A RETROSPECTIVE ANALYSIS OF THE COSTS, IMPACTS, AND BENEFITS OF THE U.S. DEPARTMENT OF ENERGY COAL RD&D PROGRAM

Prepared For

The U.S. Department of Energy

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July 2020

TABLE OF CONTENTS

ABSTRACT

There is currently a general perception concerning the purported disadvantages of fossil fuels – especially coal. This report addresses the issue by estimating and assessing the costs, impacts, and benefits of the DOE coal RD&D program from 1976 through 2019. As shown in Table AB-1 and Figure AB-1, **the benefits of the DOE coal RD&D program through 2019 -- $236.7 billion (2019 dollars) -- far exceed the costs -- $28.6 billion (2019 dollars)**. This implies a rough benefit-cost (B-C) ratio of greater than 8-to-1. This is notable: B-C ratios above 2 or 3 are desirable, and ratios higher than that are impressive. The B-C ratio greater than 8-to-1 derived here is robust since it is based on official published federal government data and is corroborated by independent studies. The number of jobs created over the period 2000 – 2019 -- 1.6 million, about 78,600/yr. -- is large, and job creation is especially important in local areas and in specific sectors, industries, and occupations. The local job impacts are especially relevant at present given historical levels of joblessness in the U.S.

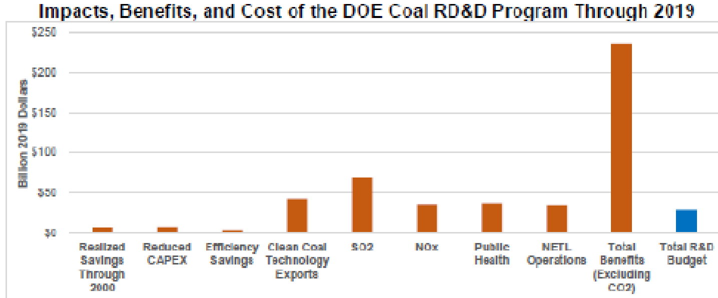
Table AB-1
Impacts of the DOE Coal RD&D Program Through 2019

Category	Impacts (billions of 2019 dollars)
Realized Savings Through 2000	$7.3
Reduced CAPEX	$7.6
Efficiency Savings	$2.9
Clean Coal Technology Exports	$42.6
SO_2	$68.5
NO_x	$35.9
CO_2	42.1Mt
Public Health	$36.9
NETL Operations	$35.0
Jobs	78,600 jobs/yr.*
Total	$236.7
Total, including CO_2	$239.1

*Annual average for the period 2008 – 2019.

Source: Management Information Services, Inc.

Figure AB-1
Impacts, Benefits, and Cost of the DOE Coal RD&D Program Through 2019



Source: Management Information Services, Inc.

The report finds that the DOE coal RD&D program budget has been subject to wide variations over time, often over short periods. While the overall budget has been relatively stable in real terms over about the past decade, program funding priorities have changed substantially over this period. The most important recommendation derived here is, first, that the anticipated, prospective benefits of the current DOE coal RD&D program be forecast, monetized, and assessed against the forecast cost of the program. Over 80% of the DOE FY 2020 coal RD&D budget is devoted to RD&D programs -- primarily carbon capture, utilization, and storage (CCUS) -- with benefits that are anticipated well into the future. This is the proper structure for an RD&D program, which should focus on technologies of the future, but adequate program funding requires justification. Second, the job impacts of DOE programs are of critical importance, and are especially noteworthy in the current environment where job losses and unemployment are at record levels not seen since the Great Depression of the 1930s. Third, a portfolio approach must be used to assess the DOE RD&D program. Some coal RD&D programs are among DOE's most successful programs and they have produced benefits that far exceed their costs: The benefits of DOE high-risk, high-payoff programs can greatly exceed their costs, while other RD&D programs produce benefits that are difficult to quantify. Finally, the findings reported here will be useful in preparing budget requests, justifications, and defenses, in Congressional testimony, and for other purposes, and it is essential that they be widely distributed. This research has been completed and remains to be disseminated.

EXECUTIVE SUMMARY

Review of Previous Studies

We reviewed relevant reports and studies over the past two decades in the existing body of literature on the economic and jobs impacts and the costs and benefits of the DOE coal research, development, and demonstration (RD&D) program, including:

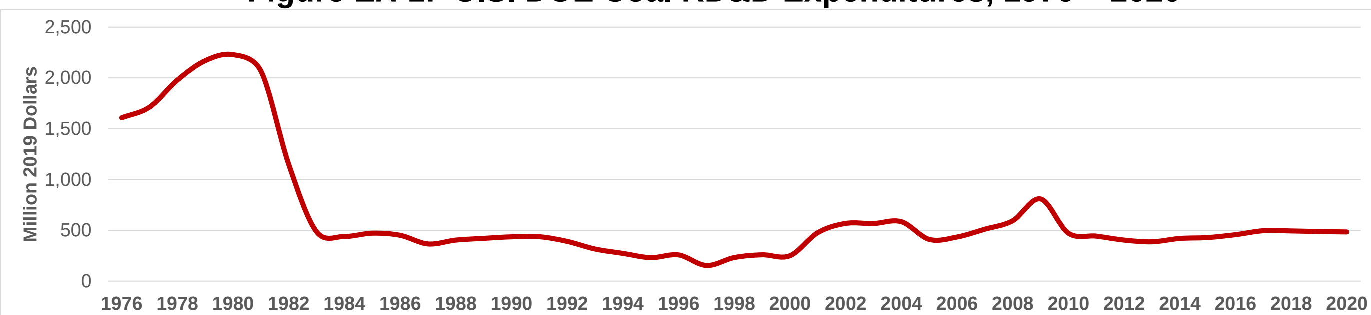
- The 2001 National Research Council (NRC)/National Academies of Science (NAS) retrospective analysis of the benefits and costs of DOE RD&D programs.
- The 2005 National Energy Technology Laboratory (NETL) study of the benefits of DOE Programs for advanced fossil-fuel electricity generating technologies.
- The 2004 Clean Coal Technology (CCT) roadmap report.
- The 2005 NRC/NAS prospective analysis of the benefits and costs of DOE RD&D programs.
- The 2006 NETL report on the results from the Clean Coal Technology Demonstration Program.
- The 2007 NETL assessment of the national, state, and regional economic and environmental impacts of NETL.
- The 2007 NETL assessment of the national, state, and regional economic and environmental impacts of NETL on the Pennsylvania-West Virginia region.
- The 2009 Management Information Services, Inc. (MISI) analysis of the return on investment of DOE's CCT program.
- The 2009 NETL analysis of the national and state economic impacts of NETL.
- The 2009 BBC Research and Consulting study of the employment and other economic benefits from advanced coal electric generation with carbon capture and storage.
- The 2013 DOE fossil energy benefits study.
- The 2013 MISI study of the economic, environmental, and job impacts of increased efficiency in existing coal-fired power plants.
- The 2015 National Coal Council analysis of the benefits and accomplishments of the DOE CCS/CCUS program.
- The 2017 Union of Concerned Scientists discussion of three major reasons why Congress should maintain support for federal energy RD&D programs.
- The 2017 MISI assessment of the NETL RD&D program economic and jobs benefits.
- The 2018 Congressional letter of support for the DOE fossil energy RD&D program.
- The 2018 NETL study of the national and regional impacts of NETL.
- The 2019 MISI and Leonardo Technologies Inc. study of the economic impact of CCUS retrofit of the Comanche Generating Station.

The DOE Coal RD&D Budget

Over the past six decades, the federal government has funded a substantial coal research program, including RD&D for coal production, resource assessment, mining techniques, mining health and safety, coal utilization, coal gasification, clean coal technologies, CCUS, fuel cells, advanced technologies, Magnetohydrodynamics, pollution control and abatement, and other programs. MISI estimated the detailed DOE coal RD&D program expenditures from 1976 through 2020 and converted them to constant 2019 dollars using the implicit price deflator.

Figure EX-1 shows the history of the DOE coal RD&D budget from 1976 through 2020 and illustrates the trajectory of RD&D spending over the past five decades. It shows that over the period, the cumulative budget totaled $29.12 billion (2019 dollars), but the distribution of expenditures was very uneven.

Figure EX-1: U.S. DOE Coal RD&D Expenditures, 1976 – 2020*



*1976 transition quarter (TQ) funding included in year 1976 budget.

Source: U.S. Department of Energy and Management Information Services, Inc.

Figures EX-1 and EX-2 identify the major program beneficiaries over the period 1976 – 2020 and show that: 1) Coal Liquefaction received the most funding: $4.85 billion – 17% of the total RD&D budget; 2) Coal Gasification received the second highest level of funding: $4.67 billion -- 13% of the total; 3) CCUS received the third highest level of funding: $2.49 billion – 8.6% of the total; 4) Advanced Research and Technology development received the fourth highest level of funding: $2.46 billion – 8.4% of the total; 5) Coal Liquefaction and Coal Gasification combined received a total of $8.5 billion -- nearly 30% of the total RD&D expenditures; 6) four major programs which have not been funded for the past quarter century -- Coal Liquefaction, Coal Gasification, Magnetohydrodynamics, and Mining RD&D – were among the top ten funded and combined received $11.6 billion – 40% of the total RD&D budget.

Table EX-1 identifies the major programs funded in 1980, 1990, 2000, 2010, and 2020 and illustrates the changing priorities of the RD&D program over the past five decades.

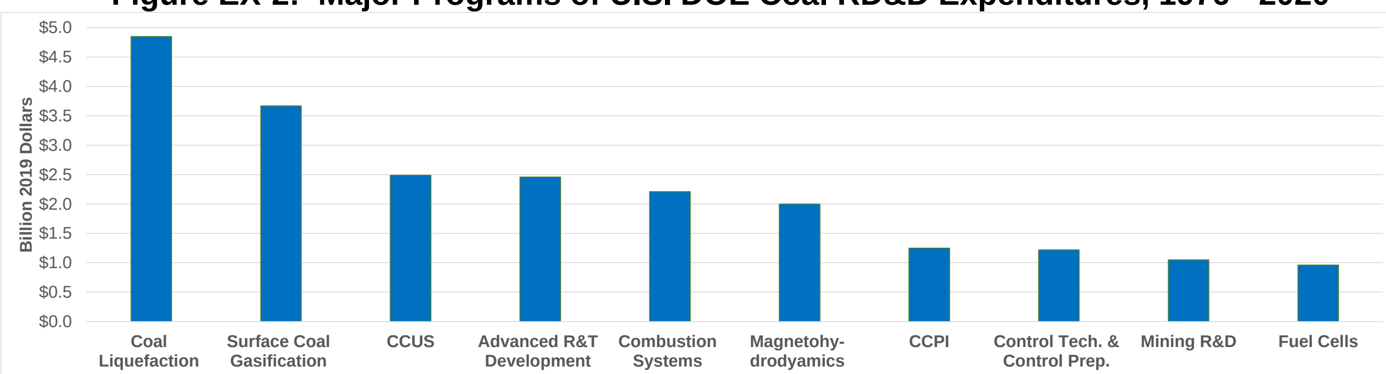
Economic and Job Impacts

We assessed the impacts and benefits resulting from: Realized Savings Through 2000; Reduced CAPEX; Efficiency Savings; Clean Coal Technology Exports; SO_2; NO_x; CO_2; Public Health; NETL Operations; Jobs. NRC/NAS estimated that realized economic benefits through 2000 from the DOE coal RD&D programs totaled approximately $7.3 billion (2019 dollars). In addition, we estimate that, in 2019 dollars, excluding CO_2

benefits, the benefits attributable to the DOE coal RD&D program through 2019 total about $237 billion (2019 dollars), including:

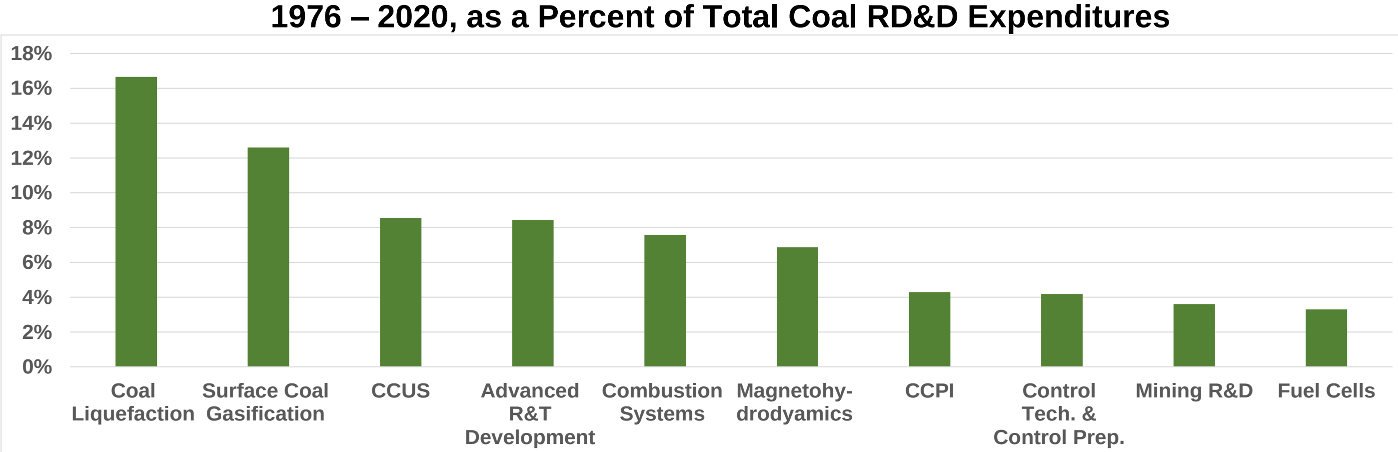
1. The total savings through 2019 from reduced capital costs of new plants and control technologies for existing plants was approximately $7.6 billion.
2. The cumulative fuel cost savings resulting from efficiency improvements through 2019 totaled about $3 billion.
3. The cumulative U.S. clean coal technology export benefits through 2019 – Figure EX-4 -- totaled approximately $42.6 billion.
4. The total environmental benefits of SO_2 emissions reductions – Figure EX-5 -- through 2019 totaled about $68.5 billion.
5. The environmental benefits in terms of NO_x reductions – Figure EX-6 – totaled $35.9 billion.
6. Using the 2013 IWG SCC estimate, the total estimated value of the CO_2 captured by the Petro Nova plant is about $0.2 billion (2019 dollars). The implied monetized CO_2 emissions savings from the Petra Nova plant and the high efficiency low emissions (HELE) plants – Table EX-2 -- totaled approximately $2.4 billion.
7. The total public health benefits through 2019 totaled approximately $36.9 billion.
8. The beneficial impacts of NETL operations, 2000-2109, totaled $35 billion.

Figure EX-2: Major Programs of U.S. DOE Coal RD&D Expenditures, 1976 - 2020



Source: U.S. Department of Energy and Management Information Services, Inc.

Figure EX-3: Major Programs of U.S. DOE Coal RD&D Expenditures, 1976 – 2020, as a Percent of Total Coal RD&D Expenditures



Source: U.S. Department of Energy and Management Information Services, Inc.

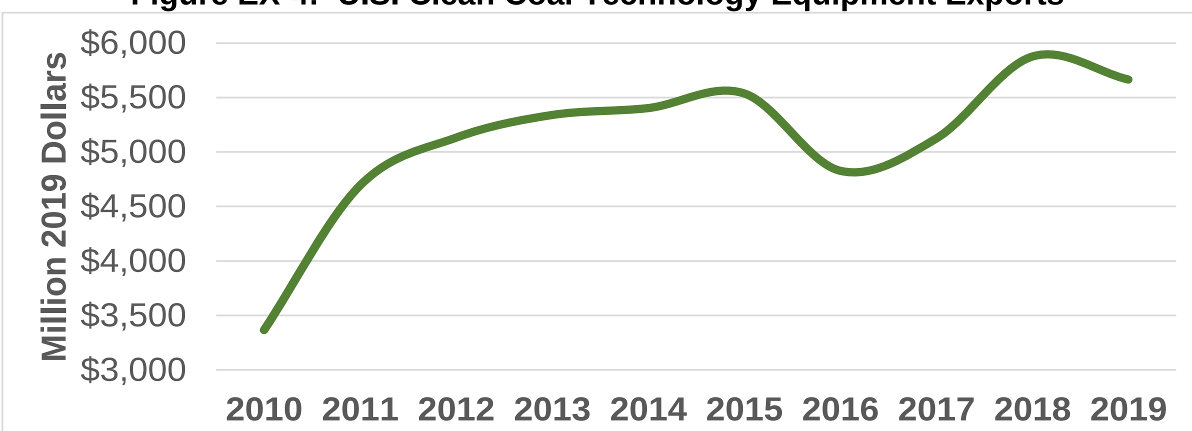
Table EX-1: Major Programs of U.S. DOE Coal RD&D Expenditures, 1980, 1990, 2000, 2010, 2020 (millions of 2019 dollars)

1980		1990		2000		2010		2020	
Program	**Funding**	**Program**	**Funding**	**Program**	**Funding**	**Program**	**Funding**	**Program**	**Funding**
Advanced R&T Develop.	175	Control Tech. & Coal Prep.	107	Advanced R&T Develop.	33	Innovations for Existing Plants	61	Advanced Energy Systems	148
Coal Liquefaction	620	Advanced R&T Develop.	47	Indirectly Fired Cycle	10	Advanced IGCC	73	Cross Cutting Research	48
Combustion Systems	217	Coal Liquefaction	65	Gasification Combined Cycle	50	Advanced Turbines	181	CCUS	215
Heat Engines	182	Combustion Systems	61	Pressurized Fluid Bed	17	Sequestra-tion	37	STEP	16
Magnetohy-drodynamics	234	Heat Engines	38	Advanced Res. & Environ.	34	Fuels	29	Transforma-tional Coal Pilots	20
Surface Coal Gasification	493	Magnetohy-drodynamics	73	Coal Liquefaction	10	Fuel Cells	58	NETL Coal RD&D	37
Mining RD&D	195	Surface Coal Gasification	43	Steelmaking Feedstock	10	Advanced Research	33		
				Fuel Cells	65				
Total*	**2,229**		**436**		**250**		**472**		**484**

*Total includes funding for programs not listed separately.

Source: U.S. Department of Energy and Management Information Services, Inc.

Figure EX-4: U.S. Clean Coal Technology Equipment Exports*



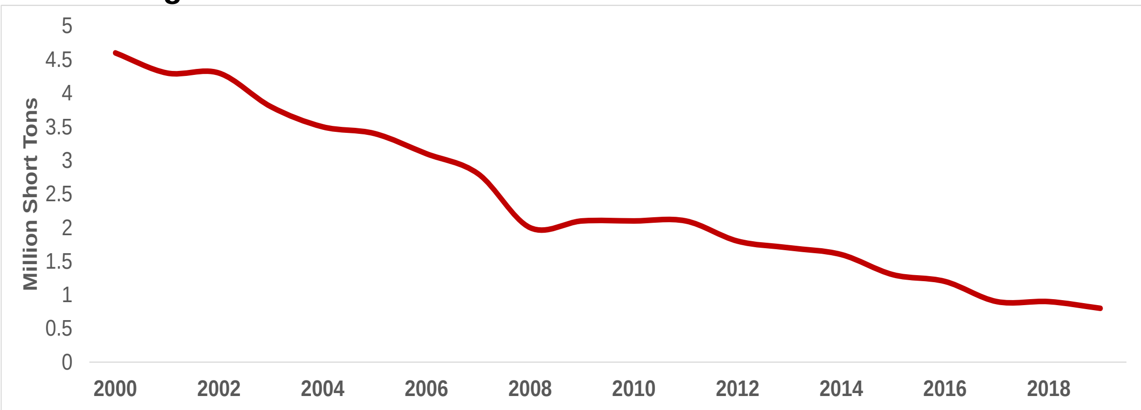
*Based on HS Codes 840490, 841620, 842139, and 842199.

Source: U.S. International Trade Administration, U.S. Commercial Service, UN Comtrade, BP Plc. and F. Pasimeni.

We estimate that the jobs created over the period 2000 – 2019 totaled approximately 1,572,000 -- about 78,600/yr. The number of jobs created is important, but it is also important to disaggregate the employment generated into occupations and skills. The jobs generated will be disproportionately concentrated in fields related to the construction, energy, utilities, technology export, mining, industrial, and related sectors.

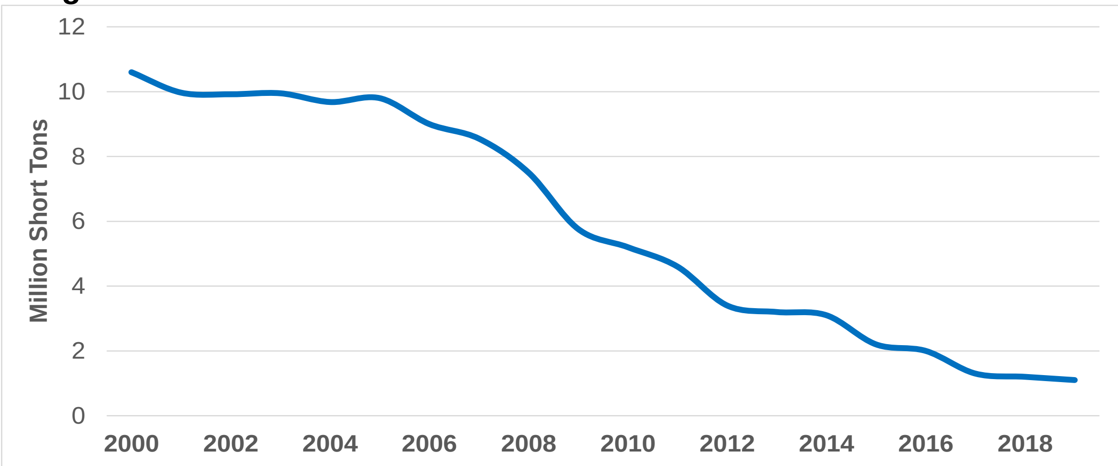
While numerous studies have found that government RD&D is a classic public good and that the benefit-cost (B-C) ratio of this RD&D is high, there is little consensus on what this ratio is. Previous research has estimated RD&D B-C ratios that range from 4-to-1 to 180-to-1.

Figure EX-5: NO_x Emissions from U.S. Coal Power Plants



Source: U.S. Energy Information Administration.

Figure EX-6: SO_2 Emissions from U.S. Coal Power Plants



Source: U.S. Energy Information Administration.

Table EX-2: Top U.S. HELE Power Plants by Efficiency

Power Plant & Unit	State	EIA HELE Category	Capacity (MW)	Efficiency (%)	Start Year
John W. Turk Jr. 1	AK	Ultra-supercritical	614	37.9	2012
Longview Power 1	WVA	Supercritical	700	39.7	2011
Trimble County 2	KY	Supercritical	747	39.6	2011
Latan 2	MO	Supercritical	850	38.6	2010
Sandy Creek 1	TX	Supercritical	927	38.6	2013
Prairie State PC 1	IL	Supercritical	800	37.9	2012
Cliffside 6		Supercritical	800	37.9	2012
Prairie State PC 2	IL	Supercritical	800	37.9	2012
Elm Road 2	NC	Supercritical	634	37.8	2011
J.K. Spruce 2	IL	Supercritical	780	37.7	2010
Weston 4	WI	Supercritical	535	37.5	2008
Oak Grove 1	TX	Supercritical	817	37.4	2009
Oak Grove 2	TX	Supercritical	827	37.4	2010

Source: WoodMackenzie

Substantial benefits have been realized by numerous companies in the private sector due to assistance from the NETL RD&D program. These include Carpenter Technology Corporation, LumiShield Technologies, KW Associates, Harbison Walker, Liquid Ion Solutions, Boston Scientific Corporation, and Pyrochem Catalyst Corporation.

The DOE coal RD&D program has significant economic and job impacts on specific cities and regions throughout the U.S., including Pennsylvania and West Virginia. In addition, MISI estimated the jobs impacts on Reading, Pennsylvania, where Carpenter Technology is located. This NETL success helped create a total of about 575 jobs (direct and indirect) in the Reading area and, absent these NETL facilitated jobs, the unemployment rate in Reading would have been 5.3% instead of 5.0% -- a meaningful difference.

Findings

Table EX-3 and Figure EX-7 show that the benefits of the DOE coal RD&D program through 2019 total about $237 billion (2019 dollars) – about $239 billion including a monetized value for CO_2 emissions, and annual creation of nearly 79,000 jobs, or about 1.6 million cumulative jobs over the period 2000 – 2019. Thus, the impacts and benefits of the DOE coal RD&D program through 2019 substantially far exceed the costs -- $28.6 billion (2019 dollars). This implies a rough B-C ratio of more than 8-to-1.

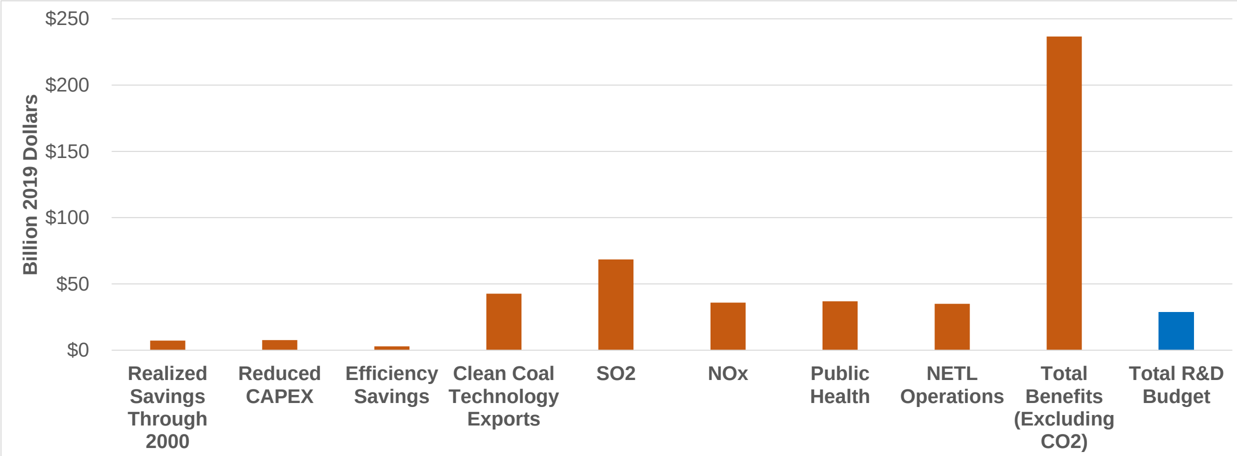
Table EX- 3: Impacts of the DOE Coal RD&D Program Through 2019

Category	Impacts (billions of 2019 dollars)
Realized Savings Through 2000	$7.3
Reduced CAPEX	$7.6
Efficiency Savings	$2.9
Clean Coal Technology Exports	$42.6
SO_2	$68.5
NO_x	$35.9
CO_2	42.1Mt*
Public Health	$36.9
NETL Operations	$35.0
Jobs	78,600 jobs/yr.**
Total	$236.7
Total, including CO_2	$239.1

*Using the 2013 IWG SCC value of $52/ton of CO_2 (2019 dollars), we estimate that the implied CO_2 emissions savings, 2008 – 2019, total approximately $2.4 billion (2019 dollars).
**Annual average for the period 2008 – 2019.
Source: Management Information Services, Inc.

A B-C ratio above one is desirable and a ratio over 8-to-1 is extremely attractive. It is also reasonable when compared to B-C ratios for other RD&D programs. Analyses of other RD&D programs found B-C ratios ranging from 4-to-1 up to an incredible 180-to-1. On this basis, the DOE coal RD&D program B-C ratio of 8-to1 is conservative. Further, a study of 15 leading economies estimated an overall B-C ratio for RD&D of about 20-to-1. Thus, on this basis also the DOE coal RD&D program B-C ratio of 8-to1 is reasonable.

Figure EX-7: Impacts, Benefits, & Cost of the DOE Coal RD&D Program Through 2019



Source: Management Information Services, Inc.

Knowledge benefits are scientific knowledge and useful technological concepts resulting from RD&D that have not yet been commercialized but hold promise for future utilization or are useful in unintended applications. The DOE coal RD&D program has yielded significant benefits in terms of important technological options and important additions to the stock of engineering and scientific knowledge in a number of fields and it facilitated numerous commercial spin-offs. MISI did not quantify knowledge benefits. Nevertheless, these are real and substantial and should be recognized as a key result of the program.

Conclusions

The DOE coal RD&D program budget has been subject to wide variations over time, often over short periods. For example, in real terms: 1) The budget declined 80% 1980 - 1983; 2) it declined 20% from 1986 to 1987; 3) it declined 40% from 1996 to 1997; 4) it increased more than twofold 2000 - 2002; 5) it declined more than 50% 2009 - 2011. Such fluctuations are not conducive to coherent, long term RD&D. The budget has been relatively stable in real terms over about the past decade, but program funding priorities within the budget changed substantially over this period.

Large portions of the coal RD&D program budgets were comprised of expenditures on technologies that were not successful. Subtracting expenditures on just three of these – Coal Liquefaction, $4.9 billion, Coal Gasification, $3.7 billion, and Magnetohydro-dynamics, $2.0 billion – which combined comprised more than 35% of the total DOE coal RD&D budget through 2020, leaves a cumulative DOE coal RD&D budget of $18.0 billion. However, a portfolio approach must be used to assess RD&D programs. Some DOE coal RD&D programs are among DOE's most successful RD&D programs, they have produced benefits that far exceed their costs, and the estimated benefits of DOE high-risk, high-payoff programs can greatly exceed their projected cost. Nevertheless, RD&D programs often have impacts that are difficult to quantify.

The most important conclusion derived here is that the benefits of the DOE coal RD&D program through 2019 -- $237 billion (2019 dollars) -- far exceed the costs -- $28.6 billion (2019 dollars). This implies a rough B-C ratio of over 8-to-1. This is impressive: B-C ratios above 2 or 3 are desirable, and ratios higher than that are very attractive. Some other energy RD&D programs have purported B-C ratios much higher than this. However, upon close scrutiny many of these are of questionable validity.

The conclusion that the impacts and benefits of the DOE coal RD&D program far exceed the costs is robust and is reasonable: 1) It is robust because the cost estimate is based on official published Federal government data, and many of the benefit estimates have been verified by independent studies; 2) it is reasonable – and perhaps even conservative – when compared to benefit-cost estimates for other RD&D programs. Purported astronomical B-C ratios simply do not past the laugh test.

The number of jobs created over the period 2000 – 2019 totaled about 1.6 million -- about 78,600/yr. – and is large, and job creation is especially important in specific local areas and in specific sectors, industries, and occupations. These local job impacts can be of critical importance – especially in the current environment of widespread job losses.

Relying on other measures, such as patents, papers published, or conference presentations, as criteria for RD&D success can be inaccurate, misleading, and subject to conflict of interest. Finally, knowledge benefits can be significant. Indeed, the DOE coal RD&D program has yielded benefits in terms of important technological options for potential application and additions to the stock of engineering and scientific knowledge in many fields. While these benefits are difficult to quantify, they are nevertheless real and should be recognized as an important result of the RD&D program.

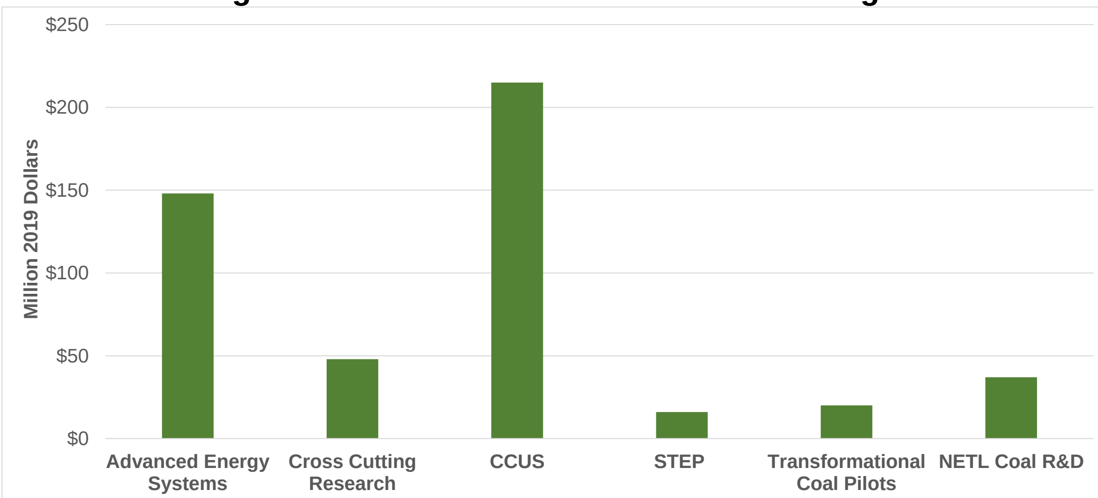
Recommendations

<u>First,</u> the most important recommendation derived here is that the future benefits of current DOE coal RD&D programs must be forecast, monetized, and assessed against the forecast cost of the programs. Here we estimated the historical DOE coal RD&D budget and the retrospective impacts of the RD&D programs to date. However, the most relevant questions concern the future size and composition of the DOE coal RD&D budget. Obviously, simply because the past program has produced impressive results is no guarantee that the program will continue to do so.

Figure EX-8 shows the 2020 DOE coal RD&D budget. The largest program is CCUS, receiving more than 44% of the total, followed by Advanced Energy Systems, 31%. Adding Transformational Coal Projects, 4%, and STEP, 3%, indicates that over 80% of the budget is devoted to RD&D with benefits anticipated well into the future. This is the proper structure for an RD&D program: It should focus on technologies of the future. In particular, CCUS is not only a current major focus of the DOE program but, to date, it is the third most generously funded coal RD&D program – even though funding for it did not begin until FY 2001. Policy-makers have realized that any ambitious decarbonization goals are not feasible without CCUS. Notably, three of the major emphases in the DOE

FY 2021 fossil energy budget request are i) utilization of coal and CO_2 for the production of critical materials and products; ii) transformational CO_2 capture technologies; and iii) CO_2 storage.

Figure EX-8: DOE FY 2020 Coal RD&D Budget



Source: U.S. Department of Energy and Management Information Services, Inc.

DOE and Congress are interested in determining the economic and jobs impacts of CCUS, and over the past three decades have expended $2.5 billion on DOE CCUS RD&D. CCUS is vital for the DOE coal RD&D program: 1) It is a DOE greenhouse gas (GHG) reduction technology; 2) DOE has a long history and acknowledged expertise in CCUS; 3) it is a program that enjoys strong bipartisan support in Congress; 4) it is a program that will likely be strongly supported well into the future; 5) when combined with EOR, it is economically viable.

DOE CCUS program funding requires justification, which must be derived from the forecast economic and jobs benefits of the CCUS program. Here we estimated the CO_2 emissions reduction benefits to date from the Petra Nova plant and the HELE plants. However, these reductions have only just begun to accrue and the benefits from widespread CCUS and CCUS/enhanced oil recovery (EOR) over the next several decades have to be estimated and evaluated. Thus, DOE can assess the economic, energy, environmental, and jobs impacts of future DOE–facilitated CCUS initiatives. This research could provide estimates of the impacts that would result from the CCUS asset construction and operation and from the associated CO_2/EOR oil production. It should estimate the economic and job impacts of CCUS capacity build-out and CO_2-EOR oil production through 2050. In addition, the economic impacts of the 2018 45Q CCUS tax credits can be compared with the impacts of those proposed in 2017 and with other proposed CCUS tax credits and incentives.

Further, research has estimated that the DOE CCUS RD&D program alone could create 14 to 16 million jobs. It also found that RD&D is much more cost-effective than tax credits, and that the marginal impacts of the DOE RD&D program are substantial. Nevertheless, to maximize job creation both CCUS RD&D and tax credits and need to be implemented in a coordinated manner, and these impacts need to be further researched.

Second, the job impacts of DOE programs are of critical importance, and are especially relevant in the current environment where job losses and unemployment are at record levels not seen since the Great Depression of the 1930s. It really does come down to "jobs, jobs, jobs!" It is impossible to over-emphasize the importance of jobs and employment impacts. For example:

- Over the past two decades the DOE coal RD&D program has generated a cumulative total of 1.6 million jobs -- about 78,600/yr. This finding needs to be widely disseminated.
- Regional disaggregation is required of the jobs created, especially at the state level. There is great Congressional and decision-maker interest in these data and there will be a large and influential audience for the estimates. The importance of estimating benefits to specific states and regions is obvious, for the debate at the state and regional level inevitably centers upon jobs.
- The number of jobs created is important, but it is also important to disaggregate employment generated into occupations and skills, and jobs created are across a wide spectrum in many industries and occupations, and research is required to estimate these impacts. The importance of jobs in some occupations is much greater than in others, and coal-related jobs impacts by sector, industry, and occupation/skills, including new and emerging occupations, must be estimated.
- Coal will continue to be important for U.S. electricity production. Further, rapid expansion of coal retrofit CCUS, CO_2/EOR, CO_2 pipelines, and associated infrastructure can facilitate the creation of new industries, increased industry sales and profits, increased GDP, millions of jobs, and expanded high skilled, well-paying employment opportunities. These have to be estimated and assessed.
- Research should be initiated on the potential jobs impacts of future CCUS retrofits. This should be based on appropriate assumptions regarding CO_2 taxes and tax credits, industry requirements, deployment of CCUS technology, resource levels, EOR projects, and other relevant parameters.

Third, a portfolio approach must be used to assess DOE coal RD&D benefits. As noted, some DOE coal RD&D programs are among DOE's most successful RD&D programs, they have produced benefits that far exceed their costs, and the benefits of DOE high-risk, high-payoff programs can greatly exceed their cost. On the other hand, other RD&D programs produce impacts and benefits that are difficult to quantify. This is very important in evaluating the overall DOE RD&D program, but it is not widely appreciated. Decades ago, no one knew which RD&D programs would be successful and which would not. This is a basic fact of any RD&D enterprise, and will be as true in the future as in the past.

Finally, there is currently a widespread general perception concerning the purported disadvantages of fossil fuels – especially coal. DOE can counter this by facilitating the dissemination of rigorous, credible research illustrating the economic and job benefits the DOE coal RD&D program – such as that provided here. These findings will be useful in preparing budget requests, justifications, and defenses and in Congressional testimony.

It is also important that these findings be publicized and distributed in the media, in the scholarly literature, and at appropriate professional venues. The findings can be used to prepare white papers, summaries, abstracts, and one-pagers appropriate for widespread distribution, articles for publication in peer-reviewed national and international energy and policy journals, and presentations at relevant professional conferences, seminars, and meetings. The research has been conducted and remains to be disseminated.

I. THE ISSUE: COSTS AND IMPACTS OF THE DOE COAL RD&D PROGRAM

Studies and reports – many of questionable validity – emphasizing the purported myriad evils of fossil fuels -- especially coal -- are continually being released. However, over the past four decades DOE has expended nearly $30 billion (2019 dollars) on coal RD&D. This RD&D has produced many favorable economic and jobs impacts and societal benefits. Unfortunately, these impacts have not been comprehensively identified, monetized, assessed, or articulated, nor have the benefits of this RD&D been evaluated against the cost of the RD&D programs. This report addresses this and will allow DOE to disseminate findings illustrating the economic and job benefits and advantages and the favorable return on investment of the coal RD&D program.

This research is urgently required. For example, the findings derived here can be used to support DOE coal RD&D budget requests and justification. The DOE FY 2021 Congressional Budget Request states that DOE coal RD&D will increase U.S. energy exports, create domestic jobs, and support our partners abroad -- reducing energy poverty in African and Asian nations, while providing affordable electricity and opportunities for economic prosperity to people worldwide.[1] It also states that DOE RD&D develops technologies that create jobs, reduce U.S. reliance on foreign resources, increase energy affordability, improves energy security, supports environmental stewardship, and offers Americans a broader range of energy choices.[2] This report allows DOE to support these types of statements with rigorous, credible, estimates of how its coal RD&D programs have achieved and are achieving these objectives. The research conducted here provides the necessary information.

Similarly, in Congressional testimony DOE officials will benefit from the credible impact assessments and benefit-cost estimates of coal RD&D programs presented here.[3] This information supports the value and return on investment (ROI) of the RD&D programs. Such information is valued by Congress and Congressional staff and is too often lacking.

For example, in order to support current and future Carbon Capture, Utilization, and Storage (CCUS) RD&D programs, DOE needs to determine the costs, economic and jobs impacts, and benefits of CCUS. This report provides DOE with this critical information.

As another example, a Presidential Executive Order (EO) issued on April 25, 2017 established an Interagency Task Force on Agriculture and Rural Prosperity, which includes the Secretary of Energy, to "Identify legislative, regulatory, and policy changes to promote in rural America agriculture, economic development, job growth, infrastructure

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[1]Office of Chief Financial Officer, *Department of Energy FY 2021 Congressional Budget Request*, February 2020.
[2]Ibid.
[3]For example, see "Testimony of Secretary Rick Perry U.S. Department of Energy Before the U.S. House Committee on Energy and Natural Resources Subcommittee on Energy," May 9, 2019.

improvements, technological innovation, energy security, and quality of life."[4] The research here provides information relevant to this EO, as well as other Presidential initiatives.

More generally, there is great interest in the type of information developed here and there is a large and influential audience for the data. For example, the results of this research show that the DOE coal RD&D program has had very substantial, positive economic and jobs benefits and has yielded high benefit-cost ratios. Further, the implications of determining the jobs benefits of coal RD&D programs to specific states and regions are obvious, for the debate at the state and regional level inevitably revolves around "jobs, jobs, jobs."

Thus, the research presented here has produced a plethora of useful data and estimates, many of which break new ground and which will contradict current thinking, and develops a large amount of information that has direct relevance to ongoing economic, energy, and environmental policy debates. The findings can be used to prepare briefing papers, testimonies, OMB submissions, budget and program defenses, one-pagers appropriate for widespread distribution, and presentations at relevant conferences, seminars, and meetings. The findings derived here can, if desired, be publicized and distributed in the media, in the scholarly literature, and at appropriate professional venues.

The report is organized as follows:

- Chapter II summarizes previous analyses of the costs, benefits, and impacts of DOE coal RD&D programs.
- Chapter III reviews the DOE coal RD&D program, estimates the detailed expenditures by program element, 1976-2000, and converts expenditures to constant 2019 dollars.
- Chapter IV assesses the economic and jobs impacts of the DOE Coal RD&D program.
- Chapter V develops benefit-cost (B-C) estimates of the DOE coal RD&D program and assesses these compared to other energy and RD&D programs.
- Chapter VI derives findings, conclusions, and recommendations.

[4]https://www.whitehouse.gov/presidential-actions/presidential-executive-order-promoting-agriculture-rural-prosperity-america/.

II. ASSESSMENT OF PREVIOUS ANALYSES

II.A. Review of Previous Studies

This chapter identifies and reviews relevant reports and studies over the past two decades in the existing body of literature on the economic and jobs impacts and the costs and benefits of the DOE coal RD&D program. MISI searched the existing body of literature over the past two decades for relevant articles and reports that assessed the DOE coal RD&D programs, including coal power generation, advanced coal power technologies, coal-to-liquids operations, coal gasification, CO_2 enhanced oil recovery (EOR), integrated gasification combined cycle (IGCC), Clean Coal Power Initiative, CCUS, advanced systems, DOE laboratory programs and initiatives, and related coal RD&D. MISI determined that over the past several decades there have been a number of pertinent studies, but they are not comprehensive and they are dated. Several of the more relevant studies are summarized here.

II.B. NRC/NAS 2001 Study

In 2000, Congress requested that the National Research Council (NRC) of the National Academies of Science (NAS) evaluate the benefits that have accrued to the nation from the R&D conducted since 1978 in DOE's energy efficiency and fossil energy programs. The resulting report analyzed whether the benefits of DOE programs justified the considerable expenditure of public funds, and, unlike earlier evaluations, involved a comprehensive examination of the actual outcomes of DOE's research over two decades.[5]

NRC/NAS noted that from 1978 through 1999, the federal government expended $91.5 billion (1999 dollars) on energy R&D, mostly through DOE programs. This federal investment constituted about a third of the nation's total energy R&D expenditure, the balance having been spent by the private sector.

The two program areas -- energy efficiency and fossil energy -- that were within the scope of the study expended about $22.3 billion in federal funds over the 22 year period -- about 26 percent of the total DOE expenditure on energy R&D of approximately $85 billion (1999 dollars). Here we focus on the fossil energy (FE) program evaluation

To assess the benefits of the energy efficiency and fossil energy programs within this evaluation framework, the committee prepared a series of case studies on technologies and programs selected by the committee for examination.[6] NRC/NAS

[5]National Research Council, *Energy Research at DOE: Was It Worth It?* Committee on Benefits of DOE R&D on Energy Efficiency and Fossil Energy, Commission on Engineering and Technical Systems, Washington, D.C.: National Academies Press, 2001.
[6]There were large differences in project scale, size, complexity, and time horizon between the energy efficiency and fossil energy programs. In particular, the fossil energy program tended to be characterized by relatively large, long-term projects.

selected 22 case studies that covered almost all of the research expenditures in DOE's Office of Fossil Energy (OFE) program since between 1978 and 1999. These case studies account for nearly $11 billion (73 percent) of the $15 billion appropriated to OFE for RD&D during the period.

NRC/NAS found that the most difficult analytic problem is assigning to DOE a proportion of the overall benefit of an R&D program that properly reflects DOE's contribution to it. In most of the case studies, DOE, industry, and sometimes other federal and nonfederal governmental research organizations contributed to the outcome of the research program. NRC/NAS found no reliable way to quantify the DOE contribution in most cases, and doing so remains a methodological challenge. For the purposes of the study, NRC/NAS simply attempted to specify in its case study analyses the specific role that DOE played -- the outcome that would not have happened had DOE not acted. Based on this assessment, the committee used conservative judgment to characterize the DOE contribution for purposes of developing findings and recommendations.

NRC/NAS found that research in OFE has historically focused on two programs: The Office of Coal and Power Systems and the Office of Natural Gas and Petroleum Technology. Very large budgets from 1978 through 1981 were provided in response to the energy crises of the 1970s and early 1980s. During that period, over 73 percent of the money was provided for technologies to produce liquid and gas fuel options from U.S. energy resources -- coal and oil shale. Over the 1978 to 2000 study period, 58 percent of the expenditures were for RD&D in coal utilization and conversion. Of this, approximately one-half was spent on direct liquefaction and gasification for building and operating large, commercial-scale demonstration plants between 1978 and 1981. In 1978, the coal conversion and utilization portion of the budget represented 68 percent of total fossil energy expenditures, but since then, as funding for direct liquefaction and gasification declined, it has represented a considerably lower percentage. In 2000, it represented only 30 percent of the overall fossil energy budget for the technology programs analyzed.

The share of OFE funds devoted to environmental characterization and control was about four percent of the total over the study period, partly because EPA maintained a large program in this area prior to 1985. The share of funds for the electricity production programs averaged 24 percent over the study period, and the share of funds for the oil and gas programs averaged 14 percent, one-third of which was for shale oil R&D in the early period.

NRC/NAS analyzed whether the benefits of DOE R&D programs justified the expenditures, and involved a comprehensive examination of the actual outcomes of DOE's research over two decades. NRC/NAS found that DOE's RD&D programs in fossil energy have yielded significant benefits, important technological options for potential application, and important additions to the stock of engineering and scientific knowledge. NRC/NAS also found that how DOE's research programs were organized and managed made a real difference to the benefits that were produced by the research.

NRC/NAS concluded that DOE FE RD&D programs over the period 1978-1999 produced economic benefits, options for the future, and knowledge benefits, and the net realized economic benefits in the energy efficiency and fossil energy programs were judged to exceed the DOE investment. NRC/NAS estimated that the realized economic benefits associated with the fossil energy programs that it reviewed amounted to nearly $11 billion (1999 dollars) over the 22-year period, 1978 – 1999, some of which it attributed to costs avoided by demonstrating that more stringent environmental regulation is unnecessary for waste management and for addressing airborne toxic emissions. The realized economic benefits of FE programs instituted from 1986 to 2000, $7.4 billion, exceeded the $4.5 billion cost of the programs. The committee found that DOE's RD&D programs in fossil energy have yielded significant benefits (economic, environmental, and national security-related), important technological options for potential application in a different (but possible) economic, political, and/or environmental setting, and important additions to the stock of engineering and scientific knowledge in a number of fields.

II.C. NETL 2002 Study

NETL noted that EIA annually produces forecasts of U.S. energy activities and that the forecasts are generated by the National Energy Modeling System (NEMS) and are published in the EIA's *Annual Energy Outlook* (AEO). AEO is based on a business-as-usual forecast, called the Reference case, of what is most likely to happen given existing legislation and known trends for economic, technological, and demographic growth. After producing the Reference case forecast, EIA reruns the Reference case with selected changes in the assumptions. These reruns, called "alternate" cases, selectively vary assumptions for economic growth, fuel supplies, and rates of improvements in energy technologies. Many of the alternate cases are designed to forecast the benefits of certain DOE R&D programs. One of the side cases, called the "High Fossil Electricity Technology" (HFET) case, assumes that the goals of fossil energy R&D programs are met for the following fossil-fuel electricity generating technologies: Advanced single-cycle combustion turbines, advanced natural-gas combined cycle (NGCC), and integrated coal gasification combined cycle (IGCC).

This 2002 NETL report provided a detailed analysis of the EIA HFET case.[7] The HFET case predicted that if the goals of DOE R&D programs are met for advanced fossil-fuel electricity generating technologies, these technologies will capture the majority (62 percent, 230 GW) of the market for new electricity generating plants over the next 20 years. Because these technologies generate electricity at lower costs, they will produce cumulative benefits exceeding $100 billion (year 2000 dollars) in electricity cost savings for U.S. consumers by the year 2020.

[7]Frank Shaffer and Melissa Chan, *Forecasting the Benefits of DOE Programs for Advanced Fossil-Fuel Electricity Generating Technologies: The EIA High Fossil Electricity Technology Case*, National Energy Technology Laboratory, October 2002.

Under the HFET case, by the year 2020 use of natural gas for electricity generation is 22 percent lower and natural gas prices are nine percent lower than in the AEO Reference case. Use of coal for electricity generation increases four percent by 2020 under the HFET case. Despite the reduced use of natural gas and increased use of coal for electricity generation under the HFET case, emissions of SO_2, NO_x, CO_2, and Hg do not increase (as compared to the Reference case) because of the higher generating efficiency and better pollution controls of advanced fossil-fuel electricity technologies.

The HFET case includes only the goals of DOE/FE programs for advanced fossil-fuel electricity generating technologies, and the cost and performance of all other technologies are the same as in the Reference case. The HFET case does not include the goals of DOE programs that will produce other advanced electricity generating technologies such as nuclear, renewables, or hydro. Thus, the HFET case provides a specific, targeted forecast of the benefits of DOE/FE programs only. The HFET case uses DOE/FE R&D program goals for the cost and performance of advanced single-cycle combustion turbines, NGCC, and IGCC.

NETL found that advanced fossil-fuel electricity generating technologies developed under FE programs will result in lower electricity prices and this will reduce the national average price of electricity. Under the HFET case, the average price of electricity will be 7% lower by the year 2020 than in the Reference case. Further:

- NETL estimated that, with 5,000 billion kWh of electricity generated in the U.S. in 2020, the 7% decline in the national average cost of electricity translated into a national savings of $19 billion in electricity costs (2000 dollars) in the year 2020. U.S. consumers will realize cumulative savings of more than $100 billion in electricity costs between 2010 and 2020.
- Advanced technologies with lower SO_2 emissions developed under FE programs will cause a reduction in the market price of SO_2 allowance permits, and the average SO_2 allowance price between 2000 and 2020 is predicted to be $230/ton under the Reference case and $187/ton under the HFET case.
- Advanced technologies with lower NO_x emissions developed under FE programs will create a slight (4.3%) reduction in national NO_x emissions by 2020 and a 17.4% reduction in the price of NO_x emissions allowances by 2020. National emissions of mercury were forecast to increase by 10% under the HFET case, and this was attributed to the use of a 35% mercury removal rate for IGCC.

II.D. Clean Coal Technology Roadmap, 2004

In 2004, the Department of Energy, the Electric Power Research Institute, and the Coal Utilization Research Council developed the Clean Coal Technology (CCT) Roadmap to develop a unified coal program roadmap, set performance/cost targets, specify destinations and critical technology needs, and quantify coal program benefits[8] The

[8]U.S. Department of Energy, the Electric Power Research Institute, and the Coal Utilization Research Council, "Clean Coal Technology Roadmap," 2004; National Energy Technology Laboratory, "Clean Coal Technology Roadmap: CURC/EPRI/DOE Consensus Roadmap, Background Information," April 20, 2004.

roadmap addressed the needs of both the existing fleet of coal-fired power plants and future near-zero emission plants: Current plants needed technologies to help meet current and emerging regulations for mercury, nitrogen oxides, and particulate matter, and future plants needed cost-effective technologies for near-zero emissions and managing CO_2. The roadmap was designed to

- Review current DOE and industry performance and cost
- Assess targets and develop a unified roadmap
- Span current state-of-the-art through 2020
- Incorporate current and emerging regulations
- Address existing fleet improvements and new plants
- Address fuels production and CO_2 management
- Estimate program benefits and compare these with costs

The key assumptions of the roadmap included:

- EIA coal power capacity forecasts were used as references
- The time period was 2004 to 2020
- The major goals were near-zero emission coal plants and CCS capability
- Roadmap destinations represent commercially available products not yet in widespread use
- 2020 environmental objectives represented best achievable performance
- Innovative, new technologies were needed to achieve new plant targets at costs competitive with alternative options having comparable environmental performance
- Technology applied to existing plants would improve environmental performance and maintain competitive electricity costs

Performance targets were identified for new coal-fired power plants and represented the best emission performance that would be available consistent with the integrated system efficiency and cost targets.

To estimate benefits, the roadmap selected five savings categories: Savings in fuel cost, savings due to the reduced capital cost of building new plants, savings in the cost of control technology used on existing plants, savings from avoided environmental costs from the reduction in emissions achieved by advanced technology, and increased technology exports resulting from more competitive U.S. technology. Actual avoided environmental costs for health, infrastructure, and agriculture depended on geographic location, urban vs. rural environment, and many other factors. Benefits were estimated only through 2020. Other benefits not included are knowledge products from the R&D, such as work by DOE contributing to a decision not to classify coal-ash by-products as a hazardous waste resulting in cost savings, savings in other business sectors due to implementation of advanced coal processing technology -- freeing natural gas use for other sectors, and potential savings if CO_2 regulations are enacted. The roadmap estimated that the CCT costs totaled about $10.7 billion, the benefits totaled about $100 billion, and the benefit-cost ratio was thus about 10-to-1.

