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The return on investment of the clean coal technology program in the USA

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HIGHLIGHTS

- ▸ Its benefits far exceed costs, and benefits are increasing rapidly.
- ▸ The ROIs to federal govt. and private industry are very high.
- ▸ It will create 100,000 jobs annually.
- ▸ Independent reviews find it to be exemplary and well-managed.

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ABSTRACT

We analyze the return on investment of the U.S. federal government's clean coal technology (CCT) program for the period 2000–2020. We estimate total costs to government and industry and quantify 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. We find 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. We also find that the return on investment 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.

"Coal is an abundant resource in the world. It is imperative that we figure out a way to use coal as cleanly as possible". Dr. Steven Chu, Secretary of Energy, at his Senate Confirmation Hearing, January 13, 2009.

1. Introduction

Coal was the most rapidly growing fuel in the world during the past decade and will be the fastest growing fuel over the next decade, and will continue to be the leading source of electric power in the USA for decades to come. At the global level, increasing coal consumption and environmental goals necessitate the rapid deployment of clean coal technologies. The clean coal technology program in the USA has pioneered these critical technologies and demonstrates the benefits of the research and development program.

2. The clean coal technology program

"Clean coal technology" (CCT) describes a new generation of energy processes that significantly reduce air emissions and other pollutants from coal-burning power plants. The clean coal technology demonstration program (CCTDP) was initiated 1985 to develop and demonstrate, at commercial scale, 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 CCTDP was developed as a government-industry partnership, with the share of federal funds limited to a maximum of one-half of the funding for each project.

The first CCTDP projects started in 1987, and over the course of the program 33 projects were completed at a cost of $3.3 billion, with the U.S. Department of Energy (DOE) investing $1.3 billion. Because of the program's success, the Power Plant Improvement Initiative (PPII), was begun in 2001. This program resulted in five projects and cost $71 million, with DOE contributing $32 million. A third program followed the PPII—the Clean Coal Power Initiative (CCPI). This resulted in 12 projects

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Table 1
CCT technologies.
Source: U.S. Department of Energy, Office of Fossil Energy, 2009.

Technology	Impact
Low nitrogen oxide burners	Now on 75% of U.S. coal power plants 1/2 to 1/10 the cost of older systems 25 million ton reduction in U.S. NO_x emissions through 2005 $25 billion national benefit
Selective catalytic reduction	Achieves NO_x reduction of 80% to 90% or more Technology today costs half what it did in the 1980s, and is deployed on about 39% of U.S. coal plants
Flue gas desulfurization (FGD)	Systems now cost 1/3 what they did in the 1970s More than 400 commercial units deployed 7 million ton reduction in SO_2 (beyond what would have occurred without DOE R&D) through 2005 Over $50 billion savings from the lower FGD costs and environmental improvement
Fluidized bed combustion (FBC)	170 units deployed in the U.S.; 400 units worldwide Highly commercialized with more than $6 billion in domestic sales and nearly $3 billion in overseas sales Inherently low NO_x emitting technology capable of using coal waste fuels not previously usable Providing economic/environmental benefits of $2 billion through 2020
Integrated gasification combined cycle (IGCC)	In early stage, but 7.5 GW projected to be operating in U.S. by 2020 Estimated economic/environmental benefits of over $12 billion by then Key component of *Futuregen*

costing $2.7 billion, with the DOE contribution totaling $530 million (U.S. Department of Energy, 2009). All three programs, including the PPII and the CCPI, are commonly referred to as the CCTDP.

Technologies in four categories were demonstrated under the CCTDP: Advanced Electric Power Generation, Environmental Control Devices, Coal Processing for Clean Fuels, and Industrial Applications. The program's critical technology needs include Integrated Plants, Emissions Control, Advanced Combustion, Advanced Gasifier System, Gas Cleaning, Syngas Utilization for Power and Fuels, CO_2 Capture, and CO_2 Sequestration. In the late 1980s and early 1990s, DOE conducted a joint program with industry and state agencies to demonstrate the best of these new technologies at scales large enough for companies to make commercial decisions. More than 20 of the technologies tested in the original program achieved commercial success (U.S. Department of Energy, Assistant Secretary for Fossil Energy).

The early program focused on the environmental challenges of the time—primarily concerns over the impact of acid rain on forests and watersheds. In the 21st century, additional environmental concerns have emerged, such as the potential health impacts of trace emissions of mercury, the effects of microscopic particles on people with respiratory problems, and the potential global climate-altering impact of greenhouse gases (GHGs). Building on the successes of the original program, the new clean coal initiative encompasses a broad spectrum of research and large-scale projects that target pressing environmental challenges.

The CCPI is providing government co-financing for new coal technologies that can help utilities reduce sulfur, nitrogen, and mercury pollutants from power plants—Table 1. In addition, some of the early projects are showing ways to reduce GHG emissions by increasing the efficiency of coal plants. DOE provides up to 50 percent of the project funding for the Clean Coal projects. The Power Plant Improvement Initiative Program successfully completed the fourth and final project, and the Clean Coal Technology Demonstration Program concluded with 33 successfully completed demonstration projects (National Energy Technology Laboratory, 2009). In addition, DOE manages a portfolio of clean coal programs that research and develop CCS technology or demonstrate its application (Gaffigan, 2009).

