilities may be designed for storage in a combination of EOR and saline geologic structures in order to provide operational flexibility. Additionally, near-term gasification-based systems likely will co-produce energy or chemical products in addition to electricity, in part due to the relatively high dollar value of these non-power products. EOR-based and polygeneration systems are too varied and site-specific in nature to be explicitly modeled in the Roadmap analysis.

Some of the Roadmap's recommended research relates to improvements in the efficiency of power production from coal. The average efficiency of the current fleet of coal-fired power plants is 33%.New coal plants built without carbon capture systems (and their need for a portion of the produced power) can increase efficiency from 39%, reflecting today's best performing new units, to about 45% for units built after 2025, with potentially higher efficiencies for units built after 2035. With higher efficiency, units use less fuel and emit less air pollution, including CO_2. Along with other improvements related directly to carbon capture systems, these efficiency-related improvements mean that net plant efficiency for CCS-equipped power plants can increase from the 28-31% efficiency possible with today's technology to 43-44% efficiency for plants built after 2035.

Conclusions

Over the last three decades, a collaborative effort between the private and public sectors has achieved dramatic improvements in technologies related to coal-based power production. The resulting technologies provided major economic, energy security, and environmental benefits to the United States.

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been identified, a specific technology is not currently under development. Such breakthroughs are reasonable to expect in a research program spanning 20 years.

[56] It is difficult to project the competiveness of advanced coal systems with CCS versus natural gas-fueled power plants because of the large uncertainty associated with future natural gas prices, gas infrastructure needs, the impact of liquefied natural gas exports on domestic natural gas prices, and future environmental regulations on natural gas production and use.

Implementation of the technology development steps identified in the Roadmap will result in large reductions in emission rates from power generated from coal. This improvement occurs in both traditional and climate-related emissions. In addition, by providing low-cost electric power, the Roadmap facilitates the displacement of petroleum-based power systems for cars with electric power. The deployment of electric vehicles should provide additional environmental benefits, particularly in urban areas.

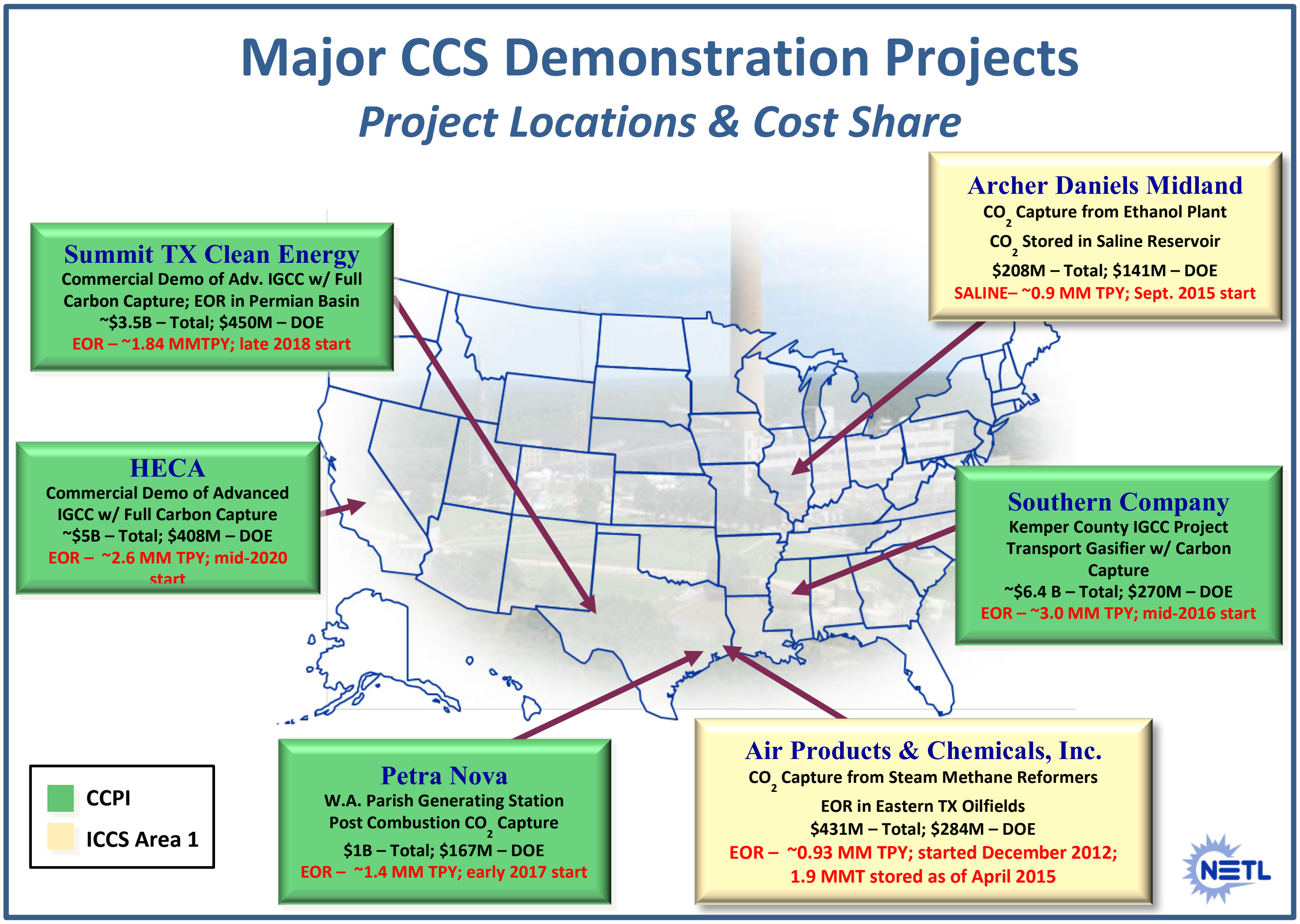
The Roadmap also projects a reduction over time of water withdrawals, consumption and water effluent discharges from power generation. New plants built after 2035, for example, could consume about 70% less water per megawatt-hour and withdraw less than 40% as much water per megawatt-hour as new plants built today. These technology improvements could also result in zero water discharge from the plants.

