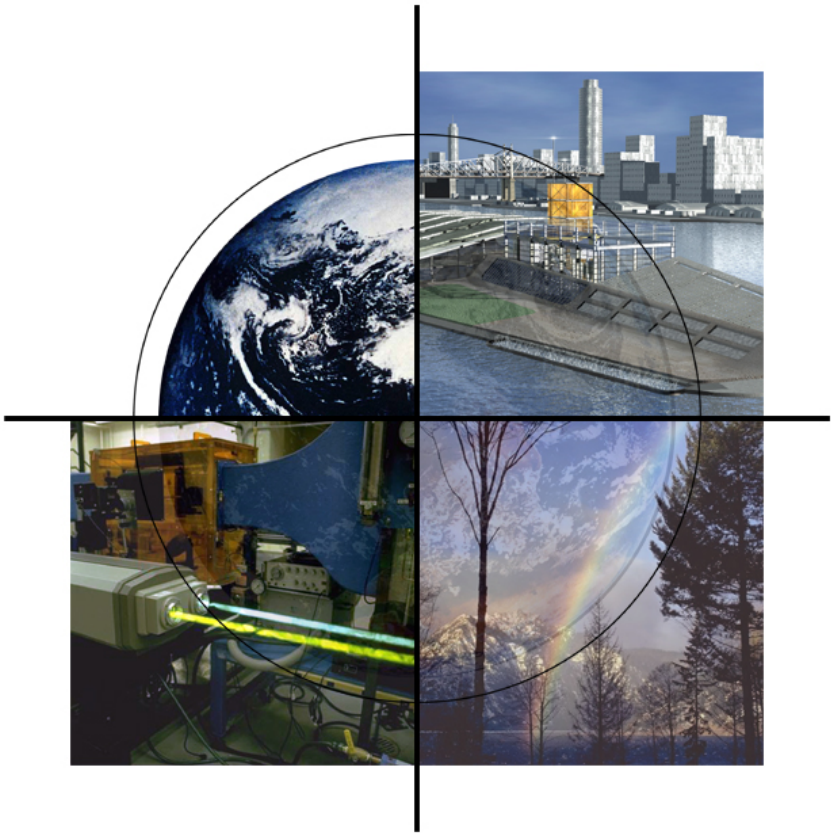
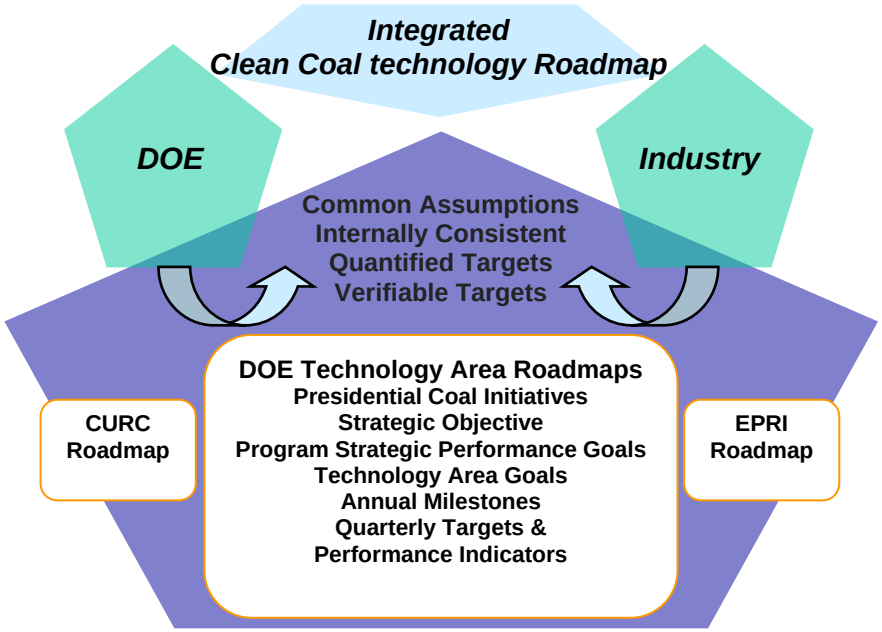
Clean Coal Technology Roadmap
"CURC/EPRI/DOE Consensus Roadmap"
Background Information