Table 2
CCTDP funding (millions of 2008 dollars).
Source: U.S. Department of Energy and Management Information Services, Inc.

FY	Funding	FY	Funding
1986	$171	1998	$(131)
1987	249	1999	(52)
1988	323	2000	(175)
1989	296	2001	11
1990	831	2002	10
1991	567	2003	(56)
1992	589	2004	(109)
1993	0	2005	(176)
1994	315	2006	(21)
1995	48	2007	(21)
1996	195	2008	0
1997	$(3)	Total	$2978

3. Estimating CCT costs and benefits

3.1. Costs

Congress appropriated a net amount of $2.1 billion (2.98 billion in 2008 dollars) for the CCTDP based on appropriations bills that began in 1986 (Table 2).

Table 3 summarizes the funding by fiscal year for the PPII and CCPI programs and shows that funding totaled $727 million ($887 million in 2008 dollars). The amount of appropriated funds available for project awards is reduced by Program Support, the Small Business Innovation Research (SBIR) program, the Small Business Technology Transfer (STTR) program, and other adjustments. Program Support provides for a share of the DOE administrative expenses of the programs. The SBIR program implements the Small Business Innovation Development Act of 1982, and provides funding for small, innovative firms in selected research and development areas. The STTR program implements the Small Business Technology Transfer Act of 1992, which provides funding for small business concerns performing cooperative R&D efforts. Other adjustments include across-the-board general and omnibus reductions imposed by Congress.

Projects in the CCTDP, PPII, and CCPI are subject to similar requirements and oversight. A principal characteristic of the demonstration projects is the cooperative funding agreement between the participant and the federal government referred to

Table 3
Funding for the CCPI and PPII programs (thousands of dollars).
Source: U.S. Department of Energy.

	Fiscal year								Total
	2001	2002	2003	2004	2005	2006	2007	2008[c]	
PPII projects	93,843								91,843
CPPI-1 projects		144,565	143,626						288,191
CPPI-2 projects				163,471	47,446				210,917
CPPI-3 projects						47,633	58,154	TBD	105,787
Program support	948	1,500	1,400	1,701	493	495	604		7,231
SBIR & STTR[a]		3,935	3,900	4,709	1,372	1,372	1,675		16,967
Other adjustments[b]	209		975	2,119	694	500			
Total	95,000	150,000	150,000	172,000	50,000	50,000	60,433	TBD	727,433

[a] Small business innovative research (SBIR) and small business technology transfer (STTR) programs. All fossil energy programs are required to contribute to these programs on an equal percentage basis.
[b] Across-the-board general and omnibus reductions required by the annual appropriations bills.
[c] As of September 30, 2007 appropriates for FY 2008 had not yet been signed into law.

as cost-sharing, and the federal government may not finance more than 50 percent of the total costs of a project.

Cumulative funding through 2008 for the CCTDP, PPII, and CCPI programs totaled, in 2008 dollars, about $3.9 billion. In addition, over the past decade, the federal government has been spending between $100 and $300 million annually on clean coal-related R&D in addition to the CCTDP, PPII, and CCPI programs (U.S. Energy Information Administration, 2011b; Bezdek and Wendling, 2012a).

Using these data, and assuming that private industry will cost-share about 50 percent of the CCT costs over the next decade, we estimate that, over the period 2000–2020, federal–private CCT investments will total approximately $17 billion (2008 dollars) – about $8.5 billion federal expenditures and about $8.5 billion industry spending.

3.2. *Benefits*

The benefits estimates derived here include actual benefits that accrued 2000–2008 and those forecast to be realized over the period 2009–2020. In forecasting the benefits for the latter period, MISI generally followed the conventions that EIA uses in developing its annual energy forecasts in the Annual Energy Outlook (AEO). That is, benefits and impacts of any program are based on legislation in place at the time the forecast was made (U.S. Energy Information Administration, 2012).

3.2.1. *Reduced capital costs*

A major portion of the CCT benefits 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 CCT benefits these savings sometimes accounted for nearly half of the total benefits estimated. However, in recent years, fewer new coal plants have come on-line than were originally anticipated, and EIA has significantly reduced its forecasts of new coal capacity that will be installed by 2020. Actual plant capacity commissioned since 2000 has been far less than the new capacity announced: The 2002 report of announcements reflected a schedule of over 36,000 MW to be installed by 2007, whereas only about 4500 MW (12 percent of the capacity announced in 2002) was achieved (Shuster, 2009). Further:

- The trend over several years has reflected the bulk of power plant developments shifting out in time due to project delays.
- Delays and cancelations have been attributed to regulatory uncertainty 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 fulfilling all projects in the queue become impractical.