II.E. NRC/NAS 2005 Study

Subsequent to the 2001 study, Congress funded NRC/NAS to build on the retrospective methodology developed to construct a methodology for assessing prospective benefits.[9] Three considerations were particularly important in formulating this project. One was that NRC/NAS adapt the work of the retrospective study. The second consideration was that NRC/NAS develop not only a methodology that is rigorous in its calculation of benefits and assessment of risks, but also a practical and consistent process for applying that methodology across a variety of DOE programs. The third consideration was that the methodology developed be transparent and easy to use and be cognizant of the resources required for implementation. NRC/NAS organized the project work into subtasks to:

- Review the methodologies for assessing R&D benefits developed by DOE, OMB, and other agencies.
- Propose a conceptual framework that captured the key features of prospective benefits evaluation.
- Appoint expert panels to apply the framework to three DOE programs.
- Evaluate the experience reported by the panels and modify the methodology accordingly.

NRC/NAS recognized that because the proposed methodology relies on expert opinion and analytic approximations, it leaves room for subjective judgments; however, it believed that eliminating such disagreements would be undesirable if not impossible. With the proposed methodology, NRC/NAS provided a structure for facilitating key judgments and a process that encourages consistent application of the structure. In addition, the methodology was designed to report the results of the analysis in a way that makes transparent the underlying assumptions and range of judgments. The methodology was not fully tested, but its use by the panels led to the identification of a number of inconsistencies and weaknesses in DOE's benefits estimates. NRC/NAS concluded that the consistent application of the methodology will improve the quality and comparability of benefits estimates in ways that should enhance the confidence that decision makers can place in the analysis.

II.F. Clean Coal Technology Demonstration Program Study, 2006

A 2006 NETL report presented a summary of sales data and projections that resulted from the Clean Coal Technology Demonstration Program (CCTDP).[10] The data were collected over the years from industry newsletters, journals, websites, and contacts

[9] National Research Council, *Prospective Evaluation of Applied Energy Research and Development at DOE (Phase One): A First Look*, Committee on Prospective Benefits of DOE's Energy Efficiency and Fossil Energy R&D Programs, Washington, D.C.: National Academies Press, 2005.
[10] *Sales and Benefits of Technology from Clean Coal Demonstration Projects*. National Energy Technology Laboratory, 2006.

with technology owners, users, and trade associations. Sales were included only for the demonstration technologies and those derived from those technologies.

The technologies that were demonstrated under the CCTDP were established in several broad categories: Environmental Control Technologies, Advanced Power Generation, Industrial Technologies, and Coal Processing for Clean Fuels. The study found that, in addition to maintaining an adequate supply of affordable electricity, the CCTDP resulted in several types of benefits to industry participants and the general public. These include technology sales, employment, improved health, and cleaner air. The CCTDP resulted in substantial sales for the private sector participants, and estimates of past and pending sales were derived. If no reliable sales prices or estimates could be obtained, the value of the sales was not included.

The report found that the CCTDP resulted in creation of many jobs: Temporary jobs were created during the construction phase of the demonstration projects and permanent jobs were created for those projects that continue to operate as commercial facilities. If actual data were not available, the number was estimated using a method suggested in a personal communication with a participant: The authors assumed that half of the plant cost is due to labor and that one man-year equals $200,000. Jobs resulting directly from the projects also resulted in indirectly induced jobs, which the Bureau of Labor Statistics Estimate Calculation Factors sets at 1.2 induced jobs for each direct job. In addition, a large number of jobs have been created and will continue to be created as the result of sales of the technologies. Specifically:

- Project construction created 1,871 direct jobs and 2,245 induced jobs
- Continued operations created 439 direct jobs and 526 induced jobs
- Technology sales created 66,799 man-years of employment
- Pending sales created 400,281 man-years of employment

Monetized health benefits due to improved air quality have been estimated in a number of reports including, "Estimating the Public Health Benefits of Proposed Air Pollution Regulations," by the NRC/NAS Board on Environmental Studies and Toxicology.[11] It was estimated that by 2010, compliance with the 1990 Clean Air Act Amendments (CAAA) will account for $107.9 billion in annual medical cost savings. The CCTDP has been instrumental in gaining compliance with many of the 1990 CAAA requirements with regard to NO_x, SO_2, and ozone. The monetized health benefits from reductions in those pollutants alone will amount to $1.96 billion annually. Applying this figure to the nine-year period from 1995 (Phase I compliance under the CAAA of 1990) to 2004 yielded a monetized health benefit of $17.6 billion.

[11]National Research Council, Board on Environmental Studies and Toxicology, "Estimating the Public Health Benefits of Proposed Air Pollution Regulations," Washington, D.C.: National Academies Press, 2002.

II.G. NETL National and Regional Impact Studies, 2007

II.G.1. NETL National Impacts

A 2007 NETL report documented the development of state-level input-output (I-O) models for Pennsylvania and West Virginia, a regional Pennsylvania/West Virginia (PA/WV) model, and the augmentation of the national I-O model with employment data.[12] NETL collaborated with Carnegie Mellon University (CMU) and West Virginia University (WVU) to conduct this report as part of the University Partnership program. The models were developed to assess the economic and environmental impacts of expenditures and employment at NETL and R&D awards originating from the NETL sites located in Pittsburgh and Morgantown. The scope of the analysis did not extend to the impacts related to the market adoption of NETL-sponsored technologies, nor did it include induced impacts, and the estimates of NETL's impacts derived in this study were thus considered to be conservative.

The primary goal was to develop a defensible and transparent means for routinely estimating national, state, and regional economic and environmental impacts derived from NETL employment and activity. The development of this methodology and these models allows NETL to assess its influence with respect to the various economic regions and to evaluate scenarios that represent alternative activity levels and expenditure allocations.

This analysis expanded NETL's analytical capabilities by producing economic models that allow the calculation of direct and indirect impacts of NETL's final demand on economic and environmental factors, as well as employment levels. In addition, the work conducted through this collaborative effort prepared the groundwork for future analyses to be completed using a consistent methodology.

The report noted that NETL is an important component of the PA/WV economy, and the models developed help to assess the regional impact of NETL activity as an economic catalyst. These models also provide the platform from which NETL could develop future model versions that could be used to evaluate the impact of technology developed by NETL.

The study noted that constructing new models for an economic and environmental analysis presented four primary challenges which led to the identification of several key decision points. The four primary challenges were: 10 Identifying quality data sets for economic and environmental parameters; 2) Selecting a methodology for regionalizing the national model; 3) Identifying and collecting NETL data sets; and 4) Defining sensible approaches to implementing the model.

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[12] *National, State, and Regional Economic and Environmental Impacts of NETL*, report prepared by Lisa Phares, National Energy Technology Laboratory, Deborah Lange and Christopher Hendrickson, Carnegie Mellon University, and Randall Jackson and David Martinelli, West Virginia University, DOE/NETL-404.02.01, June 30, 2007.

This project used I-O models to derive the economy-wide impacts of NETL's activity. The I-O construct used for these models is CMU's National Economic Input-Output (EIO) model, which allows for the estimation of both economic and environmental impacts of a supply-side change in the economy. To generate the regional tables for Pennsylvania, West Virginia, and the combined (Pennsylvania and West Virginia) region, the established location quotient (LQ) method was used in conjunction with the employment vectors

The data used to represent NETL's 2006 activity at the Pittsburgh, PA and Morgantown, WV sites included:

- Federal employment: 510 employees
- Federal wages and salaries: $56.4 million
- Federal operational expenditures: $80.8 million.
- Federal R&D award obligations: $752.4 million (all NETL sites)
- Federal R&D award costs: $535.0 million (all NETL sites)
- Site Support Contractor employment: 668 employees
- Site Support Contractor wages and salaries: $40.2 million
- Site Support Contractor expenditures: $13.6 million

The results derived showed that the economic output multiplier for the two-state regional model is 1.47. Thus, for every $1 million of NETL final demand that remains within Pennsylvania and West Virginia, the regional economy grows by $1.47 million. The regional employment multiplier of 2.7 indicates that for every employee at NETL, an additional 1.7 employees are needed throughout the two-state economy. Similarly, employment increases by about 20 persons for each $1 million that remains in the region.

Economic output multipliers reflect the region's ability to fulfill the requirements of an industry's supply chain. The study found that the output multiplier for the state of West Virginia is lower than those for the other regions, and this implies that the state economy of West Virginia is less able than the state of Pennsylvania to supply the direct and indirect inputs required by the Scientific Research and Development Services sector. The economic output multipliers generated in this study suggest opportunities for the region to expand through backward linkages so that the region may be more able to provide a greater proportion of regional industries' input needs in the future.

Alternative scenarios were also developed to determine potential impacts under a "buy-local" strategy. The buy-local strategy assumed that NETL will increase its share of Federal operational expenditures and/or allotment of R&D awards and grants that are spent in or granted to establishments in Pennsylvania and West Virginia. Nine alternative scenarios were defined and represented increasing the local shares of expenditures and/or awards by 50 percent, 100 percent, or 150 percent over their current share of total expenditures and awards. The impacts of the alternative scenarios were calculated only for the combined Pennsylvania and West Virginia region so as to limit the number of scenarios to a reasonable level.

The study found that, as expected, the multiplier on expenditures is consistent with the multiplier generated in the baseline scenario. This supported the underlying assumption of linearity that exists in IO models. Further, this result emphasized that the goal of the buy-local strategy is to increase intra-regional final demand. However, this type of impact does not change the inter-industry structure of the region, so the economic output multiplier remains static as the intra-regional final demand changes.

The report found that increasing the amount of expenditures and R&D awards injected into the local economy will spur growth and employment in the region. However, because total expenditures and R&D awards were held constant, direct employment was assumed to be unchanged, that is, changing the state in which expenditures and R&D awards are allocated did not change the number of needed employees. Therefore, indirect employment increased while direct employment was constant, resulting in higher employment multipliers. This study demonstrated the value of an accessible, flexible, multi-stakeholder tool which allows for routine evaluation of the economic and environmental impacts of NETL activities in Pittsburgh and Morgantown.

II.G.2. NETL Regional Impacts

Another 2007 NETL report noted that throughout Pennsylvania, West Virginia, and the U.S. NETL provides support for scientific R&D and for science education. Through these actions, and participation in the two-state economy from employment and operational activities, NETL serves as an important economic catalyst for the region. To quantify the laboratory's economic and environmental impacts on the combined Pennsylvania-West Virginia region, NETL developed a regional-level environmental input-output (IO) model.[13]

NETL estimated its direct impact on Pennsylvania and West Virginia's economy during 2006, including employment, wages, and salaries of Pennsylvania and West Virginia residents employed at NETL's sites in Morgantown, West Virginia and Pittsburgh, Pennsylvania. It also included NETL's direct operational expenditures and R&D award and grant monies spent within the region. The analysis determined that NETL directly supported the employment of 1,166 Pennsylvanians and West Virginians in 2006 and injected $192 million into the state economy.

Because the Pennsylvania and West Virginia economies supply a portion of NETL's total employment and operational demand, NETL activities produce extended (indirect) impacts on the region's economy. NETL estimated that the economic output multiplier for the Pennsylvania-West Virginia region is 1.47. Therefore, for every $1 million of NETL final demand that remains within the states of Pennsylvania and West Virginia, the regional economy grows by $1.47 million. The employment multiplier of 2.73 indicates that for every one employee at NETL, an additional 1.73 employees are needed throughout the region to fulfill the regional demands of NETL's supply-chain. This yields a total employment impact of 3,180 jobs. On an employment-per-dollar basis, the

[13]*National, State, and Regional Economic and Environmental Impacts of NETL: Pennsylvania-West Virginia Region*, U.S. Department of Energy, National Energy Technology Laboratory, September 2007.

analysis showed that employment increases by approximately 20 persons for each $1 million that remains in the region.

NETL's analysis excluded induced income impacts -- those resulting from households spending their salaries in the regional economy and also excluded impacts stemming from the deployment of NETL-sponsored technologies. Therefore, NETL's impact on the Pennsylvania-West Virginia region, as estimated in this study, is a conservative estimate.

II.H. Study of the Clean Coal Technology Program, 2009

In 2009, MISI analyzed the return on investment (ROI) of DOE's Clean Coal Technology (CCT) program for the period 2000–2020.[14] The CCT program is a government-industry partnership initiated to develop innovative technologies that meet strict environmental standards and allow electric power utilities and other industries to cleanly and efficiently use coal as an energy source. The program has a wide range of well-documented technological successes and has produced substantial benefits for U.S. taxpayers – benefits that far exceed the federal government's CCT investments. The benefits include cleaner air, reduced pollution, improved public health, increased energy efficiency, support for U.S. manufacturing, increased U.S. exports, enhanced national security, and job creation.

MISI estimated total costs to government and industry and quantified benefits for: (1) Reduced capital costs of advanced technologies in new plants; (2) Reduced capital and operating costs at existing plants to remain compliant with environmental regulations; (3) Reduced fuel costs due to higher efficiencies; (4) Avoided environmental costs; (5) The value of clean coal technology export sales; (6) Jobs created. It found that benefits over the 20-year period total $111 billion (2008 dollars); the benefits in individual categories range from $15 billion in fuel cost savings to $39 billion for capital and technology cost savings in new and existing plants; and that total jobs created exceed 1.2 million, with an annual average of about 60,000 jobs created. MISI also found that the ROI to DOE from the CCT program is favorable and is growing rapidly: By 2020, the cumulative DOE costs will likely total $8.5 billion, for an ROI of more than 13.

It is also significant to note that independent reviews of the CCT program over the years have found it to be an exemplary, well-managed program that is providing substantial benefits. For example:

[14]Management Information Services, Inc., *Benefits of Investments in Clean Coal Technology*, prepared for American Coalition for Clean Coal Electricity, Washington, D.C., October 2009; Roger Bezdek and Robert Wendling, "The Return on Investment of the Clean Coal Technology Program in the USA," *Energy Policy*, March 2013, Vol. 54, pp. 104-112.

- The U.S. General Accountancy Office – perhaps the most respected and skeptical critic of federal programs – has repeatedly found the federal CCT program to be exemplary and well managed.[15]
- These GAO findings are corroborated by NRC/NAS studies that concluded that the CCT programs are among DOE's most successful R&D programs and that they have produced benefits that far exceed the federal investments. In fact, since many R&D programs produce little or no quantifiable benefits, NRC/NAS found that most of the benefits of DOE's entire R&D program come from just a few programs. The coal-related R&D and technology program is one of those programs that produce very substantial benefits and contribute a disproportionately large portion of the total return on the entire DOE R&D program.[16]

These findings have implications beyond the CCT program. Based at least in part on the success of the CCT program, the federal government initiated major carbon control and sequestration (CCS) R&D, technology, and investment programs to address climate change concerns. The major objectives of these programs are to reduce the amounts of greenhouse gas emissions from coal-fired power plants and to develop economic methods of sequestering carbon dioxide (CO_2). The findings reported here with respect to the costs and benefits of the federal government's CCT program indicate that federal CCS investments will also produce significant benefits and will repay initial costs many times over.

Thus, MISI found that by any measure, the benefits of the CCT program vastly exceed the costs, and this favorable relationship increases in magnitude as time progresses. That is, the CCT program represents a cost effective investment for DOE, for industry, and for the nation as a whole. This is an important finding, and it is consistent with previous studies of CCT and DOE program costs and benefits. For example, DOE, Electric Power Research Institute (EPRI), and National Energy Technology Laboratory (NETL) research conducted over the past decade has found the CCT program to be a cost effective investment with benefits that substantially exceed costs.

In addition, if anything, the MISI estimates may actually underestimate the long term benefits of the CCT program. MISI did not include the potential benefits of CO_2 reductions in the CCT program benefits forecast here. If it had, the cumulative CCT benefits would have been $2 to $8 billion higher – depending on the anticipated price of CO_2 emissions. In the carbon-constrained future that appears increasingly likely, these CO_2-related benefits will become increasingly important.

Finally, basic economic principles suggest that the private sector undertakes research and commercializes technologies when private firms can capture economic benefits in excess of the costs of achieving them. Justification for public sector investment

[15]U.S. General Accounting Office, *Fossil Fuel R&D: Lessons Learned in the Clean Coal Technology Program*, GAO-01-854T, June 12, 2001; U.S. General Accounting Office, *Fossil Fuels: Lessons Learned in DOE's Clean Coal Technology Program,* GAO/RCED-94-174, May 26, 1994.
[16]National Research Council, op. cit.

in the CCT and CCS programs rests on the observation that the private sector cannot capture most of the benefits of these programs. Environmental and public health benefits not recognized in market prices provide an important example of this principle, but there are others, including the difficulty of capturing proprietary benefits from R&D. As demonstrated here, these and related public benefits strongly justify federal investments in the CCT and CCS programs.

More significant, MISI did not attempt to estimate the potential benefits that the CCT program could have by helping to maintain a relatively low-cost supply of reliable coal-based electricity. In states with high coal use (greater than 60 percent) the average cost of electricity is 30 – 40 percent less per kWh than in states with less than 50 percent coal use. Studies have shown that the benefits of lower-priced electricity over the next decade could total from $500 billion to $1 trillion and could include the creation of nearly 1 million additional jobs.[17]

II.I. NETL State and National Level Impacts, 2009

This project assessed the state and national level impacts of the NETL facilities located in Pennsylvania, West Virginia, and Oregon.[18] State and national impacts assessment of NETL FY 2008 employment, operations, and research funding were conducted using NETL employment and activity data as well as IMPLAN aggregated industry data. The project objective was to develop a means for regularly estimating state-level and national economic impacts generated by NETL employment as well as operational activities, onsite contractor support, and awards that support external research. The main goal of the project was to develop the underlying models, assessment methodologies, and a software tool that can be used for current and future impact assessments by NETL and the research partners on this task.

The report documented the development of state-level input-output models for Pennsylvania, West Virginia, and Oregon and the augmentation of the national input-output model that was developed previously for the project Valuing Domestically Produced Natural Gas and Oil.[19] The state I-O models were developed to assess the economic impacts of expenditures, employment, and R&D awards at the NETL sites located in Pittsburgh, PA, Morgantown, WV, and Albany, OR. The national I-O model was developed to assess the economic impacts of NETL site expenditures, awards, and employment at the national level.

The primary goal of the project was to develop a fully defensible and transparent means for routinely estimating state and national economic impacts derived from NETL employment and activity. The development of this methodology and these models allows

[17] *Coal: America's Energy Future*, Volume II, "Appendix: Economic Benefits of Coal Conversion Investments," National Coal Council, prepared by Professor Tim Considine, Pennsylvania State University, March 2006.
[18] Randall Jackson, Amanda Krugh, Brian LaShier, and Ronald Munson, "National and State Economic Impact of NETL," West Virginia University, Regional Research Institute, October 2009.
[19] National Energy Technology Laboratory, NETL, *Valuing Domestically Produced Natural Gas and Oil*, DOE/NETL-2009/1355, 2008.

NETL to assess its influence with respect to the regional economy and to evaluate scenarios that represent alternative activity levels and expenditure allocations.

The project expanded NETL's analytical capabilities by producing economic models that allow for the estimation of direct, indirect and induced employment, income, and output impacts, and total tax impacts. Further, the work conducted through this collaborative effort laid the groundwork for future analysis to be completed using a consistent methodology. I-O models were chosen for this project because they represent the economic relationships between all the sectors of the economy and because the underlying theory of I-O models has been well tested and documented.

This project provided a basis for annual laboratory impact assessments of NETL facilities, standardization of NETL data collection for annual impact assessments, and development of models and an assessment methodology that can be used by NETL and its partner research universities for current and future impact assessments. The project provided the means to identify geographic differences in impacts of changing economic structure, allows for the estimation of economic impacts of the actions of PA, WV, and OR NETL facility actions and job creation.

The project reported that the NETL job multiplier within the state of Pennsylvania was 6.5, was 5.8 within the state of West Virginia, and was 3.5 within the state of Oregon. For the U.S. as a whole, the NETL job multiplier was 19.0.

II.J. BBC Clean Coal Technologies Study, 2009

This BBC study, conducted for a coalition of labor and energy industry groups, estimated that the next generation of advanced clean coal technologies – those utilizing CCUS -- will create millions of high-skilled, high-wage jobs for American workers.[20] The purpose of this study was to illustrate the potential job and other economic benefits from the deployment of advanced coal-fueled electric generation using carbon capture and storage technologies ("CCUS-only benefits").

BBC estimated the employment and economic benefits resulting from deployment of advanced coal-based power plants equipped with CCUS technologies that reduce CO_2 emissions. Depending on how many CCUS-equipped plants are deployed, the report estimated that five to seven million man-years of employment could be created during construction and a quarter of a million permanent jobs added during operations.

[20]BBC Research and Consulting, *Employment and Other Economic Benefits from Advanced Coal Electric Generation with Carbon Capture and Storage*, report prepared for the Industrial Union Council, AFL-CIO; the International Brotherhood of Boilermakers, Iron Ship Builders, Blacksmiths, Forgers, and Helpers; the International Brotherhood of Electrical Workers; the United Mine Workers of America; and the American Coalition for Clean Coal Electricity, Denver, Colorado, February 2009.

The study assumed that 20, 65, and 100 GW of advanced coal-based electricity generation equipped with CCUS are added to the nation's generation mix. In addition, the study estimated the benefits of HR 6258, introduced by Representative Boucher in 2008, that provides independent funding for the early commercial demonstration of CCUS technologies. It estimated the capital, operating, and maintenance costs (O&M), jobs and other economic benefits associated with the deployment of advanced coal generation with CCUS.

BBC emphasized that, while development of wind and solar power are important, the only realistic course for the U.S. is to minimize CO_2 emissions from coal generation, which, along with nuclear power, will continue to be a vital part of the U.S. energy mix for the foreseeable future. It found that CCUS technology is essential for enabling the responsible use of U.S. strategic coal reserves -- a resource essential if the nation is to make energy independence a reality. It demonstrated that CCUS also has the potential to create thousands of good paying jobs for many union building trades.[21]

The results of this study illustrated the importance of deploying CCUS technologies, not only because of their potential to reduce GHG emissions, but also because of their substantial economic and job benefits. BBC also emphasized that it must be ensured that these technologies are developed and commercialized as rapidly as possible to achieve the estimated benefits.

The analysis found that development and broad deployment of CCUS technologies can be a key part of a national strategy to reduce CO_2 emissions and address climate change concerns. It also found that initiatives to reduce GHG emissions are likely to stimulate the deployment of new, advanced coal generation facilities with carbon capture and storage, provided CCUS technology development is successful and timely.

In addition to environmental benefits, this study also showed that the development and deployment of CCUS technologies can serve as an economic stimulus. Study results were developed at the national level to illustrate the potential magnitude of job, GDP, and income benefits associated with the construction and operation of these new advanced coal-fueled electric generation technologies.

The study also analyzed HR 6258, the "Early Carbon Capture and Storage Commercial Demonstration Act of 2008," which is designed to advance the commercial deployment of advanced coal CCUS facilities. It estimated that, assuming that the proposed $10 billion in funding under HR 6258 for early commercial deployment of CCUS technology leads to development and operation of six plants:

- Including multiplier effects, construction would stimulate between $33 billion and $36 billion in total economic output, about 225,000 total job-years of employment, and about $12 billon in labor income.

[21]The authors recommended that policymakers recognize these findings as they move forward in regulating greenhouse gas emissions, and take appropriate steps to encourage the commercialization of CCS technology.

- Ongoing operations and maintenance would support about 7,500 permanent jobs throughout the economy and about $500 million in annual labor income.
- Economic benefits would occur in virtually all sectors of the economy, but the largest number of jobs from new facility development would be in the construction, manufacturing, and professional services sectors.
- The largest number of jobs supported by ongoing operations would be in mining, transportation, and utilities.

II.K. DOE Fossil Energy Benefits Study, 2013

DOE found that FE R&D helped increase domestic energy supplies and security, lowered costs, improved efficiencies, and enhanced environmental protection over the past 30 years, including:[22]

- Pioneering EOR technologies that contribute 13% of total U.S. oil production as well as a means for injecting and permanently storing CO_2 in geologic formations.
- Producing 20 innovative technologies – such as low NO_x burners, flue gas desulfurization, and fluidized bed combustion – through the CCTDP, 1986-93, many of which are now in the marketplace and benefitting energy production and air quality improvements.
- Advancing drilling, fracturing, and environmental technologies that have helped oil and natural gas production from abundant shale resources increase significantly over the past decade.
- Developing methane hydrate research to the point where U.S resources have been identified, exploration models tested and confirmed, and production concepts refined and ready for initial field testing.
- Amassing extensive expertise and advisory capability in ultra-deepwater resource location, production, safety, and environmental protection, helping these energy sources to now account for 32% of domestic crude oil production and 13% of total dry gas production.
- Achieving advances in numerous other areas critical to U.S. energy production and environmental protection, including coal bed methane; the recycling and reuse of solid waste materials from coal combustion; proving the readiness of activated carbon injection to meet expected air quality regulatory standards for coal-based mercury emissions; and pioneering advanced turbine technologies.

II.L. Jobs Benefits of Increasing the Efficiency of Coal Power Plants, 2013

In 2013, MISI published findings from research for NETL that estimated the potential economic and jobs impacts of a U.S.-wide coal power plant efficiency improvement program (CPPEI).[23] Specifically, MISI estimated the costs of coal power

[22] https://www.energy.gov/fe/about-us/benefits-research.

[23] Roger Bezdek and Robert Wendling, "Economic, Environmental, and Job Impacts of Increased Efficiency in Existing Coal-Fired Power Plants," *Journal of Fusion Energy*, Volume 32, Number 2 (April 2013), pp. 215-220.

plant efficiency improvements, estimated the costs of a widespread coal power plant efficiency improvement program, and assessed the potential impacts of the program, including the jobs created by the program and the potential occupational impacts. MISI found that a five percentage point increase in the efficiency of the U.S. coal plant fleet is equivalent to increasing total coal plant fleet generating capacity by about 15%. It found that in 2017, about 42,000 jobs would be created in the U.S.

The electricity price-induced jobs created by the CPPEI program are orders of magnitude greater than the jobs impacts of the construction, O&M, and mining activities. Under one option simulated, the more electricity generation option, in the year of maximum impact (2019) a total of about 42,100 construction and O&M jobs would be created, and in 2020, and thereafter, about 1,500 permanent O&M jobs would be maintained. Under the other option simulated, the equal amount of electricity generation option, in the year of maximum impact (2019) a total of about 30,100 construction and O&M jobs would be created, and in 2020, and thereafter, about 10,500 jobs would be permanently lost. Clearly, the job impacts of the CPPEI program resulting from lower electricity costs would overwhelm by orders of magnitude the impacts resulting from construction, O&M, and coal mining.

This finding and the estimates provided of the likely magnitude of the impacts are significant and have potentially far-reaching implications. First, the major economic and job impacts of the CPPEI program would result not from the retrofit construction and O&M activities. Rather, while these would be important -- especially at the local and regional level where the retrofitted plants are located, they would be literally swamped by the effects on the economy that CPPEI would have in increasing the availability of low-cost electricity. Second, and at least as important, these findings may indicate a need to rethink current estimates of the impact of energy costs on the economy and of the likely effects of environmental policies that would greatly increase these costs and reduce coal utilization.

MISI determined that, even on the basis of the preliminary results developed, some things are clear. Most of the focus on the economic and job impacts of different types of energy programs and initiatives is often on the effects of program expenditures. While these can be large, especially for multi-billion dollar programs, the findings here indicate that these effects may likely be overwhelmed by orders of magnitude by the impact of these programs on energy and electricity prices. This issue is too little explored and poorly understood. Further, even when these effects are recognized, the remedies proposed often miss the mark. For example, in the current debate over GHG control legislation it is generally recognized that a cap-and-trade program would increase electricity prices. Although estimates of the magnitude vary, in some states for some utility customers electricity prices could double. The remedies for this are often advanced as means to reimburse electricity consumers for part of the cost increase and to protect low income consumers who may be especially hard hit by the electricity price increases. While these are important concerns and the feasibility and efficacy of such policies need to be debated, the whole discussion misses the main point.

As MISI demonstrated here, the major negative impact that should be of concern is the impact on industry, business, commerce, and the economy of these anticipated energy cost increases. Policies that forcibly and significantly reduce coal-fired electricity production may have serious negative consequences for the U.S. economy and for jobs. MISI found that for every 1% reduction in coal generated electricity, somewhere between about 24,000 and 36,000 jobs may be at risk. One does not have to accept these estimates at face value to be concerned. Even if they are high, the implications are ominous. For example, even using the mean estimate, a 20% reduction in coal generation could cause an annual, permanent net job loss of nearly 500,000. And some GHG control proposals could cause coal generation to decrease by much more than 20%.

II.M. National Coal Council Study, 2015

In 2015, the National Coal Council (NCC) assessed the benefits and accomplishments of the DOE CCS/CCUS Program: [24]

- Post Combustion Carbon Capture: Emphasis on post combustion capture is appropriate given the large amount of existing combustion capacity in the U.S. and throughout the world. The National Carbon Capture Center (NCCC) provides a valuable resource for the DOE program and developers utilizing the NCCC, and developers from around the world are utilizing the NCCC. There has also been success in advancing amine scrubbing. Another post combustion capture technology that has advanced is Alstom's chilled ammonia process. The most evident progress in the carbon storage program can be seen in the RCSP program.
- Advanced Combustion: DOE is developing advanced combustion technologies that, when coupled with CO_2 capture, are highly efficient energy conversion platforms that significantly reduce the energy penalty and costs when capturing CO_2. Such technologies include oxy-combustion and chemical looping. Oxy-combustion, in particular, appears to be relatively advanced, with a number of projects underway or planned worldwide. In the early 2000s, DOE supported a 3 MW testing of oxy-CFB, as well as extensive technical/economic studies of oxy-combustion power plants evaluated against alternate CCS approaches. Starting in 2008, a comprehensive program was launched that focused on utility scale oxy-combustion power plants based on tangentially fired boilers.
- Progress is also being made in the development of chemical looping and pressurized oxy-combustion technologies.
- CCS/CCUS Demonstration Programs: There is currently only one commercially operating CCS/CCUS demonstration project of 1 million tons/year capacity supported by DOE: The Air Products Port Arthur (Texas) project under the ICCS program. In June 2014, Air Products announced that it had successfully captured more than 1 million metric tons of CO_2 at Port Arthur for use in CO_2 EOR.

[24] National Coal Council, *Fossil Forward -- Revitalizing CCS*, Washington, D.C., 2015.

II.N. Union of Concerned Scientists Study, 2017

In 2017, the Union of Concerned Scientists (UCS) identified three major reasons why Congress should maintain support for federal energy R&D programs:[25]

1. Federal investments in energy R&D strengthen the economy and create jobs: 110,000 people are employed by DOE national labs, and universities currently receive 60% of their research funding from the federal government, helping to train the next generation of scientists and engineers in STEM education. DOE R&D leads to ideas and technology that entrepreneurs can pick up and run with. ONRL opened an office in Chattanooga in order to "link local companies to its resources and expertise." ARPA-E has been successful in overcoming the long-term and high risk barriers to developing innovative energy technologies. Since 2009, ARPA-E has funded over 400 energy technology projects. As of 2016, ARPA-E has formed 36 new companies, and 45 projects teams attracted more than $1.25 billion in private-sector follow-on funding.
2. Federal investments in energy R&D are critical to advancing new life-changing technologies. At DOE, decades of investments in R&D on hydraulic fracturing and horizontal drilling techniques have opened up unconventional oil and gas resources, leading to a dramatic decline in natural gas prices over the last ten years. These investments have fundamentally changed our electricity system. R&D for CCS is critical to making this technology cost effective. DOE's work modernizing the electricity grid is critical.
3. Federal investments in energy R&D demonstrate and maintain American leadership. Federal investments in R&D ensure that America maintains a competitive advantage globally.

II.O. Examples of NETL R&D Economic and Jobs Benefits, 2017

In 2017, MISI identified numerous NETL R&D program economic and jobs benefits.[26] For example, NETL helped develop stent material that resulted in the creation of manufacturing jobs at Carpenter Technologies in Reading, Pennsylvania. Carpenter Technology Corporation develops, manufactures, and distributes cast/wrought and powder metal stainless steels and special alloys including high temperature (iron-nickel-cobalt base), stainless, superior corrosion resistant, controlled expansion alloys, ultra-high strength and implantable alloys, tool and die steels, and other specialty metals, as well as cast/wrought titanium alloys. It also manufactures and rents down-hole drilling tools and components used in the oil and gas industry. It currently has annual revenues of $1.8 billion and a total of 4,500 employees worldwide – of which about 2,300 are in Reading.

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[25] Union of Concerned Scientists, "Three Reasons Why Federal Energy R&D is a Wise Investment," January 2017.

[26] Management Information Services, Inc., "Examples of Economic and Jobs Impacts of the 2017 NETL ALP," prepared for the National Energy Technology Laboratory, August 2017.

It is reasonable to assume that NETL's assistance facilitated about 5% of the Carpenter Technology jobs in Reading – about 115 jobs. Each job in steel manufacturing has a total U.S. national job multiplier of about 7 and a regional job multiplier of about 5.[27] Thus, MISI estimated that this NETL success helped create a total of about 575 jobs (direct and indirect) in the Reading area.

In 2017, Reading had an unemployment rate of 5% and had 10,200 unemployed workers. Thus, absent these NETL facilitated jobs, the unemployment rate in Reading would have been 5.3% instated of 5.0%. The net fiscal impact of the 575 jobs that would have been lost (or not created) includes tax revenue losses, unemployment compensation, SNAP, welfare payments, etc. and increases in various social problems.

Corrosion-related issues cost the U.S. economy $276 billion a year. NETL teamed with Carnegie Mellon University (CMU) to create a revolutionary, cost-effective technology to reduce that impact -- work that resulted in the creation of a new CMU/NETL spin-off that signed a licensing agreement with NETL. The new process, which electrodeposits aluminum using standard equipment available in most electroplating shops, is set to make its mark on the industry by replacing coatings based on heavy metals, such as cadmium and chromium, which are expensive and toxic. Electroplating is the process of depositing a metal coating onto an object by putting a negative charge on it and immersing it in a solution. Called the "Ionic Liquid Solvent for Aluminum Electroplating Process," the innovation has been licensed by LumiShield Technologies, a Pittsburgh-based CMU/NETL spin-off that was created based on the new technology. LumiShield specializes in corrosion-resistant metal products that are less expensive and less environmentally harmful than existing approaches.

NETL issued two licenses involving its Arc Position Sensing (APS) technology to KW Associates, LLC in 2016, an Oregon-based company founded by the technology's inventors. One license issued is exclusively for application to three fields of use: Steel, specialty steel and alloy processing, and industrial microwave processing. The second, non-exclusive license is for application to solid state energy systems and other high-temperature industrial processes. With these two licenses, KW Associates is building, testing, and selling APS systems.

APS technology is a patented, award-winning measurement technology developed for the specialty metals industry to identify arc distribution conditions during arc melting. The unique technology allows operators to optimize the processing to improve material yield, decrease energy use, and improve safety systems. Specialty metals, such as titanium or zirconium, that are used in aerospace, airline, and other advanced applications often undergo a metallurgical casting process called vacuum arc remelting (VAR) to refine an alloy's chemical and physical homogeneity. During the process, electrical power heats a consumable electrode by means of an electric arc -- a luminous electrical discharge like a lightning strike -- and the melting material drops into a water-cooled copper crucible. Poor processing can lead to defects in the resulting ingot; the defects, in turn, can cause

[27]Timothy J. Considine, "Economic Impacts of the American Steel Industry," University of Wyoming, 2011.

failure in engineering applications, so manufacturers must perform extensive testing on all ingots.

NETL's APS technology is a first-of-its-kind technology that can digitally monitor arc locations during VAR. Knowing where the arcs are helps the engineer control them and the melting process to produce consistently defect-free materials. Ultimately, the technology is expected to increase a manufacturer's yield and decrease the energy required to manufacture high-quality alloys.

NETL issued a license to Harbison Walker, International (HWI). HWI is one of the world's leading refractories materials and services providers, and is leader in the manufacture and supply of innovative refractories products for a wide range of industry applications presenting, among other things, challenging heat-intensive or chemically corrosive production environments. Headquartered in Pittsburgh, Pennsylvania, HWI has a network of 18 manufacturing facilities and 28 distribution centers to serve markets across North America, manufacturing facilities in the UK, Indonesia, and Mexico, as well as a lab and testing facility in China. Industries served include cement and lime, energy, chemicals, non-ferrous metals, glass, iron and steel, aluminum, copper, hydrocarbon and minerals processing, and environmental technology.

NETL executed licenses with Liquid Ion Solutions LLC, a Pittsburgh-based chemicals start-up, in 2016. CCS from fossil fuel-based power generation systems are critical strategic components to curb emissions of atmospheric carbon dioxide (CO_2). Currently available carbon capture processes are limited, and they significantly reduce the efficiency of power generation and increase electricity costs. Working in collaboration with partners at Carnegie Mellon University, NETL researchers developed a number of novel ionic liquids and polymers that provide a more efficient and economical process for CO_2 capture. The suite of technologies, covering the syntheses and use of ionic liquids, has been exclusively licensed to Liquid Ion Solutions.

In addition to CO_2 capture, ionic liquids have potential applications in areas including separation of chemical species from mixtures, batteries and fuel cells, solvents, coatings, lubricants, and biological systems. The company has initiated small-scale manufacturing of the materials for sale into a variety of research markets. The company is also focusing on collaborative research to further expand product applications in emerging industrial markets.

II.P. 2018 Congressional Support Letter, 2018

In 2018, two Members of Congress sent a letter to their colleagues stating that the FE R&D program has a proven record of accomplishment of developing and cultivating technologies that deliver real, tangible benefits.[28] This program is directly responsible for

[28]"Support FY19 Funding for the Bipartisan DOE's Carbon Capture & Fossil Energy Research and Development Program (FE R&D)," David B. McKinley, P.E. Mike Doyle, Members of Congress, March 12, 2018.

developing control technologies that are used at 75% of our domestic coal-burning power plants, which reduced SO_2 and NO_x by an average of 85%. DOE-supported R&D is needed to improve the efficiency and maintain the reliability of operations of existing units under a range of "cycling modes." This is why DOE's Coal R&D program is increasingly important as coal continues to face challenges both home and abroad

In addition, it is imperative that Congress ensures that ample funding is provided to DOE's Cross Cutting Program, a subprogram of the Coal CCS & Power Systems Program, which is aimed at improving the operations, efficiency, and environmental performance of advanced energy systems. Particularly important is the Ultra Supercritical Materials Program and the Supercritical CO_2 Materials Program.

Over the last 40 years, technology advances have led to impressive improvements in coal's environmental footprint. Compared to 1970, today's plants emit 95% less SO_2 and NO_x, and 90% less mercury. Significant advances also have been achieved in managing solid wastes from coal combustion. Today's modem coal-fueled power plants can achieve conversion efficiencies of 39% and more compared to coal plants constructed in the 1970's that achieved conversion efficiencies of 33% or less. These increases in efficiency alone result in more than a 15% reduction in potential CO_2 emissions.

II.Q. NETL National and Regional Impacts, 2018

NETL conducted an economic analysis using an input-output (I-O) model to quantify the laboratory's economic impacts on the United States in 2018.[29] NETL estimated the employment and salaries of individuals employed in the United States at NETL as either federal employees or site support contractors (full-time equivalents), as well as NETL's spending on grants, R&D awards, contracts, cooperative agreements, and purchase orders within the country. The analysis revealed that NETL injected $711 million directly into the nation's economy in 2018 and that its Federal employment and site support contractor (full-time equivalent jobs) totaled 1,180.

The analysis determined that the impact of NETL on the U.S. economy is greater than the total of the lab's direct spending, because money spent by NETL is spent again by the recipient employees and businesses. This economic "ripple effect" is captured in the model through a series of multipliers that provide estimates of the impact of each dollar of direct spending cycling through the national economy in the form of additional (indirect and induced) spending, personal income, and employment. It was found that NETL had a total estimated impact of $1,907 million on the U.S. economy in 2018 and created a total of 10,067 jobs.

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[29] National Energy Technology Laboratory, "Economic Impacts of NETL – United States," 2018, https://netl.doe.gov/sites/default/files/2019-05/National_Impact_Factsheet.pdf.

II.R. DOE Colorado CCUS Study, 2019

In 2019, DOE sponsored a techno-economic case study of adding CCUS to the Comanche Generating Station as a representative coal plant.[30] This preliminary analysis identified Colorado as an ideal location because it currently has existing natural CO_2 resources as well as pipeline infrastructure that is used to transport CO_2 to the Permian Basin for use in enhance oil recovery (EOR). The study also noted that the Comanche Generating Station (CGS) would be an ideal case study since it is the coal-fired power plant that is closest to a major CO_2 pipeline, the Sheep Mountain Pipeline, which originates at the Sheep Mountain natural CO_2 source field in Colorado.

Xcel Energy has developed the "Colorado Energy Plan" (CEP) portfolio, an electricity generating portfolio, as part of the company's 2016 Electric Resource Plan. Among the major components of the CEP are the proposed early retirement of 660 MW of two coal-fired generation units at the CGS: Unit 1 by the end of 2022, and Unit 2 no later than the end of 2025. Under the proposal, Unit 3 would remain in service. Xcel's CEP portfolio was approved by the Colorado Public Utility Commission (CPUC) in 2018.

This report was developed based on publicly available information to identify whether there was a business case for adding CCUS to existing coal plants in Colorado, using the CGS as a representative plant, and what the costs and benefits under the best business case scenario would be. The report examined the hypothetical scenario where all three of the CGS coal units would continue to operate after being retrofitted with carbon capture. In this scenario, the CO_2 captured from these units would be used for EOR in the Permian Basin. In addition, the report compared the likely economic and job impacts of CCUS retrofits of the three units of the CGS to the CEP and to a business as usual (BAU) scenario.

The impacts of the CCUS retrofit option and the CEP option were evaluated over 23 years, from 2020 to 2042. Compared to the CEP, the CCUS option:

- Reduces CO_2 emissions by 460 million metric tons (MMT), relative to baseline 2005 emission levels (65% reduction over 23 years). The CEP reduces CO_2 emissions by 369 MMT (52% reduction over 23 years),
- Generates $10.21 billion in CO_2 revenues,
- Creates 11,200 jobs in Pueblo; the CEP creates 3,100 jobs in Pueblo,
- Creates 18,600 jobs in Colorado; the CEP creates 13,300 job in Colorado.

In addition, from 2020 to 2042, the CCUS retrofit option:

- Increases Pueblo wage and salary earnings by over $500 million,
- Increases Colorado wage and salary earnings by more than $900 million,
- Increases Colorado income tax revenues by over $40 million,
- Increases Pueblo real estate tax revenues by nearly 60% -- by more than $800 million,

[30] Management Information Services, Inc. and Leonardo Technologies Inc., "Economic Impact Assessment of CCUS Retrofit of the Comanche Generating Station," prepared for the U.S. Department of Energy and the National Energy Technology Laboratory, June 2019.

- Transforms the Pueblo School District from a relatively poor one to one of Colorado’s wealthiest.

The analysis demonstrated that the CCUS retrofit option:

- Delivers lower-cost power for Xcel customers,
- Takes advantage of 45Q tax incentives,
- Accelerates the transformation to a low-carbon economy,
- Generates significant economic development in Pueblo and Colorado,
- Provides significant CO_2 reductions, and,
- Continues progress Colorado has made on cleaner air and reduces its carbon footprint.

Thus, the analysis found that the CCUS Retrofit Option would benefit Pueblo, the State of Colorado, and Colorado ratepayers. The report demonstrated a highly favorable business opportunity that supports further investigation of the potential for integration of CCUS technology.

III. DOE COAL RD&D PROGRAM EXPENDITURES, 1976 – 2020

III.A. Background

The U.S. has relied on coal as a major energy source for two centuries, and over the past decade it provided about one third of U.S. electricity and about one-sixth of its total energy supply.[31] Nevertheless, for many years the coal industry operated at relatively low earnings compared to other major U.S. industries. In addition, the industry lacked the highly specialized multi-disciplinary laboratories and skills required for effective research.

Over the past six decades, the federal government has funded a substantial coal research program, including RD&D for coal production, resource assessment, mining techniques, mining health and safety, coal utilization, coal liquefaction and gasification, clean coal technologies, CCUS, fuel cells, advanced technologies, Magnetohydro-dynamics, pollution control and abatement, and other programs. This research has been conducted at the Bureau of Mines (BOM) of the U.S. Department of the Interior, the U.S. Environmental Protection Agency (EPA), The Energy Research and Development Administration (ERDA), and DOE.

From the 1940s through 1996 (when it was abolished), the BOM conducted extensive RD&D pertaining to coal mining, preparation, and utilization and coking coal characteristics. This research included mining methods and systems, mechanization of operations, coal cleaning processes, and factors to increase the productivity of mines, as well as experiments in longwall mining, the use of diamond drills, and the development of roof bolting. For many years, the BOM made field and laboratory examinations and analyses of the chemical constituents of coal on a mine-by-mine basis and regularly published reports on them. In addition, the BOM developed improved coal treatment technologies to upgrade the quality of coal by reducing the amount of ash, sulfur, and other coal constituents.

The major market for coal (aside from exports) is the electric utility industry, which is meets requirements for electric power. Among the major factors limiting the use of coal are environmental regulations, particularly air pollution standards, which prescribe limits on particulates, sulfur dioxide, nitrogen oxide and other coal residuals and carbon dioxide. Accordingly, extensive research has been conducted within federal agencies to provide viable anti-pollutant processes, including different types of scrubbers, fluidized bed combustion, solvent refining and other processes. This includes expenditures by EPA -- in addition to those expended by the BOM, ERDA, and DOE -- for research to mitigate the environmental impact of using coal as a fuel, especially for electricity generation.

In addition to research and development on coal combustion techniques, DOE has engaged in extensive research on coal gasification, coal liquefaction, pulverized coal combustion, CCUS, and solvent refining. Considerable research also has been conducted by both the federal government and industry on the preparation of coal to

[31] U.S. Energy Information Administration, *Annual Energy Outlook,* various years, 2010 – 2020.

reduce impurities, including sulfur, as an alternative to post-combustion abatement. Research on new uses of coal, including low-rank coals such as lignite, has been conducted for many years.

The residual content of coal has become an increasingly important factor in the production and utilization of coal, as has the relative heating values (Btu) of coals, both in their direct relation to environmental regulations and their costs. Generally, coals of high Btu value command the highest prices.

III.B. The DOE Coal Research Program

DOE Coal RD&D includes a wide variety of technologies for promoting the use of coal in an environmentally responsible manner, recognizing the continued use of U.S. coal in coming decades. The objective of this program has been to conduct research necessary to strengthen the scientific and engineering technology base on which industry can draw in developing new products and processes. The program funds generic and technology-based research and development and environmental research. It supports experimental facilities with unique capabilities and includes pilot plants and test facilities. The research program provides for a limited federal role in support of longer-term, high-risk RD&D conducted at universities, national labs, and Energy Technology Centers, as well at private sector firms. The current program emphasizes CCUS and activities that increase the efficiency and availability of systems integrated with CCUS. Program activities, including NETL RD&D, support early-stage RD&D focused on:[32]

- Novel fossil-fueled power systems and components that improve the reliability and efficiency of new and existing units;
- Advanced materials and computational systems;
- Utilization of coal and CO_2 for the production of critical materials and products;
- Transformational CO_2 capture technologies applicable to both new and existing fossil-fueled facilities; and
- CO2 storage, with emphasis on storage in depleted oil and gas fields; offshore geologic reservoirs; and addressing injection challenges across all reservoir types.

Advanced Energy Systems and CCUS focus on solving the nation's most pressing fossil energy challenges by:

- Advancing the Coal FIRST (Flexible, Innovative, Resilient, Small, Transformative) initiative: RD&D on technologies for coal plants of the future that are highly efficient and flexible, with zero or near-zero emissions;
- Improving the performance, reliability, and efficiency of the existing coal-fired fleet;
- Reducing the cost and risk of carbon capture for commercial deployment; and,
- Creating new market opportunities for coal.

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[32]See Office of Chief Financial Officer, *Department of Energy FY 2021 Congressional Budget Request*, DOE/CF-0167, February 2020.

DOE's Office of Fossil Energy (OFE) has launched an effort -- the Coal FIRST (Flexible, Innovative, Resilient, Small, and Transformative) initiative -- to support RD&D insights and integrated designs of the coal plant of the future needed to provide secure, stable, and reliable power. The Coal FIRST initiative will make future coal-fired power plants more adaptive to the modern electric grid and eliminate emissions. The initiative is focused on early stage RD&D that benefits multiple technologies for use with different coal types and regions throughout the U.S. across a broader coal and power industry, including publically available reports on the results of the RD&D.

Through innovative technologies and advanced approaches to design and manufacturing, the initiative will look beyond today's utility-scale power plant concepts (e.g. base-load units) in ways that facilitate electrical grid integration both domestically and internationally. Modular Coal FIRST technologies could increase U.S. energy exports, create domestic jobs, and support our partners abroad -- reducing energy poverty in African and Asian nations, while providing affordable electricity and opportunities for economic prosperity to people worldwide.

DOE envisions that the future coal fleet may be based on electricity generating units possessing traits such as:

- Zero or near-zero emissions including carbon dioxide or even negative emissions when combined with biomass cofiring;
- High overall plant efficiency (40%+ HHV or higher at full load, with minimal reductions in efficiency over the required generation range);
- Small, high-quality, low-cost units that minimize field construction time;
- Ramp rates and minimum loads compatible with 2050 estimates of renewable energy integration;
- Integration with thermal or other energy storage (e.g., chemical production) to mitigate inefficiencies and equipment damage;
- Minimized water consumption;
- Accelerated design, construction, and commissioning schedules;
- Enhanced maintenance features, including technology advances with monitoring and diagnostics to reduce downtime;
- Integration with coal upgrading, or other plant value streams (e.g., co-production); and,
- Capable of natural gas co-firing.

The mission of the Advanced Energy Systems (AES) subprogram is to increase the availability, efficiency, and reliability of fossil energy power systems while maintaining environmental standards. Early-stage RD&D will focus on developing and testing power plant components; novel combustion processes; advanced coal processing; and advanced materials for components, turbines, and fuel cells that will improve the competitiveness of new and existing coal-fired power plants. Development of advanced coal power plants of the future will restore U.S. technical leadership in this area while maintaining the required technical advancements to service the existing fleet for grid stability. Specific efforts will focus on seven RD&D activities:

- Advanced Combustion/Gasification Systems;

- Advanced Turbine;
- Solid Oxide Fuel Cells;
- Advanced Sensors and Controls and Other Novel Concepts;
- Advanced Coal Processing;
- Advanced Energy Materials; and,
- Power Generation Efficiency.

The Crosscutting Research subprogram advances and accelerates promising fossil energy technology by supporting innovative early-stage RD&D that improves the reliability, availability, efficiency, and environmental performance of advanced fossil-based power systems. The program also aims to obtain new knowledge regarding plant performance and operation that can be incorporated into a new generation of plant control technologies. Crosscutting Research is focused on six activities:

- Critical Minerals (CM);
- Water Management RD&D;
- Modeling, Simulation and Analysis;
- Advanced Energy Storage Initiative (AESI);
- University Training and Research (UTR), which comprises funding for University Coal Research (UCR), Historically Black Colleges and Universities (HBCU) and other Minority-Serving Institutions (MSI); and,
- International Activities.

The CCUS subprogram is focused on early-stage RD&D that reduces the cost of capturing CO_2 from fossil industrial sources and from the atmosphere, systems that result in negative CO_2 emissions; advances approaches to safely and securely store CO_2 underground long-term; and advances novel approaches to using CO_2, such as developing useable products and fuels. Specifically, carbon capture RD&D is focused on the development of transformational CO_2 separation technologies -- membranes, sorbents, solvents, and cryogenic -- for both pre- and post-combustion coal-fired power plants systems that will capture CO_2 at approximately $30 per ton. The program will also use its previous and existing CCUS RD&D efforts for other applications such as natural gas power, industrial sources, and negative emissions technologies such as direct air capture.

Many of the technologies developed for pre- and post-combustion carbon capture can be applied to these sectors. Carbon utilization RD&D is focused on using captured CO_2 and/or carbon-containing substances, or directly using CO_2 from flue gas or other gas streams, and conversion into valuable products. Carbon storage RD&D supports the development and testing of advanced sensing and data telemetry capabilities, fault/fracture network characterization, stress state, fluid/pressure migration, and wellbore integrity that advanced real-time, decision-making capabilities. A goal of the CCUS subprogram is to support a new coal-fired plant with CO_2 capture at a cost of electricity at least 30% lower than a supercritical pulverized coal (PC) with CO_2 capture, or approximately $30 per ton of CO_2 captured by 2030. For existing plant retrofits, the subprogram's goal is to reduce the cost of capture by 30% (actual cost of capture varies for each unit).

The National Energy Technology Laboratory (NETL) coal RD&D program funds all NETL in-house research efforts. In addition to supporting research capabilities in the areas of computational engineering, material engineering and manufacturing, and geological systems, the program funds collaboration activities with universities, other national laboratories, state and local governments, and industry. NETL will use funding to explore collaborative models for partnerships with other laboratories, industry, and academia in accordance with laws, regulations, and policies. This program also encompasses strategic energy analysis and research data management activities.

III.C. Current and Constant Dollar Estimates

This analysis spans a period of five decades (1976–2020), during which the general price level in the United States increased nearly four-fold. Further, price increases were not distributed uniformly over the period. Thus, the only meaningful way to compare and analyze federal energy expenditures over this period is to use values expressed in constant dollars. It would be misleading to equate a dollar expended in 1980 with one spent in 2019, since the price level in the latter year is more than 2.5 times that of the former year. Aside from the general distortions, use of current dollar data in the analysis would, for example, seriously undercount coal RD&D expenditures incurred during the 1970s and early 1980s, which were substantial, and overestimate RD&D expenditures in more recent years. Therefore, throughout this report all the estimates given are stated in constant 2019 dollars.

MISI derived the constant 2019 dollar data (2019 = 1.00) using GDP deflators to convert current dollar data into 2015 base year estimates. It is preferable in an analysis such as this to use the GDP deflators instead of the more widely known U.S. Consumer Price Index (CPI) deflators.

The CPI is a measure of the average change in prices over time in a fixed “market basket” of goods and services purchased either by urban wage earners and clerical workers or by all urban consumers, and is compiled by the Bureau of Labor Statistics (BLS) of the U.S. Department of Labor.[33] The index is based on prices of food, clothing, shelter, fuels, transportation fares, charges for doctors’ and dentists’ services, drugs, etc., purchased for day-to-day living. In calculating the index, each item is assigned a weight to account for its relative importance in consumers’ budgets. Price changes for the various items in each location are then averaged. The CPI is the most widely publicized measure of inflation, and it is broad-ranging and readily comprehensible. However, the implicit GDP deflator is the most comprehensive price index available not the CPI.