Go to Roadmap

DOE & Industry -- Realizing Coal's Benefits



The Clean Coal Technology Roadmap is the U.S. Department of Energy's plan to develop the technology needed for future energy plants that use coal to produce electricity and, when economically favored, transportation fuels, and other valuable energy products as well; have near-zero emissions including CO_2; are highly efficient; and have costs comparable to today's technology. The Roadmap was developed cooperatively by the National Energy Technology Laboratory, the national laboratory of the DOE Office of Fossil Energy, and the coal and power industry, notably the Coal Utilization Research Council (CURC) and the Electric Power Research Institute (EPRI). The Roadmap effectively integrates the CURC, EPRI, and previous DOE product line roadmaps, while supporting the Presidential Coal Initiatives (see page 4) and DOE strategic objectives and performance goals.

The background information contained herein provides perspective on the targets selected and the technology needs that were identified to realize the targets. The comments on work being carried out relate to DOE supported activities. It is recognized that work being carried out solely in the private sector, work supported by other agencies (e.g. states), and international projects also represent important contributions to achieving the roadmap goals.

Clean Coal Technology Roadmap Embodies Vision 21 Objectives

Remove environmental concerns associated with fossil fuel use for electricity & transportation fuels through better technology

- "Near-zero" emissions (coal as clean as gas)
- CO_2 management
- High efficiency
- Water use
- By-product utilization
- Sustainable (no future legacies)
- Flexible (feedstocks, products, siting)
- Timely deployment of new technology
- Affordable, competitive with other energy options

Vision 21 is the DOE's initiative to effectively remove environmental concerns associated with the use of fossil fuels for producing electricity and transportation fuels through better technology. The goal of Vision 21 is to develop the design basis for near-zero emission, high-efficiency energy plants by the year 2015, and begin to deploy these plants by 2020. Vision 21 coordinates objectives and activities in the DOE product lines to achieve its goals by 2020. Vision 21 addresses all environmental issues of concern, including sulfur and nitrogen oxides, CO_2, water use, and by-product utilization, as well as flexibility (with respect to feedstocks, products and plant siting), time of deployment of new technology, and cost competitiveness.

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Coal Roadmap Defines Pathway to Near-Zero Emissions

- **Unifies government & industry coal program roadmaps**
  - Integrates CURC, EPRI, DOE roadmaps
  - Supports U.S. National Energy Policy & Presidential Initiatives
- **Maintains high-level approach**
  - Sets performance/cost targets
  - Specifies destinations & critical technology needs
- **Quantifies coal program benefits**
  - Economic, environmental, security

Near-zero emissions targets include air, liquid, and solid discharges such as SO_x, NO_x, particulate matter, Hg, scrubber effluents, and fly ash. The Roadmap supports the U.S. National Energy Policy[1] and the Presidential Initiatives[2]. The Roadmap maintains a "high-level" approach, setting performance and cost targets for improvements to existing plants and also future generations of plants. Roadmap "destinations" are established and the critical technology needed to achieve those destinations are described. The roadmap also quantifies the benefits of the Coal and Power research, development, and demonstration program, and compares the quantified benefits to the program costs.

[1] National Energy Policy, May 2001, U.S. Government Printing Office, Washington, DC 20402.

[2] The Presidential Initiatives include Clear Skies (caps SO_x, NO_x and Hg emissions), Clean Coal Power (demonstrates advanced coal technologies), Climate Change (reduces emissions of the greenhouse gas, CO_2), Homeland Security (increased the security of our energy production and delivery infrastructure), and Hydrogen (the FutureGen initiative aims to design, construct, and operate a 275 MW (nominal) plant that combines an integrated gasification combined cycle (IGCC) plant that produces electricity and hydrogen with CO_2 sequestration.

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Clean Coal Technology Roadmap Addresses Short- and Long-Term Needs

- **Short-term: existing fleet**
  - Cost-effective environmental control technologies to comply with current and emerging regulations
- **Long-term: Vision 21**
  - Near-zero emissions power and clean fuels plants with CO_2 management capability

The Clean Coal Technology Roadmap addresses the needs of both the existing fleet of coal-fired power plants and future near-zero emission plants. Current plants need technologies to help meet current and emerging regulations, notably for mercury, nitrogen oxides, and particulate matter. Future plants need cost-effective technologies for near-zero emissions and managing CO_2.