The potential implications of plant cancellations are significant, and cancellations are predominately due to current economic, environmental, and regulatory uncertainty. Thus, announced projects that are canceled before or during the permitting phase are not unusual, and announced projects are not necessarily reliable indicators of capacity additions. Nevertheless, delayed or abandoned projects represent future opportunities: Land, fuel, transportation, and water availability still exist and mine mouth opportunities and waste coal piles are still available. The U.S. National Energy Technology Laboratory (NETL) found that opportunities involving conventional technologies, such as subcritical pulverized coal (PC) and circulating fluidized bed (CFB), are more plentiful and tend to be more advanced due to earlier start in development (Shuster, 2009). Specifically:

- Advanced technologies proposed, such as supercritical PC and IGCC, reflect more recent trends in development activity, and thus fewer have achieved permitted status.
- Regulatory uncertainty for GHG legislation is a key issue impacting technology selection and reliability of economic forecasts.
- Returns on investment for conventional plants, including super-critical, can be severely compromised by the need to subsequently address CO_2 mitigation.
- Higher capital costs incurred for IGCC may make such new plants less competitive unless their advantage in CO_2 mitigation is assured.

Historically, actual capacity has been shown to be significantly less than proposed capacity. For example, the 2002 NETL coal plant report listed 11,455 MW of proposed capacity for the year 2005, when actually only 329 MW were constructed. In 2007, DOE forecast that 151 plants would be built in coming years; DOE's latest forecast put the figure at far less than 100.

Decisions to add capacity and the choice of fuel type depend on electricity demand growth, the need to replace inefficient plants, the costs and operating efficiencies of different options, fuel prices, and the availability of federal tax credits for some technologies. On the basis of NETL estimates of coal plant completions and cancellations and EIA forecasts of new capacity and replacement, we estimate that the total new and replacement coal capacity over the period 2000–2020 will total about 70 GW. The capital cost savings reflect savings of between $125/kW in 2000 and $250/kW in 2020 (2008 dollars). The savings in control technology include savings from the lower cost of air emissions control and savings resulting from increased by-product utilization (the largest savings in later years). We estimate that the total savings over the 20 year period from the capital costs of new plants and the control technologies for existing plants will be approximately $39 billion (2008 dollars).

3.2.2. *Reduced fuel costs*

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, and in 2011 EIA forecast that coal will provide about 45 percent of U.S. generation in 2035 (U.S. Energy Information Administration, 2011a). EIA forecasts that CFPPs built prior to 2007 generate 37 percent of all electricity in 2030 and account for 62 percent of power sector CO_2 emissions (National Energy Technology Laboratory, 2008b).

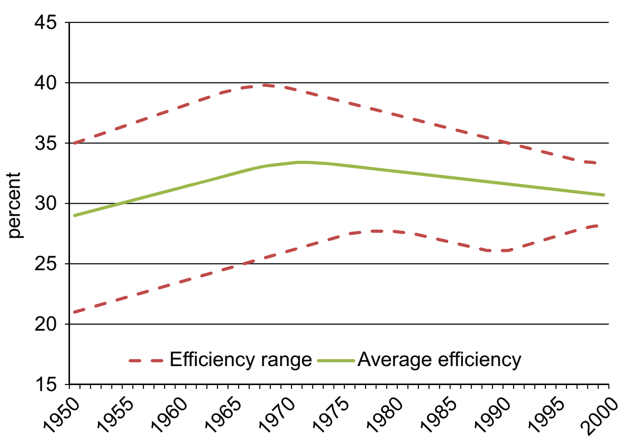

Fig. 1. Average efficiency and range for CFPP's by online year for 2007. *Source*: National Energy Technology Laboratory.

Table 4
Potential power plant efficiency improvements.
Source: National Energy Technology Laboratory.

Power plant improvements	Efficiency increase (percentage points)
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 levels (reduce)	1.1
Steam turbine (refurbish)	0.84 to 2.6

Fig. 1 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.

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, fuel costs could be reduced significantly and emissions of more than 250 MMmt of CO_2 could be avoided annually (National Energy Technology Laboratory, 2008b).

In general, the existing CFPP fleet is less efficient at converting fuel into electricity than is technically and economically possible. The fleet average efficiency is 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 (National Energy Technology Laboratory, 2007). Some PC power plants that came on line over 50 years ago achieved an efficiency of 37 percent or higher in 2007.

Advanced process control systems – particularly combustion controls and furnace sootblower controls – have become popular choices to improve power plant efficiency. Another recent development to improve 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 4. These NETL estimates are corroborated by a number of independent studies, including power plant efficiency improvements estimated by Asia-Pacific Economic Cooperation (APEC) (Levelton Engineering, Ltd., 2001).

As shown in this table, a wide range of power plant retrofits, upgrades, and refurbishings is 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 this table 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 CCT initiatives.