The implicit price deflator (IPD), compiled by the Bureau of Economic Analysis (BEA) of the U.S. Department of Commerce, is a by-product of the deflation of GDP and is derived as the ratio of current- to constant-dollar GDP (multiplied by 100).[34] It is the weighted average of the detailed price indices used in the deflation of GDP, but they are

[33]U.S. Bureau of Labor Statistics, “Consumer Price Index,” https://www.bls.gov/cpi/.
[34]U.S. Bureau of Economic Analysis, “Implicit Price Deflator,” https://www.bea.gov/help/faq/513.

combined using weights that reflect the composition of GDP in each period. Thus, changes in the implicit price deflator reflect not only changes in prices but also changes in the composition of GDP. It is issued quarterly by BEA.

The IPD is not independently derived by a direct price collection program. Rather, as noted, it represents the ratio between current-dollar GDP and constant-dollar GDP multiplied by 100. The result is an aggregate price index that is affected by changing expenditure patterns each year.

Because of its indirect derivation, the quality of the IPD is closely correlated to that of the various price series used in converting national output to constant dollars. In contrast, the CPI is a fixed weight index in which the contents of the “market basket” are kept constant over a long period (five to 10 years). It is specifically designed to measure directly changes in prices of identical or comparable items over time. Conceptually, the IPD measures the general price level of all final goods and services (including government) produced during a specific period. Thus, the IPD is the only official index that attempts to measure overall price behavior of all goods and services in the nation. The CPI is restricted to a narrower universe. The movement of the IPD usually closely parallels the movement of the CPI but is rarely identical to it. The implicit GDP deflators are the ones used in this study, and the deflators for 1975 - 2019 are listed in Table III-1.[35]

[35]FY20 expenditures were deflated incorporating a preliminary projection of a 2.0% annual increase in the 2020 calendar year GDP deflator.

Table III-1
U.S. Gross Domestic Product Deflators, 1975 - 2019
(2019 = 100)

Year	Deflator	Year	Deflator
1975	26.57	1998	66.80
1976	28.03	1999	67.83
1977	29.76	2000	69.37
1978	31.85	2001	70.95
1979	34.48	2002	72.04
1980	37.59	2003	73.48
1981	41.10	2004	75.50
1982	43.65	2005	77.92
1983	45.38	2006	80.32
1984	46.99	2007	82.46
1985	48.49	2008	84.07
1986	49.47	2009	84.71
1987	50.73	2010	85.75
1988	52.51	2011	87.52
1989	54.55	2012	89.13
1990	56.57	2013	90.57
1991	58.45	2014	92.19
1992	59.78	2015	93.18
1993	61.20	2016	94.14
1994	62.51	2017	95.95
1995	63.81	2018	98.25
1996	64.97	2019	100.00
1997	66.09		

Source: U.S. Bureau of Economic Analysis and Management Information Services, Inc.

III.D. DOE Coal RD&D Expenditures, 1976 - 2020

The major DOE coal RD&D program components supported since 1976 include:

- Gasification Combined Cycle
- Pressurized Fluid Bed
- Fuel Cells
- Carbon Capture and Sequestration
- Transportation Fuels and Chemicals
- Control Technology and Coal Preparation
- Advanced Research and Technology Development
- Coal Liquefaction
- Combustion Systems
- Heat Engines

- Magnetohydrodynamics
- Surface Coal Gasification
- Underground Coal Gasification
- Mining RD&D
- Advanced Environmental Control Technology
- FutureGen
- Clean Coal Power Initiative
- Advanced Turbines
- Advanced Energy Systems
- Cross Cutting Research
- Supercritical CO_2 Technology (STEP)
- CCUS
- Transformational Coal Pilots

These expenditures, in 2019 dollars, for the period 1976 – 2020 are given in Tables III-2 through III-8.

Two caveats should be noted:

1. For the past five decades, as discussed, both DOE/ERDA and EPA conducted substantial coal/environmental RD&D. In particular, EPA maintained a large RD&D program in environmental characterization and control – although for about the past two decades these expenditures have been very small compared to DOE coal RD&D expenditures. MISI did not include the EPA coal/environmental expenditures. The objective of the MISI project is to assess the benefits and costs of the DOE coal RD&D program.
2. From 1976 through 1996, as discussed, the BOM conducted extensive coal RD&D. MISI also excluded BOM coal RD&D expenditures, since the objective of the MISI project is to assess the benefits and costs of the DOE coal RD&D program.

Table III-2
U.S. DOE RD&D Expenditures for Coal, by Major Program, FY1976-FY1988
(millions of 2019 dollars)

	FY76	76tq	FY77	FY78	FY79	FY80	FY81	FY82	FY83	FY84	FY85	FY86	FY87	FY88
Control Technology & Coal Preparation	--	--	--	--	--	--	--	61	66	59	79	69	79	89
Advanced Research & Technology Development	136	35	160	171	145	175	132	138	85	89	89	70	66	51
Coal Liquefaction	381	99	406	380	651	620	875	563	90	66	57	69	51	54
Combustion Systems	180	54	204	232	187	217	160	100	57	42	66	61	30	51
Heat Engines	--	--	--	--	184	182	119	37	13	15	27	27	24	37
Magnetohydrodynamics	132	35	147	246	189	234	211	69	69	69	68	59	57	70
Surface Coal Gasification	302	61	524	722	506	493	286	132	91	85	70	87	52	45
Underground Coal Gasification	--	--	--	--	47	29	27	20	14	14	16	9	5	6
Mining Research & Development	--	--	189	211	240	195	113	28	--	--	--	--	--	--
Advanced Environmental Control Tech	--	--	--	--	22	69	132	--	--	--	--	--	--	--
Miscellaneous	148	45	84	16	--	14	14	--	--	--	--	--	--	--
U.S. DOE RD&D	1,279	329	1,713	1,979	2,170	2,229	2,068	1,148	485	440	472	451	366	404

Source: U.S. Department of Energy and Management Information Services, Inc.

Table III-3
U.S. DOE RD&D Expenditures for Coal, by Major Program, FY1989-FY1997
(millions of 2019 dollars)

	FY89	FY90	FY91	FY92	FY93	FY94	FY95	FY96	FY97	Total FY76-FY97
Control Technology & Coal Preparation	96	107	99	87	72	75	66	54	45	1,205
Advanced Research & Technology Development	51	47	55	52	45	47	38	31	27	1,936
Coal Liquefaction	61	65	76	68	62	42	42	23	15	4,817
Combustion Systems	52	61	66	66	62	75	68	68	48	2,207
Heat Engines	44	38	43	30	6	--	--	--	--	828
Magnetohydrodynamics	72	73	70	69	51	8	--	--	--	1,999
Surface Coal Gasification	43	43	27	17	17	27	16	13	10	3,671
Underground Coal Gasification	1	1	1	--	--	--	--	--	--	190
Mining Research & Development	--	--	--	--	--	--	--	69	8	1,053
Advanced Environmental Control Tech	--	--	--	--	--	--	--	--	--	223
Miscellaneous RD&D	--	--	--	--	--	--	--	--	--	322
U.S. DOE RD&D	421	436	437	391	316	273	231	258	154	18,450

Source: U.S. Department of Energy and Management Information Services, Inc.

Table III-4
U.S. DOE RD&D Expenditures for Coal, by Major Program, FY1998-FY2000
(millions of 2019 dollars)

	FY98	FY99	FY00	Total FY98–FY00
Advanced Electric Power Systems	111	131	114	356
Advanced Pulverized Coal Technology	26	21	2	49
Indirectly Fired Cycle	6	12	10	28
Gasification Combined Cycle	33	48	50	131
Pressurized Fluid Bed	28	21	17	66
Advanced Research and Environmental	19	29	34	82
Advanced Clean Fuel Research	22	22	28	72
Coal Preparation	6	6	5	16
Coal Liquefaction	10	14	10	35
Steelmaking Feedstock	5	--	10	15
Advanced Research and Environmental	1	2	2	6
Advanced Research and Tech Development	28	30	33	91
Fuel Cells	61	65	65	191
Miscellaneous RD&D	10	10	9	30
U.S. DOE RD&D	232	259	250	741

Source: U.S. Department of Energy and Management Information Services, Inc.

Table III-5
U.S. DOE RD&D Expenditures for Coal, by Major Program, FY2001-FY2003
(millions of 2019 dollars)

	FY01	FY02	FY03	Total FY01–FY03
Clean Coal Power Initiative	--	204	199	404
Central Systems	285	131	127	542
Innovations for Existing Plants	29	31	30	91
Advanced Systems	120	100	97	317
Integrated Gasification Combined Cycle	59	59	59	178
Pressurized Fluidized Bed	16	15	14	45
Turbines	44	26	23	93
Power Plant Improvement Initiative	135	--	--	135
Sequestration	28	44	54	126
Fuels	33	45	42	120
Transportation Fuels and Chemicals	12	35	29	76
Solid Fuels and Feed stocks	5	6	9	20
Advanced Fuels Research	6	5	3	14
Steelmaking	10	--	--	10
Advanced Research	42	44	44	131
Coal Utilization Science	9	9	13	31
Materials	10	10	13	34
Technology Crosscut	17	15	15	48
Other Advanced Research	5	9	3	17
Fuel Cells	76	79	80	236
Miscellaneous RD&D	14	20	20	54
U.S. DOE RD&D	477	568	567	1,612

Source: U.S. Department of Energy and Management Information Services, Inc.

Table III-6
U.S. DOE RD&D Expenditures for Coal, by Major Program, FY2004-FY2010
(millions of 2019 dollars)

	FY04	FY05	FY06	FY07	FY08	FY09	FY10	Total FY04–FY10
Clean Coal Power Initiative	227	62	63	72	83	343	--	850
Central Systems	120	101	125	--	--	--	--	346
FutureGen	--	--	--	65	89	--	--	154
Innovations for Existing Plants	--	--	--	20	43	58	61	182
Advanced IGCC	--	--	--	68	65	75	73	281
Advanced Turbines	--	--	--	119	143	174	181	617
Sequestration	54	57	84	23	29	33	37	317
Fuels	42	40	36	27	30	28	29	232
Fuel Cells	92	97	78	77	66	66	58	535
Advanced Research	50	54	48	40	44	33	33	301
U.S. DOE RD&D	585	411	434	511	594	809	472	3,816

Source: U.S. Department of Energy and Management Information Services, Inc.

Table III-7
U.S. DOE RD&D Expenditures for Coal, by Major Program, FY2011-FY2016
(millions of 2019 dollars)

	FY11	FY12	FY13	FY14	FY15	FY16	Total FY11–FY16
Carbon Capture	67	75	71	97	94	107	511
Carbon Storage	137	126	118	115	107	113	716
Advanced Energy Systems	192	109	102	108	111	112	734
Cross Cutting Research	47	54	50	45	53	54	303
Supercritical CO_2 Technology	--	--	--	--	11	16	27
NETL Coal RD&D	--	40	46	55	54	56	250
U.S. DOE RD&D	443	404	387	420	429	457	2,540

Source: U.S. Department of Energy and Management Information Services, Inc.

Table III-8
U.S. DOE RD&D Expenditures for Coal, by Major Program, FY2017-FY2020
(millions of 2019 dollars)

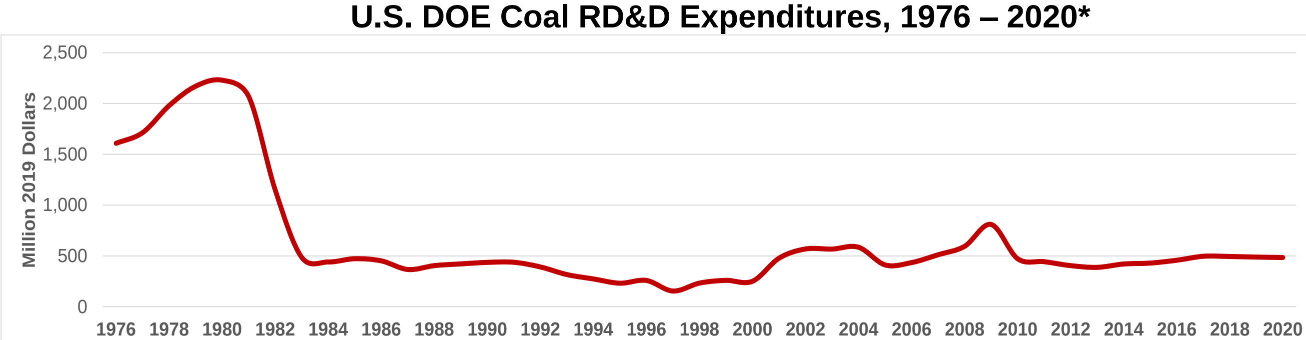
	FY17	FY18	FY19	FY20*	Total FY17–FY20
Advanced Energy Systems	123	143	159	148	572
Cross Cutting Research	51	47	46	48	193
CCUS	205	204	200	215	824
STEP (Supercritical CO_2 Technology)	25	25	22	16	88
Transformational Coal Pilots	52	36	25	20	133
NETL Coal RD&D	40	39	36	37	152
U.S. DOE RD&D	496	494	488	484	1,962

*FY20 expenditures were deflated incorporating a preliminary projection of a 2.0% annual increase in the 2020 calendar year GDP deflator.

Figure III-1 shows the history of the DOE coal RD&D budget from 1976 through 2020 and illustrates the trajectory of RD&D spending over the past five decades. It shows that over the period, the cumulative budget totaled $29.12 billion (2019 dollars), but the distribution of expenders was very uneven. For example, in 2019 dollars:

- Funding rose substantially from 1976 to 1980, reaching a high of $2.23 billion in the latter year.
- It then decreased dramatically to $440 million in 1984.
- Funding ranged between $440 and $470 million in the period 1984 to 1991.
- It decreased continually from 1991 to 1997, reaching an all-time low of $154 million in 1997.
- Funding then increased to $585 million in 2004.
- It decreased and then increased again reaching its highest level since 1984 in 2009 -- $809 million.
- Funding ranged between about $400 million to $500 million from 2010 to 2020

Figure III-1
U.S. DOE Coal RD&D Expenditures, 1976 – 2020*



*1976 transition quarter (TQ) funding included in the year 1976 budget.
Source: U.S. Department of Energy and Management Information Services, Inc.

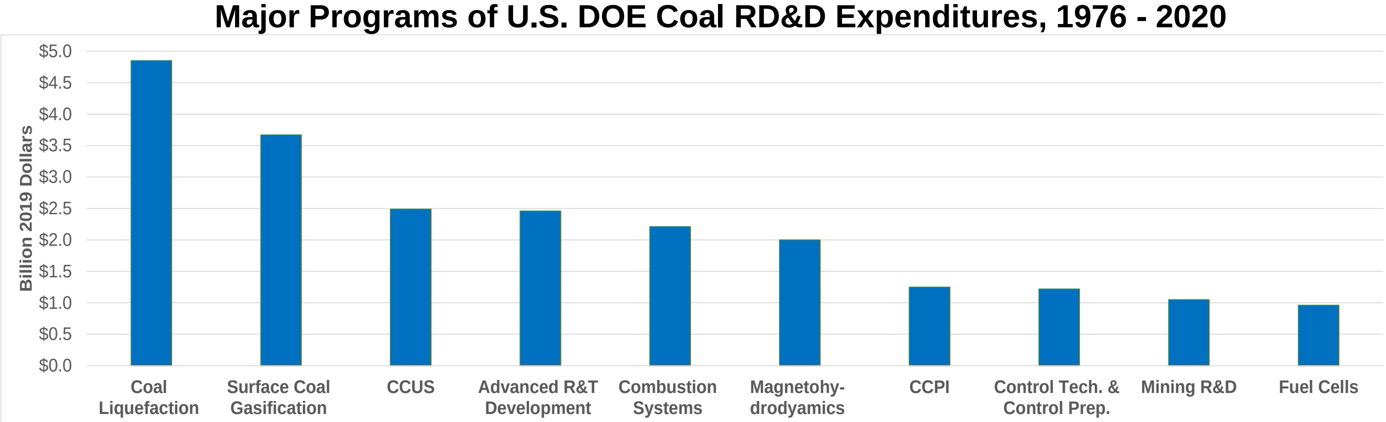
Thus:

- The highest level of funding was in 1980 -- $2.23 billion.
- In 1984, the budget was only 20% of what it was in 1980.
- The highest funding level after 1980 was $809 million in 2009, which was only 36% of what it was in 1980.
- In 2020, the budget was only 22% of what it was in 1980, only 60% of what it was in 2009, and was equal (in real terms) to about want it was in 1983.
- 42% of the budget was expended in the eight years 1976-1983
- Expenditures over the past decade, 2011 through 2020, comprised 15% of the total cumulative budget for the period 1976 - 2020.

Figures III-2 and III-3 identify the major program beneficiaries over the period 1976 – 2020 and show that:

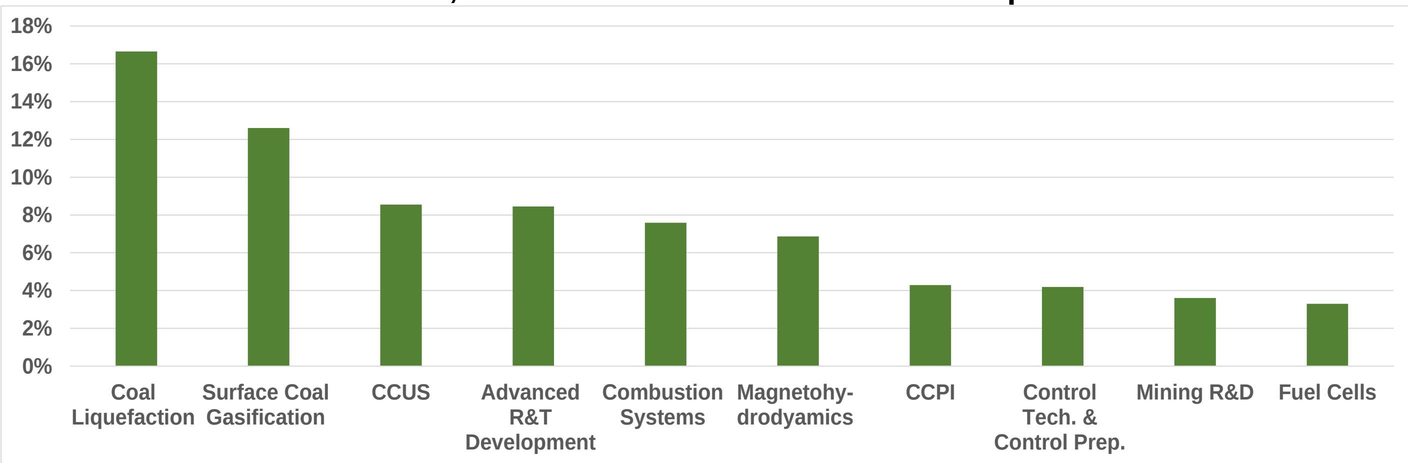
- Coal Liquefaction received the most funding: $4.85 billion – 17% of the total RD&D budget.
- Surface Coal Gasification (SCG) received the second highest level of funding: $4.67 billion -- 13% of the total.
- CCUS received the third highest level of funding: $2.49 billion – 8.6% of the total.
- Advanced Research and Technology development received the fourth highest level of funding: $2.46 billion – 8.4% of the total.
- Coal Liquefaction and SCG combined received a total of $8.5 billion -- nearly 30% of the total RD&D expenditures.
- Four major programs which have not been funded for the past quarter century -- Coal Liquefaction, Coal Gasification, Magnetohydrodynamics, and Mining RD&D – were among the top ten funded and combined received $11.6 billion – 40% of the total RD&D budget.

Figure III-2
Major Programs of U.S. DOE Coal RD&D Expenditures, 1976 - 2020



Source: U.S. Department of Energy and Management Information Services, Inc.

Figure III-3
Major Programs of U.S. DOE Coal RD&D Expenditures, 1976 – 2020, as a Percent of Total Coal RD&D Expenditures



Source: U.S. Department of Energy and Management Information Services, Inc.

Table III-9 identifies the major programs funded in 1980, 1990, 2000, 2010, and 2020 and illustrates the changing priorities of the RD&D program over the past five decades. It shows:

- The first decade of the program was dominated by the energy crises of the 1970s and focused on producing liquid and gaseous fuels from coal. As noted, Coal Liquefaction and SCG were the two programs that received the most funding 1976 – 2020. In addition, Underground Coal Gasification received $190 million.
- In 1990, Control Technology and Coal Preparation received the most funding and Coal Liquefaction and SCG were still major programs, as was Magnetohydro-dynamics.
- In 2000, not only had funding decreased to a near all-time low, but program priorities had changed and Fuel Cells received, by far, the most funding. Coal Liquefaction, Coal Gasification, and Magnetohydrodynamics were no longer being funded.
- In 2010, Sequestration was a major program, Advanced Turbines and Advanced IGCC received the most funding, and Fuel Cells was also a major program.
- Fuel Cells was a major program funded between 1998 and 2010.
- In 2019, CCUS dominated funding, receiving 44% of the total for that year, Advanced Energy systems received the second highest level of funding, and Fuel Cells were no longer in the budget.

Table III-9
Major Programs of U.S. DOE Coal RD&D Expenditures, 1980, 1990, 2000, 2010, 2020
(millions of 2019 dollars)

1980		1990		2000		2010		2020	
Program	**Funding**	**Program**	**Funding**	**Program**	**Funding**	**Program**	**Funding**	**Program**	**Funding**
Advanced R&T Develop.	175	Control Tech. & Coal Prep.	107	Advanced R&T Develop.	33	Innovations for Existing Plants	61	Advanced Energy Systems	148
Coal Liquefaction	620	Advanced R&T Develop.	47	Indirectly Fired Cycle	10	Advanced IGCC	73	Cross Cutting Research	48
Combustion Systems	217	Coal Liquefaction	65	Gasification Combined Cycle	50	Advanced Turbines	181	CCUS	215
Heat Engines	182	Combustion Systems	61	Pressurized Fluid Bed	17	Sequestra-tion	37	STEP	16
Magnetohy-drodynamics	234	Heat Engines	38	Advanced Res. & Environ.	34	Fuels	29	Transforma-tional Coal Pilots	20
Surface Coal Gasification	493	Magnetohy-drodynamics	73	Coal Liquefaction	10	Fuel Cells	58	NETL Coal RD&D	37
Mining RD&D	195	Surface Coal Gasification	43	Steelmaking Feedstock	10	Advanced Research	33		
				Fuel Cells	65				
Total*	**2,229**		**436**		**250**		**472**		**484**

*Total includes funding for programs not listed separately.

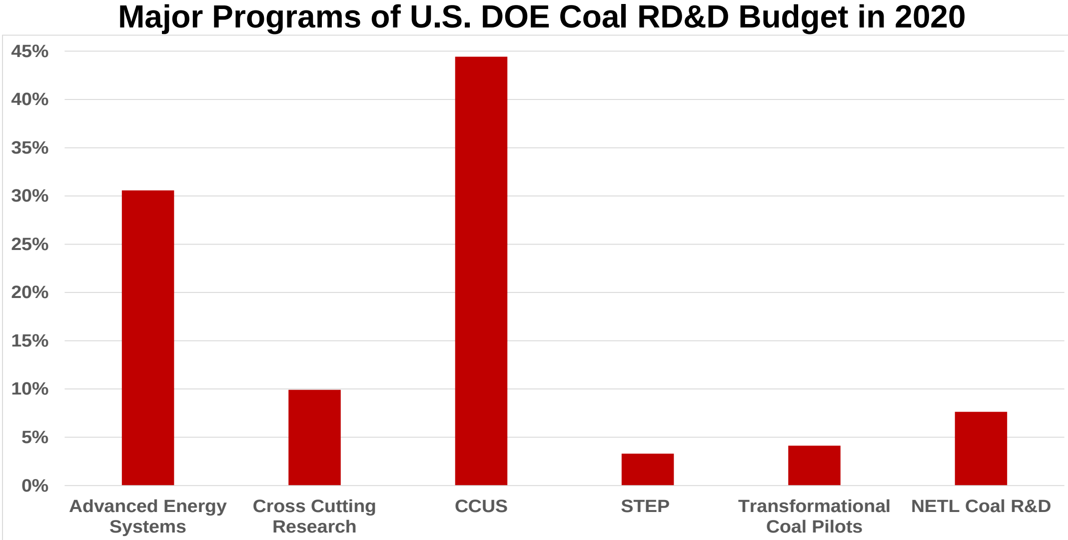
Source: U.S. Department of Energy and Management Information Services, Inc.

Figure III-4 illustrates the finding priorities in the FY 2020 DOE coal RD&D budget. This figure shows that in the FY 2020 budget the major program priorities were:

1. CCUS – 44% of the budget
2. Advanced Energy Systems – 31% of the budget
3. Cross Cutting Research – 10% of the budget

Together, these three programs comprised 81% of the coal RD&D budget.

Figure III-4
Major Programs of U.S. DOE Coal RD&D Budget in 2020



Source: U.S. Department of Energy and Management Information Services, Inc.

The DOE Clean Coal Technology (CCT) program included the Clean Coal Technology Demonstration Program (CCTDP) – $3,682 million in 2019 dollars; the Power Plant Improvement Initiative (PPII) -- $135 million in 2019 dollars; and the Clean Coal Power Initiative (CCPI) -- $1,253 million in 2019 dollars.[36] Combined, these three programs cumulatively totaled $5,070 million (2019 dollars). CCTDP funds were committed to demonstration projects selected through five competitive solicitations. The PPII was established by appropriations made for FY 01 through a transfer of funding previously appropriated for the CCTDP. Funds were committed to demonstration projects from a single solicitation issued in February 2001. The CCPI supported increased investment in clean coal technology. It was a cost-shared partnership between government and industry designed to demonstrate advanced coal based technologies, with the goal of accelerating commercial deployment of promising technologies.

Figure III-5 compares the DOE coal RD&D program funding and DOE CCT program funding – which includes the CCTDP, the PPII, and the CCPI -- for the years that elements of the CCT program were funded: 1986 – 2009. Note:

- CCT program funding is usually dominated by CCTDP expenditures, and is negative in some years due to CCTDP budget rescissions.
- There is substantial double counting between the CCT program and the coal RD&D program.

IGCC and PFBC are included in Figure III-6: GCC/IGCC -- $590 million (2019 dollars); PFBC -- $111 million (2019 dollars).

SCG was a separate line item in the ERDA/DOE coal RD&D budget from 1976 through 1997. Gasification Combined Cycle, and IGCC were separate DOE coal RD&D budget line items FY 98 through FY 03 – see Tables III-4 and III-5. The DOE coal RD&D budget line item Underground Coal Gasification was funded between FY 79 and FY 91 for a cumulative total of $190 million (2019 dollars) – see Figure III-7.

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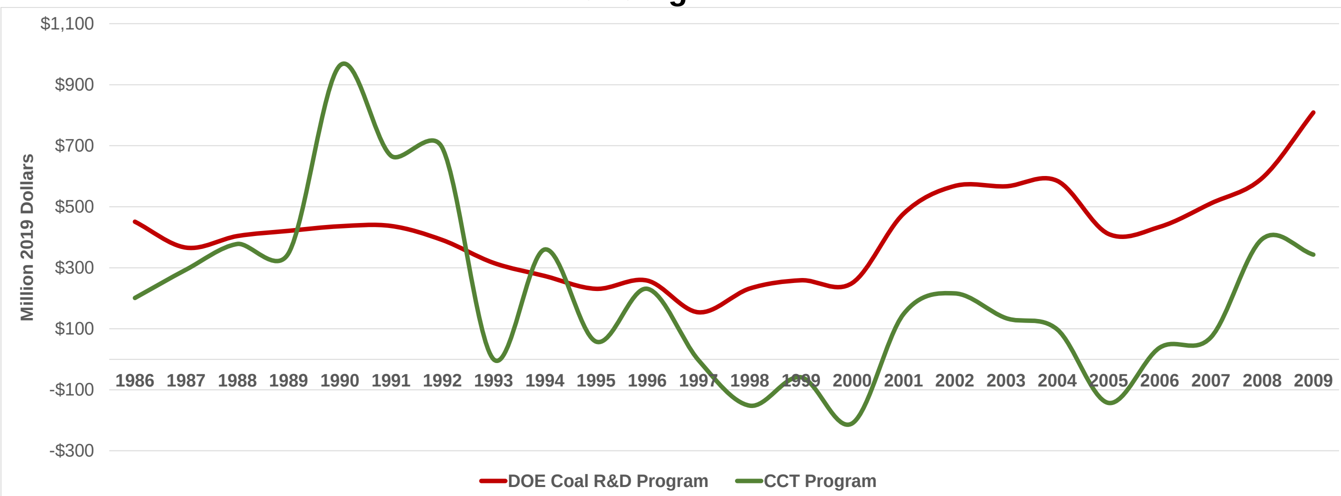
[36]See Frank Shaffer and Melissa Chan, op. cit.; Roger Bezdek and Robert Wendling, "The Return on Investment of the Clean Coal Technology Program in the USA," op. cit.; U.S. Department of Energy, Office of Fossil Energy, "Clean Coal Technology: From Research to Reality," 2007; U.S. Department of Energy, Assistant Secretary For Fossil Energy, "Clean Coal Technology: The Investment Pays Off," November 1999; National Research Council, *Energy Research at DOE: Was It Worth It?* Op. cit.; National Research Council, *Prospective Evaluation of Applied Energy Research and Development at DOE (Phase One): A First Look*, Committee on Prospective Benefits of DOE's Energy Efficiency and Fossil Energy R&D Programs, op. cit.; U.S. Department of Energy, Assistant Secretary for Fossil Energy, "Clean Coal Technology Programs: Program Update 2007," DOE/FE-0514, Washington, D.C., January 2008; U.S. Department of Energy, the Electric Power Research Institute, and the Coal Utilization Research Council, op. cit.; National Energy Technology Laboratory, "Clean Coal Technology Roadmap, CURC/EPRI/DOE Consensus Roadmap, Background Information," April 2004; Ben Yamagata, "Clean Coal Technology to Meet Growing Electricity Needs," Coal Utilization Research Council, March 2007; National Energy Technology Laboratory, "Clean Coal Power Initiative (CCPI)," December 2006.

SCG and IGCC were separate DOE budget items. SCG was funded from FY 76 through FY 97 for a cumulative total of $3,671 million. IGCC was funded as a separate DOE coal RD&D budget line item from FY 98 through FY 03 and from FY 07 through FY 10 for a cumulative total of $590 million (2019 dollars) – see Tables III-4, III-5, and III-6.

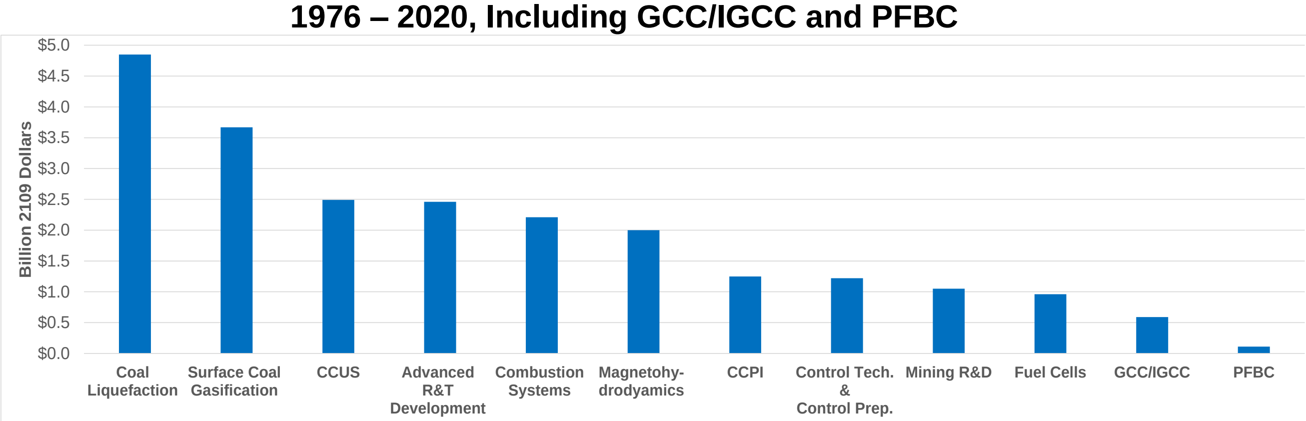
Figure III-5*
Comparison of DOE Coal RD&D Program Funding and DOE CCT Program Funding



*CCT program funding is usually dominated by CCTDP expenditures, and is negative in some years due to CCTDP budget rescissions. There is substantial double counting between the CCT program and the coal RD&D program.

Source: U.S. Department of Energy and Management Information Services, Inc.

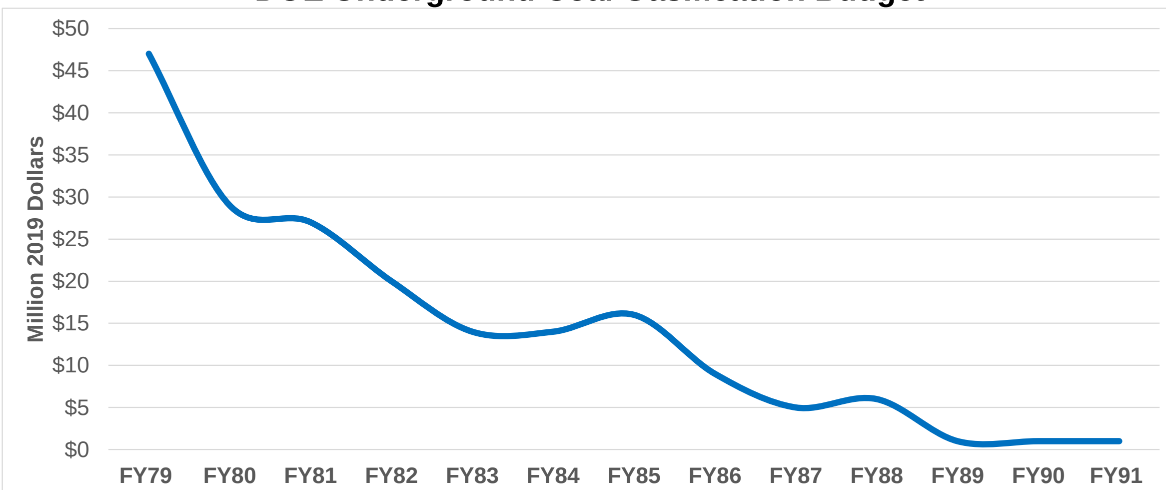
Figure III-6
Major Programs of DOE RD&D Expenditures, 1976 – 2020, Including GCC/IGCC and PFBC



Source: U.S. Department of Energy and Management Information Services, Inc.

Pressurized Fluidized Bed, Gasification Combined Cycle, and IGCC were separate DOE coal RD&D budget line items FY 98 through FY 03 – see Tables III-4 and III-5. Total cumulative PFB expenditures over this period were $111 million (2019 dollars). Total cumulative Gasification Combined Cycle and IGCC expenditures over this period were $590 million (2019 dollars).

Figure III-7
DOE Underground Coal Gasification Budget



Source: U.S. Department of Energy and Management Information Services, Inc.

IV. ECONOMIC AND JOBS IMPACTS OF THE DOE COAL RD&D PROGRAM

IV.A. Assessing Impacts

Assessing the economic and jobs impacts and benefits and costs of the DOE coal RD&D program is the key objective of this project, but it is also complex and difficult. Nevertheless, following previously developed methodologies and studies, here we assessed the impacts and benefits to government and the private sector resulting from:

- Realized Savings Through 2000
- Reduced CAPEX
- Efficiency Savings
- Clean Coal Technology Exports
- SO_2
- NO_x
- CO_2
- Public Health
- NETL Operations
- Jobs

IV.B. NRC/NAS/NAS Realized Economic Benefits Through 2000

The NRC/NAS studies identified economic net benefits from DOE RD&D programs based on changes in the total market value of goods and services that can be produced in the U.S. economy under normal conditions, where "normal" refers to conditions absent energy disruptions or other energy shocks and the changes are made possible by technological advances stemming from RD&D.[37] They identified "realized benefits" as benefits that are almost certain -- that is, those for which the technology is developed and for which the economic and policy conditions are favorable for commercialization of the technology.

NRC/NAS recognized two dimensions of publicly funded RD&D: 1) DOE research is expected to produce public benefits that the private economy cannot reap, and 2) some benefits may be realized even when a technology does not enter the marketplace immediately or to a significant degree. Importantly, it found that DOE's evaluations tend to focus on economic benefits from the deployment of technologies, rather than taking into account the broader array of benefits (realized and otherwise) flowing from these investments of public funds.

Although NRC/NAS was not always able to separate the DOE contribution from that of others, substantial net realized economic benefits in the coal RD&D programs were identified and estimated. These economic benefits are distinct from the environmental

[37]National Research Council, *Energy Research at DOE: Was It Worth It?* Op. cit.; National Research Council, *Prospective Evaluation of Applied Energy Research and Development at DOE (Phase One): A First Look*, Committee on Prospective Benefits of DOE's Energy Efficiency and Fossil Energy R&D Programs, op. cit.

public health, and security benefits that were estimated.[38] Realized economic benefits were estimated from coal RD&D programs including Fluidized Bed Combustion, Flue Gas Desulfurization, Waste Management/Utilization Technologies, and the Coal-bed Methane Program. NRC/NAS estimated that the cumulative net economic benefits from these RD&D programs through 2000 totaled $4.95 billion (1999 dollars).[39] Using the IPD deflator described in III.C, MISI estimated these benefits to total approximately $7.3 billion in 2019 dollars, and this estimate is used here.

IV.C. Reduced Capital and Operating Costs

A portion of the benefits of the DOE Coal RD&D program is realized from savings due to the reduced capital cost of building new plants and savings in the cost of control technology used on existing plants. In previous studies of DOE program benefits these savings frequently accounted for a substation portion of the total benefits estimated.[40] However, over the past two decades, many fewer new coal plants have come on-line than were originally anticipated, and EIA currently forecasts no new U.S. coal plants will be built through 2050.[41]

Actual plant capacity commissioned since 2000 has consistently been far less than the new capacity announced. For example:

- NETL's year 2002 report of announcements reflected a schedule of nearly 12,000 MW to be installed by 2005, whereas only 329 MW (three percent of the capacity announced in 2002) were achieved.[42]
- NETL's year 2002 report of announcements reflected a schedule of over 36,000 MW to be installed by 2007, whereas only about 4,500 MW (12 percent of the capacity announced in 2002) was achieved.[43]

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[38]NRC/NAS noted that quantifying realized economic benefits is usually easier than quantifying other kinds of benefits. However, it felt that environmental and security benefits, while harder to value in dollar terms, are equally important objectives of public funding.

[39]NRC/NAS estimated that all of the fossil energy programs that it reviewed generated realized economic benefits of approximately $11 billion (1999 dollars) through 2000. Of these, $4.95 (1999 dollars) billion resulted from the DOE coal R&D programs and the remaining $6.05 billion (1999 dollars) from the other fossil energy programs it evaluated.

[40]See Frank Shaffer and Melissa Chan, op. cit.; Roger Bezdek and Robert Wendling, "The Return on Investment of the Clean Coal Technology Program in the USA," op. cit.; U.S. Department of Energy, Office of Fossil Energy, "Clean Coal Technology: From Research to Reality," 2007; U.S. Department of Energy, Assistant Secretary For Fossil Energy, "Clean Coal Technology: The Investment Pays Off," November 1999; National Research Council, *Energy Research at DOE: Was It Worth It?* Op. cit.; National Research Council, *Prospective Evaluation of Applied Energy Research and Development at DOE (Phase One): A First Look*, Committee on Prospective Benefits of DOE's Energy Efficiency and Fossil Energy R&D Programs, op. cit.

[41]U.S. Energy Information Administration, *Annual Energy Outlook 2020*, January 2020.

[42]Erik Shuster, "Tracking New Coal-Fired Power Plants," National Energy Technology Laboratory, October 10, 2007.

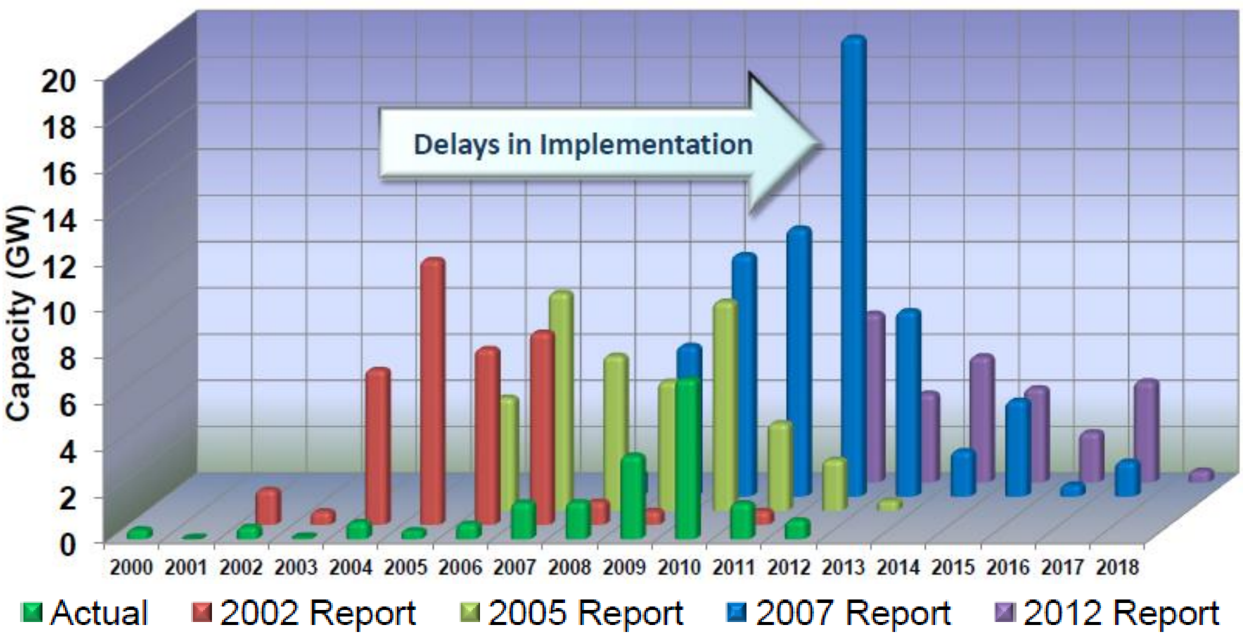
[43]Erik Shuster, "Tracking New Coal-Fired Power Plants," National Energy Technology Laboratory, April 6, 2009.

- NETL's year 2007 report of announcements reflected a schedule of nearly 14,000 MW to be installed by 2011, whereas only about 2,343 MW (17 percent of the capacity announced in 2007) was achieved.[44]

Further:

- The trend over many years has reflected the bulk of power plant developments shifting out in time due to project delays -- Figure IV.1
- Delays and cancelations have been attributed to regulatory uncertainty (regarding climate change and other environmental issues) or strained project economics due to escalating costs in the industry.
- New announcements combined with delayed projects have tended to increase the backlog of plants in the queue.
- Cancellations become more prevalent as prospects of completing all projects in the queue become impractical.

Figure IV.1
Past Capacity Announcements vs. Actual



Source: National Energy Technology Laboratory.

Over the past decade, new coal builds in the U.S. have been vastly overwhelmed by coal plant retirements – Figure IV-2. This figure illustrates that over the period 2010-2019 an average of more than 7 GW of coal capacity has been retired each year.[45]

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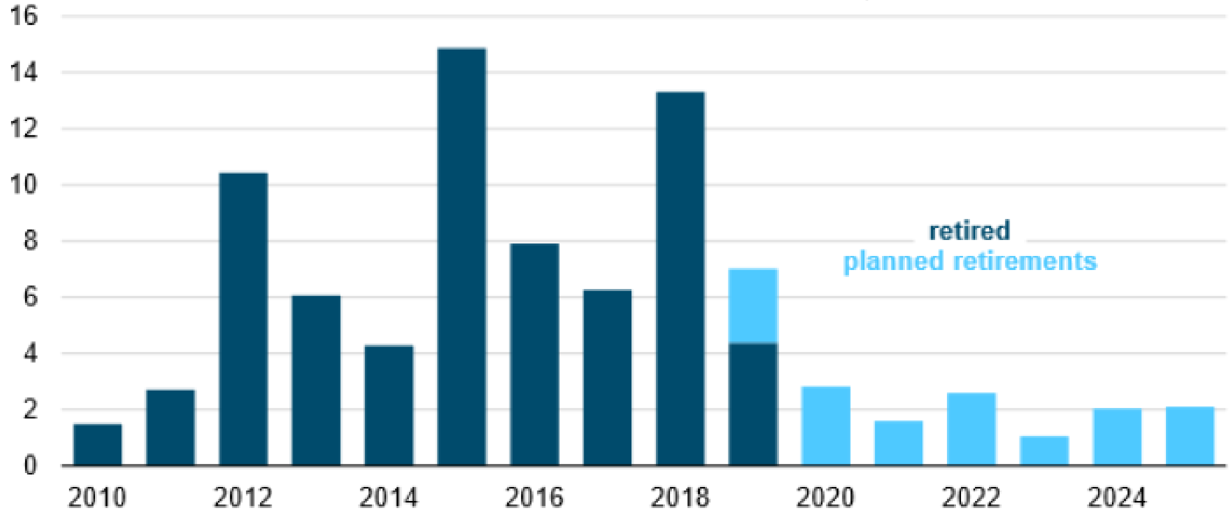
[44]Erik Shuster, "Tracking New Coal-Fired Power Plants," National Energy Technology Laboratory, January 13, 2012.
[45]U.S. Energy Information Administration, "More U.S. Coal-Fired Power Plants Are Decommissioning as Retirements Continue," July 26, 2019.

Figure IV-2
Total Net Summer Capacity (GW) of Retired and Retiring Coal Units (2010-2025)



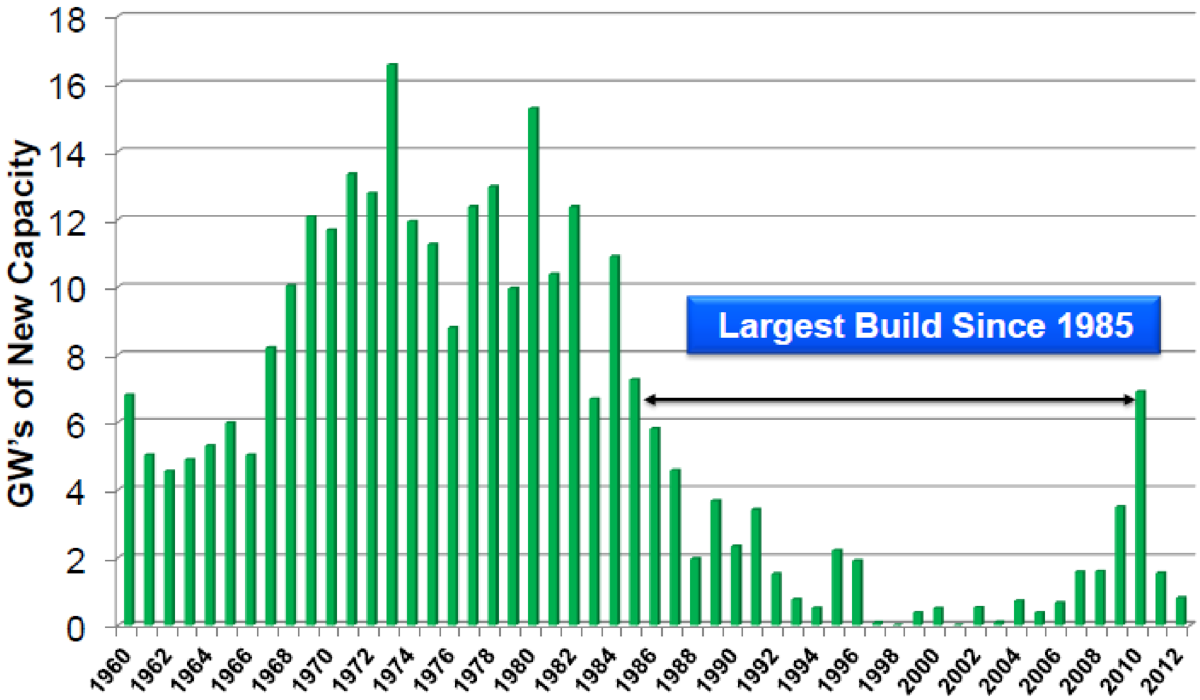
Source: U.S. Energy Information Administration.

Figure IV-3 shows the new U.S. coal capacity installed over the period 1960 – 2012. This figure illustrates that new U.S. coal capacity:

- Increased dramatically during the 1960s and early 1970s, reaching an all-time high in 1973.
- After 1973, increased and decreased for the next 12 years.
- After 1985, decreased until 2005.
- After 2005, increased until 2010 – which year experienced the largest build since 1985.
- Declined after 2010.

After 2013, little new coal capacity came on line and EIA projects none through 2050.

Figure IV-3
New U.S. Coal Capacity Installed, 1960 – 2012



Source: National Energy Technology Laboratory.

In 2007, coal-fired power plants (CFPPs) accounted for 49 percent of total generation in the U.S. and 82 percent of power sector carbon dioxide emissions. These plants are low-cost and reliable, and in 2007 EIA projected that very few would retire over the coming decades. However, since then the situation has changed dramatically.[46] Figures IV.4, IV.5, and IV.6 show that:[47]

- EIA vastly overestimated the number of new coal plants that would be built over the coming decade.

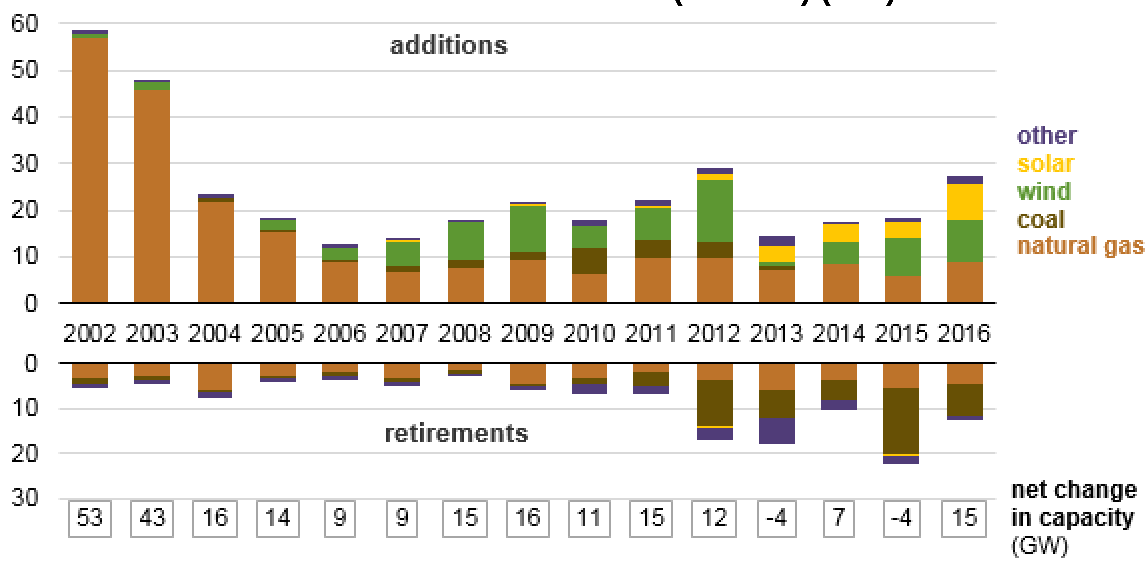
[46]See Roman Mendelevitch, Christian Hauenstein, and, Franziska Holz, "The Death Spiral of Coal in the USA: Will New U.S. Energy Policy Change the Tide?" DIW Discussion Papers, No. 1790, German Institute for Economic Research, 2018; Joel Jean, David C. Borrelli, and Tony Wu, Mapping the Economics of U.S. Coal Power and the Rise of Renewables," an MIT Energy Initiative Working Paper, Massachusetts Institute of Technology, March 2016; Congressional Research Service, "Prospects for Coal in Electric Power and Industry," February 4, 2013; https://www.carbonbrief.org/mapped-worlds-coal-power-plants; Global coal plant tracker, New coal plants by country: https://docs.google.com/spreadsheets/d/1W3pt5FhqitHwbVWvvgfRr0S6QfqfOuea9pt3-Mlxp5M/edit#gid=1748822159.

[47]U.S. Energy Information Administration, New Electric Generating Capacity in 2019 Will Come From Renewables and Natural Gas, January 10, 2019; U.S. Energy Information Administration, "More Than 60% of Electric Generating Capacity Installed in 2018 Was Fueled by Natural Gas," March 11, 2019; U.S. Energy Information Administration, "Most Coal Plants in the United States Were Built Before 1990," April 17, 2017; Source: U.S. Energy Information Administration, "U.S. Electric Generating Capacity Increase in 2016 Was Largest Net Change Since 2011," February 27, 2017; U.S. Energy Information Administration, "Annual Electric Generator Report" (EIA-860) Data Files for 2018.