The CURC-EPRI Roadmap outlines an RD&D program to ensure that the nation can expand the economic, energy security, and environmental benefits derived from coal use in the United States and inclusion of coal in a diverse national generation technology portfolio. CURC's members and others in the private sector have provided substantial private sector funding to make past technology improvements related to coal, and they are committed to make the needed investments in future technologies as well. The challenge today, in a time of increasing financial stress on the taxpayer, is for the public sector to understand the value of these technology improvements, and the value of making a similar financial commitment to share in their development.

Attachment 1. CURC Membership

ADA Environmental Solutions
Aerojet Rocketdyne (now Gas Technology Institute)
Air Products and Chemicals
Alstom Power, Inc.
American Coal Council
American Coalition for Clean Coal Electricity (ACCCE)
American Electric Power
Arch Coal, Inc.
The Babcock & Wilcox Company
Basin Electric Power Cooperative
Battelle/Pacific Northwest National Laboratory
Caterpillar Global Mining
Cloud Peak Energy
CONSOL Energy, Inc.
Duke Energy Services
Edison Electric Institute (EEI)
Electric Power Research Institute (EPRI)
Energy Industries of Ohio
FutureGen Industrial Alliance
Greater Pittsburgh Chamber of Commerce
Illinois Coal Association
Illinois Department of Commerce and Economic Opportunity
Kentucky Office of Energy Policy
LG&E Energy
Lehigh University
Lignite Energy Council
The Linde Group
LP Amina
Mitsubishi Heavy Industries America
National Rural Electric Cooperative Association (NRECA)
Ohio State University
Peabody Energy
Penn State University
Pennsylvania Coal Alliance
Schlumberger Carbon Services
Southern Company
Southern Illinois University
State of Ohio, Air Quality Development Authority
Tri-State Generation & Transmission Association
United Mine Workers of America
University of Kentucky
University of North Dakota, Energy and Environmental Research Center
University of Wyoming
West Virginia Coal Association
West Virginia University
Wyoming Infrastructure Authority
Wyoming Mining Association

Attachment 2. Federally Supported CCS Demonstration Projects Currently Under Development



At time of this writing, the future of FutureGen 2.0 is uncertain giving the expiration of American Reinvestment and Recovery Act funding. CURC has consistently stated that for CCS to be technically and economically viable, investment in and demonstration of the technology is needed **now** on FOAK systems to gain the operational experience and data necessary to implement the technology on next-of-a-kind systems and to apply this learning to second generation and transformational technologies in the future. As acknowledged in this Roadmap, CURC supports funding for cutting edge, FOAK technologies such as that envisioned by the FutureGen 2.0 project, and the technology being utilized in FutureGen 2.0 is one of the key technology demonstrations identified in the Roadmap as necessary to advance CCS technology. If the project, and other demonstrations like it, do not proceed, development and commercialization of the technology will be significantly delayed.