Using actual fuel costs for 2000–2008, projections of fuel costs for 2009–2020, and estimated, gradual efficiency improvements resulting from CCT program over the period 2000–2020, we estimate that the cumulative fuel cost savings through 2020 will total about $15 billion (2008 dollars). While substantial, this is a conservative estimate of the fuel savings possible and represents a reduction in total electricity costs, 2000–2020 of less than 0.5 percent. By comparison, U.S. electricity costs currently total nearly $300 billion annually (U.S. Energy Information Administration, 2011a).

3.2.3. *SO_2 emissions*

Even prior to enactment of the Clean Air Act Amendments (CAAA), the CCT program was addressing the likely effects of the anticipated regulations on electric power generation, and the CAAA sent a clear signal 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" (U.S. Department of Energy, 2001). Interim response to the regulation included fuel switching, allowance trading, and some installation of available emissions controls. However, meeting the post-2000 cap on SO_2 emissions required high-efficiency control technologies. Prior to the CCT 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 CCT demonstration projects redefined the state of the art in scrubber technology. Use of innovative capture technologies have nearly halved 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 are now in operation that provide SO_2 removal efficiencies of 95–98 percent. The CCT 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 three million tons. Over the first four years of the CCT program, SO_2 emissions from the 263 largest, highest emitting utility plants were about five million tons below their 1980 levels. The overall reduction in SO_2 emissions between 1990 and 1999 was 21 percent, and these reductions in emissions have occurred where they are most needed—in some of the highest emitting areas of the country.

SO_2 emissions from electric power plants in 2030 are forecast to be more than 50 percent below their 2007 level (U.S. Energy Information Administration, 2011a.) EIA projects that SO_2 emissions will decline even though coal-fired generating capacity expands, as more than 100 GW of existing coal-fired capacity is retrofitted with FGD equipment in the reference case through 2030. The amount of new coal-fired capacity added in the reference case has little impact on SO_2 emissions, because EIA assumed that all new capacity will include extensive emissions control systems. In contrast, implementation of a GHG emissions control policy could lower SO_2 and other emissions significantly by reducing generation from older, less efficient coal-fired power plants without FGD equipment.

Thus, EIA forecasts that annual SO_2 emissions from electricity generation will decline from 11.4 million tons in 2000 to 3.9 million tons in 2020. Two questions were addressed here: (i) How much of this decline can be legitimately attributed to the CCT program? (ii) What is the proper value of the SO_2 emissions avoided?

With respect to the first question – attribution of SO_2 emissions reductions to the CCT program – the methodology developed in the National Research Council (NRC) studies of federal energy R&D programs is critical. This methodology recognized that, while the CCT program was instrumental in developing SO_2 reduction technologies for electric power plants, all the future benefits of these reductions could not legitimately be attributed to the CCT program (National Research Council, 2001, 2005). Even in the absence of the CCT program, electric utilities would have been eventually forced to reduce SO_2 emissions. Therefore, NRC recommended that early in the years following the CCT program practically all the emissions reductions be attributed to the CCT program, with the portion of the attributed benefits gradually declining over the forecast period. This is the methodology we followed. Thus, for example, we attributed most of the emissions reductions in 2000 to the CCT program, but we credited only a relatively small portion of the SO_2 emissions reductions by 2020. Accordingly, we estimated that, over the period 2000–2020, the CCT program will be responsible for SO_2 reductions totaling about 37 million tons.

While the price of SO_2 emissions has fluctuated widely in recent years (Enviromarkets, 2009a), here we used a representative value of \$250/t (2008 dollars) for the period 2000–2020. Therefore, we estimate that the benefits over the period of SO_2 emissions reductions attributable to the CCT program total about \$9 billion.

3.2.4. NO_x emissions

The Acid Rain Program (Title IV of the CAAA) required major reductions in NO_x emissions, and the CCT 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 CCT program, NO_x control technology proven in U.S. utility service was essentially nonexistent (U.S. Department of Energy, 2001). However, the CCT program developed and incorporated 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 CCT program for NO_x control include:

- 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 optimize the operational and environmental performance of boilers.

As a result, over three quarters of U.S. coal-fired generation plants have installed LNBs, and reburning and artificial intelligence systems have also achieved significant market penetration. 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/MMBtu (8.6 mg/MJ) for SO_2 and 0.08 lb/MMBtu (34.4 mg/MJ) for NO_x.

While overall NO_x emissions have remained relatively constant at about 23 million tons/year since the 1980s, the average emissions rate (in terms of lb NO_x/MMBtu) 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 significantly, as have vehicle miles traveled per year.

EIA forecasts that states will need to reduce NO_x emission in order to meet the CAA standards for ground-level ozone. However, it assumed that the states will not use a cap-and-trade program, and there is thus no allowance price for NO_x.

EIA anticipates that NO_x emissions in 2030 will be about 35 percent below the 2007 level (U.S. Energy Information Administration, 2011a). Just as in the case of SO_2 emissions, the reduction occurs even as more electricity is generated at coal-fired power plants. The reference case assumes that states will require older coal-fired plants to be retrofitted with SCR equipment, and that new plants will be required to have pollution control equipment that meets the CAA New Source Performance Standards. Through 2030, an estimated 95 GW of existing coal-fired capacity is retrofitted with SCR equipment in the reference case.