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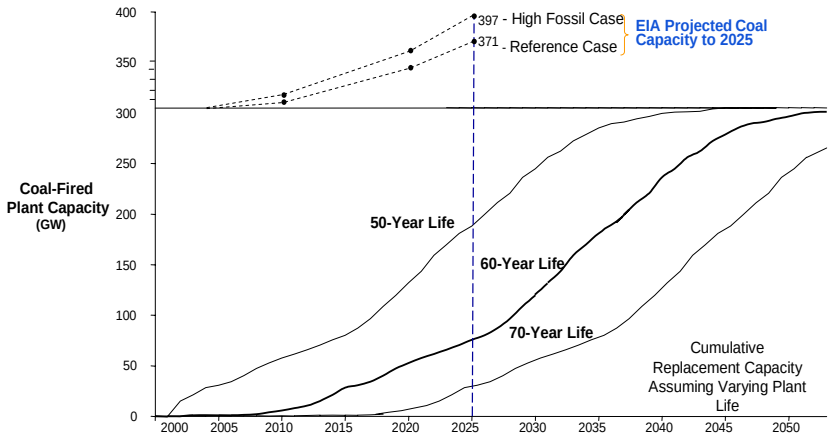
Market for New Coal Power Plant Technology



Coal fired power plants generate approximately 56% of the U.S. electricity. A healthy economy requires the effective utilization of the existing infrastructure as new technologies are introduced. New plant technology will be needed to replace existing plants and to meet increased power generation needs. The figure provides perspective on the current coal-fired electricity capacity in the U.S., the projected capacity to 2025 based on the Energy Information Agency projections[3], and the potential need for existing coal plant replacement based on age.

Life extension or replacement of existing plants: There is approximately 300 GW of coal-fired power generation capacity in the U.S. today. The figure shows what replacement capacity would be required if plants were to shut down after a given age -- cumulative replacement capacity assuming plant life of 50, 60 and 70 years. Thus, in 2020, if plants were shut down and no longer used once they reached a life of 60 years, the cumulative replacement power generation capacity (or the need for life extension technology such as repowering) would be approximately 50 GW.

New coal capacity needs: The Energy Information Administration (EIA) issues an annual outlook each year that forecasts the electric power generation needs for the U.S. The Annual Energy Outlook for 2003 presents forecasts of energy supply, demand and prices through 2025 using the National Energy Modeling System (NEMS). These projections include forecasts for coal plant capacity. The total coal capacity projected for the reference case in 2025 is 371 GW. The high fossil case assumes the introduction of advanced technology and projects 94 GW of IGCC plants by 2025.

Current Trends: Recent developments with the price of natural gas and the resulting implications for the use of gas for power generation are expected to result in the EIA projections being conservative with regard to the need for increased coal capacity.

[3] Annual Energy Outlook 2003, DOE/EIA – 0383 (2003), January 2003.

Key Assumptions

- **Innovative, new technologies needed to achieve goals**
  - Today's technologies not designed for near-zero emissions or carbon management
  - Incremental improvements will not meet future requirements
  - Adding on equipment to existing plants too complex & costly

- **Effectively managing transition to new technologies is critical**
  - 60% of available U.S. capacity 20-40 years old
  - New technologies needed in 10-15 years to replace retiring plants
  - Must meet electricity demand & minimize disruptions

Issues

- **Requirements of existing fleet & new plants are different**
  - Existing plants: meet regulations at lowest cost
  - Future plants: meet Vision 21 objectives
  - Approach: separate targets for existing & new plants

- **All technologies not equal**
  - Performance capabilities differ
  - Technology choice depends on application
  - Approach: Roadmap targets represent best performance achievable

Technology Advances are Required
Current Technology Cannot Meet Our Future Requirements

Most of today's coal-fired power generation plants are based on 50-100 year-old technology. As environmental concerns evolved over time old technologies were retrofitted with add-on equipment to accommodate various environmental regulations as opposed to developing new integrated system designs. The basic technology was not developed to be ultra-clean or to accommodate the potential need to minimize greenhouse gas emissions such as CO_2. Given the state of coal plant technology, there is a need to develop lower cost, efficient technology options that will permit the effective use of our existing coal plant asset base while meeting environmental regulations as well as new plant technologies to meet future needs. Thus the coal program roadmap identifies separate targets for existing and new plants.