- EIA vastly underestimated the number of coal plants that would be retired over the coming decade.[48]

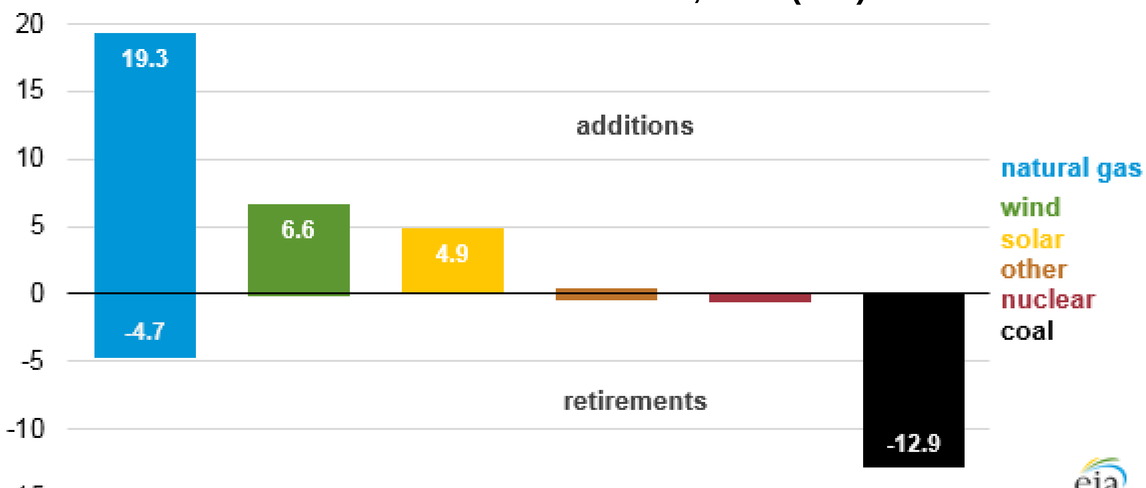
As a result, in 2018, CFPPs accounted for only 27 percent of total generation in the U.S. and 65 percent of power sector carbon dioxide emissions.[49]

Figure IV-4
U.S. Utility-Scale Electric Generating Capacity Additions and Retirements (2002-16) (GW)



Source: U.S. Energy Information Administration

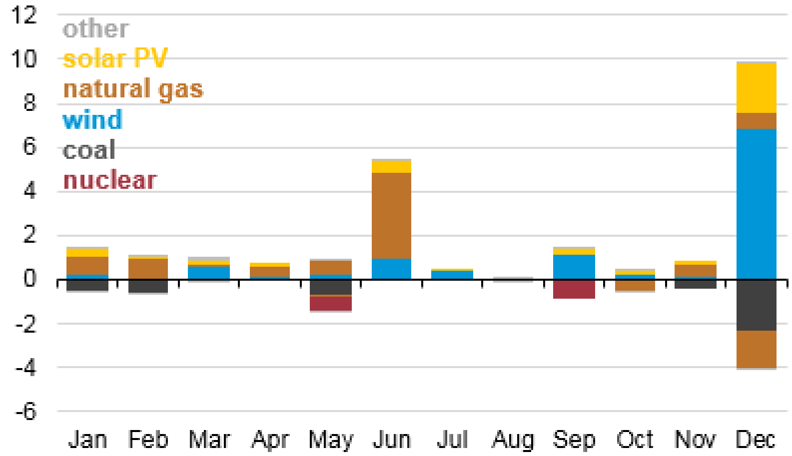
Figure IV-5
Total U.S. Utility-Scale Electric Generating Capacity Additions and Retirements, 2018 (GW)



Source: U.S. Energy Information Administration

[48]U.S. Energy Information Administration, *Annual Energy Outlook 2007*, February 2006.
[49]U.S. Energy Information Administration, *Annual Energy Outlook 2020*, January, 2020.

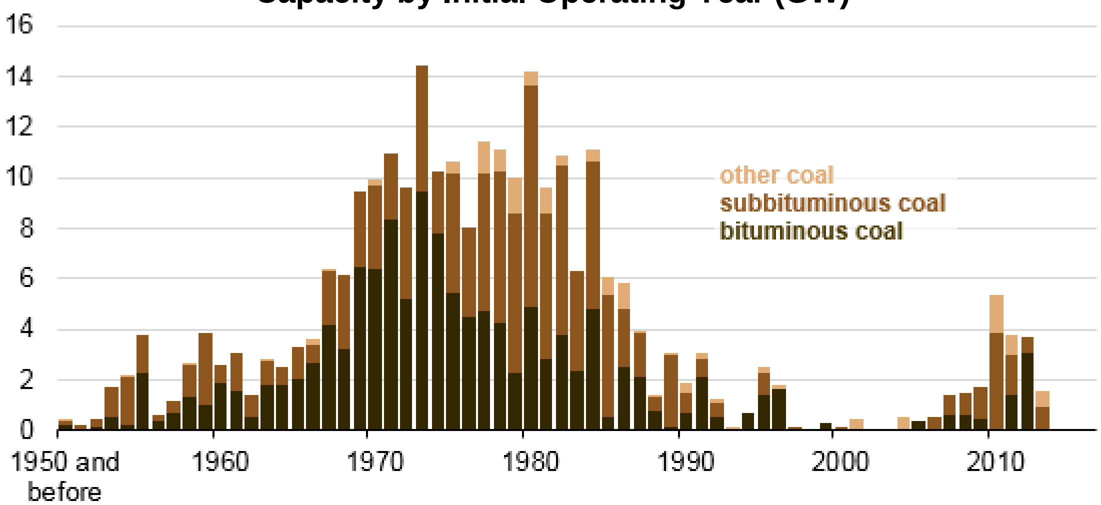
Figure IV-6
U.S. Electric Capacity Additions and Retirements, 2019 (GW)



Source: U.S. Energy Information Administration

Figure IV-7 shows that the U.S. coal fleet has continued to age. Relatively few new plants have come on-line since 2010 and virtually none since 2013.

Figure IV-7
U.S. Utility-scale Coal-fired Electric Generating Capacity by Initial Operating Year (GW)



Source: U.S. Energy Information Administration

Tables IV-1 and IV-2 indicate that only 8.2 GW of new coal plant capacity has come on-line since 2010, and 129 MW since 2013.

Table IV-1
New U.S. Coal Plants That Initiated Operations 2008 - 2010

Plant Name	State	Starte Date	Capacity (MW)
Plum Point Energy	Arkansas	Sep-10	55
Plum Point Energy	Arkansas	Sep-10	55
Plum Point Energy	Arkansas	Sep-10	161
Plum Point Energy	Arkansas	Sep-10	460
Iatan	Missouri	Aug-10	110
Iatan	Missouri	Aug-10	500
Iatan	Missouri	Aug-10	165
Iatan	Missouri	Aug-10	32
Iatan	Missouri	Aug-10	107
ADM Columbus Cogeneratior	Nebraska	Jul-10	71
Trimble Station (LGE)	Kentucky	May-10	104
Trimble Station (LGE)	Kentucky	May-10	104
Trimble Station (LGE)	Kentucky	May-10	507
Trimble Station (LGE)	Kentucky	May-10	119
Comanche (CO)	Colorado	May-10	69
Comanche (CO)	Colorado	May-10	214
Comanche (CO)	Colorado	May-10	574
J K Spruce	Texas	May-10	878
Wygen III	Wyoming	Apr-10	60
Wygen III	Wyoming	Apr-10	27
Wygen III	Wyoming	Apr-10	29
Oak Grove Steam Electric Sta	Texas	Apr-10	909
Willmar	Minnesota	Mar-10	2
Willmar	Minnesota	Mar-10	2
Oak Creek Power Plant	Wisconsin	Feb-10	58
Oak Creek Power Plant	Wisconsin	Feb-10	584
Oak Creek Power Plant	Wisconsin	Feb-10	58
Springerville Generating Stat	Arizona	Dec-09	458
Oak Grove Steam Electric Sta	Texas	Dec-09	932
Dallman	Illinois	Nov-09	280
Nebraska City	Nebraska	May-09	738
Clinton (IA ADM)	Iowa	Apr-09	105
Hugh L Spurlock	Kentucky	Apr-09	329
Clinton (IA ADM)	Iowa	Feb-09	75
Riverland Biofuels LLC	Illinois	Aug-08	7
Weston	Wisconsin	Jun-08	179
Weston	Wisconsin	Jun-08	417
TS Power Plant	Nevada	Jun-08	242
Cross	South Carolina	May-08	652
Wygen II	Wyoming	Jan-08	95

Source: EIA and NETL

Table IV-2
New U.S. Coal Plants That Initiated Operations Since 2011

Plant Name	State	Starte Date	Capacity (MW)
Univ of Alaska Fairbanks	Alaska	Aug-19	17
Kodak Park Site	New York	Apr-15	3
Morton Salt Rittman	Ohio	Feb-15	3
Spiritwood Energy	North Dakota	Nov-14	106
Edwardsport	Indiana	Jun-13	618
Sandy Creek Energy Station	Texas	May-13	1008
John W Turk Jr Power Plant	Arkansas	Dec-12	73
John W Turk Jr Power Plant	Arkansas	Dec-12	49
John W Turk Jr Power Plant	Arkansas	Dec-12	43
John W Turk Jr Power Plant	Arkansas	Dec-12	445
James E Rogers Energy Complex	North Carolina	Dec-12	910
Prairie State Energy Campus	Illinois	Nov-12	883
Virginia City Hybrid Energy Center	Virginia	Jul-12	668
Prairie State Energy Campus	Illinois	Jun-12	883
Longview Power	West Virginia	Jan-12	808
Dry Fork Station	Wyoming	Aug-11	449
Dry Fork Station	Wyoming	Aug-11	34
Whelan Energy Center	Nebraska	Jun-11	17
Whelan Energy Center	Nebraska	Jun-11	39
Whelan Energy Center	Nebraska	Jun-11	90
Whelan Energy Center	Nebraska	Jun-11	90
Whelan Energy Center	Nebraska	Jun-11	11
Oak Creek Power Plant	Wisconsin	Jan-11	58
Oak Creek Power Plant	Wisconsin	Jan-11	584
Oak Creek Power Plant	Wisconsin	Jan-11	58
John Twitty Energy Center	Missouri	Jan-11	300

Source: EIA and NETL

The last major U.S. coal power plants built include the Longview Power Plant,[50] 700 MW, which came on-line in 2011, the Prairie State Plant,[51] 1,600 MW, and the SWEPCO John W. Turk Plant,[52] 440 MW, both of which came on line in late 2012, the Sandy Creek Energy Station,[53] 940 MW, and Edwardsport,[54] 618 MW, both of which came on line in 2013. The last major coal power plant to come on-line in the U.S. was Spiritwood Energy in North Dakota, in November 2014, 99 MW;[55] the last plant of any size was the University of Alaska Fairbanks campus, 17 MW, which came on line in late 2018.[56] Over the period 2012-2019, only a total of about 6.5 GW of new coal plant capacity has come on line – none of it recently.

In January 2020, Sunflower Electric Power Corporation finally canceled plans to build the $2.8 billion Holcomb Plant Expansion.[57] In April 2020, Georgia regulators halted the last proposed coal plant in the U.S. after denying project developers more time to start construction on the proposed Plant Washington coal project – a $2 billion, 850 MW plant that had been planned for Sandersville, Georgia.[58]

The capital cost savings reflect savings of between $150/kW in 2000 and $265/kW (2019 dollars). The savings in control technology include savings from the lower cost of air emissions control and savings resulting from increased by-product utilization. Previous research estimated that the savings through 2008 from the capital costs of new plants and the control technologies for existing plants totaled approximately $3.2 billion (2019 dollars).[59] Here we estimate that the savings over the period 2009 – 2019 from the

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[50]After Longview began operation in 2011, construction defects and major changes in the power markets led to the company's Chapter 11 bankruptcy in 2013. Longview attributed its need for bankruptcy "in large part because it has been plagued by design, construction, and equipment defects and failures" In early 2015 the company reached a comprehensive settlement of all construction claims, and two of its major contractors agreed to remediate plant defects at their own expense. As a result, Longview Power emerged from bankruptcy in April 2015 with the full remediation of the plant underway and new ownership led by private equity firms including KKR, Centerbridge, Ascribe, and Third Avenue. "Longview, First New W.Va. Coal Plant in 18 Years, Fires Up This Month," *State Journal*, April 8, 2011; "SNL: Longview Touts 155 Days of Operation as it Aims to Demonstrate Coal Technology," www.snl.com; "Longview Wins Approval to Exit Chapter 11 Protection," *Dow Jones Institutional News*, March 16, 2015; "A Closer Look at the Longview Power Bankruptcy," Fox Rothschild LLP, September 8, 2013.

[51]"Prairie State Energy Campus, Illinois, USA: One of the Cleanest Coal Plants in the Nation," Bechtel, 2020; John Funk, "Coal-fired Prairie State Plant at Full Power, Supplying Cleveland, Others," The Plain Dealer, November 07, 2012.

[52]W. Greg Carter, "John W. Turk Power Plant Update," RRVA Texarkana, May 31, 2012.

[53]https://www.naes.com/locations/sandy-creek-energy-station/download/.

[54]https://www.duke-energy.com/our-company/about-us/power-plants/edwardsport.

[55]https://lignite.com/mines-plants/poly-generation-plants/spiritwood-station/.

[56]"UA Coal-Fired Power Plant Wins Power Magazine Top Plant Award," *Alaska Business*, August 14, 2019; Dylan Brown, "Here's the Nation's Only New Coal Plant. Is it the last?" *E&E News*, April 15, 2019.

[57]Sonal Patel, "Sunflower Finally Scraps Plans for 895-MW Kansas Coal Plant," *Power*, January 16, 2020.

[58]Carlos Anchondo, "Regulators Kill Last Proposed U.S. Coal Plant," *E&E News*, April 15, 2020.

[59]See Frank Shaffer and Melissa Chan, op. cit.; Roger Bezdek and Robert Wendling, "The Return on Investment of the Clean Coal Technology Program in the USA," op. cit.; U.S. Department of Energy, Office of Fossil Energy, "Clean Coal Technology: From Research to Reality," 2007; U.S. Department of Energy, Assistant Secretary For Fossil Energy, "Clean Coal Technology: The Investment Pays Off," November 1999; National Research Council, *Energy Research at DOE: Was It Worth It?* Op. cit.; National Research Council, *Prospective Evaluation of Applied Energy Research and Development at DOE (Phase One): A*

reduced capital costs of new plants and from the control technologies for existing plants totaled about $4.4 billion (2019 dollars). We thus estimate that the total savings through 2019 from the capital costs of new plants and the control technologies for existing plants was approximately $7.6 billion (2019 dollars).

IV.D. Reduced Energy Costs Due To Higher Efficiencies

The overall average efficiency of the U.S. coal fleet has increased gradually over the past two decades, from about 32% in 2007 to about 34% in 2019.[60] This resulted from two causes: The new coal plants that came on line since 2007 were significantly more efficient than the existing fleet, and the numerous plants that were retired over this period tended to be older and less efficient.

Steam turbines are at the heart of coal-fired power plants. A typical coal-fired power plant (CFPP) has multiple generating units, each with its own steam generating boiler. Coal is usually pulverized by a combination of crushing and grinding until a desired degree of fineness is achieved. The coal is sieved, and dried using heated air before it is conveyed to a furnace where it is burned to produce steam. Steam pressure and temperature are specifically related, as steam's temperature rises with increasing steam pressure. The pressure and temperature of the steam produced have been rising steadily over the years, ranging from traditional sub-critical units to current ultra-super critical units.[61]

Subcritical steam generation units operate at pressures such that water boils first and then is converted to superheated steam. At supercritical pressures, water is heated to produce superheated steam without boiling. Due to the improved thermodynamics of expanding higher pressure and temperature steam through the turbine, a supercritical steam generating unit is more efficient than a subcritical unit. Ultrasupercritical steam (USC) generation currently is the most efficient technology for producing electricity fueled by pulverized coal. A USC unit operates at supercritical pressure and at advanced steam temperatures of 1,100º F. These temperatures and pressures enable more efficient operation of the turbine cycle. This increase in efficiency reduces coal consumption, and thereby reduces emissions, solid waste, water use, and operating costs.[62]

First Look, Committee on Prospective Benefits of DOE's Energy Efficiency and Fossil Energy R&D Programs, op. cit.; U.S. Department of Energy, Assistant Secretary for Fossil Energy, "Clean Coal Technology Programs: Program Update 2007," DOE/FE-0514, Washington, D.C., January 2008. Converted to 2019 dollars by MISI.

[60]See National Energy Technology Laboratory, Reducing CO_2 Emissions by Improving the Efficiency of the Existing Coal-fired Power Plant Fleet, DOE/NETL-2008/1329.Phil DiPietro and Katrina Krulla, "Improving the Efficiency of Coal-Fired Power Plants for Near Term Greenhouse Gas Emissions Reductions," DOE/NETL-2010/1411, April 16, 2010. Richard J. Campbell, "Increasing the Efficiency of Existing Coal-Fired Power Plants," Congressional Research Service, December 20, 2013; U.S. Energy Information Administration, *Electric Power Annual*, various years, 2007 – 2019.

[61]Richard J. Campbell, op. cit.

[62]Sonal Patel, "First U.S. Ultrasupercritical Power Plant in Operation," *Power*, January 31, 2013.

The overall efficiency of a power plant encompasses the efficiency of the various components of a generating unit. The thermal efficiency of electricity production is represented by the heat rate, which measures the amount of energy used to generate one kWh of electricity.[63] A generating unit with a lower, or more efficient, heat rate can generate the same quantity of electricity while consuming less fuel, compared with a unit with a higher heat rate.[64] Lower fuel use per unit of electricity generated also reduces the corresponding emissions of pollutants such as sulfur dioxide (SO_2), nitrogen oxide (NO_x), mercury (Hg), and carbon dioxide (CO_2). Consequently, improving heat rates at power plants can lower fuel costs and help achieve compliance with environmental regulations.[65]

Minimizing heat losses is the greatest factor affecting the loss of CFPP efficiency, and there are numerous areas of potential heat losses in a power plant. Efficiency of older CFPPs becomes degraded over time, and lower power plant efficiency results in more CO_2 being emitted per unit of electricity generated. The options most often considered for increasing the efficiency of CFPPs include equipment refurbishment, plant upgrades, and improved operations and maintenance schedules.[66]

NETL found that while the average efficiency of U.S. plants was 32% in 2007, the efficiency of the top 10% was over five points higher at 37.4%. NETL found that if GHG emissions reduction was a goal, then heat rate efficiency improvements could enable a power plant to generate the same amount of electricity from less fuel and decrease CO_2 emissions. NETL concluded that if generation levels were held constant at 2008 levels, overall fleet efficiency could be raised from 32% to 36%.[67] According to subsequent analyses, NETL concluded that retirements of lower efficiency units combined with increased generation from higher efficiency refurbished units, and advanced refurbishments with improved operation and maintenance, would be necessary to achieve this goal.

These improvements would generally be considered low to medium cost upgrades. However, at the higher cost end are major plant retrofits and upgrades (i.e., conversion of subcritical CFPP units to super- or ultra-supercritical CFPP units), which would raise efficiencies more substantially.[68]

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[63]Robert Peltier, "Plant Efficiency: Begin with the Right Definitions," *Power Magazine*, January 2010; U.S. Energy Information Administration, "Analysis of Heat Rate Improvement Potential at Coal-Fired Power Plants," May 2015.

[64]U.S. Energy Information Administration, "Approximate Heat Rates for Electricity, and Heat Content of Electricity," *Monthly Energy Review*, March 2020.

[65]Timothy Fout, Travis Shultz, Mark Woods, Marc Turner, Alexander Zoelle, and Robert James, "Cost and Performance Baseline for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity, Revision 4," Presented at EUEC 2019, February 2019.

[66]"Coal-Fired Generation Cost and Performance Trends," *Power Magazine*, May 1, 2011.

[67]Reducing CO2 Emissions by Improving the Efficiency of the Existing Coal-fired Power Plant Fleet. DOE/NETL-2008/132

[68]Mark Brown, "Utility Infrastructure Improvements for Energy Efficiency," Franklin Energy Services, LLC, prepared for Minnesota Office of Energy Security, November 2010.

A lower heat rate represents a more efficient generating unit, since it requires less heat input to generate a kWh of electric energy. A generating unit can thus improve its efficiency by reducing the fuel it uses relative to a specific amount of electricity generated, thus reducing the amount of CO_2 emitted.[69]

A percentage improvement in heat rate is nearly equivalent to an equal percentage improvement in the emissions rate in terms of the change in CO_2 emissions.[70] The heterogeneity in heat rates across coal-fired generation units can partly be explained by technical characteristics determined at the time of plant construction that cannot be changed without a major overhaul. This category includes size, age, firing type, and the technology employed. Higher efficiency is generally associated with plants that are used more heavily because efficient units are less costly to operate.

A second factor is how the boiler is used. The relationship between the heat rate and utilization is nonlinear, as efficiency tends to be lower at very low and very high levels of utilization. Units with lower utilization may be ramped up and down more frequently, which requires additional fuel input as temperature in the boiler fluctuates. The result could involve efficiency losses at least partly outside the control of plant decision makers. Plant managers control several other factors that affect heat rates. Techniques, management, or technology may improve the efficiency of the plant by targeting the major components of the coal combustion process: oxygen, temperature, and pressure.[71] Excessive deviations in any of these areas may decrease efficiency through waste or shortfalls. Maintenance and performance testing are also critical for identifying and preventing losses.[72]

Therefore, in practical terms, a power plant's heat rate can be affected by a number of factors and power plants systems. Heat rate may present one measure of efficiency, but when considering power plant GHG emissions, measuring carbon dioxide emissions per unit of energy output (i.e., per kWh or per MWh of generation) may provide a more useful measure.

NETL researchers found that, facing a cost for emitting CO_2, U.S. entities that own coal-fired power plants have a number of options to pursue as alternatives to retiring the plant and investing in a new one with lower carbon emissions.[73] These include:

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[69]Sam Nierop and Simon Humperdink, "International Comparison of Fossil Power Efficiency and CO_2 Intensity, 2018," Navigant, September 2018.
[70]The difference stems from the small variation in carbon per Btu across coal varieties.
[71]Phillip Graeter and Seth Schwartz, "Recent Changes to U.S. Coal Plant Operations and Current Compensation Practices," Energy Ventures Analysis, Inc., prepared for the National Association of Regulatory Utility Commissioners, January 2020.
[72]U.S. Energy Information Administration, "Fuel Used in Electricity Generation Is Projected to Shift over the Next 25 Years," July 30, 2012.
[73]They found that the market for coal fired power plants that could be retrofitted with near commercial CCS technology under carbon cost scenarios ranging from 45 - 60 \$/MTCO_2e (metric ton CO_2 equivalent) is on the order of 100 GW. However, while refurbishing can extend the market for either retrofitting or repowering, its impact will depend on the extent to which efficiency as well as other cost related factors can be collectively upgraded. See Rodney Geisbrecht and Phil Dipietro, "Evaluating Options For U.S. Coal Fired Power Plants in the Face of Uncertainties and Greenhouse Gas Caps: The Economics of Refurbishing,

- Continuing to operate business as usual and obtaining emission allowances as needed;
- Switching to or cofiring low carbon fuels;
- Retrofitting with carbon capture and sequestration (CCS);
- Repowering with an advanced coal technology incorporating CCS;
- Refurbishing to improve plant efficiency in combination with any of the previous options.

NETL found that the 2008 U.S. CFPP fleet had a generation-weighted average efficiency of 32.5% while the top ten percent of the fleet had an efficiency of 37.6%, five percentage points higher.[74] The generating units in the top ten percent are diverse (they are not all new, large, super critical plants), indicating an opportunity for fleet-wide efficiency improvement. NETL segmented the fleet into 13 groups based on characteristics that limit efficiency, and calculated the best-in-class efficiency within each group. Based on each group achieving an average efficiency equal to its 90th percentile, the overall CFPP fleet average efficiency would be 35.2%. NETL set forth a vision of 36% based on retirements of low efficiency units, and improvements within the best-in-class. Under a scenario where generation from coal is constant at the 2008 level, increasing the average efficiency from 32.5% to 36% reduces U.S. GHG by 175 MMmt/year or 2.5% of total U.S. GHG emissions in 2008. However, as noted, in 2019 the overall average efficiency of the U.S. coal fleet had increased to only about 34%.

Similarly, GE used a propriety set of data to analyze each coal and gas-fired plant in the world to identify opportunities to improve plants' heat rate and lower CO_2 emissions. GE determined that the average global efficiency of coal plants can be improved from 34% to 38%: 2.5% more efficient through hardware improvements such as turbines and boiler upgrades and 1.5% more efficient through software solutions and data analytics.[75]

The International Energy Agency (IEA) compared the coal-fired power fleets in China, Japan, the EU and the USA. Data from existing plants of 300 MW or larger capacity, as well as those under construction and planned were reviewed. The plants were compared in terms of deployed technology (subcritical, supercritical, and ultra-supercritical) as well as their age and installed pollution control equipment. Examples of some of the most efficient plants included the John Turk Jr. plant in Arkansas.[76]

Retrofitting, and Repowering," *Energy Procedia*, Vol. 1, 2009, pp. 4347–4354; Phil DiPietro and Katrina Krulla, "Improving the Efficiency of Coal-Fired Power Plants for Near Term Greenhouse Gas Emissions Reductions," DOE/NETL-2010/1411, April 16, 2010; Tim Fout, Alexander Zoelle, Dale Keairns, Marc Turner, Mark Woods, Norma Kuehn, Vasant Shah, Vincent Chou, and Lora Pinkerton, "Cost and Performance Baseline for Fossil Energy Plants Volume 1: Revision 3," National Energy Technology Laboratory, 2015.

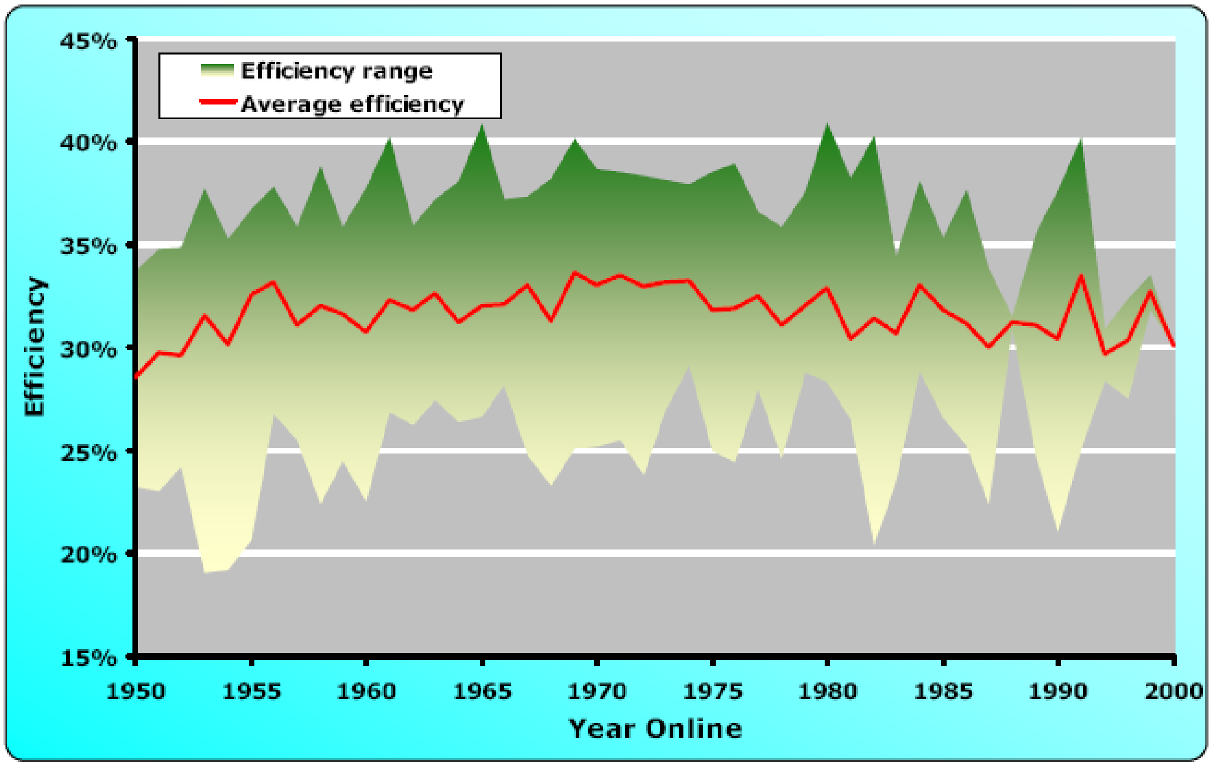
[74]National Energy Technology Laboratory, "Reducing CO_2 Emissions and Maintaining Electricity Generation Through Efficiency Improvements at Existing Coal-fired Power Plants," 2008.

[75]GE also estimated that annual CO_2 emissions from coal plants can be reduced by 924 mt or 11% (8,749 mt to 7,825 mt) -- more than 10X the annual CO_2 emissions of Texas and Indiana combined (840 mt). See General Electric, "GE Global Power Plant Efficiency Analysis," 2016.

[76]Malgorzata Wiatros-Motyka, "An Overview of HELE Technology Deployment in the Coal Power Plant Fleets of China, EU, Japan and USA," IEA Clean Coal Centre, IEACCC Ref: CCC/273, December 2016.

Figure IV.8 shows the range of efficiencies achieved by CFPPs in the U.S. in 2007. Power plants are grouped by their online year, and for each online year group this figure shows the minimum, maximum, and median efficiency. NETL found that aside from a unit's age and steam cycle type, plant attributes such as location and emissions control equipment do not account for variation in efficiency, and this indicates that operational practices and maintenance play large roles in determining the efficiency of a unit and suggests that improvements are possible.[77]

Figure IV.8
Average Efficiency and Range For CFPP's by Online Year For 2007



Source: National Energy Technology Laboratory.

The existing coal-fired power plant fleet is relatively old, and in 2007 over 46 percent of all electricity in the U.S. was generated by CFPPs over 20 years old. In general, the existing CFPP fleet is much less efficient at converting fuel into electricity than is technically and economically possible. The fleet average efficiency was then around 32 percent; however, a new state-of-the-art pulverized coal power plant with a supercritical steam cycle will have design efficiencies of 39 percent.[78] Some pulverized coal power plants that came on line over 50 years ago achieved an efficiency of 37% or higher in 2007.

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[77]Ibid.
[78]National Energy Technology Laboratory, "Cost and Performance Baseline for Fossil Energy Power Plants Study, Volume 1: Bituminous Coal and Natural Gas to Electricity" Report DOE/NETL-2007/1281, May 2007.

One reason for this discrepancy is that during the prime building time for CFPP's -- from the 1950's through the 1960's – coal was relatively cheap, and there was little incentive to improve a plant's heat rate, especially if those improvements came at the expense of a plant's planned availability. During the 1970's, coal prices experienced a significant peak that corresponded with the construction of a large number of higher efficiency, supercritical plants. However, by about 1980, coal prices were again relatively low and this reduced the incentives to build supercritical plants. State control of utility rates also likely contributed to lower efficiencies. Prior to electricity deregulation and restructuring, regulatory commissions pressured electric utilities to keep rates low, and postponing or even eliminating refurbishing projects was one method used to comply with state regulators.

Numerous studies have found that significant efficiency improvements in existing coal-fired power plants are possible.[79] Retrofit measures that can lead to energy savings include improvements in a plant's heat recovery system (economisers) and heat transfer (including condensers); better energy management supported by variable control of energy consuming devices (such as pumps and fans), better combustion control, and the use of more efficient turbine blades (when blade replacement is necessary), boiler chemical cleaning, feedwater heater improvements, reduced thermal losses (steam trap, valve and insulation upgrades), and other improvements.

NETL conducted a literature search of published articles and technical papers that identified potential coal-fired power plant efficiency improvement methods and identified efficiency improvement methods for most power plant components/systems. It found that advanced process control systems – particularly combustion controls and furnace sootblower controls – have become popular choices to improve power plant efficiency. Another method for improving efficiency is the use of coal drying for plants that use low rank coals. A summary of the range of efficiency improvement performance data for a variety of power plant components/systems identified by NETL is given in Table IV.3. These NETL estimates are corroborated by a number of independent studies. For example, the IEA Clean Coal Centre and the National Association of Clean Air Agencies provided data on the potential improvements in plant efficiency in several different areas, as shown in Table IV.4.[80]

[79]See the discussion in Bezdek and Wendling, "Economic, Environmental, and Job Impacts of Increased Efficiency in Existing Coal-Fired Power Plants," op. cit.
[80]National Association of Clean Air Agencies, "Implementing EPA's Clean Power Plan: A Menu of Options," May 2015, http://www.4cleanair.org/sites/default/files/Documents/NACAA_Menu_of_Options_LR.pdf.

Table IV.3
Potential Power Plant Efficiency Improvements

Power Plant Improvements	Efficiency Increase (percentage points)[14]
Air Preheaters (optimize)	0.16 to 1.5
Ash Removal System (replace)	0.1
Boiler (increase airheater surface)	2.1
Combustion System (optimize)	0.15 to 0.84
Condenser (optimize)	0.7 to 2.4
Cooling System Performance (upgrade)	0.2 to 1
Feedwater Heaters (optimize)	0.2 to 2
Flue Gas Moisture Recovery	0.3 to 0.65
Flue Gas Heat Recovery	0.3 to 1.5
Coal Drying (Installation)	0.1 to 1.7
Process Controls (installation/improvement)	0.2 to 2
Reduction of Slag and Furnace Fouling (magnesium hydroxide injection)	0.4
Sootblower Optimization	0.1 to 0.65
Steam Leaks (reduce)	1.1
Steam Turbine (refurbish)	0.84 to 2.6

Source: National Energy Technology Laboratory.

A decade ago, NETL found that coal-based plants using current technology were capable of producing electricity at relatively high efficiencies of about 39% higher heating value (without CO_2 capture) on bituminous coal while meeting or exceeding current environmental requirements for criteria pollutants.[81]

[81]National Energy Technology Laboratory, "Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity Revision 2," November 2010, DOE/NETL-2010/1397.

Table IV-4
Potential Efficiency Improvements for Power Plants in the U.S.

Area of Improvement	Efficiency increase, percentage points
Air heaters (optimise)	0.16–1.5
Ash removal system (replace)	0.1
Boiler (increase air heater surface)	2.1
Combustion system (optimise)	0.15–0.84
Condenser (optimise)	0.7–2.4
Cooling system performance (upgrade)	0.2–1
Feedwater heaters (optimise)	0.2–2
Flue gas moisture recovery	0.3–1.5
Flue gas heat recovery	0.3–1.5
Coal drying (installation)	0.1–1.7
Process controls (installation/improvement)	0.2–2
Reduction of slag and furnace fouling (magnesium hydroxide injection)	0.4
Soot blower optimisation	0.1–0.65
Steam leaks (reduce)	1.1
Steam turbine (refurbish)	0.84–2.6

Source: National Association of Clean Air Agencies.

Table IV-5 shows the potential heat rate reductions from system or equipment modifications for a typical coal-fired power plant. To derive the data in this table, Sargent & Lundy used an average boiler heat rate of 10,400 BTU/kWh.[82] Although most of the projects in the table are discrete, the "combined VFD and fan" row represents a sum of the "ID axial fan" and the "VFD" projects. If all of the projects listed in the table were to be completed, and if all achieved the maximum possible heat rate improvement, thermal efficiencies could possibly be improved by more than ten percent. However, these data are based on discussions with equipment vendors. Sargent & Lundy was not able to exhaustively survey US coal-fired power plants and was able to locate actual case examples for only a subset of the plant inventory.

[82]Sargent & Lundy, *Coal-Fired Power Plant Heat Rate Reductions,* SL-009597, January 2009.

Table IV.5
Potential Heat Rate Reductions (BTU/kWh) From System or Equipment Modifications for a Typical Coal-Fired Power Plant

System or Equipment Modified	Power Plant Size 200 MW	500 MW	900 MW
Economizer	50–100	50–100	50–100
Neural Network	50–150	30–100	0–50
Intelligent Soot Blowers	30–150	30–90	30–90
Air Heater and Duct Leakage Control	10–40	10–40	10–40
Acid Dew Point Control	50–120	50–120	50–120
Turbine Overhaul	100–300	100–300	100–300
Condenser	30–70	30–70	30–70
Boiler Feed Pumps	25–50	25–50	25–50
Induced Draft (ID) Axial Fan and Motor	10–50	10–50	10–50
Variable Frequency Drives (VFD)	20–100	20–100	20–100
Combined VFD and Fan	10–150	10–150	10–150

Source: Sargent & Lundy and National Association of Clean Air Agencies

As shown in these three tables, a wide range of power plant retrofits, upgrades, and refurbishings are feasible. The efficiency impacts of the individual improvements vary widely, from efficiency increases of less than one percent to five or six percent. It is unlikely that all of the improvements identified in these tables could be implemented at every plant – the type and number of projects available will depend on a number of factors specific to each plant such as original design, coal type, and location. Nevertheless, these data indicate the significant levels of fuel savings possible from efficiency improvements.[83]

Most of the major U.S. coal plants that have come on line over the past decade have been high efficiency, low emission (HELE) power plants – Table IV-6. Their average efficiency is about 38% -- significantly more efficient than the coal fleet average.[84] The John W. Turk, Jr. coal power plant in Arkansas is the only ultra-supercritical plant in the U.S., but the Longview Power in West Virginia plant is the most efficient plant power plant

[83]Tracey Lilly, "Who Has the World's Most Efficient Coal Power Plant Fleet?" *Power Magazine*, April 1, 2017. Richard F. Storm, "The Most Efficient Thermal Power Generation Plants in America," Williamson College, 2018; "World's Most Efficient Coal Plants," *Power Magazine*, April 2017, http://www.powermag.com/who-has-the-worlds-most-efficient-coal-power-plant-fleet/.
[84]"Outlook and Benefits of an Efficient U.S. Coal Fleet," WoodMackenzie, 2019.

and unit.[85] NETL is continuing research into increasing the efficiency of U.S. coal power plants.[86]

Table IV.6
Top U.S. HELE Power Plants by Efficiency

Power Plant & Unit	State	EIA HELE Category	Capacity (MW)	Efficiency (%)	Start Year
John W. Turk Jr. 1	AK	Ultra-supercritical	614	37.9	2012
Longview Power 1	WVA	Supercritical	700	39.7	2011
Trimble County 2	KY	Supercritical	747	39.6	2011
Latan 2	MO	Supercritical	850	38.6	2010
Sandy Creek 1	TX	Supercritical	927	38.6	2013
Prairie State PC 1	IL	Supercritical	800	37.9	2012
Cliffside 6		Supercritical	800	37.9	2012
Prairie State PC 2	IL	Supercritical	800	37.9	2012
Elm Road 2	NC	Supercritical	634	37.8	2011
J.K. Spruce 2	IL	Supercritical	780	37.7	2010
Weston 4	WI	Supercritical	535	37.5	2008
Oak Grove 1	TX	Supercritical	817	37.4	2009
Oak Grove 2	TX	Supercritical	827	37.4	2010

Source: WoodMackenzie

HELE plants have other benefits that are not usually monetized using conventional power plant economics. For example, they:[87]

- Do not require significant network upgrades;
- Do not require backstop generation or energy storage (e.g. batteries);
- Provide greater reliability, strengthen energy security and improve US competitiveness (key trading partners are using HELE technology and it enhances their competitive position);
- Provide ancillary services (spinning reserve, voltage regulation, resiliency);
- Do not require a new market paradigm;

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[85]"AEP/SWEPCO John Turk Plant," *Power Magazine*, http://www.powermag.com/aeps-john-w-turk-jr-power-plant-earns-powers-highest-honor/; "Longview Power, Plant of the Year," *Power Magazine*, 2016, http://www.powermag.com/longview-power-plant-rehabilitation-results-efficient-u-s-coal-plant/.Subcritical steam operating conditions are generally at pressures of 2,400 pounds per square inch gage (psig); i.e., relative to atmospheric pressure per 1,000º F of superheated steam. Supercritical steam cycles typically operate at 3,600 psig, with 1,000 ºF to 1,050 ºF steam conditions. See American Electric Power Company, Pulverized Coal Technologies, 2013, http://www.aep.com/about/IssuesAndPositions/Generation/Technologies/PulverizedCoal.aspx.

[86]See National Energy Technology Laboratory, "NETL Leads Drive for Efficiency in Fossil Fuel-based Power Plants," January 21, 2020; National Energy Technology Laboratory, "The Transformative Power Generation Program," 2018; "DOE Providing $39 Million for Coal-Fired Power Fleet Research," *Power Engineering*, June 10, 2019.

[87]"Outlook and Benefits of an Efficient U.S. Coal Fleet," op. cit.

- Expand payrolls and tax bases and increase revenues for local contractors, suppliers, service providers, and ancillary businesses
- Increase construction jobs;
- Stimulate U.S. manufacturing industry.

In addition, HELE power plants help reduce uncertainty in the power markets, which is a benefit not recognized by the industry and the public.

The potential for CFPP efficiency improvements can be assessed based on the assumption that the lower-performing CFPPs in each online year group should be capable of achieving about the same level of efficiency as the better performing plants. In 2007, the average CFPP efficiency was 32 percent, whereas the efficiency of the top 10 percent performing power plants was five percentage points higher, 37 percent. If all CFPPs were improved to the efficiency of the top 10 percent of their online year group, NETL estimated that fuel costs could be reduced significantly and emissions of more than 250 MMmt of CO_2 could be avoided annually.[88]

Previous research estimated that the cumulative fuel cost savings resulting from efficiency improvements attributable to the DOE coal RD&D program through 2007 totaled about $0.8 billion (2019 dollars).[89] Here we estimated the fuel cost savings over the period 2008 – 2019 by assessing the amount of electricity produced by the U.S. coal fleet, 2008 – 2019, the average efficiency of the existing coal fleet compared to the new plants which came on line over this period, the more efficient electricity generation resulting from DOE funded RD&D, the electricity produced by the newer, more efficient plants, and the resulting savings in electricity costs in each year and cumulatively. We estimated that the cumulative fuel cost savings over the period 2008 – 2019 totaled about $2.1 billion (2019 dollars). We thus estimate that the total fuel cost savings through 2019 totaled about $2.9 billion (2019 dollars). While substantial, this is, if anything, a conservative estimate of the actual fuel savings, and even these cumulative savings represent a portion of 2019 electricity costs of less than 0.8 percent -- U.S. electricity costs currently total about $400 billion annually.[90]

IV.E. Value of Clean Coal Technology Exports

Thanks in large part to the DOE coal RD&D program, the U.S. has been a world leader in many areas of clean coal and related technologies, although in recent years this lead has been eroding and currently faces increasing competition from other nations. In particular, China is practicing a leapfrogging strategy and is becoming a leader in some

[88]National Energy Technology Laboratory, "Cost and Performance Baseline for Fossil Energy Power Plants Study, Volume 1: Bituminous Coal and Natural Gas to Electricity," op. cit.
[89]Roger Bezdek and Robert Wendling, "The Return on Investment of the Clean Coal Technology Program in the USA," op. cit. MISI converted the estimate to 2019 dollars.
[90]U.S. Energy Information Administration, *Electric Power Annual*, 2019.

market segments.[91] Research also determined that a nation in which no new coal power plants are being built, such as the U.S., may lose some of these first mover technology advantages.[92] Nevertheless, over the past two decades, U.S. technological prowess presented important opportunities for exporting equipment and to license technology to countries such as India and, especially China, where coal-fired electricity production was (and is) rapidly increasing. This section estimates the U.S. exports of clean coal and related technologies to the worldwide market through 2019. We use methodology and data from the U.S. International Trade Administration (ITA) the U.S. Commercial Service (USCS), the U.S. Trade and Development Agency (TDA), the United Nations, the World Trade Organization, previous research, and other sources.

ITA has estimated the U.S. market share of clean coal technologies (CCT) based on Harmonized Tariff Schedules (HS) categories, which include equipment that is used coal power plants and in related industrial applications.[93] The HS code was used to derive the potential exports of clean coal equipment used in supercritical coal-fired power plants and the HS codes include, for example, parts of coal-fired power plants that are used with boilers; furnace burners for pulverized solid fuels; filters and purifying machinery, including electrostatic precipitators and selective catalytic reduction units; other filter purifying machinery, and related products.

ITA initially analyzed nine countries (according to their high current and projected coal usage rates for power production) -- Table IV.7.[94] It found that, in 2005, most of Mexico's imported boilers, furnace burners, filters, and purifying systems for coal-fired power plants were imported from the U.S.; for the EU, the majority of its imported equipment came from South Africa; South Africa's imported equipment came from Germany. In 2005, China's primary trade partners for imported CCT equipment were Japan and Germany, while India imported most of its CCT equipment from Thailand and Germany (Table IV.7).

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[91]Jens Horbach, Qian Chen, Klaus Rennings, and Stefan Vögele, "Lead Markets for Clean Coal Technologies: A Case Study for China, Germany, Japan and the USA," Discussion Paper No. 12-063, http://ftp.zew.de/pub/zew-docs/dp/dp12063.pdf; Jens Horbach, "Do Lead Markets for Clean Coal Technology Follow Market Demand? A Case Study for China, Germany, Japan and the USA," 35th DRUID Celebration Conference 2013, Barcelona, Spain, June 17-19.

[92]Ibid.

[93]Shannon Fraser and Stefan Osborne, *Potential Exports of U.S. Clean Coal Technology Through 2030*, U.S. Department of Commerce, International Trade Administration, November 2007.

[94]ITA used the *World Trade Atlas* and the HTS codes to derive the U.S. imports and worldwide imports of CCT equipment for 2005, the most recent year for which data for all countries analyzed was then available.

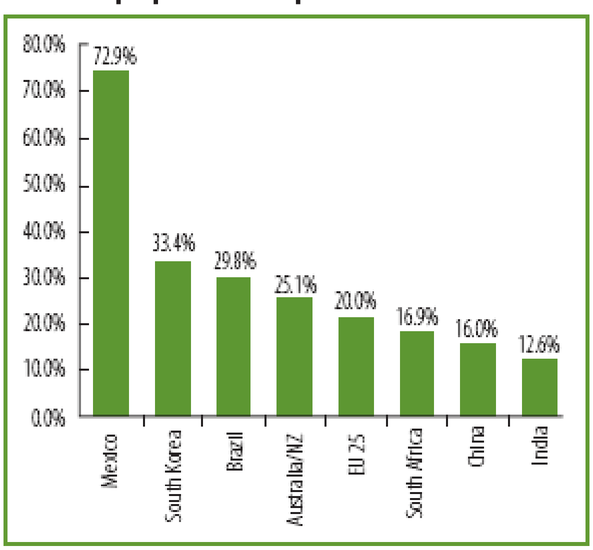
Table IV.7
Clean Coal Technology Equipment Imports in 2005
(Millions of Dollars)

Country	U.S. rank	Imports from the United States	Imports from the world
Australia and New Zealand	1	52.33	208.77
Brazil	1	34.93	117.34
China	3	168.68	1,054.31
EU 25	2	470.54	2,351.59
India	3	20.50	162.62
Mexico	1	290.35	398.22
South Africa	2	15.87	93.79
South Korea	1	90.17	269.60
Total		1,143.37	4,656.24

Source: International Trade Administration and the *World Trade Atlas* database.

ITA derived the percentage of CCT equipment imports from the U.S. to each of those countries in 2005 by dividing the dollar amount of imports from the U.S. by the dollar amount of imports from the world. For example, it estimated that Mexico imported 72.9 percent of its CCT equipment from the U.S., followed by South Korea, which imported 33.4 percent of its equipment from the U.S. (Figure IV.8).

Figure IV.8
Percentage of CCT Equipment Imports Sourced from the U.S. in 2005



Source: International Trade Administration and the *World Trade Atlas* database.

Subsequent ITA and USCC analyses expanded this research. For example, ITA found that the U.S., together with Japan and Germany, has been one of the major clean coal technology (CCT) equipment exporters to China, and the U.S. share of China's CCT equipment imports has comprised 20-30% of the country's CCT imports in recent years.[95] ITA found that, as China has been seeking to equip all of its coal-fired facilities with clean coal technology and emissions abatement equipment, its demand for advanced waste treatment and purifying machinery presented huge trade opportunities for U.S. exporters. Accordingly, U.S. exports of purifying machine parts to China accounted for approximately 30 percent of China's total imports of such parts. Best-selling CCT equipment in China include filtering machinery for gases, steam and vapor generating boiler auxiliary plant parts, and furnace burners for solid, gas, or combination fuel.[96]

Parts of Asia, especially China and India, continue to use coal as their primary source of power. The economies of both China and India have been growing rapidly, and both of these coal-rich countries have been relying greatly on their domestic energy resources to facilitate economic development. Approximately three-quarters of all currently planned coal-fired power plants worldwide are being installed in one of these two countries. With this growth, China, India, and other nations required increased investments in mining operations, power plants, and power distribution systems. The increased demand for CCT equipment provided opportunities for U.S. exporters to supply this rapidly growing market.

China's environmental regime has improved in recent years with the development of a national legal framework that supports the mitigation of pollution across all three environmental media.[97] Accordingly, over the past decade, Chinese plants provided an abundance of both retrofit and new installation opportunities for stationary source emission reduction and control technologies. The types of technologies needed for a given power plant depend on regulatory requirements, and the type of coal to be burned is also relevant since pollutant levels vary for different kinds of coal. In addition to the demand for more traditional technologies used to limit or control NO_x, SO_x, particulate matter, and mercury emissions, state-of-the-art emerging technologies – particularly those designed for multipollutant control – are of great interest to the Chinese and other foreign buyers. Emerging technologies include non-carbon sorbents for removal of flue gas mercury and non-thermal plasma and activated coke for multi-pollutant removal.[98]

More recently, as worries mount over a slowing economy and energy security, coal use has increased despite China's claims to be leading the climate change fight. In 2019, coal consumption returned to near peak levels after rebounding over the past three years, despite China's pledges to make substantial reductions in coal utilization.[99] China is

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[95]U.S. International Trade Administration, "Clean Coal Technology," March 2017.
[96]Ibid.
[97]U.S. International Trade Administration, "2017 Top Markets Report Environmental Technologies: A Market Assessment Tool for U.S. Exporters," 2018.
[98]Ibid.
[99]Stephanie Yang, "In Tougher Times, China Falls Back on Coal," *Wall Street Journal*, December 23, 2019.

currently building more coal-fired plant capacity than the rest of the world combined -- it is building new coal-fired power plants every seven to 10 days.

As a result, in order to reduce air pollution China has invested massively in upgrading and building new clean coal power stations. Having realized the importance of advanced coal technology, the Chinese government has been reaching out to developed economies and actively encouraging clean coal equipment imports. China has four top priorities relative to development of clean coal technologies for power generation: IGCC, supercritical coal-fired power plants, atmospheric fluidized bed combustion, and pressurized fluidized bed combustion.[100]

China plans to equip all coal-fired facilities with clean coal technology and emissions abatement equipment, and its demand for advanced waste treatment and purifying machinery has presented huge trade opportunities for U.S. exporters. Best-selling CCT equipment in China include filtering machinery for gases, steam and vapor generating boiler auxiliary plant parts, and furnace burners for solid, gas or combination fuel.[101]

Coal is the main source of China's CO_2 emissions, and, faced with massive air pollution, it has pledged to peak its carbon dioxide emissions by 2030.[102] Efforts have been made by the Chinese government to promote cleaner use of coal and to facilitate emission-cutting technologies for coal-fired power stations.[103] China has established ambitious standards for reducing coal utilization and for reducing coal power pollution by 60 percent by upgrading its current power stations with "ultra-low emission" technologies.

China is thus emerging as a major influence on CCUS deployment, with several planned and operational demonstration projects.[104] The U.S. has been facilitating large-scale deployment of CCUS technologies to commercialization. It is in a prime position due to the political and economic characteristics of its energy economy, resource wealth, and innovation-driven manufacturing sector.[105]

While China has just recently begun the construction of coal gasification plants in northwestern parts of the country, the U.S. has been producing SNG since the 1980s, indicating mature U.S. coal gasification technology and expertise. Moreover, there are two major problems with coal gasification in China. Coal gasification produces more CO_2 than a traditional coal plant, and it is one of the more water-intensive forms of energy

[100]"China Buys Clean Coal Technology From U.S.," www.Export.gov.
[101]U.S. International Trade Administration, "2017 Top Markets Report Environmental Technologies: A Market Assessment Tool for U.S. Exporters," op. cit.
[102]Oluwasola E., Omoju, "Effectiveness of Clean Coal Technologies in Global Carbon Emission Mitigation: Evidence and Summary," TEMTI Series of Economic Perspectives on Global Sustainability, EP 01-2015, TEMTI –CEESP/IUCN, 2015.
[103]U.S. Commercial Service, "China City & Industry Report: A Guide for U.S. Exporters," 2017; U.S. Commercial Service, "China Buys Clean Coal Technology From U.S.," www.Export.gov.
[104]*Global Status of CCS*, The Global CCS Institute, 2019.
[105]Lee Beck, "Carbon Capture and Storage in the USA: The Role of US Innovation Leadership in Climate-Technology Commercialization," *Clean Energy*, October 2019.

production.[106] As such, U.S. exporters have found opportunities in licensing new technology and selling wastewater treatment equipment that used to address these two problems in China's western regions.[107]

The recently-amended Air Pollution Law follows on China's nationally determined contribution (NDC) commitments by expanding the list of centrally-controlled pollutants beyond solely NO_x and SO_x to include particulate matter, Volatile Organic Compounds (VOCs) and greenhouse gases.[108] This emissions reduction effort requires the implementation of control technologies in various industries, including iron, cement and steel plants; oil refineries; non-ferrous metallurgical plants; coal boilers; and petrochemical plants.[109]

Highly efficient coal plants are also important -- the supercritical, ultra-supercritical, and coal gasification technologies that China and India are increasingly turning to in order to reduce coal feed and to lower emissions. These are the high-efficiency, low-emissions (HELE) coal solutions advocated by the International Energy Agency.[110]

The major clean coal and related technologies in demand in China include:[111]

- Wet/dry scrubbers (particularly systems that remove multiple pollutants)
- Carbon injection systems (for reduction in mercury and organics)
- Particulate matter control systems (particularly new bagging systems)
- NO_x, mercury, CO_2 and particulate matter monitoring and continuous monitoring systems
- Selective catalytic and non-catalytic reduction controls
- Oxygen enrichment, fuel injection and other efficient combustion technologies
- Mixing technologies
- Pumping and fluid handling equipment
- Engineering and plant design
- Leak detection equipment
- Continuous emissions monitoring systems
- Dry sorbent injection technologies
- Flue gas desulfurization equipment
- Activated carbon injection technologies
- Inspection, adjustment, maintenance and repair services

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[106]Xi Lua, Liang Caoa, Haikun Wangd, Wei Penge, Jia Xinga, Shuxiao Wanga, Siyi Caia, Bo Sheng, Qing Yangh, Chris P. Nielsenj, and Michael B. McElroyj, "Gasification of Coal and Biomass as a Net Carbon Negative Power Source For Environment-Friendly Electricity Generation in China," *Proceedings of the National Academy of Sciences*, April 2, 2019.
[107]U.S. Commercial Service, "Clean Coal Technology," 2017.
[108]https://climateactiontracker.org/countries/china/.
[109]Cai Jingjing and Joyce Tang, "Will China's New Air Law Solve its Pollution Crisis?" *NewSecurityBeat*. China Environment Forum.
November 25, 2015. http://www.newsecuritybeat.org/2015/11/chinas-air-law-solve-pollution-crisis/.
[110]International Energy Agency Clean Coal Center, "Realizing Decarbonization Through Efficiency Gains." http://cornerstonemag.net/tag/efficient-use-of-coal/.
[111]U.S. International Trade Administration, "2017 Top Markets Report Environmental Technologies A Market Assessment Tool for U.S. Exporters," 2018.