Thus, EIA forecasts that annual NO_x emissions from electricity generation will decline from 5.3 million tons in 2000 to 2.1 million tons in 2020. As was the case with SO_2 emissions, we address two questions here: (i) How much of this decline can be legitimately attributed to the CCT program? (ii) What is the proper value of the NO_x emissions avoided?

As discussed with respect to SO_2 emissions, the methodology developed in the NRC studies recognized that, while the CCT 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. Nevertheless, NRC found that the DOE NO_x R&D program was one of the most successful and cost-beneficial of all DOE R&D programs; see (National Research Council, 2001, 2005) We estimated that, over the period 2000–2020, the CCT program will be responsible for NO_x reductions totaling about 16 million tons.

While the price of NO_x emissions has fluctuated widely in recent years (Enviromarkets, 2009b), here we used a representative value of $1000/t (2008 dollars) for the period 2000–2020 (Enviromarkets, 2009b). Therefore, we estimate that the benefits over the period of NO_x emissions reductions attributable to the CCT program total about $16 billion.

3.2.5. CO_2 emissions

The CCT program is an important component in addressing GHG concerns. Advanced coal-based technologies being demonstrated in the CCT program offer utilities an option to make substantial reductions in GHG emissions through enhanced efficiency of first-generation systems. However, as discussed, here we followed the EIA conventions in the AEO reports and included the effects only of legislation that has been enacted at the time the analysis is conducted. At present, no federal CO_2 control legislation has been enacted, and no related benefits from the CCT program have been included in the benefits estimation. Nevertheless, on the basis of NETL and EIA estimates of the potential impact of CO_2 control technologies, and utilizing a realistic range of CO_2 prices, we estimate that the CCT program could yield benefits over the period 2000–2020 of between $2 billion and $8 billion (2008 dollars).

3.2.6. CCT exports

The U.S. is a world leader in CCT technology and this leadership presents an opportunity to export the equipment and to license the technology to countries such as China and India, where coal-fired electricity production is rapidly increasing. We estimated the potential for U.S. exports of CCT to a growing worldwide market using methodology and data from the International Trade Administration (ITA) of the U.S. Department of Commerce (Fraser and Osborne, 2007). The ITA estimate of potential U.S. CCT exports assumed:

- All new coal-fired facilities will incorporate CCT and emissions abatement equipment.
- All coal-fired facilities will be on the scale of a supercritical 402 MW plant.
- The current market shares of CCT equipment for both the world and the U.S. will continue in their current proportions to 2030.
- Coal-fired electricity generation in 2030 will equal EIA forecasts.

The nine countries ITA analyzed are listed in Table 5—the *World Trade Atlas* and the HTS codes were used 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 available. 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.

3.2.7. Potential worldwide CCT equipment exports

ITA forecast potential CCT exports using several assumptions about future demand for U.S. CCT in Australia, Brazil, China, India, Mexico, New Zealand, South Africa, South Korea, and the EU 25. In those countries, coal is used primarily for power generation, and estimating the potential market for CCT technology required an approximation of the total world demand for imported CCT equipment and an estimate of the U.S. market share for those imports.

ITA derived the potential market for CCT from the EIA's 2030 estimates of coal-fired electricity generating capacity in those countries. It then estimated the potential world market for CCT equipment for the countries by multiplying the projected increase in coal-fired GW from 2003 to 2030 by the cost of a GW of CCT equipment in 2005 dollars ($298 million). The resulting amount is a cumulative total of CCT equipment imports from 2003 to 2030 in millions of 2005 dollars.

Table 5
Clean coal technology equipment imports in 2005 (Millions of dollars).
Source: International Trade Administration and the *World Trade Atlas* database.

Country	U.S. rank	Imports from the U.S.	Imports from the world
Australia and New Zealand	1	52.33	208.77
Brazil	1	34.93	117.34
China	3	168.68	1054.31
EU 25	2	470.54	2351.59
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

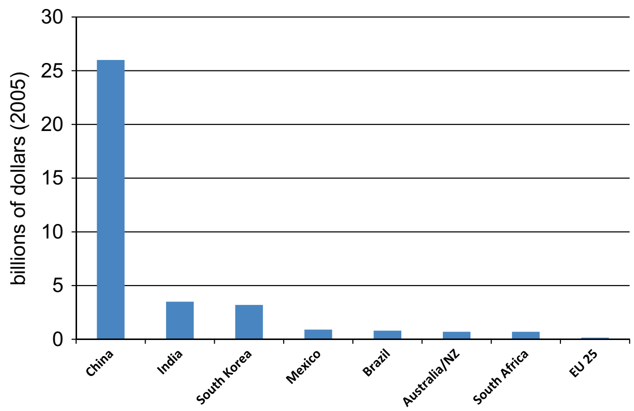

Fig. 2. Total U.S. market for CCT equipment, cumulative, 2003–2030.
Source: U.S International Trade Administration and *World Trade Atlas*.