There are many candidate approaches to meet the long-term need for near-zero emission coal plants. Innovative combustion technology can use oxygen making it easier to capture CO_2. Gasification allows for the production of multiple products such as electricity and transportation fuels and allows feedstock flexibility. Hybrid concepts such as combined combustion and gasification or combining power generation components such as fuel cells and combustion turbines can achieve high system efficiencies. The Roadmap allows for the development of a range of technologies to meet the range of applications and constraints anticipated for future U.S. energy systems.

Coal Power Plant Performance Criteria

- **Air Emissions**
  - SO_2
  - NO_x
  - Particulate Matter
  - Hg
- **Carbon Management**
- **By-Product Utilization**
- **Water Use and Discharge**
- **Plant Thermal Efficiency**
- **Reliability/Availability**
- **Capital and Product Cost**

Environmental and economic performance targets for new coal-fired plants are established for 2010 and 2020. Emission control and economic performance targets for existing plants are defined for 2005 and 2010.

There is interest to understand other concerns that are not incorporated into the performance targets. These include studies on trace components of solid by-products from coal utilization (e.g. stringent drinking water regulations may influence current utilization and disposal practices) and consideration of non-mercury HAPs (hazardous air pollutants of interest include arsenic, cadmium, chromium, nickel). Specific performance targets were not projected for these environmental concerns since there is no consensus on what level of control may be required. It is noted that the advanced technology being considered for the future near-zero emission plants would address these concerns.

Clean Coal Technology Roadmap
New Plant Performance Targets
(Represents best integrated plant technology capability)

	Reference Plant[1] *	2010	2020 Vision 21
Air Emissions	98% SO_2 removal	99%	>99%
	0.15 lb/10^6 Btu NOx	0.05 lb/10^6 Btu (1)	<0.01 lb/10^6 Btu
	0.01 lb/10^6 Btu Particulate Matter	0.005 lb/10^6 Btu (2)	0.002 lb/10^6 Btu
	Mercury (Hg)	90% removal (3)	95% removal
By-Product Utilization	30%	50%	near 100%

Footnotes (1), (2), (3) refer to existing plant targets; see text at right.

* Plant that can be built using current state-of-the-art technology; plant meets New Source Performance Standards (NSPS).

Performance targets are identified for new coal-fired power plants. These targets represent the best emission performance that would be available consistent with the integrated system efficiency and cost targets. The following comments provide perspective on the reference plant and the targets.

Reference Plant:

- NO_x levels below 0.15 lb/10^6 Btu can be achieved with a combination of advanced combustion and SCR technologies
- Some Hg reduction achieved as co-benefit with existing environmental control technologies
- By-product utilization represents an average for existing plant locations; actual plant utilization ranges from essentially zero to near 100%

New Plant Targets:

- By-product utilization in 2020 assumes technology will be available for near 100% use; the market size will depend on economics

Existing Plant Targets: Targets for existing plant emission performance are:

(1) For NOx, reduce cost for achieving <0.10 lb/10^6 Btu and 0.15 lb/10^6 Btu to ¾ that of SCR by 2010 and 2005 respectively.

(2) Achieve PM targets for existing plants in 2010: 99.99% capture of 0.1-10 micron particles.

(3) Achieve 50-70% Hg reduction at less than ¾ of the baseline cost estimates of current activated carbon injection costs by 2005.