- Selective catalytic reduction technologies
- Wet and dry electrostatic precipitators including horizontal wet electrostatic precipitators (WESPs)

India is another major market for U.S. clean coal technologies. Coal is India's primary energy source, accounting for more than 70% of energy generation in the power sector, and India is projected to become the largest source of growth in global coal use in the next 25 years.[112] Most of the country's hard coal is of poor quality, with low to medium heat values and high ash content, and this contributes to decreased efficiency in power generation and higher local emissions. With low quality coal and more than 85% of India's coal-fired power plants currently employing subcritical technology, the average efficiency for the generating fleet is less than 35%.[113] The resulting unreliable electricity supply, together with high end-use tariffs, has led energy intensive consumers, such as the steel, cement, chemicals, sugar, fertilizer and textile industries, to produce a significant portion of their own electricity.[114]

The Indian government has identified 17 high polluting industry sectors in need of greater oversight and air pollution control measures. These include a variety of industries, but the most important is thermal power plants. Studies found that industrial combustion contributes to nearly half of India's particulate matter 10 (PM_{10}) emissions.[115] As new rules for these industries evolve and are enforced, opportunities in control technologies will continue to develop. New regulations helped make India's air pollution control market worth more than $10 billion annually.[116] Similarly, India is building tens of billions of dollars' worth of new NO_x controls and flue gas desulphurization technologies.[117]

The major clean coal and related technologies in demand in India include:[118]

- Fenceline monitoring equipment
- Continuous emissions monitoring equipment
- Ambient air quality monitoring equipment
- Source emission measurement technologies
- Dry sorbent injection technologies
- Flue gas desulfurization equipment
- Activated carbon injection technologies
- Inspection, adjustment, maintenance and repair services
- Selective catalytic reduction technologies
- Selective non-catalytic reduction controls

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[112]International Energy Agency, *World Energy Outlook 2019*, November 2019.
[113]Ibid.
[114]Wealthier Indian households also typically employ backup diesel generators, contributing to worsening local air pollution, particularly from particulate matter.
[115]Arup Kumar Mitra, "India Market Opportunities for Air Pollution Control and Air Quality Monitoring Technology," U.S. Commercial Service, Kolkata, India. January 18, 2017.
[116]Ibid.
[117]PacifiCorp Webinar 5 on Front End NO_x Reduction." *Gold Dust*. September 2016.
[118]U.S. International Trade Administration, "2017 Top Markets Report Environmental Technologies: A Market Assessment Tool for U.S. Exporters," op. cit.

- Urea to ammonia reagent systems

Other major markets for U.S. clean coal technology exports over the past decade include Indonesia, Pakistan, South Korea, Turkey, and Vietnam.[119] For example, Turkey, Indonesia, and Vietnam combined plan to increase their electric generating capacity by about 160 GW. This is about as much as the output of all existing coal-fired plants in the 28 EU countries. Pakistan and Indonesia combined having a population nearing 500 million and are rapidly increasing their coal utilization: With rapidly increasing power demand, coal is seen as cheaper, more reliable, more secure, and more established.[120] In addition, Africa, Brazil, Mexico, and other nations have been rapidly increasing their electricity consumption. The corresponding increased demand for clean coal equipment provided opportunities for U.S. exporters to supply this rapidly growing market.

ITA, TDA, USCS, and others have assessed U.S. exports of clean coal technology and related technologies over the past decade. In many areas, the U.S. has led in bringing clean coal technology to commercialization and in exporting that technology to the rest of the world.[121] TDA noted that the Presidential Executive Order on Promoting Energy Independence and Economic Growth[122] is facilitating U.S. industry's engagement in coal projects in emerging markets, where coal contributes a significant share of total energy consumption.[123]

Previous research estimated that the U.S. clean coal technology exports through 2009 totaled approximately $14.4 billion (2008 dollars).[124] Using the IPD deflators in Section III.C, we translated this figure to 2019 dollars: Approximately $17.1 billion.

MISI estimated U.S. clean coal technology exports over the period 2010 – 2019. We primarily used the U.S. data available for HS Codes 840490, 841620, 842139, and 842199. As noted, these HS codes include, for example, (a) parts of coal-fired power plants that are used with boilers; (b) furnace burners for pulverized solid fuels; (c) filters and purifying machinery, including electrostatic precipitators and selective catalytic reduction units; and (d) other filter purifying machinery.[125] Since these codes are based

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[119] U.S. International Trade Administration, "2017 Top Markets Report Environmental Technologies: A Market Assessment Tool for U.S. Exporters," op. cit.

[120] Jude Clemente, "The United States as a Clean Coal Leader," *Forbes*, February 14, 2018.

[121] Joe Manchin, "Clean Coal Technologies: Vital For U.S. Energy Security, Export Opportunities," *Washington Times*, May 1, 2017; Uttara Choudhury, "Clean Coal Technologies Targets Multibillion-Ton Coal Opportunity With its Disruptive Dehydration Technology," Proactive Investors, 2019.

[122] "Presidential Executive Order on Promoting Energy Independence and Economic Growth," https://www.whitehouse.gov/presidential-actions/presidential-executive-order-promoting-energy-independence-economic-growth/.

[123] U.S. Trade and Development Agency, "USTDA Accepting Initial Proposals for Cleaner Coal Projects in Emerging Markets," February 1, 2018.

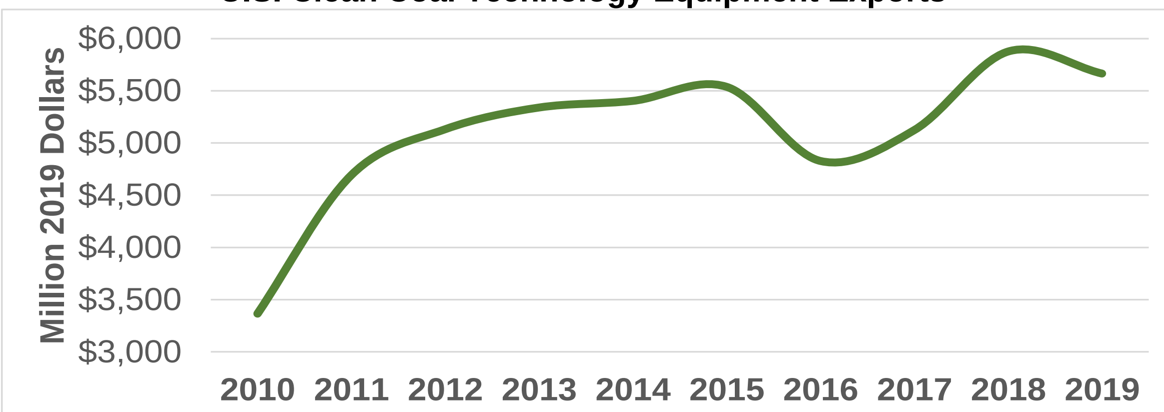
[124] Roger Bezdek and Robert Wendling, "The Return on Investment of the Clean Coal Technology Program in the USA," op. cit.

[125] HS Code 840490 includes auxiliary plant for use with boilers of heading 8402 or 8403 (for example, economizers, super-heaters, soot removerers, gas recoverers); condensers for steam or other vaper power units; parts thereof; HS Code 841620 includes furnace burners for liquid fuel, pulverized solid fuel, or gas; mechanical stokers, including their mechanical grates, mechanical ash dischargers, and similar appliances;

primarily on trade in equipment, we incorporated estimates of sales of U.S. licenses of clean coal technology equipment. Estimates of U.S. exports were derived from data available from ITA, USCS, TDA, the United Nations, the World Trade Organization, and other publicly available sources.[126]

Figure IV-9 shows that annual U.S. clean coal technology equipment exports between 2010 and 2019 varied, in 2019 dollars, between about $3.4 and $5.9 billion. These exports increased rapidly until 2012, then increased gradually to 2015, decreased in 2016, increased in 2017 and 2018, and decreased in 2019. Over the period 2010 – 2019, U.S. clean coal technology equipment exports totaled $51.0 billion (2019 dollars).

Figure IV-9
U.S. Clean Coal Technology Equipment Exports*



*Based on HS Codes 840490, 841620, 842139, and 842199.
Source: U.S. International Trade Administration, U.S. Commercial Service, UN Comtrade, BP Plc, and F. Pasimeni.

Figure IV-9 thus shows that over the period 2010 – 2019, cumulative U.S. clean coal technology equipment exports totaled $51.0 billion (2019 dollars). Here we assume that the DOE coal RD&D program facilitated at least half of these exports – valued at 26.5 billion (2019 dollars). As noted, previous research estimated that the U.S. clean coal technology exports through 2009 attributed to the DOE RD&D program totaled approximately $17.1 billion (2019 dollars). We thus estimate that the cumulative U.S.

HS Code 842139 includes Centrifuges, including centrifugal dryers; filtering or purifying machinery and apparatus for liquids or gases; parts thereof (including electrostatic precipitators and selective catalytic reductions systems); HS Code 842199 includes centrifuges, including centrifugal dryers; filtering or purifying machinery and apparatus for liquids or gases; parts thereof.

[126]U.S. International Trade Administration, "2017 Top Markets Report Environmental Technologies A Market Assessment Tool for U.S. Exporters," op. cit.; U.S. International Trade Administration, "Clean Coal Technology," op. cit., U.S. Commercial Service, "China City & Industry Report: A Guide for U.S. Exporters," 2017, op. cit.; United Nations, "UN Comtrade Database," https://comtrade.un.org/; World Trade Organization, *World Trade Statistical Review*, 2017; BP. Plc., *BP Statistical Review – 2019: China's Energy Market in 2018*, 2019; F. Pasimeni, *EU Energy Technology Trade: Import and Export*, EUR 28652 EN, Publications Office of the European Union, Luxembourg, 2017, ISBN 978-92-79-69670-1, doi:10.2760/607980, JRC107048.

clean coal technology export benefits through 2019 attributed to the DOE RD&D program total approximately $17.1 billion plus $26.5 billion -- $42.6 billion (2019 dollars).

It should also be noted that:[127]

- U.S. clean coal technology exports included more equipment than represented by the NAICS codes that included, especially in the early years, ancillary equipment such as mill, fans, control systems, along with control systems).[128]
- U.S. companies are receiving profits and licensing fees from equipment now manufactured overseas.
- Global emissions of CO_2, SO_2, NO_x, PM, and mercury were reduced using exported/licensed U.S. equipment.
- U.S. companies also provided engineering services for power plant design, retrofits, etc. using exported and licensed equipment, which returns benefits to the U.S. in addition to equipment exports.
- An example of a project using U.S. know-how initially developed with DOE support is the Manjung 1000 MW ultrasupercritical (USC) plant supplied by GE to a Chinese export/construction company from GE's manufacturing facilities in China. It was the first USC plant in Southeast Asia. While it is impossible to value such exports, the benefits are substantial and are attributable to the DOE RD&D programs.

IV.F. Avoided Environmental Costs

Environmental benefits result when the introduction of a new technology or RD&D program makes possible an improvement (or reduced degradation) in measures of environmental quality. These include particular matter (PM) reductions, water quality improvement, air quality improvement, and impacts on other criteria indicators in line with articulated clean air and water goals. The assessment and monetization of potential environmental impacts and improvements is important, but is also controversial.

IV.F.1. SO_2 Emissions

All coals contain sulfur and some of this sulfur, known as organic sulfur, is intimately associated within the coal matrix. The rest of the sulfur, in the form of pyrites or sulfates, is associated with the mineral matter. High-sulfur bituminous coals contain 1-4%, whereas low-sulfur Western coals may have sulfur content below one percent. Upon combustion, most of the sulfur is converted to SO_2, with a small amount being further oxidized to sulfur trioxide (SO_3).

Even prior to enactment of the Clean Air Act Amendments (CAAA), the DOE coal RD&D program was addressing the likely effects of the anticipated regulations on electric

[127]Information provided to MISI by DOE, June 2020.
[128]NAICS is the North American Industrial Classification System.

power generation.[129] Several projects in the DOE coal RD&D program were conducted at units designated as Phase I units under Title IV, which were required to meet SO_2 reductions by January 1, 1995. Clean coal technologies installed at Phase I units successfully reduced SO_2 emissions using advanced flue gas desulfurization (FGD) processes.

By the arrival of the January 1, 2000 deadline for Phase II of Title IV, DOE RD&D had developed a portfolio of technologies to help industry meet the more stringent SO_2 emission limits. Unit operators had the option of either meeting SO_2 reduction requirements or exceeding them to generate SO_2 credits that could be sold in the emissions credit market.

The CAAA sent a clear signal to industry in the statement, "SO_2, a primary precursor to acid rain, must cease to be a major pollutant emission by the beginning of the 21st century."[130] Interim response to the regulation included fuel switching, allowance trading, and installation of available emissions controls. However, to meet the post-2000 cap on SO_2 emissions, high-efficiency control technologies were required. Prior to the DOE coal RD&D program, scrubbers capable of high SO_2 removal were costly to build, difficult to maintain, placed a significant parasitic load on plant output, and produced a sludge waste requiring extraordinary disposal measures with considerable land use.

The DOE clean coal demonstration projects redefined the state of the art in scrubber technology. Use of innovative capture technologies significantly reduced capital and operating costs, produced valuable by-products such as wallboard-grade gypsum instead of waste, mitigated plant efficiency losses, and captured multiple air pollutants. As a result, advanced FGD systems became operable that provide SO_2 removal efficiencies of 95-98 percent. The demonstration projects involving SO_2 scrubbers predated the Title IV Phase 1 compliance date by two to three years. In 1995, the first year of compliance under Title IV, SO_2 emissions declined dramatically, by 3 million tons. Over the first four years of the demonstration program, SO_2 emissions from the 263 largest, highest emitting utility plants were about 5 million tons below their 1980 levels. The overall reduction in SO_2 emissions between 1990 and 1999 was 21%.[131]

Figure IV-10 shows coal consumption in the U.S. electric power sector, 2000 – 2019. This figure illustrates that coal use in the power sector was relatively constant from 2000-2008, declined and increased several times between 2009 and 2014, and then

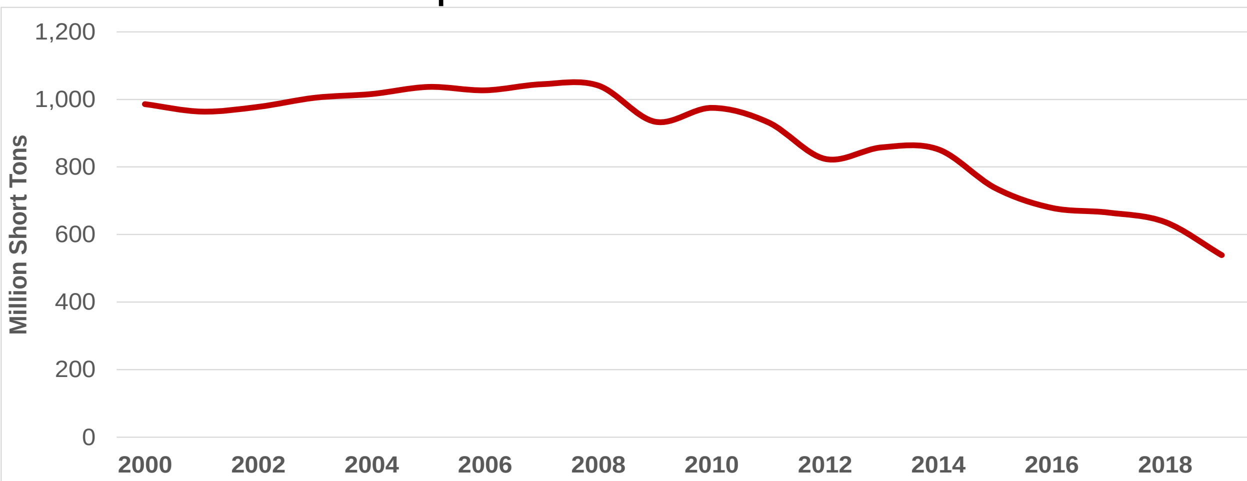
[129]National Research Council, *Energy Research at DOE: Was It Worth It?* Op. cit.; Emanuele Massetti, Marilyn A. Brown, Melissa Lapsa, Isha Sharma, James Bradbury, Colin Cunliff, and Yufei Li, "Environmental Quality and the U.S. Power Sector: Air Quality, Water Quality, Land Use and Environmental Justice," Oak Ridge National Laboratory, ORNL/SPR-2016/772, 2017.

[130]U.S. Department of Energy, *Environmental Benefits of Clean Coal Technologies*, Topical Report Number 18, April 2001.

[131]These reductions in emissions have occurred where they are most needed – in some of the highest emitting areas of the country. For example, affected power plants in Ohio and Indiana reduced SO_2 emissions by about 44 percent and 50 percent, respectively. Moreover, this decrease supports an economic premise of the Acid Rain Program: Utilities have more incentive to make substantial emissions reductions at the highest emitting plants because they can achieve them at a lower cost per ton.

declined continually from 2015 to 2019. Coal consumption reach a high of 1,045 million tons in 2007 and decreased to 539 million tons in 2019.[132]

Figure IV-10
Coal Consumption in the U.S. Electric Power Sector



Source: U.S. Energy Information Administration.

SO_2 emissions from the U.S. electric power sector have declined substantially over the past two decades, largely because of the phased implementation of regulations under the Clean Air Act Amendments of 1990, but also to the retirement of many older coal power plants. For SO_2, these regulations include acid rain cap-and-trade program deadlines in 1995 and 2000.[133] In addition, EPA's Mercury and Air Toxics Standards (MATS), announced in 2011 and implemented in 2015, required power generators to comply with emissions limits for toxic air pollutants associated with fuel combustion such as mercury, arsenic, and heavy metals. Although MATS targets mercury and air toxics emissions, power plants' compliance with the rule also decreased emissions of SO_2.

Within the power sector, coal accounts for over 95% of SO_2 emissions.[134] Figure IV-11 shows SO_2 emissions from U.S. coal power plants, and illustrates that these emissions decreased much more rapidly than coal consumption in the U.S. electric power sector. SO_2 emissions from U.S. coal power plants decreased from 10.6 million tons on 2000 to 1.1 million tons in 2019 – a decrease of 90%.[135] This is compared to a decrease

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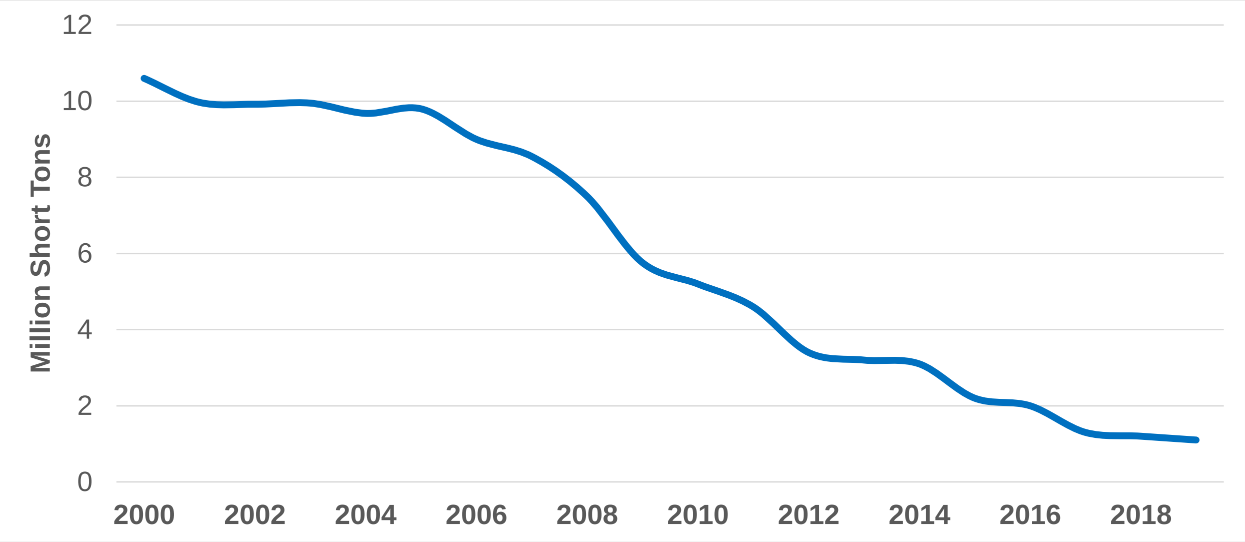
[132]U.S. Energy Information Administration, *Monthly Energy Review*, March 2020.
[133]U.S. Energy Information Administration, "Emissions From the U.S. Electric Power Sector Projected to Remain Mostly Flat Through 2050," February 11, 2019.
[134]Emanuele Massetti, Marilyn A. Brown, Melissa Lapsa, Isha Sharma, James Bradbury, Colin Cunliff, and Yufei Li, "Environmental Quality and the U.S. Power Sector: Air Quality, Water Quality, Land Use and Environmental Justice," Oak Ridge National laboratory, 2017.
[135]U.S. Energy Information Administration, *Electric Power Annual*, various years, 2000 – 2019. EIA projects that electric power sector SO_2 emissions will remain relatively unchanged throughout the AEO projection period; see U.S. Energy Information Administration, "Emissions From the U.S. Electric Power Sector Projected to Remain Mostly Flat Through 2050," op. cit.

over the same period in coal consumption in the U.S. electric power sector of about 50%. Thus, per ton of coal consumed, U.S. coal power plants currently emit much less SO_2 than they did two decades ago.

Figure IV-11
SO_2 Emissions from U.S. Coal Power Plants



Source: U.S. Energy Information Administration.

As noted, annual SO_2 emissions from coal power plants decreased from 10.6 million tons in 2000 to 1.1 million tons in 2019. There are two questions that have to be addressed here:

- How much of this decline can be legitimately attributed to the DOE coal RD&D program?
- What is the proper value of the SO_2 emissions avoided?

It is with respect to the first question – attribution of SO_2 emissions reductions to the DOE coal RD&D program – that the methodology developed in the NRC/NAS studies discussed in Section III.C is germane. This methodology recognized that, while the DOE coal RD&D program was instrumental in developing SO_2 reduction technologies for electric power plants, all of the benefits of these reductions could not legitimately be attributed to the DOE program. Even in the absence of the DOE program, electric utilities would have been eventually forced to reduce SO_2 emissions. Therefore, NRC/NAS recommended that early in the years following the CAAA and DOE programs practically all of the emissions reductions be attributed to the DOE program, with the portion of the attributed benefits gradually declining over the forecast period. This is the methodology we followed here. Thus, for example, most of the emissions reductions in 2000 were attributed to the CCT program, but by 2019 the DOE program is given credit for only a relatively small portion of the SO_2 emissions reductions.[136] Accordingly, we estimated that, over the period 2000 – 2019, the DOE program was responsible for SO_2 reductions totaling about 29.2 million tons.

What is the proper value of the SO_2 emissions avoided? Over the period 2000 – 2019, the price of SO_2 emissions has fluctuated very widely. According to EPA, prices ranged from more than $833/ton (current dollars) in 2006 to a price of $0.07/ton (current dollars) in 2019 – Figure IV-12.[137] This figure illustrates that SO_2 emission prices increased rapidly from 2000 to 2006, declined rapidly from 2007 to 2010, and collapsed after 2011.

We applied the IPD deflators described in Section III.C to convert the annual SO_2 emission prices in current dollars to constant 2019 dollars. This allowed us to estimate the environmental benefits from 2006 through 2019 of SO_2 emissions reductions attributable to the DOE program at a total of about $6.2 billion (2019 dollars). It has been previously estimated that the SO_2 savings resulting from the DOE program through 2005 totaled $62.3 billion in 2019 dollars.[138] Thus, the total environmental benefits of SO_2 emissions reductions attributable to the DOE program through 2019 total about $68.5 billion (2019 dollars).

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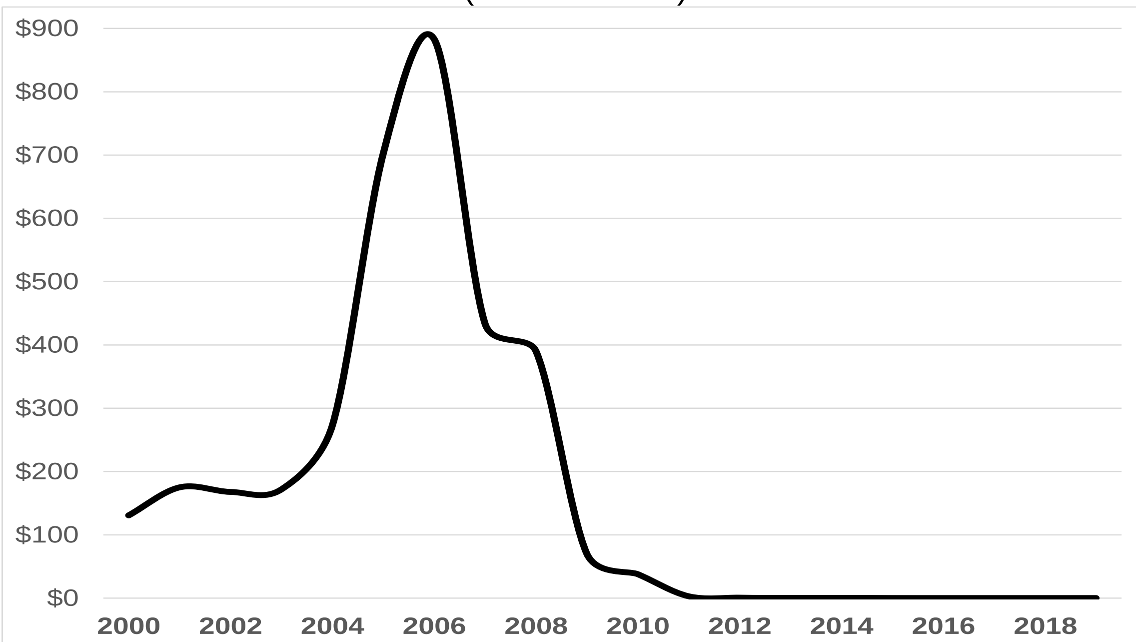
[136]Specifically, the DOE program was given credit for 95% of the 2000 SO_2 emissions reductions, phasing down linearly to 10% of the 2019 reductions.

[137]U.S. Environmental Protection Agency, "Clean Air Markets," annually, 2000-2019, https://www.epa.gov/airmarkets.

[138]See Roger Bezdek and Robert Wendling, "The Return on Investment of the Clean Coal Technology Program in the USA," op. cit.; U.S. Department of Energy, Office of Fossil Energy, "Clean Coal Technology: From Research to Reality," 2007; U.S. Department of Energy, Assistant Secretary For Fossil Energy, "Clean Coal Technology: The Investment Pays Off," November 1999; National Research Council, *Energy Research at DOE: Was It Worth It?* Op. cit.; National Research Council, *Prospective Evaluation of Applied Energy Research and Development at DOE (Phase One): A First Look*, Committee on Prospective Benefits of DOE's Energy Efficiency and Fossil Energy R&D Programs, op. cit.; Emanuele Massetti, Marilyn A. Brown, Melissa Lapsa, Isha Sharma, James Bradbury, Colin Cunliff, and Yufei Li, op. cit.; "Economic, Environmental, and Job Impacts of Increased Efficiency in Existing Coal-Fired Power Plants," *Journal of Fusion Energy*, Volume 32, Number 2 (April 2013), pp. 215-220; Frank Shaffer and Melissa Chan, "Forecasting the Benefits of DOE Programs for Advanced Fossil-Fuel Electricity Generating Technologies: The EIA High Fossil Electricity Technology Case," National Energy Technology Laboratory, October 2002 National Energy Technology Laboratory, ''Clean Coal Technology Roadmap: CURC/EPRI/DOE Consensus Roadmap, Background Information,'' 2008; Tim Considine, "Coal: America's Energy Future, Volume II, 'Appendix: Economic Benefits of Coal Conversion Investments,'' prepared for the National Coal Council, March 2006; *Sales and Benefits of Technology from Clean Coal Demonstration Projects*. National Energy Technology Laboratory, 2006.

Figure IV-12
EPA Weighted Average of SO_2 Emission Prices Per Ton
(current dollars)



Source: U.S. Environmental Protection Agency

IV.F.2. NO_x Emissions

NO_x is formed from oxidation of nitrogen contained within the coal (fuel NO_x) and oxidation of the nitrogen in the air at high temperatures of combustion (thermal NO_x). NO_x became the focus of a series of regulatory actions to severely limit emissions after being identified as a source of both acid rain (targeted under Title IV of the CAAA) and urban smog (targeted under Title I).[139] Coal-fired boilers represent a primary source of NO_x emissions and a specific target of regulatory action. Although combustion of gas and oil also results in NO_x emissions, and mobile sources contribute significantly to this problem, a major focus of the DOE coal RD&D program has been control of pollution resulting from coal combustion/gasification.

In response to the requirements for stringent emissions limits on fossil-fueled power plants imposed by the CAA and its amendments (CAAA), DOE expanded its RD&D program in the mid-1980s to seek improved options for control technology to control the stack effluents of power plants. The CAA historically focused on the criteria pollutants -- PM, SO_2, and NO_x -- that are relevant to power plant emissions, especially coal-fired plants. Emission control technology has been commercially available for all three of these pollutants since the 1970s.

[139]U.S. Department of Energy, *Environmental Benefits of Clean Coal Technologies*, op. cit.

The early technologies available for FGD and for NO_x reduction could not be applied to all plant configurations or fuels, were low in collection efficiency, and proved unreliable for plant operations. To support the timely achievement of air quality goals, in 1979 DOE initiated a major RD&D effort directed toward improvement of FGD and NO_x reduction technologies, in cooperation with the electric utility industry and equipment vendors. DOE activity complemented a parallel effort at EPA.

The NO_x Budget Trading Program (NBP) was a cap and trade program created to reduce the regional transport of NO_x emissions from power plants and other large combustion sources in the eastern U.S.[140] The NBP began in 2003 and was designed to reduce NO_x emissions during the warm summer months, referred to as the ozone season, when ground-level ozone concentrations are highest. The program was a central component of the NO_x SIP (State Implementation Plan) Call, promulgated in 1998.

From the beginning of program implementation in 2003 to 2008, the NBP dramatically reduced NO_x emissions from power plants and industrial sources during the summer months, contributing to significant improvements in ozone air quality in the eastern U.S. Beginning in 2009, the NBP was effectively replaced by the ozone season NO_x program under the Clean Air Interstate Rule, which required further summertime NO_x reductions from the power sector. Figure IV-13 summarizes the timeline of the regional programs for ozone and particulate matter control.

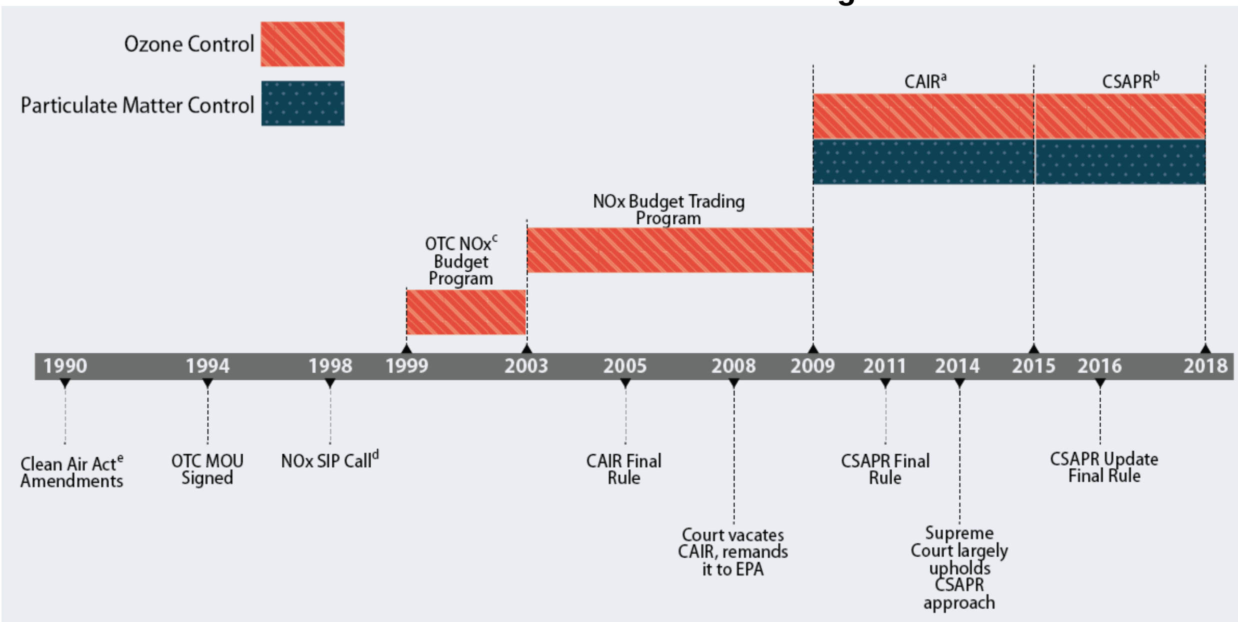
The Acid Rain Program (Title IV of the CAAA) required major reductions in NO_x emissions,[141] and the DOE coal RD&D program successfully demonstrated control techniques that are applicable to all major boiler types. Further, these technologies are applicable not only to Title IV, but also to Title I NO_x reductions.

Prior to the DOE program, NO_x control technology proven in U.S. utility service was essentially nonexistent. However, the DOE program met the regulatory challenge by developing and incorporating emerging NO_x control technologies into a portfolio of cost-effective compliance options for the full range of boiler types being used commercially. Products of the DOE RD&D program for NO_x control included:

- Low-NO_x burners (LNBs), overfire air (OFA), and reburning systems that modify the combustion process to limit NO_x formation;
- Selective catalytic and non-catalytic reduction technologies (SCR and SNCR) that remove NO_x already formed;
- Artificial intelligence-based control systems that effectively handle numerous dynamic parameters to optimize operational and environmental performance of boilers.

[140] U.S. Environmental Protection Agency, "The NO_x Budget Trading Program," https://www.epa.gov/airmarkets/nox- budget-trading-program.
[141] U.S. Environmental Protection Agency, "Acid Rain Program," https://www.epa.gov/acidrain/acid-rain-program.

Figure IV-13
Implementation Timeline of Regional Ozone and Particulate Matter Control Programs



Source: Congressional Research Service.

As a result, over three quarters of U.S. coal-fired generation plants have installed LNBs.[142] Reburning and artificial intelligence systems have also achieved significant market penetration, and sites that developed these NO_x control technologies have retained them for commercial use. In addition, numerous commercial installations of SCR and SNCR have also been implemented. The IGCC demonstration projects have achieved excellent environmental performance, with emissions as low as 0.02 lb./MBtu for SO_2 and 0.08 lb./MBtu for NO_x.[143]

Within the power sector, coal accounts for over 85% of NO_x emissions.[144] However, NO_x emissions from the U.S. electric power sector have declined over the past several decades, largely because of the phased implementation of regulations under the Clean Air Act Amendments of 1990, but also due to the retirement of many older coal plants. One of the main regulations affecting NO_x emissions was the 2003 expansion of EPA's NO_x Budget Trading Program (Title I) to include most states east of the Mississippi River. In addition, the EPA's MATS, announced in 2011 and implemented in 2015, required power generators to comply with emissions limits for toxic air pollutants associated with fuel combustion such as mercury, arsenic, and heavy metals. Although

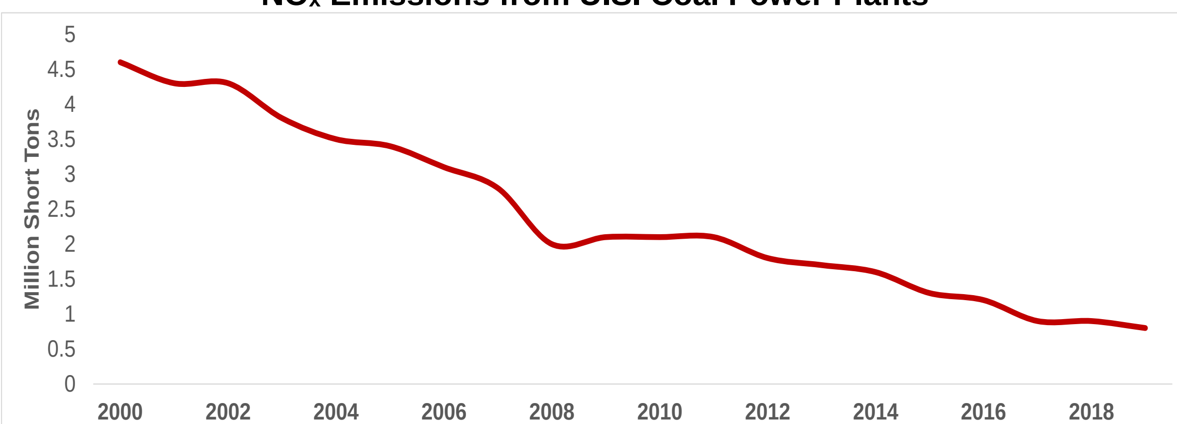
[142]U.S. Department of Energy, Office of Fossil Energy, "Clean Coal Technology Demonstration Program," https://www.energy.gov/sites/prod/files/cct_factcard.pdf.
[143]U.S. Department of Energy, *Environmental Benefits of Clean Coal Technologies*, op. cit.
[144]Emanuele Massetti, Marilyn A. Brown, Melissa Lapsa, Isha Sharma, James Bradbury, Colin Cunliff, and Yufei Li, op. cit.

MATS targets mercury and air toxics emissions, power plants' compliance with the rule also decreased emissions of NO_x.[145]

While overall NO_x emissions have remained relatively constant at about 23 million tons/yr. since the 1980s, the average emissions rate (in terms of lb. NO_x /million Btu) for power plants participating in Title IV has decreased significantly over the past two decades. Power plants generate about 30 percent of total NO_x emissions, with motor vehicles and other industrial sources contributing most of the remainder. Although cleaner technologies are now being used in power plants, the total amount of electricity generated has increased, as has the number of vehicle miles traveled per year.

Figure IV-14 shows NO_x emissions from U.S. coal power plants, and illustrates that these emissions decreased much more rapidly than coal consumption in the U.S. electric power sector. NO_x emissions decreased from 4.6 million tons on 2000 to 0.8 million tons in 2019 – a decrease of nearly 80%.[146] This is compared to a decrease over the same period in coal consumption in the U.S. electric power sector of about 50%. Thus, per ton of coal consumed, U.S. coal power plants currently emit much less NO_x than they did two decades ago.

Figure IV-14
NO_x Emissions from U.S. Coal Power Plants



Source: U.S. Energy Information Administration.

It has been previously estimated that the NO_x savings resulting from the DOE program through 2005 totaled $31.1 billion in 2019 dollars.[147] Here we estimated the

[145]U.S. Energy Information Administration, "Emissions From the U.S. Electric Power Sector Projected to Remain Mostly Flat Through 2050," op. cit.
[146]U.S. Energy Information Administration, *Electric Power Annual*, various years, 2000 – 2019. EIA projects that electric power sector SO_2 emissions will remain relatively unchanged throughout the AEO projection period. U.S. Energy Information Administration, "Emissions From the U.S. Electric Power Sector Projected to Remain Mostly Flat Through 2050," op. cit.
[147]See Roger Bezdek and Robert Wendling, "The Return on Investment of the Clean Coal Technology Program in the USA," op. cit.; U.S. Department of Energy, Office of Fossil Energy, "Clean Coal Technology: From Research to Reality," 2007; U.S. Department of Energy, Assistant Secretary For Fossil Energy, "Clean Coal Technology: The Investment Pays Off," November 1999; National Research Council, *Energy*

environmental benefits for the period 2006 – 2019 of NO_x reductions attributable to the DOE coal RD&D program.

Figure IV-14 shows that annual NO_x emissions from coal power plants decreased from 3.1 million tons on 2000 to 0.8 million tons in 2019. There are two questions that have to be addressed here:

- How much of this decline can be legitimately attributed to the DOE coal RD&D program?
- What is the proper value of the NO_x emissions avoided?

With respect to the first question – attribution of NO_x emissions reductions to the DOE program, we again utilized the methodology developed in the NRC/NAS studies discussed in Section III.C. This methodology recognized that, while the DOE coal RD&D program was instrumental in developing NO_x reduction technologies for electric power plants, all of the future benefits of these reductions could not legitimately be attributed to the CCT program. Even in the absence of the DOE program, electric utilities would have been eventually forced to reduce NO_x emissions. Therefore, NRC/NAS recommended that early in the years following the CAAA and DOE programs practically all of the emissions reductions be attributed to the DOE program, with the portion of the attributed benefits gradually declining over the forecast period. This is the methodology we followed here. Thus, for example, most of the emissions reductions in 2000 were attributed to the CCT program, but by 2019 the DOE program is given credit for only a relatively small portion of the SO_2 emissions reductions.[148] Accordingly, we estimated that, over the period 2000 – 2019, the DOE program was responsible for NO_x reductions totaling about 11.4 million tons.

What is the proper value of the NO_x emissions avoided? Over the period 2006 – 2019, the annual price of NO_x emissions has fluctuated very widely. According to EPA, EIA, and other sources, NO_x prices were nearly $1,700/ton (current dollars) in 2006, collapsed after 2009, and declined to less than $4/ton (current dollars) in 2019.[149]

Research at DOE: Was It Worth It? Op. cit.; National Research Council, *Prospective Evaluation of Applied Energy Research and Development at DOE (Phase One): A First Look*, Committee on Prospective Benefits of DOE's Energy Efficiency and Fossil Energy R&D Programs, op. cit.; Emanuele Massetti, Marilyn A. Brown, Melissa Lapsa, Isha Sharma, James Bradbury, Colin Cunliff, and Yufei Li, op. cit.; "Economic, Environmental, and Job Impacts of Increased Efficiency in Existing Coal-Fired Power Plants," *Journal of Fusion Energy*, Volume 32, Number 2 (April 2013), pp. 215-220; Frank Shaffer and Melissa Chan, "Forecasting the Benefits of DOE Programs for Advanced Fossil-Fuel Electricity Generating Technologies: The EIA High Fossil Electricity Technology Case," National Energy Technology Laboratory, October 2002 National Energy Technology Laboratory, ''Clean Coal Technology Roadmap: CURC/EPRI/DOE Consensus Roadmap, Background Information,'' 2008; Tim Considine, "Coal: America's Energy Future, Volume II, 'Appendix: Economic Benefits of Coal Conversion Investments,'' prepared for the National Coal Council, March 2006; *Sales and Benefits of Technology from Clean Coal Demonstration Projects*. National Energy Technology Laboratory, 2006; National Energy Technology Laboratory, "Sales and Benefits of Technology from Clean Coal Demonstration Projects," 2006.

148 Specifically, the DOE program was given credit for 95% of the 2000 NO_x emissions reductions, phasing down to 10% of the 2019 reductions.

149 See U.S. Environmental Protection Agency, "The NO_x Budget Trading Program," op. cit.; U.S. Energy Information Administration, Emissions Allowance Prices for SO_2 and NO_X Remained Low in 2011," February 2, 2012; U.S. Environmental Protection Agency, "Cross-State Air Pollution: "Seasonal NO_x Prices

Therefore, we estimate that the benefits over the period 2006-2019 of NO_x emissions reductions attributable to the DOE program total about $4.8 billion (2019 dollars). As noted, it has been previously estimated that the NO_x savings resulting from the DOE program through 2005 totaled $31.1 billion in 2019 dollars. Accordingly, the environmental benefits in terms of NO_x reductions of the DOE program totaled $4.8 billion plus $31.1 billion: $35.9 billion (2019 dollars).

IV.F.3. CO_2 Emissions

Global climate change is one of the primary environmental issues of the 21st century, and concerns about potential climate change driven by rising atmospheric concentrations of greenhouse gasses (GHGs) have increased over the past two decades, both domestically and abroad. In the U.S., potential policies to limit or reduce GHG emissions are in various stages of development at the state, regional, and Federal levels. However, Federal regulation of CO_2 is controversial and there is currently no federally mandated price for CO_2 emissions.

In addition to ongoing uncertainty with respect to future growth in energy demand and the costs of fuel, labor, and new plant construction, U.S. electric power companies must consider the effects of potential policy changes to limit or reduce GHG emissions that would significantly alter their planning and operating decisions. The possibility of such changes has been affecting planning decisions for new generating capacity. As noted, EIA and other organizations forecast little or no new coal power plant construction in the U.S. through 2050.[150] Even without the enactment of national emissions limits, many state governments and state utility regulators are regulating GHG emissions, banks that finance new power plants are requiring assessments of GHG emissions for new projects, and state public utility commissions are requiring that utilities address projected CO_2 emissions in their integrated resource plans (IRPs).[151]

The DOE coal RD&D program has been addressing CO_2 emissions and climate change concerns for over two decades. For example, advanced coal-based technologies demonstrated in DOE's Clean Coal Technologies program enabled utilities to make substantial reductions in GHG emissions through enhanced efficiency of first-generation systems. Further, as noted in Chapter III, CO_2 control and sequestration have appeared as line items in the DOE coal RD&D budget since FY 2001. In any case, the benefits of CO_2 emissions reductions is an important issue:

- CO_2 emissions currently is a topic of intense interest, debate, and partisan controversy.

Hold Strong Amid Increased Buying," May 2017; Emission Markets, Inc., "U.S. SO_2 and NO_x Markets." emissionsdesk@evomarkets.com; Emission Markets, Inc., "Market Update Cross State Air Pollution Rule," March 21, 2018.

[150] U.S. Energy Information Administration, *Annual Energy Outlook, 2020*, op. cit.

[151] See, for example, U.S. Energy Information Administration, "Summary of Legislation and Regulations Included in the Annual Energy Outlook 2020," February 2020; and Joseph Kruger, "Managing Uncertainty in the US Electric Power Sector: Can Shadow Carbon Prices Light the Way? Resources for the Future, 2017.

- Estimates of the costs of CO_2 emissions have been made by the Federal government, by other organizations, and by a variety of researchers.
- CO_2 emissions reductions and CCUS are the focus of substantial past, present, and likely future DOE coal RD&D expenditures.
- Nearly 45% of the FY 2020 DOE coal RD&D budget is CCUS.

However, one of the major problems in estimating the benefits of CO_2 emissions reductions is that the estimated costs of these emissions vary greatly. As discussed below, the U.S. Interagency Working Group (IWG) estimates of the Social Cost of Carbon (SSC) varied widely and ranged between \$16/ton and \$221/ton.[152] Other SCC estimates vary even more widely. For example, a recent meta-analysis of 578 estimates of the SCC from 58 studies found values of -\$13.36/tCO_2 to \$2,386.91/tCO_2, with a mean value of \$54.70/tCO_2.[153] Thus, even if we are to estimate the value of reducing CO_2 emissions based on the IWG studies, which IWG SCC value should we use: \$16/ton, \$221/ton, or something in between? Quantified benefit estimates that differ by a factor of 14 would lack credibility.

The SCC is an estimate of the discounted present value of damages from one additional ton of CO_2 equivalent emitted at a certain point in time. It is an estimate of the monetized damages associated with an incremental increase in carbon emissions in a given year, and is meant to be a comprehensive estimate of climate change damages.[154] The purpose of the IWG SCC estimates was to allow Federal agencies to incorporate the social benefits of reducing CO_2 emissions into benefit-cost analyses of regulatory actions,[155] and EPA and other federal agencies have used the SCC to estimate the climate benefits of rulemakings.

Figure IV-15 shows the evolution of the social cost of carbon for a ton of CO_2 emitted in 2010 (measured in 2007 dollars) in federal rulemaking for a sample of rules.[156] The black diamond indicates the "central estimate" (if one was identified) of the social cost and the gray bars represent the range of costs used in regulatory analyses. The variation between agencies resulted from the different assumptions made in their models.

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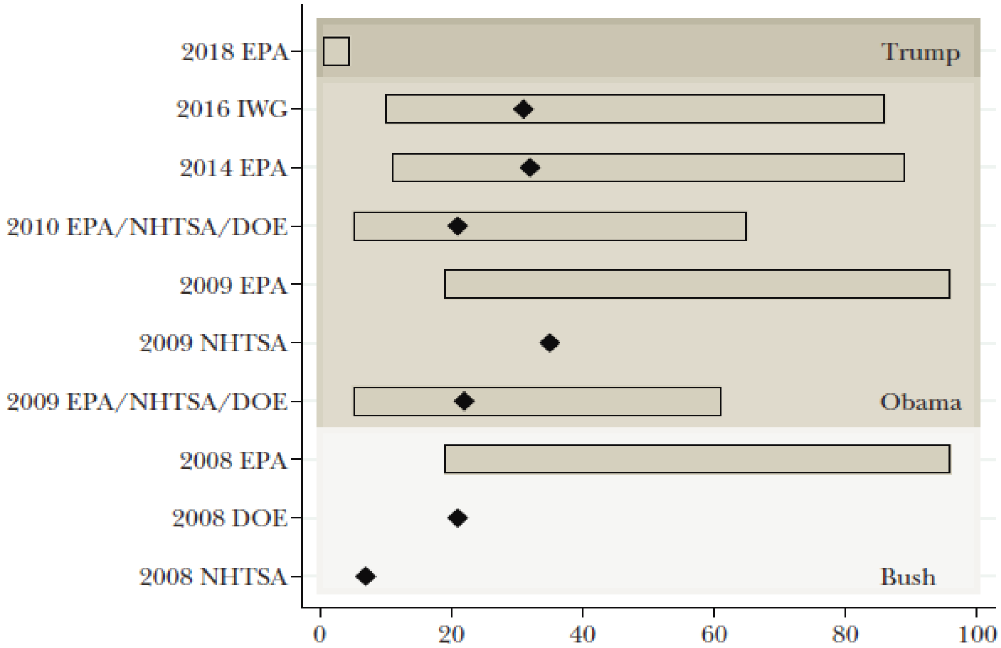
[152]Interagency Working Group on Social Cost of Carbon, United States Government, "Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866," May 2013; Interagency Working Group on Social Cost of Carbon, United States Government, "Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866," February 2010. These estimates are in 2007 dollars.
[153]P. Wang, X. Deng, X., H. Zhou, and S. Yu, S., "Estimates of the Social Cost of Carbon: A Review Based on Meta-Analysis," *Journal of Cleaner Production*, Vol. 209 (2019), pp. 1494-1507.
[154]Interagency Working Group on Social Cost of Carbon, United States Government, "Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866," May 2013; Interagency Working Group on Social Cost of Carbon, United States Government, "Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866," February 2010; U.S. Environmental Protection Agency, "The Social Cost of Carbon: Estimating the Benefits of Reducing Greenhouse Gas Emissions," www.epa.gov/climatechange.
[155]Ibid.
[156]Maximilian Auffhammer, "Quantifying Economic Damages from Climate Change," *Journal of Economic Perspectives*, Vol. 32, No. 4 (Fall 2018), pp. 33–52.

To bring some consistency, the Federal IWG on Social Cost of Carbon was created to estimate an official social cost of carbon to be used across the board in rulemaking.

Figure IV-15
Sample of Social Cost of Carbon Estimates Used in Federal Rulemakings



Social cost of carbon (2010, 2007$/tCO2)
Source: Auffhammer, 2018.

The IWG was comprised of the following 12 agencies: Council of Economic Advisers, Council on Environmental Quality, Department of Agriculture, Department of Commerce, Department of Energy, Department of Transportation, Environmental Protection Agency, National Economic Council, Office of Energy and Climate Change, Office of Management and Budget, Office of Science and Technology Policy, and Department of the Treasury. The process it used to develop the SCC estimates involved technical experts from numerous agencies meeting on a regular basis to consider public comments, exploring the technical literature in relevant fields, and discussing key model inputs and assumptions. The objective was to develop a range of SCC values using a defensible set of input assumptions grounded in the existing scientific and economic literatures.[157] In this way, the IWG felt that key uncertainties and model differences

[157]Even "official" government estimates can vary widely. For example, in 1996 the Minnesota PUC established a range of $0.28 to $2.92 per ton (1993 dollars) as the environmental cost of carbon dioxide. Translated into 2007 dollars to be consistent with the IWG estimates, this is a range of $0.38 to $3.97 per ton. See State Of Minnesota, Office of Administrative Hearings For the Minnesota Public Utilities Commission, "In the Matter of the Quantification of Environmental Costs Pursuant to Laws of Minnesota 1993, Chapter 356, Section 3 Findings of Fact, Conclusions, Recommendation," March 22, 1996.

transparently and consistently inform the range of SCC estimates used in the rulemaking process.[158]

The first IWG report was published in February 2010 and it contained four SCC values for use in regulatory analyses – Table IV-8.[159] Three values are based on the average SCC from three integrated assessment models (IAMs) — DICE, PAGE, and FUND, at discount rates of 2.5, 3, and 5 percent. The fourth value, which represents the 95th percentile SCC estimate across all three models at a 3% discount rate, was included to represent higher-than-expected impacts from temperature change further out in the tails of the SCC distribution.[160]

In May 2013, the IWG published an updated report which contained SCC estimates, shown in Table IV-9, based on new versions of each IAM. It did not revisit other interagency modeling decisions (e.g., with regard to the discount rate, reference case socioeconomic and emission scenarios, or equilibrium climate sensitivity.) Changes in the way damages are modeled were confined to those that had been incorporated into the latest versions of the models by the developers themselves in the peer-reviewed literature.[161] The new, higher SCC estimates were used for the first time in a June 2013 rule on efficiency standards for microwave ovens.[162]

The 2013 SCC estimates using the updated versions of the models are higher than those in the 2010 report. By way of comparison, the four 2020 SCC estimates reported in the 2010 TSD were $7, $26, $42 and $81 (2007$). The corresponding four updated SCC estimates for 2020 are $12, $43, $65, and $129 (2007$).[163] President Trump disbanded the IWG via Executive Order 13783 issued in March 2017.[164]

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[158]Interagency Working Group on Social Cost of Carbon, United States Government, "Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866," February 2010.
[159]Prior to 2010 the "official" U.S. government SCC estimate was, presumably, zero.
[160]Ibid.
[161]Interagency Working Group on Social Cost of Carbon, United States Government, "Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866," May 2013.
[162]U.S. Department of Energy, "Energy Conservation Program: Energy Conservation Standards for Standby Mode and Off Mode for Microwave Ovens," 10 CFR Parts 429 and 430.
[163]Ibid.
[164]The White House, "Promoting Energy Independence and Economic Growth," Executive Order 13783 of March 28, 2017.

Table IV-8
Original (2010) Social Cost of CO2, 2010 – 2050
(In 2007 dollars per metric ton of CO_2)

Discount Rate Year	5% Avg	3% Avg	2.5% Avg	3% 95th
2010	4.7	21.4	35.1	64.9
2015	5.7	23.8	38.4	72.8
2020	6.8	26.3	41.7	80.7
2025	8.2	29.6	45.9	90.4
2030	9.7	32.8	50.0	100.0
2035	11.2	36.0	54.2	109.7
2040	12.7	39.2	58.4	119.3
2045	14.2	42.1	61.7	127.8
2050	15.7	44.9	65.0	136.2

Source: Interagency Working Group on Social Cost of Carbon, United States Government, 2010.