3.2.8. CCT cumulative export benefits

ITA estimated the potential total U.S. market share for CCT equipment imports from 2003 to 2030 for each of the countries by multiplying the potential world market for CCT equipment by the current U.S. market share and derived a total of $36 billion (2005 dollars). The analysis indicated that China could potentially import $26 billion from the U.S. in CCT equipment from 2003 to 2030 and that India and South Korea may each import more than $3 billion in U.S. CCT equipment (Fig. 2).

In light of predicted increases in coal use for electricity production worldwide between 2003 and 2030, as well as overall U.S. competitiveness in emissions abatement equipment and advanced coal-fired power plants (due at least in part to the CCT program), China, India, and South Korea present the greatest value of U.S. exports of CCT, representing approximately $26 billion, $3.5 billion, and $3.2 billion, respectively. Additional markets for growth in U.S. CCT exports include Australia, Brazil, Mexico, New Zealand, South Africa, and the EU 25, for a total of $2.9 billion. U.S. exports of CCT to Australia, Brazil, China, India, Mexico, New Zealand, South Africa, South Korea, and the European Union (EU) 251 could amount to $36 billion between 2003 and 2030.

Here we modified the ITA estimates to conform to the time period and conventions of the current study:

- We converted all estimates to constant 2008 dollars.

- We estimated CCT exports for the period 2000–2020.
- We subtracted the ITA estimates for the period 2020–2030.
- Since the ITA estimates were based on trade in equipment only, we incorporated estimates of sales of U.S. licenses of CCT equipment.

We estimated the CCT technology export benefits, 2000–2020, to be approximately $32 billion.

3.2.9. CCT jobs

CCT benefits include large numbers of jobs that would be created over the period 2000–2020 by investments in new and existing coal plants, fuel cost savings, and CCT exports, which total $86 billion over the period. We first need to estimate the total number of jobs that would be created by the $86 billion, and we used two sources:

- National industry jobs estimates available from the federal government.
- Estimates of jobs impacts available from analytical studies of the employment effects of power plant investments.

With respect to national industry estimates, data are available from the U.S. Bureau of Economic Analysis (BEA) and the U.S. Bureau of Labor Statistics (BLS) that permit estimation at the national and regional levels of the likely jobs impact of expenditures on the CCT program. The nationwide economy average of all industries is about 10,700 FTE jobs per billion dollars of GDP (U.S. Bureau of Economic Analysis, 2011; U.S. Bureau of Labor Statistics, 2011). 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 large.

The North American Industry Classification System (NAICS) is the standard used by Federal statistical agencies in classifying business establishments for the purpose of collecting, analyzing, and publishing statistical data related to the U.S. business economy (North American Industry Classification System, 2012). A proxy for the CCT program includes industries such as the construction industry (NAICS 23), utilities (NAICS 22), miscellaneous manufacturing (NAICS 399), professional, scientific, and technical services (NAICS 54), and other industries. For example, in 2007:

- Employment in the construction industry was about 15,600 full-time-equivalent (FTE) jobs per billion dollars of GDP. An FTE job is defined as 2080 h worked in a year's time, and adjusts for part time and seasonal employment and for labor turnover. Thus, two workers each working six months of the year would be counted as one FTE job.
- Employment in the utilities industry (NAICS 22) was about 1700 FTE jobs per billion dollars of GDP.
- Employment in the miscellaneous manufacturing industry (NAICS 399) was about 7300 FTE jobs per billion dollars GDP.
- Employment in the professional, scientific, and technical services industry (NAICS 54) was about 9600 FTE jobs per billion dollars 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. For example, 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.

With respect to estimates of jobs impacts available from analytical studies, BBC Research and Consulting conducted a study of the jobs impact of advanced coal power plant construction programs. The study assumed that 20, 65, and 100 GW of advanced coal-based electricity generation equipped with CCS are added to the nation's generation mix. Depending on how many CCS-equipped plants are deployed, the BBC 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, with expenditures ranging from $80 billion to nearly $400 billion (BBC Research and Consulting, 2009). The BBC findings indicate that this construction program would create about 17,500 FTE jobs throughout the economy for every billion dollars of spending. Other estimates fall in the rage of about 9000 to 16,000 jobs per billion dollars of spending.

On the basis of the federal data, the BBC study, and other relevant studies we estimate that the CCT program would create about 14,000 jobs per billion dollars of expenditures (2008 dollars). Thus, over the period 2000–2020, we estimate that the CCT program will create

Table 6
Summary of CCT benefits, 2000–2020.
Source: Management Information Services, Inc.