Clean Coal Technology Roadmap
New Plant Performance Targets
(Represents best integrated plant technology capability)

	Reference Plant	2010	2020 Vision 21
Plant Efficiency (HHV)	**40%**	**45-50%**	**50-60%**
Availability	**>80%**	**>85%**	**≥90%**
Plant Capital Cost $/kW	**1000 – 1300**	**900 – 1000**	**800 – 900**
Cost of Electricity ¢/kWh	**3.5**	**3.0 - 3.2**	**<3.0**

The plant efficiency, availability and cost targets are for plants without carbon capture and sequestration and which use current cooling tower technology. Projections for the cost of electricity with carbon capture and sequestration are incorporated in the carbon management section of the Roadmap. (page 11)

There are many different coal-fired plant cycles proposed that have the potential to meet the environmental goals and cost of electricity targets. The efficiency and capital cost for each concept will differ. Therefore, a range is used for the 2010 and 2020 efficiency and plant capital cost targets. The range reflects the range in performance that is projected for different coal-fired plant cycle concepts that have the potential to meet the cost of electricity target while achieving the environmental goals.

Plant availability is important and the goal to improve on existing availability while incorporating multiple advanced component technologies is recognized to be a challenge. Availability is defined by the North American Electric Reliability Council as the percent of time capable of generating power. The cost of electricity is the bus-bar cost in today's dollars. The reference plant cost of electricity is based on $1000/kW capital cost and a fuel cost of $\$1.20/10^6$ Btu.

Carbon Management

- **Carbon management applicable to all carbon-based fuels**
  - Coal second leading CO_2 source after petroleum
  - Power plants produce 1/3 of total carbon emissions

- **Coal Roadmap includes carbon management goals**
  - >90% removal of CO_2 (including sequestration) @ <10% increase in cost of electricity
  - Near-zero emission power & multi-product plants capable of CO_2 capture & sequestration
- **Milestones on path to achieving goals**
  - Field demonstration(s) of capture/sequestration (2010)
  - Demonstrate capture/sequestration meeting program cost goal (2020)

Approximately one third of the United States carbon emissions come from power plants. These sources would be convenient for CO_2 capture except that most use air-fired combustors that exhausts CO_2 diluted with nitrogen. The Global Climate Change Initiative (GCCI) calls for an 18% reduction in the carbon intensity (the ratio of greenhouse gas emissions to economic output) of the United States economy by 2012. Given the electric power generation contribution to greenhouse gas emissions, it is important to develop options for reducing CO_2 emissions from coal-based energy systems.

Studies[4] show that carbon capture using today's power generation and capture technology result in efficiency penalties of 9-23% and increases in the cost of electricity ranging from 22 to 44%. These estimates do not include the cost of sequestration.

The Roadmap objectives are to provide cost-effective, environmentally-sound technology options that ultimately lead to a reduction in greenhouse gas intensity and stabilization of overall atmospheric concentrations of CO_2. The program goals focus on development of systems to the point of commercial deployment. The scope of work includes direct capture and sequestration of greenhouse gas emissions from fossil fuel conversion processes and the development of instrumentation and measurement technology to monitor and verify sequestration of CO_2.

[4] The Cost of Carbon Capture, David & Herzog, Fifth International Conference on Greenhouse Gas Control Technologies, August 2000.

Clean Coal Technology Roadmap
Performance Targets: Co-Production Plants*

(Electricity and Liquid Fuels or H_2)

	2010	2020 Vision 21
Plant Efficiency	45 - 65%	60 - 75%
Plant Capital Cost	$35,000/bpd	<$25,000/bpd liq. $3-7/scfd H_2
Product Cost - Liquids - Hydrogen	$30/bbl --	<$30/bbl $3-5/$10^6$ Btu

*Efficiency and costs depend on ratio of fuel to electricity.

The Vision 21 energy 'plant' uses advanced technology configurations that are tailored to meet specific market needs. The previous efficiency and cost targets focused on plants for which the only product will be electricity. Energy plants may produce electricity and other products such as clean transportation fuels, hydrogen, chemicals, or steam. The coal program roadmap includes targets for these co-production energy plants.

Two studies[5,6] projected plant performance and costs for different plant concepts that could co-produce liquid fuels or hydrogen with electric power. The performance targets for the coal-to-fuel energy plants are based on this work.

Specific co-production plant designs are being investigated as part of three NETL projects[7]. A CCPI (Clean Coal Power Initiative) project to build a co-production plant was announced in 2003[8]. The FutureGen[9] initiative aims to design, build and separate a plant that produces electricity and hydrogen with CO_2 sequestration.