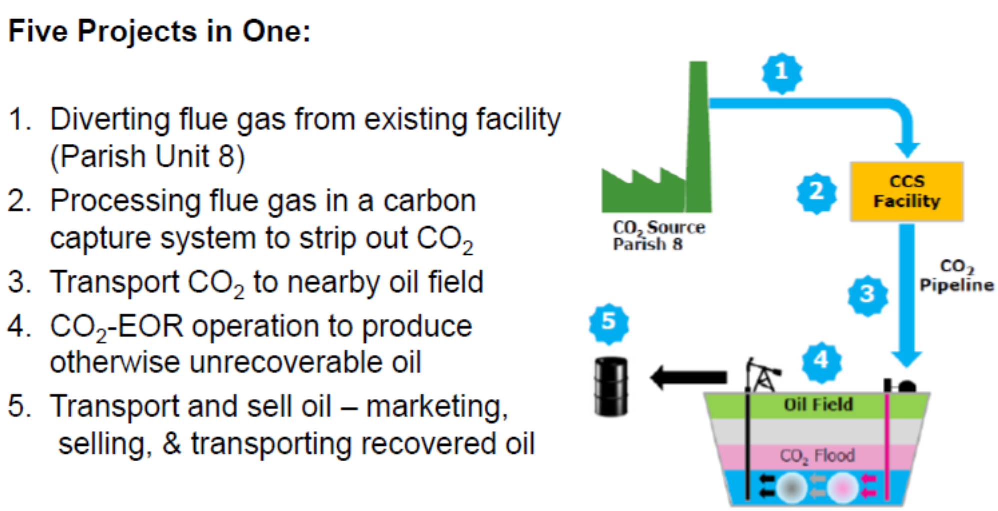
Table IV-9
Revised (2013) Social Cost of CO2, 2010 – 2050
(In 2007 dollars per metric ton of CO_2)

Discount Rate Year	5.0% Avg	3.0% Avg	2.5% Avg	3.0% 95th
2010	11	33	52	90
2015	12	38	58	109
2020	12	43	65	129
2025	14	48	70	144
2030	16	52	76	159
2035	19	57	81	176
2040	21	62	87	192
2045	24	66	92	206
2050	27	71	98	221

Source: Interagency Working Group on Social Cost of Carbon, United States Government, 2013.

Perhaps the best current example of CCUS in the U.S. is the Petra Nova facility in Texas. The Petra Nova facility, a coal-fired power plant located near Houston, is one of only two operating power plants with CCUS in the world, and it is the only such facility in the U.S. Figures IV-16 and IV-17 show the project overview and key project dates. Petra Nova's post-combustion CO_2 capture system began operations in January 2017. The 240 MW carbon capture system that was added to Unit 8 (654 MW capacity) of the existing W.A. Parish pulverized coal-fired generating plant receives about 37% of Unit 8's emissions, which are diverted through a flue gas slipstream. Petra Nova's carbon-capture system is designed to capture about 90% of the CO_2 emitted from the flue gas slipstream, or about 33% of the total emissions from Unit 8 -- CO_2 accounts for about 13% of the flue gas. The post-combustion process is energy intensive and requires a dedicated natural gas unit to accommodate the energy requirements of the carbon-capture process.[165] DOE provided a $190 million grant to the Petra Nova project as part of the Clean Coal Power Initiative program, with the goal of reducing GHGs, and NETL helped manage the project.[166]

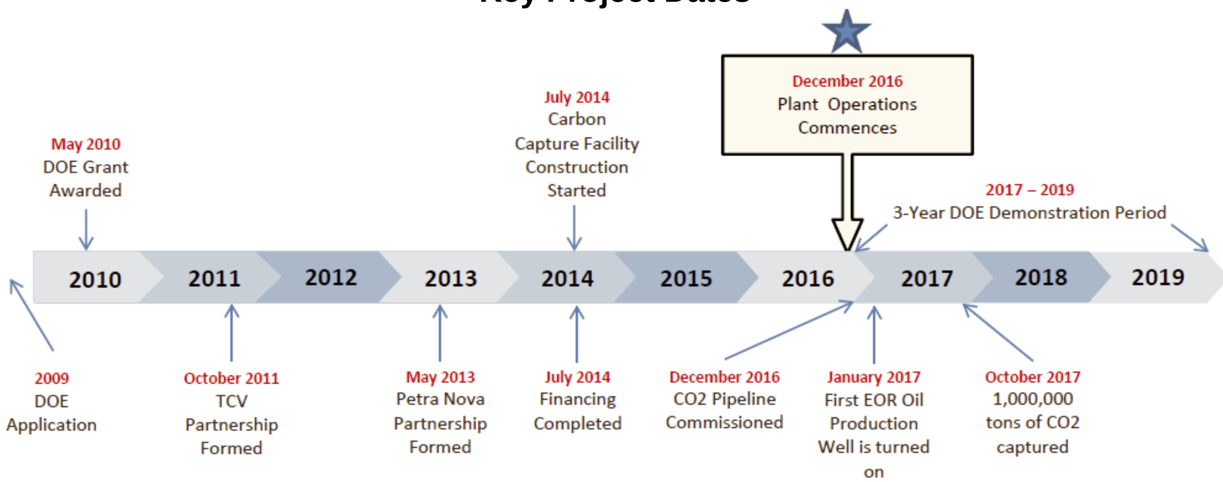
Figure IV-16
Petra Nova Project Overview



Source: Petra Nova Parish Holdings.

[165]U.S. Energy Information Administration, "Petra Nova is One of Two Carbon Capture and Sequestration Power Plants in the World," October 31, 2017.
[166]U.S. Department of Energy, Office of Fossil Energy, "Happy Third Operating Anniversary, Petra Nova!" January 10, 2020; "Carbon Capture and the Future of Coal Power," https://www.nrg.com/case-studies/petra-nova.html.

Figure IV-17
Key Project Dates



Source: Petra Nova Parish Holdings.

Petra Nova:[167]

- Is designed to reduce CO_2 emissions from the coal burning W.A. Parish Generating Station in Thompsons, Texas, southwest of Houston.
- Is a joint project of NRG Energy and JX Nippon Oil.
- Has been operating since January 2017.
- Is the world's largest post-combustion CCUS-EOR project.
- Represents the first actual commercialization of post combustion carbon capture.
- Is one of only two operating power plants with CCUS in the world, and the only such facility in U.S.
- Annually captures 33% of CO_2 emissions -- 1.6 million tons.
- Pipes CO_2 82 miles to the West Ranch Oil Field, where it is used for enhanced oil recovery (EOR).
- Allows the oil field, which had been producing 300 bbls/day, to currently produce 15,000 bbls/day.
- Has produced over 4.2 million barrels of oil through January 2020, and will produce 60 million barrels of otherwise unrecoverable oil over the next decade.
- Captures over 90% of the CO_2 from the processed flue gas.
- Uses a 240 MW equivalent slipstream of flue gas from NRG's 640 coal-fired power plant -- W.A Parish unit 8.
- When operating at 100%, captures 5,200 tons of CO_2 per day.
- Has won awards from *Engineering News-Record*, *Power Magazine*, and *POWER GEN*.

[167]U.S. Department of Energy, Office of Fossil Energy, "Happy Third Operating Anniversary, Petra Nova!" op. cit.; Petra Nova Parish Holdings, "Carbon Capture, Utilization and Storage, and Oil and Gas Technologies," Integrated Annual Review Meeting, August 2019; NRG, "Carbon Capture at Petra Nova," July 2017; Scott Madden, "Billion Dollar Petra Nova Coal Carbon Capture Project a Financial Success But Unclear If It Can Be Replicated," https://www.scottmadden.com/.

From 2017 through 2019, Petro Nova has captured approximately 3.9 million tons of CO_2.[168] The IWG 2010 value of 2020 SCC was $26.30 (2007 dollars), which is $31.80 in 2019 dollars. The IWG 2013 value of 2020 SCC was $43.00 (2007 dollars), which is $52.00 in 2019 dollars. Thus:

- The value of the 3.9 million tons of CO_2 captured thus far by Petro Nova using the 2010 IWG SCC estimate is approximately $124 million (2019 dollars).
- The value of the 3.9 million tons of CO_2 captured thus far by Petro Nova using the 2013 IWG SCC estimate is approximately $203 million (2019 dollars).

In the current research, we are estimating impacts and benefits only through 2019. However, for Petro Nova it makes more sense to estimate the long run value of the CO_2 captured, since the project would not have been constructed to operate only for the three years 2017 – 2019. To estimate the total cumulative value through 2050 of the CO_2 captured by Petro Nova, we estimate that over the period 2020 – 2050 approximately 40.3 million tons of CO_2 will be captured. Thus:

- The value of the 40.3 million tons of CO_2 captured by Petro Nova using the 2010 IWG SCC estimate is approximately $1,282 million (2019 dollars).
- The value of the 40.3 million tons of CO_2 captured by Petro Nova using the 2013 IWG SCC estimate is approximately $2,096 million (2019 dollars).

Therefore, the total estimated value of the CO_2 captured by Petro Nova over the period 2017 through 2050:

- Using the 2010 IWG SCC estimate is approximately $1,406 million (2019 dollars).
- Using the 2013 IWG SCC estimate is approximately $2,299 million (2019 dollars).

Thus, using the most recent (2013) IWG SCC estimate, the total estimated value of the CO_2 captured by Petro Nova over the period 2017 through 2019 is about $0.2 billion (2019 dollars). Using the 2013 IWG SCC estimate, the total estimated value of the CO_2 captured by Petro Nova over the period 2017 through 2050 is about $2.3 billion (2019 dollars).

Interestingly, the $190 million DOE grant to Petra Nova in 2019 dollars is about $202 million. Thus, in its first three years of operation, 2017 – 2019, the project has saved enough CO_2 to more than repay the DOE grant – and, estimated this way, the return on investment increases every month.

In addition, as noted, Petra Nova has produced over 4.2 million barrels of oil through January 2020. Using the EIA monthly WTI prices[169] for January 2017 through January 2020 and converting the data to constant 2019 dollars, we estimate that the value of this incremental oil produced totaled about $247 million (2019 dollars). Further, oil is being produced every month and the total value of the increment oil produced increases every month. As also noted, it is estimated that Petra Nova will enable the production of

[168] Petra Nova Parish Holdings, op. cit.

[169] https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=RWTC&f=M.

60 million barrels of otherwise unrecoverable oil over the next decade. However, the actual volume of oil eventually produced will depend on oil field geology and other factors.

FutureGen was a project designed to demonstrate capture and sequestration of waste CO_2 from a coal-fired power plant. The project (renamed FutureGen 2.0) was retrofitting a shuttered coal-fired power plant in Meredosia, Illinois, with oxy-combustion generators. The waste CO_2 would be piped approximately 30 miles to be sequestered in underground saline formations. FutureGen was a partnership between the U.S. government and an alliance of primarily coal-related corporations. Costs were estimated at $1.65 billion, with $1.0 billion provided by the Federal Government.

First announced by President George W. Bush in 2003, construction started in 2014 after restructuring, canceling, relocating, and restarting.[170] Citing an inability to commit and spend the funds by deadlines in 2015, DOE withdrew funds and suspended FutureGen 2.0 in February 2015.[171]

The primary objectives of the FutureGen 2.0 CO_2 Oxy-Combustion Large Scale Test Project were to site, permit, design, construct, and commission an oxy-combustion boiler, gas quality control system, air separation unit, and CO_2 compression and purification unit, together with the necessary supporting and interconnection utilities. The project was designed to demonstrate at commercial scale (168 MWe gross) the capability to cleanly produce electricity through coal combustion at a retrofitted, existing coal-fired power plant thereby resulting in near-zero emissions of all commonly regulated air emissions, as well as 90% CO_2 capture in steady-state operations. The project was to be fully integrated in terms of project management, capacity, capabilities, technical scope, cost, and schedule with the companion FutureGen 2.0 CO2 Pipeline and Storage Project, a separate but complementary project whose objective was to safely transport, permanently store and monitor the CO_2 captured at the oxy-combustion power plant.[172]

The project successfully achieved all technical objectives inclusive of front-end-engineering and design, and advanced design required to accurately estimate and contract for the construction, commissioning, and start-up of a commercial-scale "ready to build" power plant using oxy-combustion technology, including full integration with the companion CO_2 Pipeline and Storage project. Ultimately, the project did not proceed to construction due to insufficient time to complete necessary EPC contract negotiations and commercial financing prior to expiration of federal co-funding, which triggered a DOE decision to close-out its participation in the project.

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[170]David Talbot, "Construction Begins at a Carbon-Capture Plant, But Will It Ever Be Completed?" *MIT Technology Review*, September 15, 2014; "FutureGen Fact Sheet: Carbon Dioxide Capture and Storage Project," MIT Carbon Capture and Sequestration Technologies Program, October 2014.
[171]Ari Natter, "DOE Suspends $1 Billion in FutureGen Funds, Killing Carbon Capture Demonstration Project," *Energy and Climate Report*, February 4, 2015.
Peter Folger, "The FutureGen Carbon Capture and Sequestration Project: A Brief History and Issues for Congress," U.S. Congressional Research Service, February 2014.
[172]Ken Humphreys, Mark Williford, and Paul Wood, "Lessons Learned: Technology Integration, Value Improvements and Program Management," Prepared by: FutureGen Industrial Alliance, Inc. for the National Energy Technology Laboratory, September 2015.

Nevertheless, through the work that was completed, valuable technical, commercial, and programmatic lessons were learned. FutureGen significantly advanced the development of near-zero emissions technology and will be helpful to plotting the course of, and successfully executing, future large demonstration projects. Significant technology issues and lessons were learned related to CO_2 flue gas concentration, facility-wide CO_2 rate, CO_2 venting, CO_2 product cooling, and CO_2 control.[173] Further:[174]

- Projects of FutureGen's complexity and high degree of innovation require that substantial attention be paid to technology integration and maturity.
- The design must take into account not only steady-state operations compatibility, but also anticipate that the connected technologies will be required to start up and shut down safely, and will have to operate at times in upset conditions, or in a fouled or otherwise degraded state.
- Perhaps most significant, mating technologies must match not only on an expected performance basis, but in the case of fully commercialized projects, match on a guaranteed performance basis.

Value improvement lessons learned included:[175]

- The project team was able to effectively reduce CAPEX in the final design through application of value engineering and value improvement.
- FutureGen identified areas where future projects could gain additional cost savings.
- Among the most effective value improvement techniques were integrated operations strategies, utilizing less engineer-to-order (ETO) and more off-the-shelf equipment, utilizing less n+1 equipment redundancy, and more high reliability equipment.

Program management lessons learned encompassed a broad spectrum of typical project management, project controls, and commercial challenges related to safety, design development, progress monitoring, cost monitoring, and economic modeling.[176]

Commercial lessons learned related to cost-sharing, stage-gate development strategy, innovation and approvals, the value of mega-FEEDs, investor alignment, EPC contract form, guarantees, contract strategy for non-unique component technology, the value of EPC competition, plugging first-of-a-kind (FOAK) risk gaps, and litigation.[177]

Other lessons learned from FutureGen include:[178]

- Site selection & characterization prior to decisions are critical – the competitive site selection process proved highly successful.

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[173]Talbot, op. cit. and Humphreys, Williford, and Wood, op. cit.
[174]Humphreys, Williford, and Wood, op. cit.
[175]Ibid.
[176]Ibid.
[177]Ibid.
[178]Thomas Sarkus, "Lessons Learned from FutureGen 2.0," presented to the Carbon Utilization Research Council, March 18, 2018.

- Environmental Impact Statements (EISs) contain a treasure trove of information regarding CCS project integration, risk assessment, etc.
- State and local support is vital.
- Effective community outreach is essential.
- Land and pore space acquisition process was highly successful.
- Commercial equipment guarantees are a prerequisite to project financing -- equipment must function well enough to predicate an adequate revenue stream, and risk mitigation/risk sharing re: FOAK technologies at commercial-scale.
- Longer project development times can lead to potential market and/or corporate philosophy changes.
- Completing front end engineering design (FEED) as early as possible is key.
- Expect interveners including power companies, land owners, environmental organizations, and others.

More generally, the HELE plants discussed in Section IV.D are more efficient and have lower heat rates[179] than the existing coal fleet plants and generate nearly 10% less CO_2 emissions.[180] We estimate that the HELE plants that went on-line between 2008 and 2013 cumulatively saved approximately 42 million tons of CO_2 emissions over the period 2008 – 2019. Using the SCC value of $52.00 (2019 dollars), we estimate that the savings totaled about $2,184 million. Thus, the implied CO_2 emissions savings, 2008 – 2019, from the Petra Nova plant and the HELE plants totals approximately $2.4 billion (2019 dollars).

[179]Heat Rates are inversely proportional to efficiency, so that a lower heat rate connotes a more efficient power plant.

[180]Rodney Geisbrecht and Phil Dipietro, "Evaluating Options For U.S. Coal Fired Power Plants in the Face of Uncertainties and Greenhouse Gas Caps: The Economics of Refurbishing, Retrofitting, and Repowering," *Energy Procedia*, Vol. 1, 2009, pp. 4347–4354; Phil DiPietro and Katrina Krulla, "Improving the Efficiency of Coal-Fired Power Plants for Near Term Greenhouse Gas Emissions Reductions," DOE/NETL-2010/1411, April 16, 2010; Tim Fout, Alexander Zoelle, Dale Keairns, Marc Turner, Mark Woods, Norma Kuehn, Vasant Shah, Vincent Chou, and Lora Pinkerton, "Cost and Performance Baseline for Fossil Energy Plants Volume 1: Revision 3," National Energy Technology Laboratory, 2015; National Energy Technology Laboratory, "Reducing CO_2 Emissions and Maintaining Electricity Generation Through Efficiency Improvements at Existing Coal-fired Power Plants," 2008; General Electric, "GE Global Power Plant Efficiency Analysis," 2016; National Energy Technology Laboratory, "Cost and Performance Baseline for Fossil Energy Power Plants Study, Volume 1: Bituminous Coal and Natural Gas to Electricity" Report DOE/NETL-2007/1281, May 2007; National Energy Technology Laboratory, "Options for Improving the Efficiency of Existing Coal-Fired Power Plants," DOE/NETL-2013/1611, April 2014; National Energy Technology Laboratory, "NETL Leads Drive for Efficiency in Fossil Fuel-based Power Plants," January 21, 2020; National Energy Technology Laboratory, "The Transformative Power Generation Program," 2018; National Energy Technology Laboratory, "Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity Revision 2," November 2010, DOE/NETL-2010/1397; U.S. Energy Information Administration, "How Much Carbon Dioxide is Produced Per Kilowatthour of U.S. Electricity Generation?" February 2020.

IV.G. Public Health Benefits

IV.G.1. Particulate and Air Toxic Emissions

Particulate Emissions

Particulate matter (PM) is the general term for a mixture of solid particles and liquid droplets found in the atmosphere. Some particles are large enough to be seen as soot or smoke, while others are so small that they can be detected only with an electron microscope. $PM_{2.5}$ describes the fine particles that are less than or equal to 2.5 microns (μ) in diameter.[181] Coarse particles are those greater than 2.5 μ and less than 10 μ in diameter -- the latter are referred to as PM_{10}. PM originates from many different stationary and mobile sources as well as natural sources.[182] Fine particles result from fuel combustion in motor vehicles, during power generation, and in industrial facilities. Coarse particles are generally emitted from sources such as vehicles traveling on unpaved roads, materials handling, crushing, and grinding operations, and windblown dust. Some particles are emitted directly from their sources, such as smokestacks and cars, while in other cases, gases such as SO_2, NO_x, and volatile organic compounds (VOCs) interact with other compounds in the air to form fine particles. Their chemical and physical compositions vary depending on location, time of year, and weather. SO_2 reduction may contribute to meeting emissions requirements for $PM_{2.5}$ because some sulfur species are also included in $PM_{2.5}$. Within the power sector, coal accounts for over 80% of particulate emissions.[183]

Air Toxics Emissions

Air toxics is another area of environmental concern that has been addressed by the DOE coal RD&D program. Under Title I of the CAAA, EPA is responsible for determining the hazards to public health posed by 189 identified hazardous air pollutants (HAPs). The DOE program has made a significant contribution to a better understanding of this issue from power plant emissions by monitoring HAPs from several project sites. The results of these and other studies have significantly mitigated concerns about HAP emissions from coal-fired power plants and focused attention on only a few flue gas constituents. EPA has determined that emissions of mercury, a HAP of major concern, requires control.[184]

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[181]A micron is one millionth of a meter, or about 0.00004 inch.
[182]U.S. Environmental Protection Agency, "Particulate Matter Basics," https://www.epa.gov/pm-pollution/particulate-matter-pm-basics.
[183]Emanuele Massetti, Marilyn A. Brown, Melissa Lapsa, Isha Sharma, James Bradbury, Colin Cunliff, and Yufei Li, op. cit.; U.S. General Accountancy Office, "Air Emissions and Electricity Generation at U.S. Power Plants," April 2012.
[184]U.S. Environmental Protection Agency, "Basic Information About Mercury and Air Toxic Standards," https://www.epa.gov/mats/basic-information-about-mercury-and-air-toxics-standards.

IV.G.2. Quantifying Public Health Benefits

Quantifying the public health benefits of the DOE coal RD&D program is complicated because the benefits do not accrue to a particular person or a group but to the entire population through decreased morbidity and mortality levels.[185] In addition, different population groups react differently to reductions in air pollution and will receive different benefits, and valuation of air pollution effects must be consistent with wage, total income, labor supply, and other economic variables over time.[186] These economic variables produce a feedback on pollution levels. Existing methods for estimating the economic implications of environmental damage and remediation use current values of critical economic data such as wages or medical expenses, but they do not fully incorporate the economic valuation of air pollution in an integrated economic model. An investment in pollution control or reduction, such as that facilitated by the DOE program, should reduce the damage to health caused by pollution, and the damage avoided is thus one of the benefits of the RD&D program.[187]

Valuing health damages involves establishing a dose-response function; e.g. estimating how much illness a given dose of pollution causes, and second, valuing the damage.[188] Establishing a dose-response function (DRF) requires measurement of exposure and measurement of damage, and measurement of exposure may require primary data collection. Often data are available about emissions from a pollution source, but these emissions may be dispersed, and people will also be exposed in varying degrees depending on how much time they spend indoors, whether they drink purified water, etc. This indicates that correlations of emissions or even of ambient air quality with health are unlikely to be fully reliable. DRFs are frequently nonlinear and/or discontinuous and may involve thresholds below which there is no appreciable damage, and deriving a function from only a few closely-spaced observations may thus be unreliable.

Measuring damage for the purpose of valuation requires a unit of measurement amenable to a given valuation method.[189] For example, number of work days lost due to illness is amenable to valuation; direct physical measurements like diminished breathing

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[185]EPA has conducted extensive human health benefits analysis modeling, which involves estimating improvements in health outcomes that result from improvements in air quality, applying a monetary value to the improvements in health outcomes, and using the benefits information to develop optimal air regulations. See, for example, Neal Fann, "Environmental Benefits Mapping and Analysis", U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Air Benefits and Cost Group, March 2007.

[186]Marie S. O'Neill, Carrie V. Breton, Robert B. Devlin, and Mark J. Utell, "Air Pollution and Health: Emerging Information on Susceptible Populations," *Air Quality, Atmosphere, and Health*, Volume 1, number 2 (June 2012), pp. 189-201.

[187]National Research Council, *Energy Research at DOE: Was It Worth It?* Op. cit.; National Research Council, *Prospective Evaluation of Applied Energy Research and Development at DOE (Phase One): A First Look*, Committee on Prospective Benefits of DOE's Energy Efficiency and Fossil Energy R&D Programs, op. cit.; National Energy Technology Laboratory, "Sales and Benefits of Technology from Clean Coal Demonstration Projects," 2006.

[188]William K. Bellinger, *The Economic Analysis of Public Policy*, New York: Routledge, 2016.

[189]J.E. Aldy and W.K. Viscusi, "Adjusting the Value of a Statistical Life for Age and Cohort Effects." Washington, D.C.: Resources for the Future, 2006.

capacity are less so. Establishing a relationship between exposure and damage requires controlling for various confounding factors which may also influence health.[190]

Valuation Methods

Environmental valuation methods most applicable to health damages include:[191]

- Productivity loss (e.g. workdays lost due to illness)
- Cost of medical expenditures
- Hedonic methods that assess differences in the price of housing in polluted or unpolluted areas, or the difference in wages between hazardous and non-hazardous jobs. The difference indicates the value of damages avoided to those individuals or, more precisely, their willingness to pay to avoid damages.
- Contingent valuation methods (CVM) that involve surveys to determine how much people would be willing to pay to avoid damages (WTP), or how much compensation they would require to accept more damage (WTA)

Each of these methods has its strengths and weaknesses.[192] Workdays lost and medical expenditures involve thresholds: Individuals may suffer discomfort that is serious but not severe enough to require medication or time off work. Other problems include imputing wages for workdays lost from housework, or other non-cash labor, assigning an appropriate "shadow price" to wages when there are high levels of unemployment, and avoiding the implication that the lives or health of people who are poor, very old, or very young, are less valuable than those of the rich. In general, these methods are likely to give a lower bound or minimum value. Hedonic methods require well-functioning markets for housing or labor, with buyers and sellers who are well-informed about pollution risks; and matching pairs of housing or jobs that are similar in all respects except exposure to pollution.

Contingent valuation (CV) is a survey-based method designed for the valuation of public goods primarily developed by neo-classical economists.[193] CV is controversial because it involves asking individuals directly about monetary valuation. CV is also subject to many biases, including:

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[190]Obvious ones include diet, age, and smoking habits.

[191]Guy Hutton, “Considerations in evaluating the cost effectiveness of environmental health interventions,” WHO/SDE/WSH/00.10; Dallas Burtraw, Alan Krupnick, Karen Palmer, Anthony Paul, Michael Toman, and Cary Bloyd, “Ancillary Benefits of Reduced Air Pollution in the United States from Moderate Greenhouse Gas Mitigation Policies in the Electricity Sector,” Resources for the Future, December 2001.

[192]For example, the Environmental Benefits Mapping and Analysis Program – Community Edition (BenMAP-CE) model used by the EPA includes hundreds of health impact functions that quantify air pollution health impacts among populations affected by poor air quality exposure categories. See U.S. Environmental Protection Agency, Environmental Benefits Mapping and Analysis Program – Community Edition (BenMAP-CE), https://www.epa.gov/benmap; U.S. Environmental Protection Agency, “BenMAP-CE - An Open-Source Platform to Quantify the Health Impacts and Economic Value of Stressors,” briefing for Office of Water, 2013; Daewon W. Byun and J.K.S. Ching, “Science Algorithms of the EPA Models-3 Community Multiscale Air Quality (CMAQ) Modeling System,” 1999.

[193]See, for example, Knut Veisten, “Contingent Valuation Controversies: Philosophic Debates About Economic Theory,” *Journal of Socio-Economics*, Vol. 36, No. 2 (2007), pp. 204-232.

- Strategic bias -- respondents may indicate low or high willingness to pay because they think the survey results will lead them to pay for a service or for the government to provide one.
- Starting point bias, which occurs when the respondent's WTP is influenced by the phrasing of the question or experiment
- Hypothetical bias: Respondents find it difficult to answer questions like "How much would you pay to be healthier?"

Meticulous data collection to establish dose-response functions and values can be costly and time consuming,[194] and to reduce these costs, the "benefits transfer" approach is often utilized. This involves taking a value from an existing study and transferring it to a new context, and is frequently done for both DRF's and values.

Epidemiological Relationships

Epidemiological relationships have been estimated for many pollutants, as they relate to a variety of health impacts.[195] The work has focused on a set of substances often referred to as “criteria pollutants,” because EPA developed health-based criteria as the basis for setting permissible levels.[196] Tables IV-10 and IV-11 summarize the major known health effects of exposure to various pollutants, contain relationships estimated for a general healthy population, and reflect the fact that some of the relationships differ for children or the elderly as compared with the general adult population. Exposure factors (ERfct) presented in these tables are defined as a number of cases due to exposure to a pollutant ($\mu g/m^3$) over a year for morbidity health impacts, and as a percent change in the annual mortality rate due to exposure ($\mu g/m^3$) for mortality health impacts. These relationships between health and air pollution have been found to be statistically significant.[197]

One aspect of these estimated relationships in tables IV-10 and IV-11 is that they cover the entire population, and any relationship thus reflects to some degree both individual response to varying dose levels and varying vulnerability within the population. The health effects presented in these tables range from hospital admissions due to respiratory problems and restricted activity days to death due to acute or chronic exposure. The pollutants include tropospheric ozone (O_3), nitrates, SO_2, CO, and particulate matter (PM_{10} and $PM_{2.5}$).[198]

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[194] M. W. Wheeler, W. W. Piegorsch, and A. J. Bailer, “Quantal Risk Assessment Database: A Database for Exploring Patterns in Quantal Dose-Response Data in Risk Assessment and its Application to Develop Priors for Bayesian Dose-Response Analysis, *Risk Analysis*, Vol. 39, No. 3 (March 2019), pp. 616-629

[195] A.D. Davalos, T.J. Luben, A.H. Herring, and J.D. Sacks, “Current Approaches Used in Epidemiologic Studies to Examine Short-Term Multipollutant Air Pollution Exposures,” *Annals of Epidemiology*, Vol. 27, No. 2 (2017), pp. 145-153.

[196] Trent Yang, Kira Matus, Sergey Paltsev and John Reilly, “Economic Benefits of Air Pollution Regulation in the USA: An Integrated Approach,” MIT Joint Program on the Science and Policy of Global Change, Report No. 113, January 2005.

[197] The relationships shown in these tables are linear, but there remains considerable debate about whether the relationships may be non-linear in some way.

[198] The PM relationship has been the subject of contentious debate, and EPA strengthened regulations governing fine particulates. Particulate matter, unlike other substances such as CO or O_3, is not a

Table IV-10
Morbidity Health Effects of Air Pollutants on the General Population

Receptor	Impact Category	Pollutant	ER fct†
Entire Population	Respiratory hospital admissions	PM 10	2.07E-6
		Nitrates	2.07E-6
		SO_2	2.04E-6
		O_3	7.09E-6
	Cerebrovascular hospital admissions	PM 10	5.04E-6
		Nitrates	5.04E-6
	Symptoms days	O_3	3.30E-2
Children	Chronic bronchitis	PM 10	1.61E-3
		Nitrates	1.61E-3
	Chronic cough	PM 10	2.07E-3
		Nitrates	2.07E-3
Adults	Restricted activity day	PM 10	2.50E-2
		Nitrates	2.50E-2
	Minor restricted activity day	O_3	9.76E-3
		PM 10	4.90E-5
	Chronic bronchitis	Nitrates	4.90E-5
		PM 10	1.85E-5
Elderly 65+	Congestive heart failure	CO	5.55E-7
		Nitrates	1.85E-5
		PM 2.5	3.09E-5

†Units of exposure factor are [cases/(yr.-person -µg/m^3)].

Source: Massachusetts Institute of Technology, European Commission, and U.S. Environmental Protection Agency.

The impact categories ("health endpoints") must be converted into units that are economically relevant. These estimates, constructed from national income and product accounts and input-output tables, provide base data for general equilibrium models and are interpreted as physical quantities of the goods or factors in the economy. As economic aggregates, however, they must be reported in common units, and constant dollars are used. For example, national economic accounting values labor contributions at the wage rate. Thus, the labor force contribution of a high-wage individual working 40 hours per week will be larger than a low-wage individual working the same number of hours. Similarly, agricultural output or output of the steel industry is simply the total value of sales of the industry rather than tons of output.[199]

chemically well-defined substance. It is dust or soot, and is variously composed of organic carbon, black or elemental carbon, and other materials such as sulfur or nitrogen compounds and heavy metals.

[199]This weights products by their value rather than tonnage or some other unit that would obviously make comparison of computer chips and cement, or haircuts and surgery, difficult.

Table IV.11
Mortality Health Effects of Air Pollutants on the General Population

Receptor	Impact Category	Pollutant	ER fct†
Entire Population	Acute Mortality	O_3	0.06%
		SO_2	0.07%
		PM 10	0.04%
		Nitrates	0.04%
	Chronic Mortality	PM 10	0.25%

†Units of exposure factors are % change in annual mortality rate/μg/m^3.
Source: Massachusetts Institute of Technology, European Commission, and U.S. Environmental Protection Agency.

Similarly, use is made of the traditional economic valuation literature to interpret the components of value as a measure of the quantity of labor or leisure lost, or of the quantity of medical services required. Often this literature constructs the valuation estimates in this manner, identifying a hospitalization day as the medical service and then valuing it at the average cost of a day in the hospital to treat the endpoint, or identifying lost work time, and valuing it at the average wage rate. Other valuation estimates have tried to estimate the total value of the health endpoint including "non-market" effects. These estimates are based on methods such as contingent value surveys, asking people their willingness to pay to avoid the health endpoint. This should include market effects (lost wages or expenditures on health care) plus some valuation of the non-market effects of illness -- pain and suffering and associated loss of enjoyment or attention to household activities because of the illness.[200]

One set of estimates, converted to constant 2019 dollars, is shown in Table IV-12. For each health impact category related to each pollutant, such as a respiratory hospital visits due to exposure to ozone, a share of the total cost is allocated to demand for medical service, lost labor, or lost leisure. However, not all pollutants are associated with all impact categories.

Mortality and Chronic Exposure

Air pollution deaths may result from exposure to high levels of pollution experienced during a particularly bad air pollution event (acute exposure), or from exposure over many years from low levels of pollutants (chronic exposure). [201] Death

[200]Anil Markandya and Ramon Arigoni Ortiz, "Estimating Environmental Health Costs: General Introduction to Valuation of Human Health Risks," *Earth Systems and Environmental Sciences*, January 2018, DOI: 10.1016/B978-0-12-409548-9.10657-8.
[201]Early studies of the external cost of power generation in the U.S. include Robert Mendelsohn, "An Economic Analysis of Air Pollution From Coal-Fired Power Plants," *Journal of Environmental Economics and Management*, Vol. 7, no. 1 (1980), pp. 30-43; Richard L. Ottinger, et. al., *Environmental Costs of Electricity*," New York: Oceana Publications, 1990; Alan Krupnick and Dallas Burtraw, "The Social Costs

from acute exposure normally only affects those that are close to death from other causes and the commonly accepted loss of time is 0.25 to 0.5 years.

Table IV.12
Morbidity Valuation Estimates

Health Impacts	Cost (2019 dollars)
Restricted Activity Day	$153
Respiratory Hospital Admissions	$16,130
Cerebrovascular Hospital Admissions	$16,130
Symptoms Days	$15
Chronic Bronchitis Adults	$215,200
Chronic Bronchitis Children	$462
Chronic Cough for Children	$462
Congestive Heart Failure	$16,130
Asthma attacks	$75
Cough	$590
Lower Respiratory Symptoms	$16,130
Ischaemic Heart Disease	$16,130
Minor Restricted Activity Day	$15
Emergency Room Visit	$460
Acute Mortality	$43,900

Source: Massachusetts Institute of Technology, European Commission, U.S. Environmental Protection Agency, and Management Information Services, Inc.

Deaths due to chronic exposure require more complex analysis.[202] The nature of the epidemiological results is that a reduction in exposure to a given concentration level of pollution should be interpreted as a reduction by that level each year over the lifetime of the individual, that is, a proportional reduction in cumulative exposure.[203] There are various methods of valuing life ranging from contingent valuation and wage-risk studies to estimates of lifetime earnings. Usually, no claims are made as to the value of life.[204] Rather, estimates are used of the economic impact of a loss of someone at a particular age, including the lost leisure valued at the wage rate, assuming individuals are making this tradeoff at the margin.

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of Electricity: Do the Numbers Add Up?" *Resource and Energy Economics*, Vol. 18, no. 4 (1996): pp. 423-466.

[202]Ugo Fedeli, Giacomo Zoppini, Carlo Alberto Goldoni, Francesco Avossa, Giuseppe Mastrangelo, and Mario Saugo, "Multiple Causes of Death Analysis of Chronic Diseases: The Example of Diabetes, *Population Health Metrics*, Vol. 13, No 1 (August 2015).

[203]Exposure is defined as the contact between a target receptor and a pollutant at the outer boundary of the receptor. Environmental Protection Agency, https://www.epa.gov/fera/human-exposure-modeling-general.

[204]Placing a dollar value on life has always been controversial, although the federal government routinely does. For example the Consumer Product Safety Commission has used a figure of $8.7 million, EPA has used $7.4 million, and the Department of Transportation has used $9.6 million. See Austin Frakt, "Putting a Dollar Value on Life? Governments Already Do," *New York Times*, May 11, 2020.

In particular, increased morbidity and mortality are responsible for the largest share of external costs of power generation.[205] One of the main reasons behind the large difference in pollution cost estimates is that different studies often use different assumptions to monetize the value of increased mortality risk due to pollution. The literature typically uses the Value of a Statistical Life (VSL) to provide an economic estimate of the cost of one additional death caused by air pollution. The VSL is an estimate of the value that an individual places on a marginal change in the likelihood of death.[206] EPA recommends using a VSL equal to $9.2 million ($2019).[207] Some studies also use the value of a statistical life-year (VSLY) to adjust for age and account for years of expected life lost.[208]

Electricity generation accounts for the largest fraction of the external effects of the electricity system.[209] For example, studies estimate that the cost of air pollution from power generation in the U.S. during the years 2002-2011 ranged between $76 and $239 billion per year (2019 dollars).[210] However, more recent studies suggest that air pollution costs may be higher than previously estimated.[211] On the other hand, there is also some evidence that pollution costs may be declining over time.[212]

Air pollution represents the largest external cost of power generation and $PM_{2.5}$ health damages constitute the largest source of air pollution economic losses.[213] Accordingly, some studies focus on $PM_{2.5}$ health impacts alone.[214]

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[205]National Research Council, Committee on Health, Environmental, Other External Costs, Benefits of Energy Production, and Consumption, "Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use," National Academies Press, 2010; Nicholas Z. Muller and Robert Mendelsohn, "Efficient Pollution Regulation: Getting the Prices Right," *American Economic Review*, Vol 98, 2009, pp. 1714-1739; Nicholas Z. Muller, Robert Mendelsohn, and William Nordhaus. "Environmental Accounting For Pollution in the United States Economy," *American Economic Review*, Vol. 100, 2011, pp. 1649-1675.

[206]W. Kip Viscusi, and Joseph E Aldy, "The Value of a Statistical Life: A Critical Review of Market Estimates Throughout the World," *Journal of Risk and Uncertainty*, Vol. 27, no. 1 (2003), pp. 5-76.

[207]U.S. Environmental Protection Agency, *Guidelines for Preparing Economic Analyses*, Appendix B, Mortality Risk Valuation Estimates," December 2010. Converted to 2019 dollars using IPD data in Section III.C.

[208]J.E. Aldy and W.K. Viscusi, "Adjusting the Value of a Statistical Life for Age and Cohort Effects." Washington, D.C.: Resources for the Future, 2006.

[209]National Research Council, Committee on Health, Environmental, Other External Costs, Benefits of Energy Production, and Consumption, op. cit.

[210]Ibid.; Muller, Mendelsohn, and Nordhaus, op. cit.; Nicholas Z. Muller and Robert Mendelsohn, "Measuring the Damages of Air Pollution in the United States," *Journal of Environmental Economics and Management*, Vol. 54, No. 1 (2007), pp. 1-14; Paulina Jaramillo and Nicholas Z. Muller, "Air Pollution Emissions and Damages From Energy Production in the US: 2002–2011," *Energy Policy*, Vol. 90 (2016), pp 202-211. Estimates converted to 2019 dollars by MISI.

[211]For example, the AP2 model, an updated version of the air pollution impact model APEEP, estimates costs three times larger than the older version of the model, in 2002. See Emanuele Massetti, Marilyn A. Brown, Melissa Lapsa, Isha Sharma, James Bradbury, Colin Cunliff, and Yufei Li, op. cit.

[212]Ibid.

[213]National Research Council, Committee on Health, Environmental, Other External Costs, Benefits of Energy Production, and Consumption, op. cit.: Muller, Mendelsohn, and Nordhaus, op. cit.; Muller and Mendelsohn, op. cit.; Jaramillo and Muller, op. cit.

[214]Neal Fann, Charles M. Fulcher, and Bryan J. Hubbell, "The Influence of Location, Source, and Emission Type in Estimates of the Human Health Benefits of Reducing a Ton of Air Pollution," *Air Quality, Atmosphere*

There are large differences across studies in large part due to the models used to estimate the spatial distribution and the chemical transformations of air emissions, the VSL used in the study, whether the VSL or VSLY is used. While the power sector contributes to societal well-being by providing a reliable source of affordable power, it is also responsible for some external costs.

One study finds that the gross external monetized damage (GED) caused by power generation is equal to 34% of its value added, without including the external cost of carbon dioxide emissions.[215] On the other hand, Muller, Mendelsohn and Nordhaus actually contend that coal power generation has a gross external damage to value added (GED/VA) ratio equal to 2.2, meaning the pollution damages far exceed the value added.[216] They define gross external damage as marginal damages of emissions (the price) times the total quantity of emissions. However, they also identify six other industries as having air pollution damages that are "clearly larger than their value added." These industries are solid waste combustion, petroleum-fired electric power generation, sewage treatment, stone mining and quarrying, marinas, and petroleum and coal products. Thus "The fact that GED exceeds VA implies that if the national accounts included the external costs due to air pollution emissions, the augmented measure of VA for these industries would actually be negative."[217] So, coal power generation is apparently in some good company. But are we really to believe that the U.S. would be better off by eliminating all coal power plants?[218] Marinas? *Sewage treatment*? Stone mining and quarrying? Reductio ad absurdum.

Estimates of the monetized costs of air pollution from coal power generation range between $75 and $186 billion (2019 dollars) per year, using the standard $8.6 million (2019 dollars) estimate for the VSL.[219] It is estimated that about 95% of the physical and economic impacts of air pollution are caused by coal power generation because it is the

& Health, Vol. 2, No. 3 (2009), pp. 169-176; Neal Fann, Kirk R. Baker, and Charles M. Fulcher, "Characterizing the PM 2.5-related Health Benefits of Emission Reductions For 17 Industrial, Area and Mobile Emission Sectors Across the US," *Environment International*, Vol. 49, (2012), pp. 141-151; Jonathan I. Levy, Lisa K. Baxter, and Joel Schwartz, "Uncertainty and Variability in Health-Related Damages From Coal-Fired Power Plants in the United States," *Risk Analysis*, Vol. 29, No. 7 (2009), pp. 1000-1014; Jonathan J. Buonocore, Xinyi Dong, John D. Spengler, Joshua S. Fu, and Jonathan I. Levy. "Using the Community Multiscale Air Quality (CMAQ) Model to Estimate Public Health Impacts of PM 2.5 From Individual Power Plants," *Environment International*, Vol. 68 (2014), pp.: 200-208.

[215]Muller, Mendelsohn, and Nordhaus, op. cit.

[216]Ibid.

[217]Ibid.

[218]However, this does may not necessarily mean that electricity generation from coal combustion would be uneconomical if all external costs were fully incorporated. If external costs were internalized in the cost of power generation, prices would change and the estimate of the value added of the power sector would also change. Nevertheless, the estimation of external costs is plagued by empirical and political difficulties, and estimates rang very widely. In particular, certain interest groups are eager to purposefully estimate the external costs of coal power generation high enough to make coal power uneconomical – with the goal often determining the size of the external cost estimates.

[219]Estimates converted to 2019 dollars by MISI.

largest direct and indirect source of $PM_{2.5}$, the most harmful pollutant for human health.[220] The monetized cost per MWh of electricity from coal-fired power plants ranges between $36 and $188 (2019 dollars),[221] using standard assumptions on the VSL. Differences in the sulfur content of coal, in emissions control technologies, in the age and in the geographic location all contribute to make pollution costs vary greatly across power plants.[222] One study estimated that the average cost across all coal power plants is equal to 54$/MWh (2019 dollars), but that the most efficient coal power plants have external costs less than 6$/MWh (2019 dollars) while the least efficient coal power plants generate damages equal to 1,587 $/MWh (2019 dollars).[223] According to the same study, the 10% of coal-fired plants with the highest external costs account for about 40% of the total environmental damage from coal combustion.[224]

IV.G.3. Impacts by Pollutant

It is estimated that $PM_{2.5}$ causes the largest fraction of monetized costs of air pollution per ton of emissions. The estimated cost per ton of $PM_{2.5}$ varies greatly, from $34 to $151 (2019 dollars). The average of the estimates is equal to $70/ton and the median is equal to $64/ton (2019 dollars). One study estimated that only 6% of total pollution by weight is $PM_{2.5}$, but that it accounts for 23% of damages.[225] It is estimated that NO_X emissions account for 27% of emissions by weight but that they generate only 8% of total damages.[226] The cost per ton of NO_X emission varies between $3.20 and $18.25 (2019 dollars).[227]

SO_2 is estimated to be the largest source of economic damages from power plants because it is emitted in large quantities by coal power plants and is a precursor of $PM_{2.5}$, the air pollutant with the largest estimated negative health effects. Studies indicate that the cost of SO_2 emissions ranges between $18 and $102 (2019 dollars), with a mean across studies equal to $38/ton and a median cost equal to $32/ton (2019 dollars).[228] SO_2 emissions are the major source of estimated air pollution monetized damages per

[220]Muller, Mendelsohn, and Nordhaus, op. cit.; Jaramillo and Muller, op. cit.; National Research Council, Committee on Health, Environmental, Other External Costs, Benefits of Energy Production, and Consumption, op. cit.; Neal Fann, Kirk R. Baker, and Charles M. Fulcher, op. cit.

[221]Weighted average across all power plants, with weights equal to electricity generation. Estimates converted to 2019 dollars by MISI.

[222]National Research Council, Committee on Health, Environmental, Other External Costs, Benefits of Energy Production, and Consumption, op. cit.

[223]5th and 95th percentile of the distribution, respectively. Unweighted average of costs per MWh across all power plants. National Research Council, Committee on Health, Environmental, Other External Costs, Benefits of Energy Production, and Consumption, op. cit. Estimates converted to 2019 dollars by MISI.

[224]National Research Council, Committee on Health, Environmental, Other External Costs, Benefits of Energy Production, and Consumption, op. cit.

[225]Muller, Nicholas Z., Robert Mendelsohn, and William Nordhaus, "Environmental Accounting for Pollution in the United States Economy," American Economic Review, Vol. 100 (2011), pp. 1649-1675.

[226]Ibid.

[227]Fann, Fulcher and Hubbell, op. cit. Estimates converted to 2019 dollars by MISI.

[228]Ibid. Estimates converted to 2019 dollars by MISI.

unit of electricity generated using coal, whereas NO_X emissions are the major source of estimated monetized damages for electricity generated using natural gas.

The average cost of pollution from coal-fired power plants is estimated to equal about 4.30¢/kWh (2019 dollars).[229] However, differences in the sulfur content of coal, the presence of control technologies, and the vintage of the plant make the external cost per kWh vary greatly across power plants. It is estimated that the most efficient coal power plants have external costs less than 1¢/kWh, whereas the least efficient plants lead to external costs greater than 13¢/kWh (2019 dollars). The 10% of coal-fired plants with the highest estimated external costs account for about 40% of the total environmental damage from coal combustion.[230]

Health impacts are estimated to comprise the largest fraction of economic damages from air pollution.[231] In order to be comprehensive, estimated health impacts include reduced organ functionality; increased asthma attacks; doctor visits, school and work absences; emergency room visits, hospital admission and heart attacks; and premature death. Emissions of coarse particulate matter ($PM_{10-2.5}$ – i.e., particulate matter that is between 10 and 2.5 µm in diameter) cause chronic obstructive pulmonary disease, asthma, and hospital respiratory and cardio-vascular admissions but have not been associated with increased mortality.[232] However, fine particles ($PM_{2.5}$) are more harmful because they translocate from the lungs to blood and accumulate in other parts of the body, increasing short- and long-term mortality and morbidity.[233] Human exposure to ground-level ozone reduces lung function, generates inflammation of the airways, and causes symptoms such as chest pain, coughing, wheezing and shortness of breath, even for people with no pre-existing respiratory ailments.[234]

The health impacts are estimated by comparing mortality under a reference scenario and a scenario in which pollution is changed. The marginal impact of pollution estimates the change in impacts resulting from increasing the level of pollution by one unit only. The average impact of pollution is determined by dividing the total health

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[229]National Research Council, Committee on Health, Environmental, Other External Costs, Benefits of Energy Production, and Consumption, op. cit. Estimates converted to 2019 dollars by MISI.

[230]While many studies estimate the impacts of single pollutants at specific locations, studies that track the effects of pollution specifically from power generation are limited. The major difficulty is the attribution of pollution damages to one particular sector. In order to connect observed impacts to power generation emissions specifically, researchers must use models that track pollution from sources to receptors. This is a complex task that explains why few studies are available. See Emanuele Massetti, Marilyn A. Brown, Melissa Lapsa, Isha Sharma, James Bradbury, Colin Cunliff, and Yufei Li, op. cit.

[231]Environmental Protection Agency. "Regulatory Impact Analysis for the Clean Power Plan Final Rule" EPA-452/R-15-003, August 2015.

[232]B. Brunekreef and B. Forsberg, "Epidemiological Evidence of Effects of Coarse Airborne Particles on Health," *European Respiratory Journal*, Vol. 26, No. 2, (2005), pp. 309-318.

[233]Arden C. Pope III and Douglas W. Dockery, "Health Effects of Fine Particulate Air Pollution: Lines That Connect," *Journal of the Air & Waste Management Association*, Vol. 56, No. 6 (2006); pp. 709-742.

[234]Environmental Protection Agency, "Progress Cleaning the Air and Improving People's Health," 2015; Environmental Protection Agency, "National Emissions Inventory, version 2, Technical Support Document," edited by Office of Air Quality Planning and Standards, Environmental Protection Agency, Air Quality Assessment Division, Emissions Inventory and Analysis Group, Research Triangle Park, North Carolina, 2015.

impacts by the total level of pollution. A concentration-response (or dose-response) function is often used to study how the health effects change when the concentration of pollutants changes. The concentration-response function is derived from toxicological studies, human clinical trials, and observational epidemiology studies.[235] In some cases expert elicitation is used to reduce uncertainty about the relationship between pollutants and health.[236] It has been estimated that pollutants emitted by the electric power sector cause damage to human health (increased morbidity and mortality), to crops and timber production (productivity losses), and to materials (deterioration and increased maintenance costs) – Table IV-13. It has also been estimated that they reduce visibility and harm ecosystems, with losses to recreational value and ecological services.

Table IV-13
Summary of the Major Physical Impacts of the Most Common Pollutants

	Human Health	Crops and Timber	Materials	Visibility	Recreation
NO_x	COPD IHD		Material deterioration		eutrophication
SO_2	Asthma Cardiac	Damages to forests	Material depreciation		Damages to forests
O_3	Chronic asthma Acute-exposure mortality Respiratory problems Acute asthma attacks	Crop loss Timber loss	Rubber deterioration		Damages to forests and wilderness areas
$PM_{2.5}$	Premature death Nonfatal heart attacks Hospital admissions ER visits for asthma, acute bronchitis, upper and lower respiratory symptoms			Loss of visibility	
$PM_{10\text{-}2.5}$[bb]	Chronic bronchitis				

COPD: chronic obstructive pulmonary disease; IHD: ischemic heart disease.
[bb]$PM_{10\text{-}2.5}$ is coarse particulate matter with diameter between 10 and 2.5 μm.
Source: Muller, Mendelsohn, and Nordhaus; Muller and Mendelsohn; Industrial Economics; and U.S. Environmental Protection Agency

[235]Industrial Economics, "Health and Welfare Benefits Analyses to Support the Second Section 812 Benefit-Cost Analysis of the Clean Air Act," 2010.
[236]See, for example, Muller and Mendelsohn, op. cit.; National Research Council, Committee on Health, Environmental, Other External Costs, Benefits of Energy Production, and Consumption, op. cit.; Michelle L. Bell, Richard D. Morgenstern, and Winston Harrington. "Quantifying the Human Health Benefits of Air Pollution Policies: Review of Recent Studies and New Directions in Accountability Research," *Environmental Science & Policy*, Vol. 14, No. 4 (2011), pp. 357-368; Muller, Mendelsohn, and Nordhaus, op. cit.; Milan Ščasný, et al., "Quantifying the Ancillary Benefits of the Representative Concentration Pathways on Air Quality in Europe," *Environmental and Resource Economics*, Vol. 62, No. 2 (2015), pp. 383-415.

IV.G.4. Estimated Public Health Benefits

Previous research has estimated the public health benefits of the DOE coal RD&D program. For example, NETL found that, in addition to maintaining an adequate supply of affordable electricity, the DOE program has resulted in several types of benefits to industry participants and the general public, including improved health and cleaner air.[237] NETL noted that monetized health benefits due to improved air quality have been estimated in a number of reports, and that the DOE program has been instrumental in gaining compliance with many of the 1990 Clean Air Act Amendments requirements with regard to NO_x, SO_2, and ozone. The reduction in emissions resulting from the DOE Clean Coal Technology Development projects was substantial, and these projects proved the feasibility and commercial readiness of a number of environmental control technologies and technology types that lead to cleaner air and thus improved health benefits with substantial monetized health benefits from reductions in NO_x, SO_2, and ozone.[238]

NETL clean coal benefits studies utilized monetized health benefits due to improved air quality that were estimated in a number of EPA reports on the public health benefits of proposed air pollution regulations by the Board on Environmental Studies and Toxicology.[239] NETL also estimated the emissions reductions and health benefits from specific projects, including emissions reductions of VOCs, particulates, CO, and ammonia.

As another example, in the DOE/EPRI/CURC Clean Coal Technology Roadmap, estimates were made of the health benefits of avoided environmental costs.[240] The approach taken was to estimate savings from avoided environmental costs from the reduction in emissions achieved by advanced technology, and actual avoided environmental costs for health depended on geographic location, urban vs. rural environment, and many other factors. The monetary estimates of the value of the health benefits were made based on review of available projections by EPA and Resources for the Future.

In all, previous research studies have estimated that the public health benefits of the DOE coal RD&D program through 2007 totaled approximately $17.1 billion (2019 dollars).[241] Here we estimated the public health benefits of the DOE coal program for the

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[237]National Energy Technology Laboratory, "Sales and Benefits of Technology from Clean Coal Demonstration Projects," op. cit.