Benefits category	**Benefits** (dollar figures in billions of 2008 dollars)
Capital and technology cost savings in new and existing plants	$39
Fuel cost savings	$15
Avoided environmental costs	$25
CCT exports	$32
Total monetary benefits	**$111**
Jobs (thousands)	
Total cumulative	1200
Average annual	60

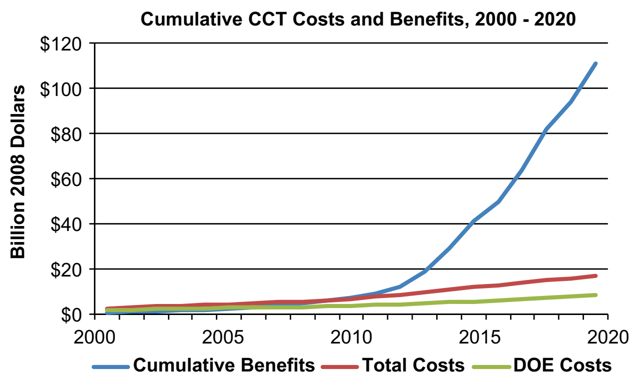

Fig. 3. Cumulative CCT costs and benefits, 2000–2020. *Source*: Management Information Services, Inc.

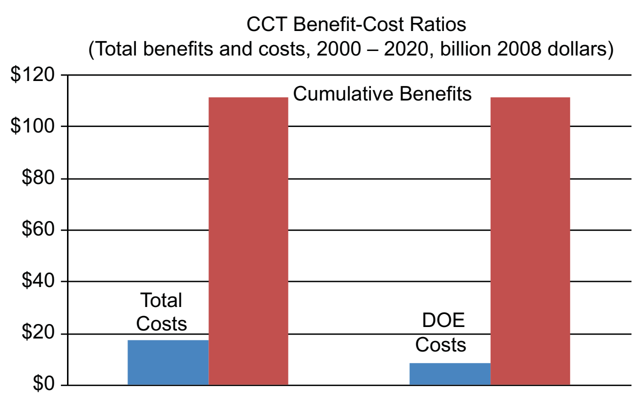

Fig. 4. CCT benefit–cost ratios. (Total benefits and costs, 2000–2020, billion 2008 dollars). *Source*: Management Information Services, Inc.

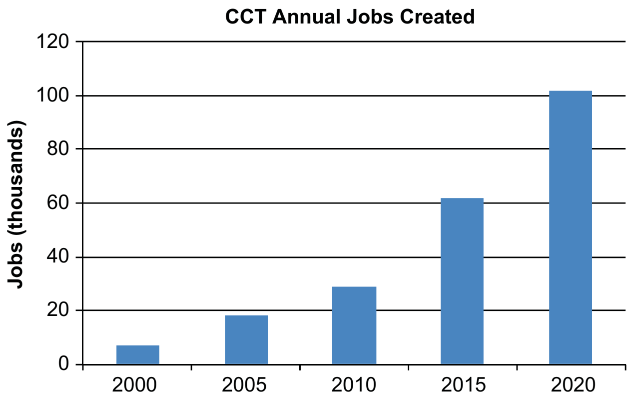

Fig. 5. CCT annual jobs created. *Source*: Management Information Services, Inc.

about 1.2 million jobs throughout the economy. The 20-year average would be about 60,000 jobs per year. However, the number of jobs will be larger in 2020 than in 2000. Thus, in 2000 the CCT program created between 5000 and 10,000 jobs and, by 2020, it will be creating about 100,000 jobs annually. At present, the program is creating nearly 30,000 jobs and by 2020 it will create over 100,000 jobs; importantly, these are predominately manufacturing-oriented, well paying jobs—which are critical importance to the U.S.

4. Summary and implications

Our major findings are summarized in Table 6 and Figs. 3–5. Table 6 summarizes the CCT program benefits by category and shows 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.
- Total jobs created total 1.2 million, with an annual average of about 60,000 jobs created.

Fig. 3 shows the cumulative CCT benefits, DOE costs, and total costs over the period 2000–2020, and Fig. 4 shows the CCT benefit cost ratios. These figures illustrate that:

- Cumulative benefits exceed cumulative DOE costs after 2005.
- Cumulative benefits exceed cumulative total costs after 2008.
- Every year after 2008, cumulative benefits exceed both total and DOE costs by larger orders of magnitude.
- Every year, the ratio of benefits to costs increases.
- By the end of the forecast period, annual benefits exceed annual total costs by about 17-to-1.
- By the end of the forecast period, annual benefits exceed annual DOE costs by more than 30-to-1.
- By the end of the forecast period, cumulative benefits exceed cumulative total costs by about 7-to-1.
- By the end of the forecast period, cumulative benefits exceed cumulative DOE costs by more than 13-to-1.
- By the end of the forecast period, cumulative benefits exceed cumulative industry costs by more than 13-to-1.

This benefit-cost pattern is typical of programs where substantial up-front investments in R&D, technology, and demonstrations are required to produce long term economic returns. Further, in both government and industry, investments with benefit-cost ratios in the range of between 7-to-1 and 13-to-1 are extremely attractive.

Fig. 5 illustrates that the CCT program will have significant job creation benefits. As noted, the total number of jobs created, 2000–2020, is approximately 1.2 million, which represents an annual average of about 60,000 jobs created. However, Fig. 5 shows that job creation increases dramatically over time: By 2020, nearly 20 times as many jobs are being created annually as in 2000.

Thus, the benefits of the CCT program greatly exceed the costs, and this favorable relationship increases in magnitude as time progresses. Further, our estimates may actually underestimate the long term benefits of the CCT program. As noted, we did not include the potential benefits of CO_2 reductions in the CCT program benefits forecast here. If we 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.

More significant, here we 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 kW h 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 $500 billion to $1 trillion and could include the creation of nearly one million additional jobs (National Energy Technology Laboratory, 2008a; Considine, 2006; Bezdek and Wendling 2012b).

Further, we did not quantify several other valuable, indirect benefits to the U.S. attributable to CCT, including: (i) National security benefits, such as reduction in oil imports, use of own-source coal, and co-production of power and environmentally attractive fuels, such as Fischer–Tropsch liquids and hydrogen; (ii) maintenance of diversity of energy resource options by avoiding over-reliance on natural gas for power generation and reducing energy price volatility and supply uncertainty; (iii) stimulation of a domestic high-technology manufacturing industry and U.S. energy technology leadership; and (iv) reduction in the U.S. trade deficit.

Finally, in this era of increasing scrutiny of federal programs and spending, it is worth noting that the U.S. General Accountancy Office (GAO) – perhaps the most respected and skeptical critic of federal programs – has repeatedly found the federal CCT program to be exemplary and well managed. For example:

- DOE has numerous examples of successes in the program, including commercialization of some technologies—the primary way DOE measures success. This program [CCT] serves as an example to other cost-share programs in demonstrating how the government and the private sector can work effectively together to develop and demonstrate new technologies (U.S. General Accounting Office, 2001.)

Table 7
Summary of the CCT program.
Source: Management Information Services, Inc.

Duration	1986—present
Technologies supported	Low NO_x burners, selective catalytic reduction, FDG, FBC, IGCC
Federal government program cost[a]	$8.5 billion (2008 dollars)
Industry cost share[a]	$8.5 billion (2008 dollars)
Total monetary benefits[a]	$111 billion (2008 dollars)
Total ROI[a]	7-to-1
Federal government ROI[a]	13-to-1
Industry ROI[a]	13-to-1
Total cumulative jobs created[a]	1.2 million

[a] Estimated through 2020.

- We noted that the Clean Coal Technology program offered an example of the government and the private sector working together effectively to develop and demonstrate new technologies. We identified lessons learned from the program that could be applied to other cost-share programs (U.S. General Accounting Office, 1994).

These GAO findings are corroborated by the NRC studies of DOE programs; for example: "By orders of magnitude, the largest benefits from the DOE R&D programs were realized as avoided environmental costs from the NO_x reductions achieved by a single fossil energy program. The NO_x reduction achieved is an environmental benefit that private markets cannot easily capture (National Research Council, 2001)."

An overall summary of the CCT program parameters, benefits, and costs is given in Table 7.

5. Why was the CCT program a success?

The CCT program was not without its problems. There were some management weaknesses, various CCT demonstration projects experienced difficulties in meeting cost, schedule, and performance goals, and two projects went bankrupt. Delays and cost overruns occurred, in part, because of changes in a project's site as well as a project's participants. Further, DOE extended deadlines several times on some projects to allow their sponsors to restructure the projects, find suitable alternative project sites, and obtain financing commitments to make the projects economically viable (U.S. General Accounting Office, 2000; U.S. General Accounting Office, 2001).

Nevertheless, the CCT program was an overall success, and this success can be attributed to a variety of factors, including:

- Full funding was provided (through advanced appropriations) to cover the total federal share of project costs, and this increased participant confidence that federal funds would be available for multiyear projects.
- Cooperative agreements between the federal government and industry allowed participants more flexibility in managing their projects, providing clear instructions on the roles and responsibilities of the government and the nonfederal participants.
- Federal cost-sharing limits helped to ensure the private sector participants' commitment.
- Early industry participation in developing solicitation documents helped industry participants structure responsive proposals.
- A comprehensive process for evaluating and selecting projects and keeping it free of political influence helped ensure the program's integrity.
- Multiple, sequential solicitations for project proposals enabled DOE to modify the program's objectives to meet changing needs and to benefit from the lessons learned.

In sum, our major finding is that the federal government's Clean Coal Technology program is a notable success: It 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, increased energy efficiency, support for U.S. manufacturing, increased U.S. exports, enhanced national security, and job creation. Further, these benefits are rapidly increasing and will continue to do so as CCT is deployed.

These findings have implications beyond the CCT program. The U.S. has initiated major carbon control and sequestration (CCS) programs to address climate change concerns. The findings reported here indicate that DOE CCS investments will also produce significant benefits and will repay costs many times over.

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