[238]Meszler Engineering Services, "Ambient Air Quality Trends: An Analysis of Data Collected by the U.S. Environmental Protection Agency," report prepared for the Foundation for Clean Air Progress, September 2004.

[239]National Energy Technology Laboratory, "Sales and Benefits of Technology from Clean Coal Demonstration Projects," op. cit.

[240]U.S. Department of Energy, the Electric Power Research Institute, and the Coal Utilization Research Council, "Clean Coal Technology Roadmap," op. cit.; National Energy Technology Laboratory, "Clean Coal Technology Roadmap: CURC/EPRI/DOE Consensus Roadmap, Background Information," op. cit.

[241]Roger Bezdek and Robert Wendling, "The Return on Investment of the Clean Coal Technology Program in the USA," op. cit.; U.S. Department of Energy, Office of Fossil Energy, "Clean Coal Technology: From Research to Reality," op. cit.; U.S. Department of Energy, Assistant Secretary For Fossil Energy, "Clean Coal Technology: The Investment Pays Off," op. cit.; National Research Council, *Energy Research at DOE:*

years 2008 – 2019. We estimated the public health benefits per MWH of coal generated electricity that resulted from the gradual introduction of more efficient coal power plants and their displacement of power production from older, less efficient coal plants over this 12 year period.[242] These public health benefits from 2008 through 2019 totaled approximately $19.8 billion (2019 dollars). Therefore, we estimate the total public health benefits through 2019 to be approximately $36.9 billion (2019 dollars).[243]

The $36.9 billion estimate may actually be conservative. There exists a credible body of research indicating that the availability of reliable, relatively inexpensive energy – such as that provided by electricity from coal plants – is beneficial for public health because it increases persons' wealth and standards of living, and "wealthier is healthier."[244] In particular, the impacts of higher electricity prices are highly regressive and especially harmful to the health and well-being of low income persons.[245] Further, the UN Human Development Index shows a very strong positive relationship between electricity consumption and human development.[246] While this is an important issue deserving comprehensive analysis, it is outside the scope of the current study.

Was It Worth It? Op. cit.*;* National Research Council, *Prospective Evaluation of Applied Energy Research and Development at DOE (Phase One): A First Look*, Committee on Prospective Benefits of DOE's Energy Efficiency and Fossil Energy R&D Programs, op. cit.; Emanuele Massetti, Marilyn A. Brown, Melissa Lapsa, Isha Sharma, James Bradbury, Colin Cunliff, and Yufei Li, op. cit.; Argonne National Laboratory, Energy Systems Division, "Updated Greenhouse Gas and Criteria Air Pollutant Emission Factors and their Probability Distribution Functions for Electric Generating Units," ANL/ESD/12-2, 2012; U.S. Department of Energy, Office of Fossil Energy, "Fossil Energy Research Benefits: Clean Coal Technology Demonstration Program," June 2012; National Energy Technology Laboratory, "Sales and Benefits of Technology from Clean Coal Demonstration Projects," op. cit.; Dallas Burtraw, Alan Krupnick, Karen Palmer, Anthony Paul, Michael Toman, and Cary Bloyd, "Ancillary Benefits of Reduced Air Pollution in the United States from Moderate Greenhouse Gas Mitigation Policies in the Electricity Sector," Resources for the Future Discussion Paper 01–61, December 2001; Estimates converted to 2019 dollars by MISI.

[242]Based primarily on the difference in external health costs of the average coal fleet over this period compared to the new, more efficient, cleaner plants.

[243]We deducted the SO_2 and NO_x benefits estimated in Sections IV.F.1 and IV.F.2 to avoid double counting.

[244]See, for example, Harvey Brenner, *Health Benefits of Low-Cost Energy: An Econometric Case Study*, Air and Waste Management Association, November 2005; Daniel E. Klein and Ralph L. Keeney, "Mortality Reductions From Use of Low-Cost Coal-Fueled Power: An Analytical Framework," Twenty-First Strategies, LLC and Duke University, December 2002; Eugene M. Trisko, "Economic and Public Health Benefits of Coal-Based Electric Energy," presented at the 20th Annual Surface Mined Land Reclamation Technology Transfer Seminar, Jasper, Indiana, December 5, 2006; Roger H. Bezdek, "Testimony Before The Office Of Administrative Hearings For The Minnesota Public Utilities Commission State of Minnesota in the Matter of the Further Investigation in to Environmental and Socioeconomic Costs Under Minnesota Statute 216B.2422, Subdivision 3," OAH Docket No. 80-2500-31888, MPUC Docket No. E-999-CI-14-643, June 1, 2015; Roger H. Bezdek, "Fossil Fuels: Benefits Far Outweigh Costs," presented at the Briefing on EPA Policy and Science, Washington, D.C., June 2017.

[245]See, for example, Roger H. Bezdek, "Potential Economic Impact of the EPA Endangerment Finding on Low Income Groups and Minorities," *Cambridge Business Review*, Vol. 16, No 1 (December 2010), pp. 127-133; Roger H. Bezdek, "Potential Harm of Regulations Stemming From the EPA Endangerment Finding to Minorities, Low-Income Persons, the Elderly, and Those Living on Fixed Incomes," report prepared for Sidley Austin as part of the "Petitioners' Motion For Partial Stay of EPA's Greenhouse Gas Regulations" filed with the U.S. Court of Appeals For the District of Columbia Circuit, September 2010.

[246]United Nations, "Human Development Index," http://hdr.undp.org/en/content/human-development-index-hdi.

IV.H. Impacts of NETL Operations

As discussed in Chapter II, NETL has conducted a series of economic analyses using I-O models to quantify the laboratory's national and regional economic and jobs impacts in 2006, 2008, 2016, and 2018.[247] NETL estimated the employment and salaries of persons employed in the U.S. at NETL as either federal employees or site support contractors (full-time equivalents), as well as NETL's spending on grants, RD&D awards, contracts, cooperative agreements, and purchase orders within the U.S. NETL then estimated the total national economic and job impacts of NETL operations in each year.

The analysis determined that the impact of NETL on the U.S. economy is greater than the total of the lab's direct spending, because money spent by NETL is spent again by the recipient employees and businesses. This economic "ripple effect" is captured in the I-O model through a series of multipliers that provide estimates of the impact of each dollar of direct spending cycling through the national economy in the form of additional (indirect and induced) spending, personal income, and employment. The analyses revealed that NETL:

- In 2008, had a total estimated impact of $941 million on the U.S. economy, created a total of 11,208 jobs, and generated $64.5 million in taxes.
- In 2016, had a total estimated impact of $2,074 million on the U.S. economy and created a total of 10428 jobs.
- In 2018, had a total estimated impact of $1,907 million on the U.S. economy in and created a total of 10,067 jobs.

MISI converted the dollar estimates into 2019 dollars using the IPD data given in Chapter III and then computed the average estimates – Table IV-IV. This table shows that NETL operations annually, on average, generated about $1,750 million (2019 dollars) in economic impacts, 10,500 FTE jobs, and $120 million (2019 dollars) in tax revenues.[248]

Table IV.14
Economic and Job Impacts of NETL Operations*

	Economic Impact	Jobs	Taxes
2008	$1,120	11,208	$77
2016	$2,198	10,428	$150
2018	$1,941	10,067	$133
Average	$1,753	10,508	$120

*Millions of 2019 dollars.

Source: National Energy Technology Laboratory, and Management Information Services, Inc.

[247] *National, State, and Regional Economic and Environmental Impacts of NETL*, op. cit.; Randall Jackson, Amanda Krugh, Brian LaShier, and Ronald Munson, "National and State Economic Impact of NETL," op. cit.; National Energy Technology Laboratory, "Economic Impacts of NETL – United States," 2018, op. cit.; National Energy Technology Laboratory, "Economic Impacts of NETL – United States," 2016; https://netl.doe.gov/sites/default/files/2019-05/National_Impact_Factsheet.pdf. The 2007 NETL study did not estimate total U.S. national impacts.

[248] Tax revenues for 2016 and 2018 estimated by MISI.

Assuming that the averages in this table are generally representative of the annual impacts of NETL operations over the past two decades, we estimate that over the period 2000 – 2019 NETL operations cumulatively generated approximately:

- $35 billion (2019 dollars) in economic impacts
- 210,000 jobs
- $2.4 billion (2019 dollars) in tax revenues

IV.I. Jobs Created at the National Level

Job creation is a key focus of this report. MISI defines a "job" as a full-time equivalent (FTE) job in the U.S.[249] An FTE job is defined as 2,080 hours worked in a year's time, and adjusts for part time and seasonal employment and for labor turnover. The use of FTEs normalizes job creation among full time, part time, and seasonal employment.[250] For example, two workers each working six months of the year would be counted as one FTE job. An FTE job assessment allows meaningful comparisons over time and across jurisdictions as it consistently measures the input of labor in the production process and is the standard that should be followed in employment analyses.[251]

Thus, a "job" created is defined as an FTE job created for one person for one year, and 50,000 jobs created will refer to 50,000 persons employed for one year. It is correct to state that "over a ten year period 500,000 cumulative jobs are created" as long as it is specified that this refers to 50,000 persons, each employed annually for 10 years.

MISI estimated the total (direct, indirect, and induced) jobs created by the DOE coal RD&D program:[252]

- Direct jobs are those created directly in the specific activity or process,

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[249]https://web.archive.org/web/20120928112059/http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Glossary:Full-time_equivalent.

[250]Ibid.

[251]These conventions are not always followed in studies of U.S. energy employment. For example, the employment figures reported in the annual *U.S. Energy and Employment Report* (USEER), which has been published annually since 2016, are supposed to refer only to direct employment and not to indirect employment or induced employment. However, the reports' employment figures do include some indirect jobs, although it is not clear how many. The latest USEER is National Association of State Energy Officials and Energy Futures Initiative, *2020 U.S. Energy and Employment Report*, Washington, D.C. 2020.

[252]The basic MISI methodology and model are documented in Management Information Services, Inc., Development of Economic and Job Impacts Analysis Tool and Technology Deployment Scenario Analysis, report prepared for the U.S. Department of Energy, National Energy Technology Laboratory, DOE/NETL-402/092509, September 2009. For applications, see Management Information Services, Inc. and Leonardo Technologies Inc., "Economic Impact Assessment of CCUS Retrofit of the Comanche Generating Station," prepared for the U.S. Department of Energy and the National Energy Technology Laboratory, June 2019; Roger Bezdek and Robert Wendling, "Economic, Environmental, and Job Impacts of Increased Efficiency in Existing Coal-Fired Power Plants," *Journal of Fusion Energy*, Volume 32, Number 2 (April 2013), pp. 215-220; Roger Bezdek and Robert Wendling, "The Return on Investment of the Clean Coal Technology Program in the USA," *Energy Policy*, March 2013, Vol. 54, pp. 104-112.

- Indirect jobs are those created throughout the required interindustry supply chain,
- Induced jobs are those created in supporting or peripheral activities,
- Total jobs are the sum or all of the jobs created.[253]

For simplicity, MISI includes induced jobs in the indirect category. The total (direct, indirect, and induced) jobs concept is the accepted methodology widely used in studies of this nature and in the peer-reviewed literature.

In estimating the impacts on the entire labor market, one lost dollar of economic output or one lost job is not the same as another. Each industry has backward linkages to economic sectors that provide the materials needed for the industry's output, and each industry also has forward linkages to the economic sectors where the industry's workers spend their income. Therefore, in addition to the jobs directly supported by an industry, a large number of indirect jobs may also be supported by that industry. The inclusion (or exclusion) of jobs and output in industries with strong backward and forward linkages to other economic sectors can cause indirect and induced impacts. Employment multipliers measure how the creation or destruction of output or employment in a particular industry translates into wider employment changes throughout the economy.[254]

In the analysis, MISI followed the conventions in EIA's *Annual Energy Outlook 2020* (*AEO 2020*), and dollar estimates are expressed in terms of constant 2019 dollars.[255] The other standard conventions of the EIA AEO reports were also adhered to. In addition, the conventions of the required U.S. Bureau of Labor Statistics, U.S. Bureau of Economic Analysis, and U.S. Census Bureau databases were followed.[256]

As discussed in Section IV.D, MISI determined that the DOE coal RD&D program was instrumental in facilitating the last trance of new coal power plants built in the U.S. over the period 2008 – 2019 – almost all of them prior to 2015.[257] We credited the DOE program with facilitating half of the new coal power plants built over this period. The preferred method of developing the jobs impact estimates of the power plant construction would be a comprehensive modeling approach.[258] Similarly, the preferred method of developing the jobs impact estimates of the exports facilitated by the DOE coal RD&D program and the O&M jobs at the coal plants would also be a comprehensive modeling

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[253]It is also not clear what "job" concept USEER utilized. There are repeated references to "employment," "workforce," "jobs," and "net jobs." Further, these concepts are sometimes used interchangeably in a confusing manner. See National Association of State Energy Officials and Energy Futures Initiative, op. cit.

[254]See, for example, "Understanding Multipliers," https://implanhelp.zendesk.com/hc/en-us/articles/115009505707-Understanding-Multipliers.

[255]U.S. Energy Information Administration, *Annual Energy Outlook 2020*, op. cit.

[256]See also U.S. Department of Commerce, Bureau of Economic Analysis, "Regional Economic Accounts, Gross Domestic Product."

[257]As noted, the last major coal power plant to come on-line in the U.S. was Spiritwood Energy in North Dakota, in November 2014.

[258]See Management Information Services, Inc., *Development of Economic and Job Impacts Analysis Tool and Technology Deployment Scenario Analysis*, report prepared for the U.S. Department of Energy, National Energy Technology Laboratory, DOE/NETL-402/092509, September 2009.

approach. A final demand vector for relevant expenditure categories, e.g., plant construction, technology exports, etc., would be constructed via detailed analysis. This final demand vector would then be used in conjunction with economic input-output analysis to estimate the total (direct and indirect) employment generated throughout the economy. This would provide an estimate of the overall jobs impact. However, due to time and resource constraints, this type of detailed analysis was not possible for this project.

There are also coal power plant operations and maintenance (O&M) job implications. After the coal plants come on-line these O&M jobs – unlike the construction jobs – continue indefinitely. We decided that the best estimate of the O&M jobs that would be required by the new coal plants is that of the average O&M jobs in existing coal power plants, and we thus estimated the O&M jobs that would be required using the average of O&M jobs in existing coal power plants.

We developed two estimates of the O&M jobs required. For the first, we used a "micro" approach by examining the actual O&M permanent employees at a number of coal plants. While the number of such employees per MW differed somewhat among different plants, it was usually in the range of about 0.15 to 0.20 per MW. For example:

- The Dave Johnston plant in Wyoming had about 0.21 permanent O&M employees per MW.
- The Karn Weadock plant in Michigan had about 0.19 permanent O&M employees per MW.
- The expanded Karn Weadock plant would have about 0.16 permanent O&M employees per MW.
- The Gorgas plant in Georgia had about 0.20 permanent O&M employees per MW.
- The Coal Creek plant in North Dakota had about 0.20 permanent O&M employees per MW.
- The Avon Lake plant in Ohio had about 0.15 permanent O&M employees per MW.
- The San Juan plant in New Mexico had about 0.22 permanent O&M employees per MW.
- The Eastlake plant in Ohio had about 0.13 permanent O&M employees per MW.
- The Comanche Generating station in Colorado had about 0.17 permanent O&M employees per MW.
- The planned Mesaba plant in Minnesota would have had about 0.17 permanent O&M employees per MW.
- The planned NRG plant in New York would have had about 0.15 permanent O&M employees per MW.
- Other plants usually had between about 0.10 and 0.20 permanent O&M employees per MW.

Thus, on the basis of these and other actual facilities, a 1,000 MW coal power plant would likely have about 100 to 200 permanent O&M employees.

To derive another estimate of the O&M jobs for a coal plant, we used a "macro" approach where we estimated the overall national average of O&M employees at U.S. coal power plants. Using an estimate of annual plant O&M expenditures and average salaries in NAICS code 2211121, fossil fuel electric power generation, we estimate that the average O&M employee per MW is about 0.15. Thus, according to this procedure, a 1,000 MW coal power plant would have about 150 permanent O&M employees.[259]

Thus, the estimate for coal plans of about 0.15 permanent O&M employees per MW seemed viable and, accordingly, here we used the estimate of 0.15 permanent O&M employees per MW for coal power plants. As discussed earlier, the preferred method of developing an estimate of the total (direct plus indirect) jobs generated by the on-site O&M jobs would be a comprehensive modeling approach.[260] However, due to time and resource constraints, this type of detailed analysis was not possible for this project, and we had to use another methodology.

As noted, employment multipliers measure how the creation or destruction of output or employment in a particular industry translates into wider employment changes throughout the economy. We used an average I-O employment multiplier as a proxy. I-O multipliers differ significantly among industries and, regionally, for the same industry.[261] However, using BEA and BLS data, the national average I-O job multiplier for the Electric Power Generation, Transmission and Distribution Industry (NAICS 2211) is about 5.6, and this is the multiplier we used.[262] As in the case of new plant construction, we gave the DOE RD&D program credit for about half of the O&M jobs created over the period. Therefore, we estimate that the total cumulative number of jobs generated throughout the economy by the coal plant O&M program, 2008 – 2019, is about 159,000.[263] We estimate

[259]EIA had estimated that the average 300 MW coal-fired power plant had 53 employees. This translates to about 0.18 permanent employees per MW.J. Alan Beamon and Thomas J. Leckey. "Trends in Power Plant Operating Costs," Energy Information Administration, EIA, 1999. NAICS is the North American Industrial Classification System.

[260]See Management Information Services, Inc., *Development of Economic and Job Impacts Analysis Tool and Technology Deployment Scenario Analysis*, report prepared for the U.S. Department of Energy, National Energy Technology Laboratory, DOE/NETL-402/092509, September 2009.

[261]See, for example, Regional Economic Analysis Division, Bureau of Economic Analysis, *Regional Input-Output Modeling System (RIMS II)*, 2018; David W. Hughes, "A Primer in Economic Multipliers and Impact Analysis Using Input-Output Models," University of Tennessee, June 2018; Josh Bivens, Updated Employment Multipliers for the U.S. Economy, Economic Policy Institute, January 2019; Rebecca Bess and Zoë O. Ambargis, "Input-Output Models for Impact Analysis: Suggestions for Practitioners Using RIMS II Multipliers," Presented at the 50th Southern Regional Science Association Conference, March 23-27, 2011, New Orleans, Louisiana.

[262]U.S. Bureau of Labor Statistics, "Employment Requirements Matrix," 2017; U.S. Bureau of Labor Statistics, "Historical Employment Requirements Tables, 1997–2016;" U.S. Bureau of Labor Statistics, "Current Employment Statistics," various years; U.S. Bureau of Labor Statistics, "Employment, Hours and Earnings – National," 2017;

U.S. Bureau of Economic Analysis, "National Income and Product Accounts," https://www.bea.gov; U.S Bureau of Economic Analysis, "GDP-by-Industry," https://www.bea.gov; U.S. Bureau of Economic Analysis, "Annual Input-Output Tables, https://www.bea.gov/industry/input-output-accounts-data; Josh Bivens, "Updated Employment Multipliers for the U.S. Economy , Economic Policy Institute, Washington, D.C., January 23, 2019.

[263]To estimate total (direct plus indirect) jobs, MISI used the job multiplier for the Electric power generation, transmission, and distribution industry: 5.6.

that these new O&M jobs are created at a constant rate as the new coal plants come on-line over the 12 years. Thus, these jobs are not distributed evenly over the period: There are only about 1,600 jobs created in 2008, but by 2019 there are nearly 17,000 jobs generated annually.

The benefits of the clean coal technology and related exports discussed in Section IV.E include large numbers of jobs that were created over the period 2008 – 2019, and these also had to be estimated.

MISI thus had to estimate the number of jobs that would be created by the DOE coal RD&D program using proxy data. There are two sources for these proxy data:

- National industry jobs estimates available from the federal government
- Estimates of jobs impacts available from analytical studies

With respect to the former, data are available from BEA and BLS that permit estimation at the national and regional levels the likely jobs impact of expenditures on various programs. The nationwide economy average of all industries is about 7,400 FTE jobs per billion dollars of GDP.[264] However, this varies by more than a factor of 10 among sectors and detailed industries, and the regional and geographic variation for individual industries is also very large.

It would seem that the best proxy for the coal power plant construction program would be primarily the construction industry (NAICS 23), with elements of the utilities (NAICS 22), machinery manufacturing (NAICS 333), and the professional, scientific, and technical services (NAICS 54) industries. In 2019:[265]

- Employment in the construction industry was about 8,600 FTE jobs per billion dollars of GDP.
- Employment in the utilities industry was about 1,600 FTE jobs per billion dollars of GDP.
- Employment in the machinery manufacturing industry was about 7,000 FTE jobs per billion dollars of GDP.
- Employment in the professional, scientific, and technical services industry was about 5,800 FTE jobs per billion dollars of GDP.

Thus, the economic and job impacts of these industries differ significantly among the industries. Further, they can also differ regionally within the same industry.[266]

[264]Estimates were derived by MISI using U.S. Bureau of Economic Analysis, *Gross Domestic Product, Value Added, and Employment by Industry*, *2019*; U.S. Department of Commerce, Bureau of Economic Analysis, National Economic Accounts, *Annual Employment and GDP by Industry*, 2019; U.S. Bureau of Labor Statistics, *Civilian Labor Force Employment, 2019*.
[265]Ibid.
[266]For example, BEA's Regional Input-Output Modeling System (RIMS) data and regional economic studies indicate that the relative employment effects of the same industry among regions can differ among regions and from the national average by 50 percent or more.

There are also estimates of jobs impacts available from analytical studies of coal power plant construction, utilities, exports, and other programs and sectors.[267] MISI utilized both sets of data to estimate the jobs impact, 2008 – 2009, of the DOE coal RD&D program. We estimated that, on average over the period 2008 – 2019, in terms of total (direct plus indirect jobs):

- New coal plant construction[268] created about 14,700/yr.
- Coal plant O&M created about 13,250/yr.
- Technology exports created about 40,100/yr.[269]

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[267]See, for example, Terry L. Headley, and Roger H. Bezdek, "How Many Coal-Dependent Jobs Are There in the U.S. and How Important Are They?" *Public Utilities Fortnightly*, June 1, 2020, pp. 75-89; Management Information Services, Inc. and Leonardo Technologies Inc., op. cit.; Tim Considine, op. cit.; Robert C. Feenstra, Hong Ma, and Yuan Xub, "U.S. Exports and Employment," *Journal of International Economics*, Vol. 120, 2019, pp. 46–58; Trade Partnership Worldwide, "Trade and American Jobs: The Impact of Trade on U.S. and State-Level Employment, 2019 Update," prepared for the Business Roundtable, February 2019; Roger H. Bezdek, "The Economic Impacts of CCUS Tax Credits," *American Coal*, Issue 1, 2019, pp. 48-51; Management Information Services, Inc., "Estimates of the Jobs Likely to be Generated by the 2018 Enacted 45Q Legislation Compared to Those Likely From the 2017 Proposed CCUS Tax Credits," prepared for the National Energy Technology Laboratory, November 2018; Management Information Services, Inc., "Analyzing the Economic and Job Impacts of the DOE R&D Program and CCS Tax Credits," prepared for the National Energy Technology Laboratory, DOE contract DE-FE 0025912, January 2018; Management Information Services, Inc., "Analyzing and Estimating the Economic and Job Benefits of U.S. Coal," prepared for the U.S. Department of Energy, September 2017; Jeffrey Hall, "Jobs Supported by State Exports, 2016," Office of Trade and Economic Analysis, Industry and Analysis, U.S. International Trade Administration, December 2017; Management Information Services, Inc., "Estimating the Economic and Job Benefits of NETL Coal R&D Programs," prepared for the National Energy Technology Laboratory, August 2017; Business Roundtable, "How the U.S. Economy Benefits From International Trade and Investment," Washington, D.C., 2015; Management Information Services, Inc., "Employment Impact Analysis of Coal Carbon Capture and Sequestration Retrofits," prepared for National Energy Technology Laboratory, August 2015; National Coal Council, *Fossil Forward -- Revitalizing CCS*, 2015; Management Information Services, Inc., "Estimates of The Jobs and Economic Benefits Resulting From the Capacity Build-Out and Oil Production Associated With the FE Technologies/EOR Market Snapshot, 2020-2100," prepared for the National Energy Technology Laboratory, September 2012; Management Information Services, Inc., "Estimates of the Jobs and Economic Benefits Resulting From the Capacity Build-Out and Oil Production Associated With The FE Technologies/EOR Market Snapshot", prepared for the National Energy Technology Laboratory, August, 2012; "Economic, Employment, and Energy Stimulus From Clean Coal Technology Deployment," chapter 2 in Harnessing Coal's Carbon Content to Advance the Economy, Environment, and Energy Security, National Coal Council, Washington, D.C., June 2012; BBC Research and Consulting, op. cit.; Daniel J. Ikenson, "Made in America: Increasing Jobs through Exports and Trade," testimony before the Subcommittee on Commerce, Manufacturing, and Trade, Committee on Energy and Commerce, United States House of Representatives, March 16, 2011; Bruce Katz and Emilia Istrate, "Boosting Exports, Delivering Jobs and Economic Growth" Brookings-Rockefeller Project on State and Metropolitan Innovation, January 2011; Management Information Services, Inc., *Economic and Employment Impacts of Increased Efficiency in Existing Coal-Fired Power Plants*, report prepared for the U.S. Department of Energy, National Energy Technology Laboratory, DOE/NETL-41817M4462, June 2009.

[268]Including the Petra Nova facility. To estimate total (direct plus indirect) jobs, MISI used a job multiplier of 1.78.

[269]The Business Roundtable estimated that in 2017, U.S. Exports totaled $2.34 trillion and created 39 million jobs. See Trade Partnership Worldwide, "Trade and American Jobs: The Impact of Trade on U.S. and State-Level Employment, 2019 Update," prepared for the Business Roundtable. To estimate total (direct plus indirect) jobs, MISI used a job multiplier of 2.50.

As discussed in Section IV.H, MISI also estimated that NETL operations over this period created about 10,500/yr.

Thus, the total jobs created over the period 2008 - 2019 averaged about 78,600/yr. If we assume that this annual job creation was about the average also for the years 2000 – 2007, then the jobs created over the period 2000 – 2019 totaled about 1,572,000.

In 2019, 78,600 jobs was less than 0.1% of the total U.S. jobs. However, the jobs created by the DOE coal RD&D program were not distributed equally among all regions or industries and in some sectors and regions the jobs created were a substantial portion of total jobs. For example:

- The jobs created by NETL operations were concentrated in regions in Pennsylvania and West Virginia.
- The O&M jobs at coal plants are often critically important to the regions in which the plants are located.[270]
- Jobs created by exports are disproportionately created in certain industries and local areas.[271]

It should be noted that the job impacts of the DOE program are of critical importance, and in 2020 are especially relevant in the current environment where job losses and unemployment are at record levels not seen since the Great Depression of the 1930s.[272] The jobs issue is discussed further in Chapter VI.

The number of jobs created is important, but it is also important to disaggregate the employment generated by into occupations and skills. Estimating the occupational and skill mix of the jobs created is a complex task that is outside the scope of the current project. However, from previous MISI work and other studies it is possible to identify some the occupations for which significant jobs would be created.[273] It is clear that the jobs generated are disproportionately concentrated in fields related to the construction, energy, utilities, technology export, mining, industrial, and related sectors, reflecting the requirements of the programs and their supporting industries.

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[270]See Headley and Bezdek, op. cit.; Management Information Services, Inc. and Leonardo Technologies Inc.; op. cit.; Management Information Services, Inc., "Analyzing and Estimating the Economic and Job Benefits of U.S. Coal," prepared for the U.S. Department of Energy, September 2017; Roger H. Bezdek, "Coal Industry and Appalachia," *Public Utilities Fortnightly*, October 1, 2017, pp. 32-36.

[271]See Feenstra, Ma, and Xub, op. cit.; Trade Partnership Worldwide, op. cit.; and Katz and Istrate, op. cit.

[272]See, for example, Sarah Chaney and Eric Morath, "April Unemployment Rate Rose to a Record 14.7%," *Wall Street Journal*, May 8, 2020.

[273]Management Information Services, Inc., "Analyzing and Estimating the Economic and Job Benefits of U.S. Coal," op. cit.; National Coal Council, "Harnessing Coal's Carbon Content to Advance the Economy, Environment, and Energy Security," June 2012; Bezdek and Wendling, "Economic, Environmental, and Job Impacts of Increased Efficiency in Existing Coal-Fired Power Plants," op. cit.; Management Information Services, Inc., *American Energy Security: Building a Bridge to Energy Independence and to a Sustainable Energy Future*, prepared for the Southern States Energy Board, Norcross, Georgia, July 2006; Roger H. Bezdek, "The Hydrogen Economy and Jobs of the Future," *Renewable Energy and Environmental Sustainability*, Vol. 4, No. 1 (2019).

The jobs created are across a wide spectrum in many industries and in professional and skilled occupations such as chemical, mechanical, electronics, and industrial engineers; electricians; sheet metal workers; geoscientists; computer software engineers; skilled service personnel; tool and die makers; computer controlled machine tool operators; industrial machinery mechanics, electricians; machinists, engineering managers, electronics technicians, carpenters; welders; and others. However, it is also true that numerous jobs are also being created at all skill levels for occupations such as laborers, truck drivers, security guards, managers and administrators, secretaries, clerks, service workers, and so forth.

Accordingly, the importance for jobs in some occupations is much greater than in others.[274] Some occupations, such as those listed initially above, will benefit greatly from the employment requirements generated. This is hardly surprising, for most of these jobs are clearly related to the construction, energy, technology export, utilities, scientific, and industrial sectors. Nevertheless, while workers at all levels in all sectors will greatly benefit from the initiatives, as noted, disproportionately large numbers of jobs will be generated for various professional, technical, and skilled occupations. Importantly, most of these workers will not realize that they owe their jobs, at least indirectly, to the DOE coal RD&D program.

In any case, it is likely that large numbers of jobs will be created for occupations including:

- Architectural and civil drafters
- Business operations specialists
- Carpenters
- Civil engineers
- Computer systems analysts
- Construction supervisors and managers
- Cost estimators
- Electrical and electronics engineers
- Electricians
- Electro-mechanical technicians
- Financial analysts
- Health and safety engineers
- Industrial engineers
- Industrial machinery mechanics
- Installation, maintenance, and repair workers
- Laborers and material movers
- Machinery maintenance workers
- Machinists
- Network and computer systems administrators
- Painters, construction and maintenance
- Pipelayers
- Plumbers, pipefitters, and steamfitters

[274] Ibid.

- Power plant operators
- Sheet metal workers
- Stationary engineers and boiler operators
- Structural iron and steel workers
- Truck drivers
- Welders, cutters, solderers, and brazers

V. BENEFIT-COST ESTIMATES

V.A. Assessing the DOE Coal RD&D Program

Assessing the costs and the economic and jobs impacts and benefits of the DOE coal RD&D program is the key objective of this project, but it is complex and difficult. Theoretically, evaluating the benefits and costs of the DOE RD&D program should be relatively straightforward. It would require estimating the total benefits and costs of the research conducted 1976 – 2019, determining what proportion of each is attributable to each DOE coal program, and calculating the difference between the DOE expenditures and the monetized benefits achieved. However, in practice, there are numerous methodological challenges. Of these, the most fundamental is how to define and systematically capture the diverse benefits that result from publicly funded research – the DOE coal RD&D program -- within a dynamic environment of marketplace activity, technological progress, societal changes, and other factors.

Justification for public sector research, such as the DOE coal RD&D program, rests on the fact that public benefits exist that the private sector cannot capture. In such cases, the private costs of developing and marketing a technology may exceed the benefits that the private sector can capture. We thus have to utilize a comprehensive framework that identifies the range of benefits and costs, both quantitative and qualitative, that should be considered in evaluating the DOE coal RD&D programs. Depending on the outcomes of the RD&D, the principal benefit of a program, for example, may be the knowledge gained and not necessarily realized economic benefits.

There are at least two dimensions of the DOE coal RD&D:

- The DOE RD&D produces public benefits that the private economy cannot provide.
- Some benefits may be realized even when a technology does not enter the marketplace immediately or to a significant degree.

Further, there are "realized benefits and costs," which pertain to benefits that are almost certain, that is, those for which the technology is developed and for which the economic and policy conditions are favorable for commercialization of the technology. There are also less certain benefits, which can be termed "options benefits and costs." These consist of benefits that may be derived from coal technologies that are fully developed but for which economic and policy conditions are not likely to be, but might become, favorable for commercialization. Still other benefits, to the extent they exist, are termed "knowledge benefits."[275]

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[275] See National Research Council, *Energy Research at DOE: Was it Worth it?* Op. cit.; National Research Council, *Prospective Evaluation of Applied Energy Research and Development at DOE (Phase One): A First Look*, op. cit.

One of the most difficult analytical problems is assigning to DOE a proportion of the overall benefit of a coal RD&D program that properly reflects DOE's contribution to it.[276] In many cases, DOE, industry, and sometimes other federal and nonfederal governmental research organizations contributed to the outcome of the research program. For example, as noted, over the past five decades EPA and BOM have funded substantial coal-related RD&D programs. Nevertheless, as noted, following previously developed methodologies and studies, here we assessed the impacts and benefits to government and the private sector resulting from:

- Realized Savings Through 2000
- Reduced CAPEX
- Efficiency Savings
- Clean Coal Technology Exports
- SO_2
- NO_x
- CO_2
- Public Health
- NETL Operations
- Jobs

Previous research has determined that a portfolio approach must be used to assess DOE coal RD&D impacts and benefits.[277] That is, some DOE coal RD&D programs are among DOE's most successful RD&D programs and they have produced benefits that far exceed their federal costs. On the other hand, other RD&D programs produce impacts and benefits that are difficult to quantify. Thus, just as with a stock portfolio where certain stocks outperform others, much of the impacts and benefits of DOE's coal RD&D program may come from a relatively small number of select programs. In fact, NRC/NAS found that the DOE coal-related RD&D and technology program is one of those programs that produce very substantial benefits and contribute a disproportionately large portion of the total return on the ***entire*** DOE RD&D program.[278] This particular finding is very important in evaluating the overall DOE RD&D program, but it is not widely appreciated.

Finally, it must be recognized that coal power plants provide reliable, dispatchable, and affordable electricity, and this has important economic and jobs impacts. In particular, there is a negative relationship between energy price changes and economic activity. Review of the literature indicates that a reasonable long run value for this elasticity for electricity is about -0.10.[279] This indicates that a ten percent increase in

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[276]In some cases for certain DOE coal technologies, there may be no reliable way to precisely estimate the DOE contribution, and doing so is a methodological challenge.
[277]National Research Council, *Energy Research at DOE: Was it Worth it?* Op. cit.; National Research Council, *Prospective Evaluation of Applied Energy Research and Development at DOE (Phase One): A First Look*, op. cit.
[278]Ibid.
[279]Wide ranges of estimates for this value have been made over the past several decades in the U.S. and elsewhere, but a value of -0.10 is credible and defensible and has been used in rigorous studies of the impact of energy and electricity on the economy. See Management Information Services, Inc., *GDP Impacts of Energy Costs*, report prepared for the U.S. Department of Energy, National Energy Technology

electricity prices will result in a decrease in GDP or gross state product of one percent and a similar reduction in jobs. For example, studies have shown that the benefits of lower-priced electricity could total $500 billion to $1 trillion and could include the creation of nearly one million additional jobs.[280] The salient point is that coal power plants produce reliable, inexpensive electricity.[281]

V.B. Estimating Return on Investment of RD&D

As noted, justification for public sector research rests on the hypothesis that public benefits exist that the private sector cannot capture. In such cases, the private costs of developing and marketing a technology may exceed the benefits that the private sector can capture and government investment in RD&D is warranted. Such government RD&D investments have been analyzed and justified in numerous studies over the past five decades. For example, the World Economic Forum determined that in the 21st century the creation of new wealth depends not just on traditional inputs like natural resources, land, or labor. Rather, new wealth in an innovation-driven economy requires the discovery and development of new ideas to solve old problems; the seizing of new opportunities with technology and ingenuity – all of which require government RD&D.[282]

While numerous studies have found that government RD&D is a classic public good and that the benefit cost (B-C) ratio of this RD&D is high, there is little consensus on what this ratio is – even within a broad range. To put this in perspective, consider:

- Economists Charles Jones and John Williams of Stanford University, the National Bureau of Economic Research, and the Federal Reserve Bank of San Francisco found that the return on investment (ROI) for publicly funded RD&D is somewhere between 30 percent and 100 percent, or more.[283]
- Over the past decade EE&RE supported a series of studies evaluating the impacts of its RD&D programs, including photovoltaics, wind energy, vehicle combustion engines, advanced battery technologies for electric-drive vehicles, geothermal energy, HVAC (heating, ventilation and air conditioning), water heating, and appliance technologies.[284] The combined results of these six RD&D studies show

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Laboratory, DOE/NETL- DOE/NETL- 402/083109, October, 2009; and Management Information Services, Inc., "The Impacts of Electricity Costs on the Economy and Jobs: Summary of the MISI Methodology," August 2018.

[280]See National Energy Technology Laboratory, ''Clean Coal Technology Roadmap: CURC/EPRI/DOE Consensus Roadmap, Background Information,'' 2008; Roger Bezdek and Robert Wendling, Economic, Environmental, and Job Impacts of Increased Efficiency In Existing Coal-Fired Power Plants, op. cit.; Tim Considine, "Coal: America's Energy Future, Volume II, 'Appendix: Economic Benefits of Coal Conversion Investments,'' prepared for the National Coal Council, March 2006.

[281]New builds are costly and will generate electricity costs that could be orders of magnitude higher than those from existing coal plants.

[282]Sean Pool and Jennifer Erickson, "The High Return on Investment for Publicly Funded Research, Center for American Progress, December 2012.

[283]Charles I. Jones and John C. Williams, "Too Much of a Good Thing? The Economics of Investment in R&D," *Journal of Economic Growth*, Volume 5 (March 2000), pp. 65–85.

[284]Jeff Dowd, "Aggregate Economic Return on Investment in the U.S. DOE, U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, October 2017; Rosalie Ruegg, Alan C. O'Connor, and

that, for the EERE RD&D investments evaluated, the aggregate B-C ratio was 33-to-1, and ranged from 4-to-1 to 180-to-1. EE&RE contends that expenditures of $12 billion in its RD&D portfolio has yielded more than $388 billion in net economic benefits to the U.S.[285]

- NASA contends that the B-C ratio for its expenditures ranges from 8-to-1 to 23-to-1, and even much higher.[286]
- MISI analyzed DOE's Clean Coal Technology program and estimated a B-C ratio of 13-to-1.[287]
- A study of 15 leading economies estimated an overall B-C ratio for RD&D expenditures of about 20-to-1.[288]
- A study of manufacturing RD&D estimated a B-C ratio for RD&D expenditures of 32-to-1.[289]
- A study of the government's investment in advanced diesel combustion RD&D estimated a B-C ratio of an incredible 70-to-1.[290]
- Finally, research on Federal investment in genomics RD&D reported a B-C ratio of an astounding (unbelievable?) 178-to-1.[291]

This issue is discussed further in Section V.E.

Ross J. Loomis, "Evaluating Realized Impacts of DOE/EERE R&D Programs," TIA Consulting Inc. and RTI International, August 2014, https://energy.gov/sites/prod/files/2015/05/f22/evaluatingrealized_rd_mpacts 9-22-14.pdf; Michael Gallaher, Troy Scott, Zachary Oliver, Kyle Clark-Sutton, and Benjamin Anderson, "Benefit-Cost Evaluation of U.S. Department of Energy Investment in HVAC, Water Heating, and Appliance Technologies," RTI International, September 2017; Albert N. Link, Alan C. O'Connor, Troy J. Scott, Sara E. Casey, Ross J. Loomis, and J. Lynn Davis, "Benefit-Cost Evaluation of U.S. DOE Investment in Energy Storage Technologies for Hybrid and Electric Cars and Trucks," RTI International, December 2013; A. O'Connor, R. Loomis, and F. Braun, "Retrospective Benefit-Cost Evaluation of DOE Investments in Photovoltaic Energy Systems," RTI International, August 2010; M. Gallaher, A. Rogozhin, and J. Petrusa, "Retrospective Benefit-Cost Analysis of U.S. DOE's Geothermal Technologies R&D Program Investments," RTI International, August 2010; Tom Pelsoci, "Retrospective Benefit-Cost Evaluation of U.S. DOE Wind Energy R&D Program: Impact of Selected Energy Technology Investments," Delta Research Co., June 2010; Al Link, "Retrospective Benefit-Cost Evaluation of U.S. DOE Vehicle Combustion Engine R&D Program: Impacts of a Cluster of Energy Technologies," prepared for the U.S. Department of Energy, May 2010.

[285]Ibid.

[286]Kimberly Amadeo, "NASA Budget, Current Funding, History, and Economic Impact, *The Balance*, February 27, 2020; Michael K. Evans, "The Economic Impact of NASA R&D Spending," prepared For the National Aeronautics and Space Administration, Chase Econometric Associates, April 1976. When MISI was working for NASA, the Agency contended that the B-C ratio for its R&D programs was 90-to-1.

[287]Management Information Services, Inc., Roger Bezdek and Robert Wendling, "The Return on Investment of the Clean Coal Technology Program in the USA," op. cit.

[288]Chris Coons, "R&D is Essential For Boosting the American Economy," *The Hill*, July 11, 2017.

[289]Stephen J. Ezell and Robert D. Atkinson, "The Case for a National Manufacturing Strategy," The Information Technology & Innovation Foundation, April 2011.

[290]Jeffrey Rissman and Hallie Kennan, "Case Studies on the Government's Role in Energy Technology Innovation: Advanced Diesel Internal Combustion Engines," American Energy Innovation Council, March 2013.

[291]"The Impact of Genomics on the U.S. Economy," Battelle Technology Partnership, prepared for United for Medical Research, June 2013.

V.C. Micro Impacts of Coal RD&D

V.C.1. NETL Facilitated Technologies

Important benefits have been realized by numerous companies in the private sector due to assistance from NETL and the NETL RD&D program.[292] Several examples are given below of the NETL impact on specific companies. All of these are in the manufacturing sector, and manufacturing is of critical importance to the U.S. economy and jobs.[293] The manufacturing sector is essential for a competitive and innovative economy, since:

- Manufacturing has a higher job multiplier than other sectors.[294]
- There is a close linkage between innovation and manufacturing, and manufacturing generates high skilled, high-wage jobs.[295]
- It creates spillover benefits to local regions.[296]
- Manufacturing firms provide 70% of U.S. innovations and more than 90% of private sector patents.[297]
- For the past two decades manufacturing productivity has increased at twice the U.S. average.[298]
- Manufacturing dominates exports, accounting for 60% of U.S. exports' value.[299]

[292]Also see the discussion in Management Information Services, Inc., "Examples of Economic and Jobs Impacts of the 2017 NETL ALP," op. cit.

[293]For a recent analysis, see Louis Uchitelle, *Making It: Why Manufacturing Still Matters*, New York: The New Press, 2017.

[294]The manufacturing job multiplier is greater than 4, and some manufacturing sectors have multipliers closer to 7. See Keith D. Nosbusch and John A. Bernaden, "The Multiplier Effect: There Are More Manufacturing Related Jobs Than You Think," *Manufacturing Executive*, March 2012; and Timothy J. Considine, "Economic Impacts of the American Steel Industry," University of Wyoming, 2011. Touring a new factory in Batesville, Mississippi, where GE is building jet engines for the Boeing 787 Dreamliner, GE CEO Jeffrey Immelt (who was chair of the President's Council on Jobs and Competitiveness) acknowledged Lesly Stahl's observation that the highly automated plant requires fewer direct employees than factories of old. But then he stated "You're going to have fewer people that do any task. In the end, it makes the system more productive and more competitive. But when you walk through Mississippi, for every person that was in that plant, there are probably seven or eight jobs in the supply chain." CBS News *60 Minutes*, "The Jobs Czar: General Electric's Jeffrey Immelt," interview with Lesley Stahl, aired October 9, 2011.

[295]The average U.S. manufacturing worker earns $78,000/yr. (pay and benefits) compared to the $57,000/yr. for the average U.S. worker.

[296]"Making in America: U.S. Manufacturing Entrepreneurship and Innovation," The Executive Office of the President, June 2014.

[297]See David Autor, David Dorn, and Gordon H. Hanson, Foreign Competition and Domestic Innovation: Evidence from U.S. Patents, National Bureau of Economic Research, November 2016; Susan Helper, Timothy Krueger, and Howard Wial, "Why Does Manufacturing Matter? Which Manufacturing Matters? A Policy Framework," Brookings Institution, February 2012.

[298]National Association of Manufacturers, "Top 20 Facts About Manufacturing," 2017, http://www.nam.org/Newsroom/Top-20-Facts-About-Manufacturing/. "The correlation between exports, manufacturing and good-paying jobs is clear." U.S. Under Secretary of Commerce, January 2012.

[299]See McKinsey Global Institute, "Manufacturing the Future: The Next Era of Global Growth and Innovation," November 2012. U.S. manufacturing exports rank third in the world, after EU and China and are 30% larger than Japan's.

- Manufacturing creates intersections of innovation and production and involves a virtuous cycle: The "industrial commons," -- ecosystems of innovative know-how, process engineering, and workforce skills required for innovation in manufacturing industries.
- Manufacturing generates high skilled, high-wage jobs: The average U.S. manufacturing worker earns $80,000/yr. (pay plus benefits) compared to $57,000/yr. for the average U.S. worker.
- "If an auto plant opens up, a Wal-Mart can be expected to follow. But the converse does not hold: A Wal-Mart opening definitely does not bring an auto plant with it."[300]

V.C.2. Carpenter Technology Corporation

NETL helped develop stent material that resulted in the creation of manufacturing jobs at Carpenter Technologies in Reading, Pennsylvania. Carpenter Technology Corporation develops, manufactures, and distributes cast/wrought and powder metal stainless steels and special alloys including high temperature (iron-nickel-cobalt base), stainless, superior corrosion resistant, controlled expansion alloys, ultra-high strength and implantable alloys, tool and die steels, and other specialty metals, as well as cast/wrought titanium alloys.[301] It also manufactures and rents down-hole drilling tools and components used in the oil and gas industry. It currently has annual revenues of $1.8 billion and a total of 4,500 employees worldwide – of which about 2,300 are in Reading.

V.C.3. LumiShield Technologies

Corrosion-related issues cost the U.S. economy $276 billion a year. NETL teamed with Carnegie Mellon University (CMU) to create a revolutionary, cost-effective technology to reduce that impact -- work that resulted in the creation of a new CMU/NETL spin-off that signed a licensing agreement with NETL.[302] The new process, which electrodeposits aluminum using standard equipment available in most electroplating shops, is set to make its mark on the industry by replacing coatings based on heavy metals, such as cadmium and chromium, which are expensive and toxic. Electroplating is the process of depositing a metal coating onto an object by putting a negative charge on it and immersing it in a solution. Called the "Ionic Liquid Solvent for Aluminum Electroplating Process," the innovation has been licensed by LumiShield Technologies, a Pittsburgh-based CMU/NETL spin-off that was created based on the new technology.

[300]Gene Sperling, Director of the White House National Economic Council, March 2012.
[301]*Carpenter Technology Corporation 2016 Form 10-K Annual Report*, 2017.
[302]"NETL Technology For Safer, Cleaner Corrosion Protecting Metal Coatings Licensed by Pittsburgh Start-Up;" https://netl.doe.gov/sites/default/files/netl-file/BDO15-013_LumiShield%20Success%20Story.pdf; https://www.energy.gov/fe/articles/netl-technology-safer-cleaner-corrosion-protecting-metal-coatings-licensed-pittsburgh.

LumiShield specializes in corrosion-resistant metal products that are less expensive and less environmentally harmful than existing approaches.

V.C.4. KW Associates

NETL issued two licenses involving its Arc Position Sensing (APS) technology to KW Associates, LLC in 2016, an Oregon-based company founded by the technology's inventors.[303] One license issued is exclusively for application to three fields of use: Steel, specialty steel and alloy processing, and industrial microwave processing. The second, non-exclusive license is for application to solid state energy systems and other high-temperature industrial processes. With these two licenses, KW Associates is building, testing, and selling APS systems.

APS technology is a patented, award-winning measurement technology developed for the specialty metals industry to identify arc distribution conditions during arc melting. The unique technology allows operators to optimize the processing to improve material yield, decrease energy use, and improve safety systems. Specialty metals, such as titanium or zirconium, that are used in aerospace, airline, and other advanced applications often undergo a metallurgical casting process called vacuum arc remelting (VAR) to refine an alloy's chemical and physical homogeneity. During the process, electrical power heats a consumable electrode by means of an electric arc -- a luminous electrical discharge like a lightning strike -- and the melting material drops into a water-cooled copper crucible. Poor processing can lead to defects in the resulting ingot; the defects, in turn, can cause failure in engineering applications, so manufacturers must perform extensive testing on all ingots.

NETL's APS technology is a first-of-its-kind technology that can digitally monitor arc locations during VAR. Knowing where the arcs are helps the engineer control them and the melting process to produce consistently defect-free materials. Ultimately, the technology is expected to increase a manufacturer's yield and decrease the energy required to manufacture high-quality alloys.

V.C.5. Harbison Walker

NETL issued a license to Harbison Walker, International (HWI). HWI is one of the world's leading refractories materials and services providers, and is leader in the manufacture and supply of innovative refractories products for a wide range of industry applications presenting, among other things, challenging heat-intensive or chemically corrosive production environments.[304] Headquartered in Pittsburgh, Pennsylvania, HWI has a network of 18 manufacturing facilities and 28 distribution centers to serve markets

[303]"NETL Issues Licenses For its Arc Position Sensing Technology," https://netl.doe.gov/sites/default/files/netl-file/BDO15-012_KW%20Success%20Story.pdf.
[304]"ANH Refractories Becomes Harbison Walker International," Ceramic Industry Magazine, January 19, 2015.

across North America, manufacturing facilities in the UK, Indonesia, and Mexico, as well as a lab and testing facility in China. Industries served include cement and lime, energy, chemicals, non-ferrous metals, glass, iron and steel, aluminum, copper, hydrocarbon and minerals processing, and environmental technology.

V.C.6. Liquid Ion Solutions

NETL executed licenses with Liquid Ion Solutions LLC, a Pittsburgh-based chemicals start-up, in 2016.[305] CCS from fossil fuel-based power generation systems are critical strategic components to curb emissions of atmospheric carbon dioxide (CO_2). Currently available carbon capture processes are limited, and they significantly reduce the efficiency of power generation and increase electricity costs. Working in collaboration with partners at Carnegie Mellon University, NETL researchers developed a number of novel ionic liquids and polymers that provide a more efficient and economical process for CO_2 capture. The suite of technologies, covering the syntheses and use of ionic liquids, has been exclusively licensed to Liquid Ion Solutions.

In addition to CO_2 capture, ionic liquids have potential applications in areas including separation of chemical species from mixtures, batteries and fuel cells, solvents, coatings, lubricants, and biological systems. The company has initiated small-scale manufacturing of the materials for sale into a variety of research markets. The company is also focusing on collaborative research to further expand product applications in emerging industrial markets.

V.C.7. Boston Scientific

A coronary stent is a small, self-expanding metal mesh tube that saves thousands of lives every year by opening blocked arteries and allowing blood to flow freely again. NETL and Boston Scientific Corporation jointly developed the first austenitic stainless steel formulation produced for the coronary stent industry with high visibility with x-ray scanning.[306] This novel alloy is the first austenitic stainless steel formulation to be produced for the coronary stent industry, with a significant concentration of an element, platinum, with high radiopacity—high visibility with x-ray scanning. Better visibility means greater ease and precision in placement of the stent inside the patient's blood vessel. In addition, the greater yield strength of the alloy allowed the stent's designers at BSCI to make a thinner, more flexible stent that is more easily threaded through the winding path of the artery without doing damage along the way which has allowed to be deployed much smaller vessels in and around the heart. Since introduction in 2010, the platinum/chromium coronary stent series, which includes the PROMUS® Element™,

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[305]NETL "Licenses Transformational Technology For Carbon Dioxide Capture," https://netl.doe.gov/sites/default/files/netl-file/BDO16001_Liquid%20Ion%20 Solutions%20Success% 20 Story.pdf.
[306]"Novel Platinum/Chromium Alloy for the Manufacture of Improved Coronary Stents," https://netl.doe.gov/sites/default/files/2019-03/BDO12-004_Coronary%20Stent.pdf.

ION™, and OMEGA™ Stent Systems, has become the leading stent platform in the world.

V.C.8. Pyrochem Catalyst Corporation

Converting heavy hydrocarbons, such as diesel and coal-based fuels, into hydrogen-rich synthesis gas is a necessary step for fuel cells and other applications. The high sulfur and aromatic content of these fuels poses a major technical challenge since these components can deactivate reforming catalysts. NETL researchers invented a novel fuel-reforming catalyst that overcomes the limitations of current catalysts by efficiently reforming diesel fuel. The catalyst was licensed to startup company Pyrochem Catalyst Company. This agreement marks the first time that an NETL-licensed technology has been used as a basis for the creation of a start-up company.[307]

V.D. Regional Impacts

The DOE coal RD&D program has significant economic and job impacts on specific cities and regions throughout the U.S. For example, as discussed in Section II.G, NETL estimated its direct impact on Pennsylvania and West Virginia's economy during 2006, including employment, wages, and salaries of Pennsylvania and West Virginia residents employed at NETL's sites in Morgantown, West Virginia and Pittsburgh, Pennsylvania. It also included NETL's direct operational expenditures and RD&D award and grant monies spent within the region. The analysis determined that NETL directly supported the employment of 1,166 Pennsylvanians and West Virginians in 2006 and injected $192 million into the state economy.

Because the Pennsylvania and West Virginia economies supply a portion of NETL's total employment and operational demand, NETL activities produce extended (indirect) impacts on the region's economy. NETL estimated that the economic output multiplier for the Pennsylvania-West Virginia region is 1.47. Therefore, for every $1 million of NETL final demand that remains within the states of Pennsylvania and West Virginia, the regional economy grows by $1.47 million. The employment multiplier of 2.73 indicates that for every one employee at NETL, an additional 1.73 employees are needed throughout the region to fulfill the regional demands of NETL's supply-chain. This yields a total employment impact of 3,180 jobs. On an employment-per-dollar basis, the analysis showed that employment increases by approximately 20 persons for each $1 million that remains in the region.[308]

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[307]"Pyrochem Catalysts for Diesel Fuel Reforming," https://netl.doe.gov/sites/default/files/netl-file/BDO13-008_Pyrochem%20R%26D%20Success%20Story.pdf.

[308]NETL's analysis excluded induced income impacts -- those resulting from households spending their salaries in the regional economy and also excluded impacts stemming from the deployment of NETL-sponsored technologies. Therefore, NETL's impact on the Pennsylvania-West Virginia region, as estimated in this study, is a conservative estimate.

As another example, Section V.C.2 summarized how NETL helped develop stent material that resulted in the creation of manufacturing jobs at Carpenter Technologies in Reading, Pennsylvania. Carpenter Technology Corporation develops, manufactures, and distributes cast/wrought and powder metal stainless steels and special alloys including high temperature (iron-nickel-cobalt base), stainless, superior corrosion resistant, controlled expansion alloys, ultra-high strength and implantable alloys, tool and die steels, and other specialty metals, as well as cast/wrought titanium alloys. It also manufactures and rents down-hole drilling tools and components used in the oil and gas industry. It currently has annual revenues of $1.8 billion and a total of 4,500 employees worldwide – of which about 2,300 are in Reading.

MISI estimated the jobs impacts on the Reading area.[309] It was assumed that NETL's assistance facilitated about 5% of the Carpenter Technology jobs in Reading – about 115 jobs. Each job in steel manufacturing has a total U.S. national job multiplier of at least 7 and a regional job multiplier of about 5.[310] Thus, MISI estimated that this NETL success helped create a total of about 575 jobs (direct and indirect) in the Reading area.

In 2017, Reading had an unemployment rate of 5% and had 10,200 unemployed workers. Thus, absent these NETL facilitated jobs, the unemployment rate in Reading would have been 5.3% instated of 5.0% -- which is a substantial increase. The net fiscal impact of the 575 jobs that would have been lost (or not created) includes tax revenue losses, unemployment compensation, SNAP, welfare payments, etc. and increases in various social problems.[311]

As a third example, researchers for the Appalachian Regional Commission estimated the economic and jobs impacts of electric power plants on regional economies using regression analysis with data from all counties in the Appalachian states that contained any electric power generation capacity during any year between 2005 and 2015.[312] They estimated wage and salary income in a county as a function of the coal-fired electric power generation capacity and the natural gas-fired electric power generation capacity in the county.

They used data on 57 coal-fired unit retirements in the Appalachian Region in a stochastic dynamic programming model to identify three primary and three secondary risk factors that shorten the economic lifetime of a coal-fired generating unit. Primary risk factors are those where a 5% change results in a greater than 5% decrease in the economic lifetime of the unit. Secondary risk factors are those where a 5% change results

[309]Management Information Services, Inc., "Examples of Economic and Jobs Impacts of the 2017 NETL ALP," op. cit.
[310]See the discussion in Section V.C and Timothy Considine, op. cit.
[311]Management Information Services, Inc., "Examples of Economic and Jobs Impacts of the 2017 NETL ALP," op. cit.
[312]Eric Bowen, Christiadi, Rebecca J. Davis, John Deskins, and Charles Sims, "The Economic Impacts and Risks Associated With Electric Power Generation in Appalachia," West Virginia University, prepared for the Appalachian Regional Commission, January 2018.

in a 1% to 5% decrease in the economic lifetime of the unit. They also identified factors that have very little influence on the economic lifetime of a coal-fired unit.[313] As a result:

- They were able to statistically identify a positive effect of coal-fired electric power generation capacity on wage and salary income in a county.
- They estimated that the effect of coal-fired electric power generation capacity on wage and salary income is relatively large for small population counties, but that the effect diminishes for sufficiently large population counties.
- Their estimates of the magnitude of the effect of a coal-fired power plant shutdown ranged dramatically. At one extreme, they estimated that the shutdown of a large coal-fired power plant in a small county can lead to a loss of around two-thirds of the county's wage and salary income. In contrast, for a mid-size plant shutdown in a mid-size county, they estimated that the plant shutdown reduces wage and salary income by around 5%.
- They could not statistically identify an effect of natural-gas fired electric power generation capacity on county-level wage and salary income.

Finally, it should be noted that the impacts on a specific region of a coal power plant closure can be devastating and difficult to recover from. For example, Public Service Company of New Mexico (PNM) has proposed to close the San Juan Generating Station (SJGS), and, effectively, the San Juan Mine (SJM) in 2022. SJGS is a four unit coal-fired generator with a net capacity of 847 MW located west of Farmington, New Mexico that entered commercial operation in 1973. Efforts to keep SJGS open failed, and the final decision to close it was made in April 2020 at a contentious New Mexico Public Regulation Commission meeting.[314]

Local government officials and representatives of the Navajo Nation fought aggressively for four years to keep SJGS and SJM in operation.[315] They fear the devastating impact that the shutdown of the plant and the mine will have on the local economy, jobs, and economic development. They estimate that:[316]

- Job losses could total nearly 1,600.
- Local area earnings would be reduced by $120 million annually.
- Over $50 million in tax revenues would be lost annually.
- Hundreds of local families and businesses would be adversely affected.

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[313]Primary risk factors include a high fixed cost of generation, low cost of retiring the unit, and a low discount rate used by utilities in decision-making. These primary risk factors are influenced by a variety of drivers including construction costs, land values, macroeconomic factors, and whether the unit is in a regulated market. Secondary risk factors include low fuel efficiency, low generation responsiveness, and low/stable generation revenues. These secondary risk factors are influenced by a variety of drivers including age, capacity factor, ramp rate, and electricity markets.

[314]Liz Weber, "Utility Company's Bid to End Operations at San Juan Generating Station Approved," *Durango Herald*, April 3, 2020.

[315]Hannah Grover, "How San Juan Generating Station Went From Powerhouse to Possible Closure," *Farmington Daily Times*, October 6, 2018.

[316]See Kelly O'Donnell, "Tax and Jobs Analysis of San Juan Generating Station Closure," O'Donnell Economics and Strategy, January 2019; Susan Montoya Bryan "Closing Generating Station Could Have Huge Economic Impacts," *Durango Herald*, September 30, 2018; Sally Burbridge, "San Juan Generating Station Closure Impacts," Four Corners Economic Development, March 2018.

- The property tax base of Central Consolidated Schools, San Juan College, and San Juan County will be enormously diminished.
- The Central Consolidated School District – where over 90% of the students are Native American and nearly 75% of the students are disadvantaged -- would lose 50% of its property tax revenues.

These fears are well founded. San Juan County suffers from a poverty rate above 20%, it is experiencing declining population and economic prospects, and its population is 60% minority.[317] The Navajo Nation is especially at risk, since it has many of the characteristics of a third world nation. For example:[318]

- Over the last 20 years, unemployment in the Navajo Nation has been nearly 50% – compared to, currently, 4.9% in New Mexico and 4% in the U.S.
- Navajo Nation median household income is $20,000 – compared to $47,000 for New Mexico and $60,000 for the U.S.
- 43% of those living in the Navajo Nation earn below the federal poverty level.
- 54% of children in the Navajo Nation live in poverty.
- In the Navajo nation, 38% percent of residences lack electrical service and running water, and 86% are without natural gas service.[319]

It is especially troubling because jobs at the SJGS and the SJM are among the highest paying and most sought after in the region. Their employees have employer sponsored healthcare and earn an average of $86,000.[320] These earnings are more than twice the local average and are even twice the average San Juan County *family* income.

V.E. Costs, Impacts, and Benefits

Table V-1 and Figure V-1 summarize the impacts, benefits, and costs of the DOE coal RD&D program through 2019 estimated here. They show that the impacts total about $237 billion (2019 dollars) – about $239 billion including a monetized value for CO_2 emissions, and annual creation of nearly 79,000 jobs. Note that the total jobs created over the period 2008 - 2019 averaged about 78,600/yr. from 2008 to 2019. If we assume that this annual job creation was also about the average for the years 2000 – 2007, then the cumulative jobs created over the period 2000 – 2019 totaled about 1,572,000.

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[317]"San Juan County Profile," https://datausa.io/profile/geo/san-juan-county-nm/.
[318]U.S. Census Bureau, "San Juan County Quick Facts," https://www.census.gov/quickfacts/sanjuancounty newmexico; Alysa Landry, "Loss of Jobs Inevitable With Closing of San Juan Generating Station," *Navajo Times*, March 23, 2017.
[319]https://navajobusiness.com/fastFacts/demographics.htm.
[320]Sally Burbridge, op. cit.

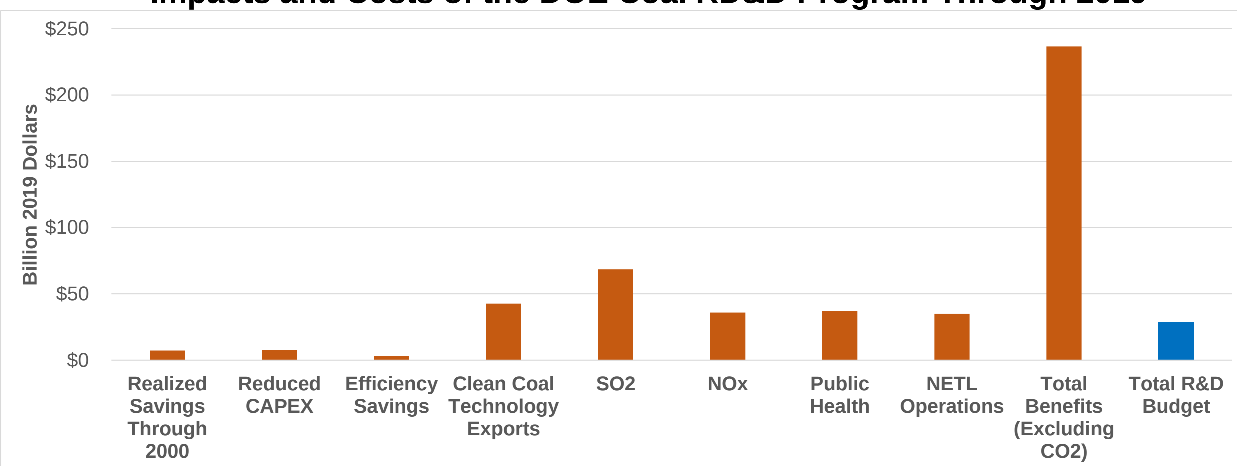
Table V-1
Impacts of the DOE Coal RD&D Program Through 2019

Category	Impacts (billions of 2019 dollars)
Realized Savings Through 2000	$7.3
Reduced CAPEX	$7.6
Efficiency Savings	$2.9
Clean Coal Technology Exports	$42.6
SO_2	$68.5
NO_x	$35.9
CO_2	42.1Mt[321]
Public Health	$36.9
NETL Operations	$35.0
Jobs	78,600 jobs/yr.*
Total	$236.7
Total, including CO_2	$239.1

*Annual average for the period 2008 – 2019.

Source: Management Information Services, Inc.

Figure V-1
Impacts and Costs of the DOE Coal RD&D Program Through 2019



Source: Management Information Services, Inc.

Thus, the impacts and benefits of the DOE coal RD&D program through 2019 clearly and substantially exceed the costs -- $28.6 billion (2019 dollars). This implies a rough benefit-cost (B-C) ratio of greater than 8 to 1. It should be noted that here we used estimated benefits through 2019, which totaled $236.7 billion, and the estimated DOE coal RD&D expenditures through 2019, which totaled $28.6 billion Including the FY 2020

[321]Using the 2013 IWG SCC value of $52.00/ton of CO_2 (2019 dollars), we estimate that the implied CO_2 emissions savings, 2008 – 2019, total approximately $2.4 billion (2019 dollars).

DOE coal RD&D of $484 million (2019 dollars) would increase the total expenditures from $28.6 billion to $29.1 billion, but would not appreciably change the B-C ratio.[322]

A B-C ratio above one is desirable and a ratio of more than 8-to-1 is extremely attractive. The questions naturally arise:

- How real are these numbers?
- How robust are the estimates?

The B-C ratio is determined by the denominator (costs) and the numerator (benefits). The denominator, $28.6 billion, is probably accurate to within about 2%: MISI derived the budget estimates from the official DOE annual budget documents and the deflator series is the official BEA IPD series.

The numerator, $236.7 billion, is inherently subject to much more uncertainty and controversy because of the assumptions made and the methodology employed. Nevertheless, several hypotheses can be explored which demonstrate that benefits of the DOE coal RD&D program through 2020 almost certainly far exceed the costs.

First, assume that MISI has overestimated total benefits by a factor of two, and that they total about $188 billion. This still yields a rough B-C estimate of about 4.1, which remains well above one and, indeed, remains impressive. If fact, for the B-C ratio to be less than one implies that MISI has overestimated benefits by a factor of more than eight. This is highly unlikely. For example, the $7.3 billion impact is an independent estimate from the NRC/NAS, and the $35 billion impact is an independent estimate from NETL. These two impact estimates, even ignoring all of the other benefit estimates, still imply benefits of $42.3 billion and a B-C ratio of 1.5. Further, MISI derived some of the other impact and benefit estimates in Table V-1 from various independent studies.

Of course, the uncertainty concerning the numerator works in both directions. What if MISI has underestimated benefits by, say, 25%? This implies that total benefits could be as high as $322 billion, which implies a B-C ratio of more than 10-to-1.

Second, how reasonable does the B-C ratio appear when compared to B-C ratios for other energy and RD&D programs? In section V.B, we noted that analyses of other RD&D programs found B-C ratios ranging from 4-to-1 up to an incredible 180-to-1. On this basis, the DOE coal RD&D program B-C ratio of 8-to1 actually looks conservative.

Third, another way of assessing this is to recall that in Section V.B we noted that a study of 15 leading economies estimated an overall B-C ratio for RD&D expenditures of about 20-to-1. Thus, on this basis also, the DOE coal RD&D program B-C ratio of 8-to 1 looks conservative.

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[322]Specifically, it would change the estimated B-C ratio from 8.28 to 8.13. Including the monetized value of estimated CO_2 savings ($2.4 billion) would also not appreciably change the B-C ratio.

Fourth, with respect to energy RD&D programs, EE&RE estimates that the weighted average B-C ratio for all of its programs analyzed totaled 33-to-1 and ranged has high as an eye watering 180-to-1. As also noted in Section V.B, NIH has estimated a B-C ratio for one of its programs as an incredible 178-to-1. Once again, based on these comparisons, the DOE coal RD&D program B-C ratio of 8-to1 appears reasonable and conservative.

It is also important to note that EE&RE did not conduct a comprehensive “portfolio approach” in its analyses – as MISI conducted here. Rather, it essentially cherry picked certain programs over specific time periods. EE&RE also failed to account for the other substantial federal, state, and local government tax incentives, mandates, and grant programs that have been in place for EE&RE programs for decades. Rather, EE&RE essentially attributed all of the growth in the EE&RE technology markets to the EE&RE RD&D program. However, to cite just one example, as Warren Buffet famously stated “On wind energy, we get a tax credit if we build a lot of wind farms. That's the only reason to build them. They don't make sense without the tax credit."[323] Accordingly, without the tax credits little or no wind energy would have been installed irrespective of the EE&RE RD&D program – and the B-C ratio for the wind program would be much less than one instead of the purported 5.3-to-1.[324]

MISI estimates that the RE RD&D budget alone through 2020 – excluding EE – totaled about $45 billion (2019 dollars). Further, this budget included substantial expenditures on programs and technologies that have yet to achieve commercial success, such as Ocean Thermal Energy Conversion, Wave Power, Solar Space Satellite, Hydrokinetics, Fuel Cells, Hydrogen, International Programs, etc. Merely including expenditures for all RE programs would have substantially reduced the EE&RE B-C ratios. Further, factoring in the impacts of even only the Federal RE incentives, which MISI estimates totaled about $150 billion (2019 dollars) through 2019, and ignoring the effects of state and local government mandates and incentives would further substantially reduce the EE&RE B-C ratios.

These points can be illustrated with respect to the DOE coal RD&D program budgets. As shown in Chapter III, large portions of the coal RD&D program budgets were comprised of expenditures on technologies that were not successful in the marketplace. Subtracting expenditures on just three of these – Coal Liquefaction, $4.9 billion, Coal Gasification, $3.7 billion, and Magnetohydrodynamics, $2.0 billion – which combined comprised more than 35% of the total DOE coal RD&D budget through 2020, leaves a DOE coal RD&D budget of $18.0 billion.

If we used the $18.0 billion as the denominator in the Coal RD&D B-C ratio we would have a B-C ratio for the DOE coal RD&D program of over 13-to-1. This is even more impressive than 8-to-1. However, it is still reasonable and conservative compared to the EE&RE B-C ratio of 33-to-1 -- not to mention the EE&RE B-C ratio of a purported 180-to-1.

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[323]Nancy Pfotenhauer, “Big Wind's Bogus Subsidies,” *U.S. News and World Report*, May 12, 2014.
[324]Pelsoci, op. cit.

Of course, such cherry picking with respect to either the coal or the EE&RE budgets – or any other RD&D budgets -- is not warranted. Decades ago, no one knew which RD&D programs would be successful and which would not. This is a basic fact of any RD&D enterprise and will be as true in the future as it has been in the past.

V.F. Other RD&D Evaluation Criteria

V.F.1. Patents, Papers, and Conferences

There are other ways of assessing the impacts of RD&D programs. For example, we can count the patents that have resulted, the papers that have been published, the conference presentations that have been made, and so forth. MISI has not attempted to analyze these types of impacts because they are inherently subjective and impossible to quantify. In addition, there are numerous problems with these measures. Many patents are essentially defensive in nature. Further, counting papers published or conference presentations made can be misleading:

- Given the proliferation of journals in recent decades, anyone capable of writing a coherent sentence can get something published somewhere.
- Similarly, professional conferences have proliferated greatly and actively seek almost anyone willing to participate and willing to pay the registration fee.
- Published papers and conference presentations are often by academics for academics, and frequently have little relevance in the real world

It should also be noted that publishing in journals and presenting at conferences is expensive, and only the wealthy or those with generous government grants can afford to engage. Professional journals have become a lucrative business, and publishing in them requires fees that range from expensive to prohibitive.[325] Similarly, conferences have also become lucrative businesses and require large registration fees, and travel and per diem expenses can be daunting. Having these fees and expenses paid by the RD&D program in question raises obvious issues of concern relating to conflict of interest.

The bottom line here is that relying on papers published or conference presentations made as criteria for an RD&D program's success can be inaccurate and misleading.

V.F.2. Security Benefits

Security benefits are based on changes in the probability or severity of abnormal energy-related events that would adversely impact the overall economy, public health and safety, or the environment.[326] Historically, these benefits arose in terms of national security issues, i.e., they were benefits that assured energy resources required for a

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[325]For example, *The Energy Journal* charges $3,000, *Energy Policy* charges $3,500, *Applied Energy* charges $3,600, and *Energy Technology* charges $3,900.
[326]National Research Council, *Energy Research at DOE: Was It Worth It?* Op. cit.

military operation or a war effort. Subsequently, they focused on dependence upon imported oil and the vulnerability to interdiction of supply or cartel pricing as a political weapon, and the economic disruptions of rapid international price fluctuations from any cause have also been emphasized.[327] This helps to explain why Coal Liquefaction was the largest DOE coal RD&D program over the period 1976 – 2020, accounting for 17% of total RD&D expenditures – the program was funded FY 1976 – FY 1997.

In particular, since the energy crises of the 1970s assessing the national security implications of oil imports has become a veritable cottage industry.[328] Often the national security costs of oil imports have been estimated as a fraction of the Department of Defense (DOD) budget. The reasoning has been that a large portion of the DOD budget is necessary simply to ensure the availability of U.S. oil imports from the Middle East. For example, it has been recently estimated that a minimum of approximately $81 billion annually is spent by the U.S. military protecting global oil supplies.[329] Further, former Secretary of the Navy John F. Lehman has recently stated "More than half the Defense budget is for the security of Persian Gulf oil." Half of the FY 2020 DOD budget of $712 billion is $356 billion.[330] Based on this reasoning, national security costs, and thus potential benefits, range somewhere between $81 billion and $356 billion per year. Attributing even a small fraction of this to the DOE coal RD&D program would increase the estimated impacts of the program several-fold and greatly increase the B-C ratio.

MISI did not attempt to quantify national security benefits. Quantifying such benefits involves obvious nearly insurmountable methodological and empirical problems, and benefits based on changing the probability of international energy disruptions are extremely difficult to estimate.[331] More important perhaps, the basic premise itself is open to scrutiny. For example, in 2019 the U.S. became an energy exporting nation for the first time in a half-century. At the same time, the DOD budget increased from $670 billion in FY 2018 to $712 billion in FY 2020.

V.F.3. Knowledge Benefits

The category "knowledge benefits" is a very broad one. Knowledge benefits are defined as scientific knowledge and useful technological concepts resulting from the RD&D that have not yet been incorporated into commercialized results of the program

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[327]The prevention or mitigation of macroeconomic losses resulting from energy disruptions can also be considered as a type of security benefit.
[328]See, for example, Jonathan Chanis and Paul Ruiz, "The Military Cost of Defending the Global Oil Supply," Securing America's Future Energy, September 2018; Eugene Gholz, "U.S. Spending on its Military Commitments to the Persian Gulf," in Charles L. Glaser and Rosemary A. Kelanic, *Crude Strategy: Rethinking the US Military Commitment to Defend Persian Gulf Oil*, Georgetown University Press, 2016; Michael, O'Hanlon, "How Much Does the U.S. Spend Protecting Persian Gulf Oil?" In Carlos Pascual and Jonathan Elkind, eds., *Energy Security: Economics, Politics, Strategies, and Implications*, Brookings Institution Press, 2010; Paul N. Leiby, Estimating the Energy Security Benefits of Reduced U.S. Oil Imports," Oak Ridge National Laboratory, ORNL/TM-2007/028, March 14, 2008.
[329]Chanis and Paul Ruiz, op. cit.
[330]Ibid.
[331]However, this did not prevent EE&RE from claiming such benefits for some of its programs.

but hold promise for future use or are useful in unintended applications. Knowledge benefits may include unanticipated, serendipitous, and not closely related technological spin-offs that are made possible by the research programs. Depending on the outcomes of the RD&D undertaken, the principal benefit of a program, for example, may be the knowledge gained and not necessarily realized economic benefits. It includes knowledge generated by programs still in progress, programs terminated as failures, and programs that were technological successes but will not be adopted because economic and policy conditions will never be favorable.

NRC/NAS found that the DOE coal RD&D program has yielded significant benefits in terms of important technological options for potential application and important additions to the stock of engineering and scientific knowledge in a number of fields. A balanced RD&D portfolio is particularly important since individual RD&D projects may well fail to achieve their goals. Rather than viewing the failure of individual RD&D projects as symptoms of overall program failure, NRC/NAS recommended that DOE and Congressional policy makers should recognize that project failures generate considerable knowledge and that a well-designed RD&D program will inevitably include such failures. Thus, "An RD&D program with no failures in individual research projects is pursuing an overly conservative portfolio."[332] However, even if a technology is never successfully developed, the knowledge gained in the program could lead to another beneficial technology.

NRC/NAS found that the DOE program had many significant technological spin-offs. Examples are given below.[333]

The RD&D conducted by DOE in both the Atmospheric Fluidized Bed Combustion (AFBC) and Pressurized Fluidized Bed Combustion (PFBC) programs added significantly to the knowledge base. Knowledge benefits included important new information on the following:

- Basic coal science;
- In situ sulfur recovery;
- Waste fuel preparation, feeding, and combustion;
- Mine acid water neutralization (utilizing FBC wastes for neutralizing coal mine acid water runoff);
- Utilization of FBC wastes for roadbed materials, cement aggregates, and other uses;
- Hot gas cleanup technology and materials that can be used for many industrial applications in addition to PFBC.

Knowledge benefits from the DOE FGD RD&D program included research conducted in chemistry, thermodynamics, reaction kinetics, sorbent structural properties, and process control instrumentation. Knowledge benefits from the DOE Waste Management/Utilization Technologies program included:

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[332] National Research Council, *Energy Research at DOE: Was It Worth It? Op. cit.*
[333] Ibid.

- Development of materials utilized form FGD sludge and ash;
- Characterization of waste material in storage and in utilized material;
- Design manual for clean coal by-product management and landfill design for combustion ash.

In addition:[334]

- Advanced materials, applied to combustion turbines, allowed for greater than 60% cycle efficiency rate, which is currently standard in industry for combined cycle. This research was funded under the DOE coal RD&D program.
- The DOE coal RD&D program is currently funding research in developing the greater than 65% cycle efficiency.
- DOE funded a significant effort on developing hydrogen turbines, and DOE coal RD&D investments initiated investments and improvements in hydrogen turbines.

Importantly, the history of RD&D is replete with examples of discoveries and breakthroughs that were unplanned, unanticipated, and serendipitous. To cite only several examples:

- Probably the most important "accidental" RD&D discovery was penicillin. In 1928, Sir Alexander Fleming, a Scottish biologist who was studying the bacterium staphylococcus, was cleaning his lab after having been on vacation. He found that a petri dish that contained Staphylococcus bacteria had been left uncovered, and he noticed that the mold had killed many of the bacteria. Fleming identified the mold as Penicillium Notatum, and after further research he discovered that it had the ability to kill other bacteria.
- Perhaps the second most well-known serendipitous RD&D discovery was the microwave oven. During World War II, an American engineer, Percy Spencer, was working at Raytheon. While running tests on an active microwave radar set, he noticed that the Mr. Goodbar candy bar he had in his pocket started to melt. The radar had melted his chocolate bar with microwaves.
- Scotchgard was discovered by 3M chemist Patsy Sherman while she was trying to develop a rubber that would not deteriorate from exposure to jet fuel. Sherman had stumbled upon a fluorochemical polymer that would repel water and oil from fabric, and it was sold as the first Scotchgard product in 1956.
- In 2003, Jamie Link, a graduate student at the University of California at San Diego, discovered "smart dust" -- programmable silicon particles -- when a silicon chip she was working on exploded. She noticed that the small pieces still maintained their properties as sensors. Smart dust has uses in medicine, pollution monitoring, equipment monitoring, and even bioterrorism surveillance.
- Engineer Wilson Greatbatch unintentionally made implantable pacemakers feasible. He was working on the battery power source for an existing pacemaker design. Meaning to build in a resistor to finish the circuit, he mistakenly used a 1-megaohm resistor instead of a 10,000-ohm one. The circuit pulsed for 1.8 milliseconds, then stopped for one second, then it repeated, just like a heartbeat.

[334]Information provided to MISI by DOE, June 2020.

- Polytetrafluoroethylene (PTFE) – Teflon -- was accidentally discovered in 1938 by Roy Plunkett, while he was working for Kinetic Chemicals in New Jersey. Plunkett was attempting to make a new chlorofluorocarbon (CFC) refrigerant. Kinetic Chemicals, a DuPont company, patented the new fluorinated plastic in 1941.
- In 1933, the first industrially practical polyethylene synthesis was discovered by Eric Fawcett and Reginald Gibson. During high-pressure experiments on ethylene, a test vessel had leaked and a trace of oxygen was present in the chemists' fresh ethylene sample, acting as an initiator. Polyethylene formed overnight. Their employer, Imperial Chemical Industries, moved toward patents and production, and it has become the most commonly used plastic.
- The adhesive behind Post-it notes was discovered in 1968 by Spencer Silver, a researcher at 3M Laboratories, who was actually seeking to a stronger adhesive than what was currently available. Instead, he found a weaker one, an adhesive that stuck to objects but could be pulled off without damaging them or leaving a residue.
- Super Glue was discovered accidentally in 1951 by Dr. Harry Coover at Eastman Kodak while working on a project researching heat resistant acrylate polymers for jet canopies. He recognized the product's remarkable rapid bonding properties, and in 1958 Eastman Kodak introduced it to the world.

MISI did not quantify the knowledge benefits resulting from the DOE coal RD&D program. Nevertheless, these benefits are real and substantial and should be recognized as an important result of the RD&D program.

VI. FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS

VI.A. Findings

VI.A.1 DOE Coal RD&D budgets

Over the past six decades, DOE has funded a substantial coal research program, including RD&D for coal production, resource assessment, mining techniques, mining health and safety, coal utilization, coal liquefaction and gasification, clean coal technologies, CCUS, fuel cells, advanced technologies, Magnetohydrodynamics, pollution control and abatement, and other programs. The cumulative budget 1976 - 2020 totaled $29.12 billion (2019 dollars), but the distribution of expenders was very uneven, and funding ranged between about $400 million to $500 million (2019 dollars) from 2010 to 2020. We found that:

- Coal Liquefaction received the most funding: $4.85 billion – 17% of the total RD&D budget.
- Coal Gasification received the second highest level of funding: $4.67 billion -- 13% of the total.
- CCUS received the third highest level of funding: $2.49 billion – 8.6% of the total.
- Advanced Research and Technology development received the fourth highest level of funding: $2.46 billion – 8.4% of the total.
- Coal Liquefaction and Coal Gasification combined received a total of $8.5 billion -- nearly 30% of the total RD&D expenditures.
- Four major programs which have not been funded for the past quarter century -- Coal Liquefaction, Coal Gasification, Magnetohydrodynamics, and Mining RD&D – were among the top ten funded and combined received $11.6 billion – 40% of the total RD&D budget.

The priorities of the RD&D program changed over the past five decades:

- The first decade of the program was dominated by the energy crises of the 1970s and focused on producing liquid and gaseous fuels from coal.
- In 1990, Control Technology and Coal Preparation received the most funding, Coal Liquefaction and Coal Gasification were still major programs, as was Magnetohydrodynamics.
- In 2000, not only had funding decreased to a near all-time low, but program priorities had changed and Fuel Cells received, by far, the most funding.
- In 2010, Sequestration was a major program, Advanced Turbines and Advanced IGCC received the most funding, and Fuel Cells was also a major program.
- Fuel Cells was a major program funded between 1998 and 2010.
- In 2020, CCUS dominated funding, receiving 44% of the total for that year.

VI.A.2. Impacts and Benefits

We assessed the impacts and benefits to government and the private sector resulting from:

- Realized Savings Through 2000
- Reduced CAPEX
- Efficiency Savings
- Clean Coal Technology Exports
- SO_2
- NO_x
- CO_2
- Public Health
- NETL Operations
- Jobs

NRC/NAS estimated that realized economic benefits through 2000 from coal RD&D programs including Fluidized Bed Combustion, Flue Gas Desulfurization, Waste Management/Utilization Technologies, and the Coal-bed Methane Program totaled approximately $7.3 billion (2019 dollars).

We estimate that, in 2019 dollars, excluding CO_2 benefits, the benefits attributable to the DOE coal RD&D program through 2019 total about $237 billion (2019 dollars):

- The total savings through 2019 from reduced capital costs of new plants and the control technologies for existing plants was approximately $7.6 billion.
- The cumulative fuel cost savings resulting from efficiency improvements through 2019 totaled about $3 billion.
- The cumulative U.S. clean coal technology export benefits through 2019 totaled approximately $42.6 billion.
- The environmental benefits of SO_2 emissions reductions through 2019 totaled about $68.5 billion.
- The environmental benefits in terms of NO_x reductions totaled $35.9 billion.
- Using the 2013 IWG SCC estimate, the total estimated value of the CO_2 captured by the Petro Nova plant over the period 2017 through 2019 is about $0.2 billion (2019 dollars). The implied monetized CO_2 emissions savings, 2008 – 2019, from the Petra Nova plant and the HELE plants totaled approximately $2.4 billion.
- The total public health benefits through 2019 totaled approximately $36.9 billion.
- The beneficial impacts of NETL operations, 2000-2109, totaled $35 billion.

We thus estimate that, excluding CO_2 benefits, the benefits attributable to the DOE coal RD&D program through 2019 total about $237 billion (2019 dollars).

We estimate that the jobs created over the period 2000 – 2019 totaled approximately 1,572,000 -- about 78,600/yr. The number of jobs created is important, but it is also important to disaggregate the employment generated by into occupations and skills. From previous MISI work and other studies it is clear that the jobs generated will be disproportionately concentrated in fields related to the construction, energy, utilities, technology export, mining, industrial, and related sectors, reflecting the requirements of the programs and their supporting industries.

VI.A.3. Benefit-Cost Estimates

There are at least two dimensions of the DOE Coal RD&D budget:

- The DOE RD&D produces public benefits that the private economy cannot provide.
- Some benefits may be realized even when a technology does not enter the marketplace immediately or to a significant degree.

While many studies have found that government RD&D is a classic public good and that the B-C ratio of this RD&D is high, there is little consensus on what this ratio is – even within a broad range. Previous research has estimated RD&D B-C ratios that range from 4 to 180.

Important benefits have been realized by numerous companies in the private sector due to assistance from DOE and the NETL RD&D program. These include many in the manufacturing sector, such as Carpenter Technology Corporation, LumiShield Technologies, KW Associates, Harbison Walker, Liquid Ion Solutions, Boston Scientific Corporation, and Pyrochem Catalyst Corporation.

The DOE coal RD&D program has significant economic and job impacts on specific cities and regions throughout the U.S., including Pennsylvania and West Virginia. MISI estimated the jobs impacts on the Reading, Pennsylvania area. MISI estimated the jobs impacts on Reading assuming that NETL's assistance facilitated about 5% of the Carpenter Technology Corporation jobs in Reading. This NETL success helped create a total of about 575 jobs (direct and indirect) in the Reading area and, absent these NETL facilitated jobs, the unemployment rate in Reading would have been 5.3% instated of 5.0% -- a substantial increase.

Table VI-1 and Figure VI-1 show that the benefits of the DOE coal RD&D program through 2019 total about $237 billion (2019 dollars) – about $239 billion including a monetized value for CO_2 emissions, and annual creation of nearly 79,000 jobs. If we assume that this annual job creation was also about the average for the years 2000 – 2007, then the cumulative jobs created over the period 2000 – 2019 totaled about 1,572,000.

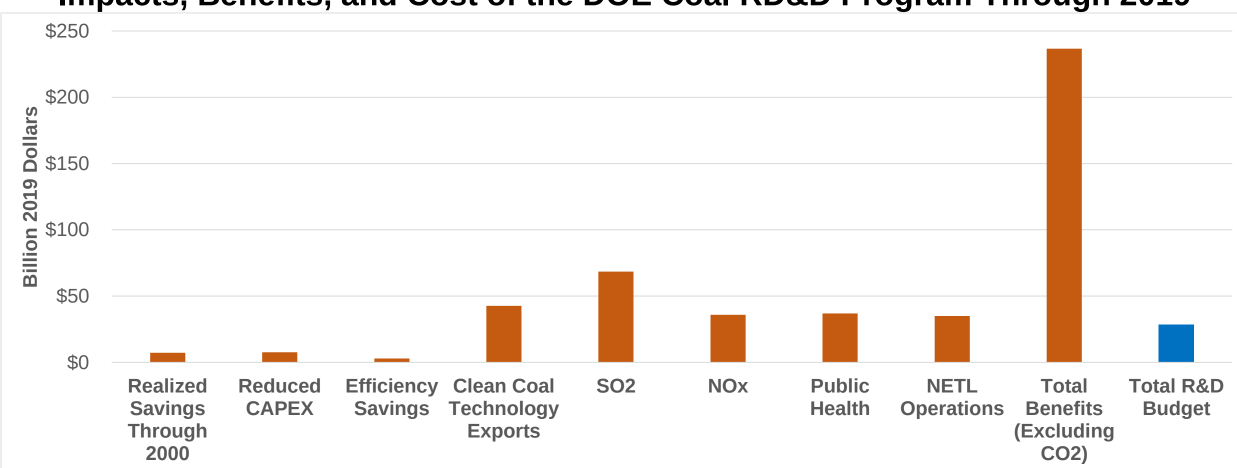
Thus, the impacts and benefits of the DOE coal RD&D program through 2019 far exceed the costs -- $28.6 billion (2019 dollars). This implies a rough B-C ratio of greater than 8 to 1. It should be noted that here we used estimated benefits through 2019, which totaled $237 billion, and the estimated DOE coal RD&D expenditures through 2019, which totaled $28.6 billion. Including the FY 2020 DOE coal RD&D of $484 million (2019 dollars) would increase the total expenditures from $28.6 billion to $29.1 billion, but would not appreciably change the B-C ratio.

Table VI-1
Impacts of the DOE Coal RD&D Program Through 2019

Category	Impacts (billions of 2019 dollars)
Realized Savings Through 2000	\$7.3
Reduced CAPEX	\$7.6
Efficiency Savings	\$2.9
Clean Coal Technology Exports	\$42.6
SO_2	\$68.5
NO_x	\$35.9
CO_2	42.1Mt
Public Health	\$36.9
NETL Operations	\$35.0
Jobs	78,600 jobs/yr.*
Total	\$236.7
Total, including CO_2	\$239.1[335]

*Annual average for the period 2008 – 2019.
Source: Management Information Services, Inc.

Figure VI-1
Impacts, Benefits, and Cost of the DOE Coal RD&D Program Through 2019



Source: Management Information Services, Inc.

A B-C ratio above one is desirable and a ratio over 8-to-1 is extremely attractive. The finding that benefits of the DOE coal RD&D program through 2019 substantially far exceed the costs is robust:

- The cost estimate of \$28.6 billion is accurate to within about 2%, since MISI derived the budget estimates from the official DOE annual budget documents and the deflator series used is the official BEA IPD series.

[335] Using the 2013 IWG SCC value of \$52.00/ton of CO_2 (2019 dollars), we estimate that the implied CO_2 emissions savings, 2008 – 2019, total approximately \$2.4 billion (2019 dollars).

- Even assuming that MISI has overestimated total benefits by a factor of two, and that they total about $128 billion, still yields a rough B-C estimate of above 4-to-1, which remains well above one and, indeed, remains impressive.
- Even discounting all of MISI's benefit estimates and using benefits estimates derived from independent studies yields a B-C ratio well above one.
- Assuming MISI has underestimated benefits by 25% implies that total benefits could be as high as $296 billion, which implies a B-C ratio of more than 10-to-1.

The estimated B-C ratio of over 8-to-1 appears reasonable when compared to B-C ratios for other energy and RD&D programs. Analyses of other RD&D programs found B-C ratios ranging from 4-to-1 up to an incredible 180-to-1. On this basis, the DOE coal RD&D program B-C ratio of 9-to1 looks conservative. Further, a study of 15 leading economies estimated an overall B-C ratio for RD&D expenditures of about 20-to-1. Thus, on this basis also, the DOE coal RD&D program B-C ratio of 8-to1 looks reasonable and conservative.

Knowledge benefits are defined as scientific knowledge and useful technological concepts resulting from the RD&D that have not yet been commercialized but hold promise for future use or are useful in unintended applications. NRC/NAS found that the DOE coal RD&D program has yielded significant benefits in terms of important technological options for potential application and important additions to the stock of engineering and scientific knowledge in a number of fields. NRC/NAS also found that the DOE program had many significant technological spin-offs. MISI did not quantify the knowledge benefits resulting from the DOE coal RD&D program. Nevertheless, these benefits are real and substantial and should be recognized as an important result of the RD&D program.

VI.B. Conclusions

The DOE coal RD&D program budget has been subject to wide variations over time, often over short periods. For example, in real terms,

- The budget declined 80% between 1980 and 1983.
- It declined 20% in one year, from 1986 to 1987.
- It declined 40% in one year, from 1996 to 1997.
- It increased more than twofold from 2000 to 2002.
- It declined more than 50% from 2009 to 2011.

Such fluctuations are not conducive to coherent, long term RD&D. Fortunately, the overall budget has been relatively stable in real terms over about the past decade; however, program funding priorities changed substantially over this period.

Large portions of the coal RD&D program budgets were comprised of expenditures on technologies that were not successful in the marketplace. Subtracting expenditures on just three of these – Coal Liquefaction, $4.9 billion, Coal Gasification, $3.7 billion, and Magnetohydrodynamics, $2.0 billion – which combined comprised more than 35% of the total DOE coal RD&D budget through 2020, leaves a cumulative DOE coal RD&D budget of $18.0 billion.

However, a portfolio approach must be used to assess DOE coal RD&D impacts and benefits. That is, some DOE coal RD&D programs are among DOE's most successful RD&D programs and they have produced benefits that far exceed their federal costs. NRC/NAS found that the estimated benefits of DOE high-risk, high-payoff programs can exceed their projected cost by a significant amount.[336] On the other hand, other RD&D programs produce impacts and benefits that are difficult to quantify. Thus, just as with a stock portfolio where certain stocks outperform others, much of the impacts and benefits of DOE's coal RD&D program may come from a relatively small number of select programs. This is very important in evaluating the overall DOE RD&D program, but it is not widely appreciated. Decades ago, no one knew which RD&D programs would be successful and which would not.[337] This is a basic fact of any RD&D enterprise and will be as true in the future as it has been in the past.

By far, the most important conclusion derived here is that the impacts and benefits of the DOE coal RD&D program through 2019 -- $237 billion (2019 dollars) -- far exceed the costs -- $28.6 billion (2019 dollars). This implies a rough B-C ratio of over 8-to-1. This is very impressive: B-C ratios above 2 or 3 are desirable, and ratios higher than that are very impressive. Some other energy RD&D programs have reported B-C ratios much higher than this. However, upon close scrutiny many of these ratios are of questionable validity.

It is important to note here that the conclusion that the impacts and benefits of the DOE coal RD&D program far exceed the costs is robust and it is reasonable:

- It is robust because the cost estimate is based on official published federal government data, and many of the benefit estimates have been verified by independent studies.
- It is reasonable – and perhaps even conservative – when compared to benefit-cost estimates for other RD&D programs. Purported astronomical B-C ratios simply do not past the laugh test.

The number of jobs created over the period 2000 – 2019 totaled about 1,572,000 -- about 78,600/yr. – and is large, and job creation is especially important in specific local areas and in individual sectors, industries, and occupations. These local job impacts can be of critical importance – especially in the current environment of widespread job losses.

Relying on other non-quantifiable measures, such as patents, papers published, or conference presentations made as criteria for an RD&D program's success can be inaccurate, misleading, and subject to conflict of interest concerns.

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[336]National Research Council, *Prospective Evaluation of Applied Energy Research and Development at DOE (Phase One): A First Look*, op. cit.

[337]"An R&D program with no failures in individual research projects is pursuing an overly conservative portfolio." National Research Council, *Energy Research at DOE: Was It Worth It? Op. cit.*

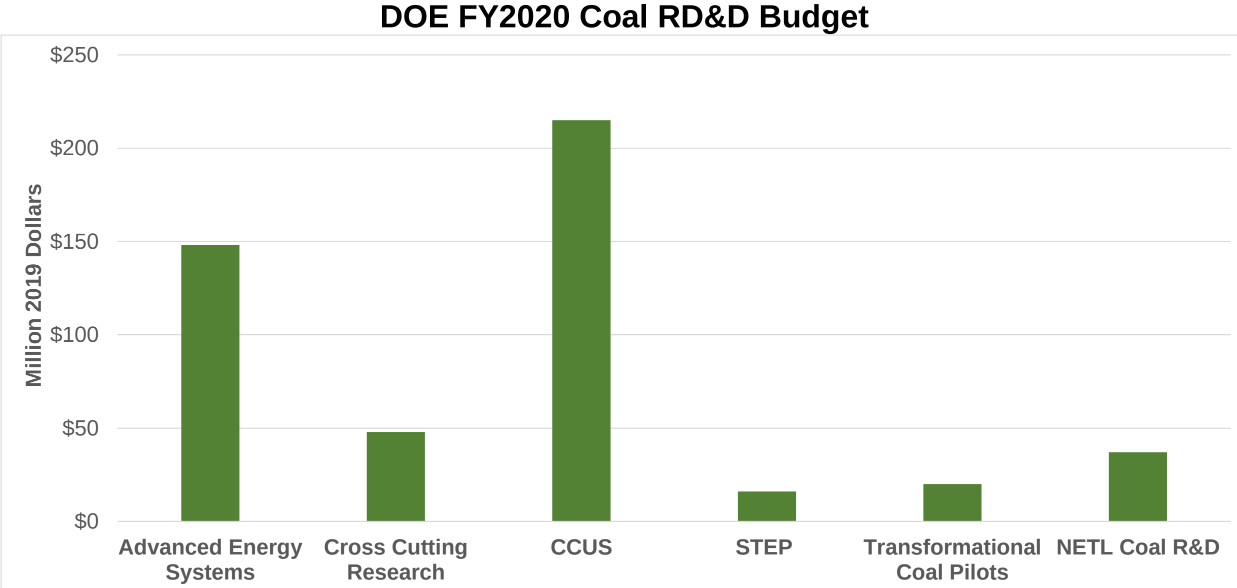
Knowledge benefits -- scientific knowledge and useful technological concepts resulting from the RD&D that have not yet been commercialized – can be very significant. Indeed, the DOE coal RD&D program has yielded significant benefits in terms of important technological options for potential application and important additions to the stock of engineering and scientific knowledge in a number of fields. While these benefits are impossible to quantify, they are nevertheless real and should be recognized as an important result of the RD&D program.

VI.C. Recommendations

<u>First</u>, the most important recommendation derived here is that the anticipated or prospective impacts and benefits of DOE coal RD&D programs be forecast, monetized, and assessed against the forecast cost of the programs. Here we estimated the historical DOE coal RD&D budget and the retrospective impacts of the RD&D programs to date. However, the most salient questions concern the current and future size and composition of the DOE coal RD&D budget and the anticipated benefits from it. Obviously, simply because the past RD&D program has produced impressive results is no guarantee that the program will continue to do so.

Consider Figure VI-2, which shows the FY 2020 DOE coal RD&D budget. The largest program is CCUS, receiving more than 44% of the total, followed by Advanced Energy Systems, 31%. Adding Transformational Coal Projects, 4%, and STEP, 3%, indicates that well over 80% of the budget is devoted to RD&D programs with payoffs and benefits that are anticipated well into the future. This is, of course, the proper structure for an RD&D program: It should be focused on technologies of the future.

Figure VI-2
DOE FY2020 Coal RD&D Budget



Source: U.S. Department of Energy and Management Information Services, Inc.

In particular, CCUS is not only a current major focus of the DOE program but it is the third most generously funded coal RD&D program since 1976 – even though funding for it did not begin until FY 2001. Analysts and policy-makers may have finally realized that any ambitious decarbonization goals are simply not feasible without CCUS. Even many environmentalists and advocates of the "Green New Deal" have accepted the need for CCUS as a necessarily large part of any future CO_2 reduction programs. The simple fact is that any ambitious decarbonization will require massive amounts of CCUS, and any CO_2 stabilization or reduction is impossible without CCUS. It is notable that three of the major emphases in the DOE FY 2021 fossil energy budget request are i) utilization of coal and CO_2 for the production of critical materials and products; ii) transformational CO_2 capture technologies applicable to both new and existing fossil-fueled facilities; and iii) CO_2 storage, with emphasis on storage in depleted oil and gas fields; offshore geologic reservoirs; and addressing injection challenges across all reservoir types.[338]

DOE and Congress are interested in determining the potential economic and jobs impacts of CCUS, and over the past three decades have expended $2.5 billion on DOE CCUS RD&D. As noted, CCUS is vital for the DOE coal RD&D program:

- It is a DOE GHG reduction technology.
- DOE has a long history and acknowledged technical expertise in CCUS.
- It is a program that enjoys strong bipartisan support in Congress.[339]
- It is a program that will likely be strongly supported for many years to come.
- When combined with EOR, it is economically viable.

Continued adequate funding for the DOE CCUS program requires justification. The justification must be derived from the forecast impacts and economic and jobs benefits of the CCUS program over the next several decades. In Section IV.F.3, we estimated the CO_2 emissions reduction benefits from the Petra Nova plant from 2017 through 2019 and from the HELE plants from 2008 through 2019. However, these CO_2 emissions reduction benefits have only just begun to accrue and the potential benefits from widespread CCUS and CCUS/EOR over the next several decades have to be estimated and evaluated.

Thus, DOE can assess the potential economic, energy, environmental, and jobs impacts of future DOE–facilitated CCUS initiatives. This research can provide estimates of the impacts that would result from the CCUS asset construction and operation and from the associated CO_2-EOR oil production. It could develop estimates of the impacts of the CCUS capacity and generation build-out and CO_2-EOR oil production for the period 2020 through 2050, and it could also analyze the implications for the industry/occupational jobs and skill requirements that will result from the coal CCUS retrofits and related initiatives.

[338]Office of Chief Financial Officer, *Department of Energy FY 2021 Congressional Budget Request*, op. cit.
[339]For example, at the FY20 DOE Budget Hearing, Representative Greg Walden stated "I am encouraged by the work DOE is doing to support transformative breakthroughs in 'carbon free' fossil energy and carbon capture technologies." Opening Statement of Republican Leader Greg Walden, Subcommittee on Energy "The Fiscal Year 2020 DOE Budget," May 9, 2019.

In addition, the likely economic impacts of the 45Q CCUS tax credits enacted in 2018 can be compared with the impacts of those proposed in 2017 and with other proposed CCUS tax credits. The enacted 45Q tax credits provided less incentives than those proposed in 2017 – primarily because they contain "sunset" provisions requiring that facilities begin construction by 1-1-24 to be eligible for the tax credit. Similarly, other proposed CCUS tax credits will have differing economic and job impacts.

Research has estimated that an ambitious CCUS RD&D program alone will create 14 to 16 million jobs.[340] It also found that to maximize cost-effectiveness and benefit-cost ratios, the DOE CCUS RD&D program is required and that RD&D is much more cost-effective than tax credits according to any criteria: Jobs, coal production, power plants, EOR, or pipelines. The marginal impacts of the DOE RD&D program are substantial.[341] With moderate oil and natural gas prices, the RD&D program creates an additional 500,000 jobs; in a high oil and natural gas prices environment the program creates about 3.3 million additional jobs – and nearly 4 million jobs with 3% economic growth. Nevertheless, to maximize job creation both CCUS tax credits and the DOE RD&D program need to be implemented in a coordinated manner, and these impacts need to be further assessed.

Second, the job impacts of DOE programs are of critical importance, and in 2020 are especially relevant in the current environment where job losses and unemployment are at record levels not seen since the Great Depression of the 1930s.[342] It really does come down to "jobs, jobs, jobs!" It is impossible to over-emphasize the importance of jobs and employment impacts. For example:

- As determined here, over the past two decades the DOE coal RD&D program has generated a cumulative total of 1.6 million jobs -- about 78,600/yr. This finding needs to be widely disseminated.
- Regional disaggregation is required of the jobs created by the DOE coal RD&D program, especially at the state level of detail. There is great Congressional and decision-maker interest in these data and there will be a large and influential audience for the estimates. The implications of determining the benefits to specific states and regions are obvious, for the debate at the state and regional level inevitably revolves around jobs.
- The number of jobs created is important, but it is also important to disaggregate the employment generated into industries, occupations, and skills. From previous MISI work it is clear that the jobs generated are disproportionately concentrated in fields related to the construction, energy, utilities, technology export, mining,

[340]Management Information Services, Inc., "Analyzing and Estimating the Economic and Job Benefits of U.S. Coal," op. cit.
[341]Management Information Services, Inc., "Analyzing the Economic and Job Impacts of the DOE R&D Program and CCS Tax Credits," op. cit.
[342]See, for example, Sarah Chaney and Eric Morath, op. cit. As noted, the April unemployment rate actually underestimated the current degree of joblessness. The regular unemployment rate excludes so-called discouraged workers – those who are not actively looking for work. In addition, it is based on surveys conducted in second week of April, and many additional workers lost their jobs in the latter half of the month. Further, many self-employed workers and others new eligible for unemployment benefits are not included in the 14.7% estimate.

industrial, and related sectors, reflecting the requirements of the RD&D programs and their supporting industries.

- The jobs created are across a wide spectrum in many industries and in professional and skilled occupations. However, it is also true that numerous jobs are also being created at all skill levels. Accordingly, the importance for jobs in some occupations is much greater than in others, and further research is required to estimate these occupation/skill impacts more definitively.
- The detailed indirect coal-related jobs impacts by sector, industry, and occupation/skills, as well as new and emerging occupations, need to be estimated. MISI research indicates that many of the jobs generated are in industries and occupations not necessarily linked to coal or related industries and are, instead, created throughout the interindustry supply chain and in supporting activities.[343] While some illustrative examples of these have been derived, this issue requires rigorous research.
- Despite continuing controversies over coal plant development and EPA regulations, coal will continue to be important for U.S. electricity production over the next several decades. Further, rapid expansion of coal retrofit CCUS, CO_2 EOR, CO_2 pipelines, and associated infrastructure can facilitate a U.S. industrial rebirth and assist in the creation of new industries, increased industry sales and profits, increased GDP, millions of jobs, and expanded high skilled, well-paying employment opportunities. These have to be identified.
- Research to determine the potential jobs impacts of future coal and industrial CCUS retrofits should be initiated. This must be based on appropriate assumptions regarding CO_2 taxes, coal retirements, new coal builds, deployment of CCUS technology, resource levels, EOR project constraints, and other relevant parameters.

Third, it is critical that a portfolio approach be used to assess DOE coal RD&D impacts and benefits. That is, some DOE coal RD&D programs are among DOE's most successful RD&D programs and they have produced benefits that far exceed their federal costs, and the benefits of DOE high-risk, high-payoff programs can greatly exceed their cost. On the other hand, other RD&D programs produce impacts and benefits that are difficult to quantify. This is very important in evaluating the overall DOE RD&D program, but it is not widely appreciated. Decades ago, no one knew which RD&D programs would be successful and which would not. This is a basic fact of any RD&D enterprise and will be as true in the future as it has been in the past.[344]

[343]Management Information Services, Inc., "Analyzing and Estimating the Economic and Job Benefits of U.S. Coal," op. cit.; National Coal Council, "Harnessing Coal's Carbon Content to Advance the Economy, Environment, and Energy Security," June 2012; Bezdek and Wendling, "Economic, Environmental, and Job Impacts of Increased Efficiency in Existing Coal-Fired Power Plants," op. cit.; Management Information Services, Inc., *American Energy Security: Building a Bridge to Energy Independence and to a Sustainable Energy Future*, op. cit.

[344]To quote the classic R&D director's lament, "I know 90% of my budget is wasted, but I do not know which 90%."

Finally, and more generally, as noted, there is currently a widespread perception concerning the purported disadvantages of fossil fuels – especially coal. DOE can counter this by facilitating the dissemination of rigorous, credible research illustrating the economic and job benefits and advantages of fossil fuels and the DOE coal RD&D program – such as that provided here. These findings will be useful in preparing budget requests, justifications, and defenses and in Congressional testimony.

It is also important that these findings be publicized and distributed in the media, in the scholarly literature, and at appropriate professional venues. The findings can be used to prepare white papers, summaries, abstracts, and one-pagers appropriate for widespread distribution, articles for publication in peer-reviewed national and international energy and policy journals, and presentations at relevant professional conferences, seminars, and meetings. The point is that the research has been conducted and remains to be disseminated.

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