[5] Coproduction of Ultra Clean Transportation Fuels, Hydrogen, and Electric Power from Coal, D. Gray and C. Tomlinson, Mitretek Technical Paper, MTR 2001-43, July 2001.
[6] Hydrogen from Coal, D. Gray and E. Tomlinson, Mitretek Technical Paper, MTR 2002-31, July 2002.
[7] Coproduction of Power, Fuels and Chemicals – NETL Topical Report #21, September 2001.
[8] NETL CCPI Fact Sheet, July 2003.
[9] FutureGen – A Sequestration and Hydrogen Research Initiative, DOE FE Techline, February 2003.

Environmental Concerns - Water

- **Water & energy production closely linked**
  - National Energy Policy recognizes environmental impacts
- **Emerging policy responding to concerns**
  - Clean Water Act changes
  - State & regional decisions
- **NETL addressing potential technology needs**
  - Performance targets being developed
  - Reduce fresh water use (target for 2010 under study)
  - Near-zero water use option for power plants (by 2020)

Electricity production requires a reliable, abundant, and predictable source of water, a resource that is in limited supply in parts of the United States and much of the world.

Current and future requirements under the Clear Water Act (CWA) and Safe Drinking Water Act (SDWA) have the potential to impact the design and operation of fossil-fuel-fired electric generators. In addition, the U.S. Environmental Protection Agency (EPA) has recently proposed regulations under §316(b) of the CWA that would potentially limit the amount of water used by power plants by requiring the installation of wet or dry closed-loop cooling systems. Furthermore, on a state or regional basis, the lack of available fresh water has prevented the siting and permitting of new power plants.

The relationship between water and electricity production is a topic that is receiving increased attention by industry, regulatory agencies, and the public. In recognition, DOE/NETL is initiating an R&D effort focused on the development of advanced technologies and concepts to improve the management of water used by coal-based power systems. Performance targets for 2010 and 2020 are currently under study.

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Clean Coal Technology Roadmap
Destinations and Critical Technology Needs

Integrated Energy Plants

Destinations

- Power & multi-product energy plants w/o CO_2 capture meeting 2010 performance targets (2010)
- Near-zero emission, sequestration-ready energy plants: Vision 21 plants (2020)

Technology Needs

- Module designs, systems integration, plant simulation capability, sensors & controls ("smart" plant operation), improved materials

Vision 21 plants will use multiple technology modules that incorporate advanced technology. These plants will have unique systems integration issues. For example, increased plant efficiency drives the need for integration to minimize thermal energy losses; the ability to meet near-zero emission targets at a lower cost drives the need to incorporate multiple process functions into single module designs (e.g., combined shift reaction and gas separation in a single unit operation) resulting in additional process control requirements. Thus, one of the critical technology needs is to demonstrate integrated energy plant operation that utilize these advanced technologies.

Systems analysis and engineering will be central to successfully integrating these advanced technologies. The sub-systems must be compatible with one another. Designs will need to be as simple as practicable, yet high thermal efficiency requires 'tight' integration of sub-systems. These requirements result in complex inter-dependencies leading to start-up, operation, control and reliability issues. Development of "smart" plant operation technology represents an important need. Future energy plants will need to achieve the high plant reliability targets (through design, operation and minimizing maintenance requirements) while adapting to multiple product demands (product flexibility and quality) and maintaining near-zero emissions. The "smart" plant will incorporate real-time monitoring and diagnostics and integral plant communication technology to realize these goals and assure safe operation. Identifying strategic integrated plant designs to test and demonstrate integrated plant operation will be an important part of the path to achieve the program goals.

Clean Coal Technology Roadmap
Destinations and Critical Technology Needs

Emissions Control - Existing Plants

Destinations

- Technology available for meeting Clear Skies, NO_x, PM, Hg, by-product, & fresh water use targets (2010)

Technology Needs

- Low-NO_x combustion, low-cost catalysts, improved gas filtration and electrostatic separation, sorbent systems, multi-pollutant controls, dry cooling systems, sensors

Technology options are sought that will enable the current fleet of coal-fired power plants to comply with future environmental regulations at a low cost, while simultaneously building the foundation for entirely new environmental management systems.

The compliance landscape is undergoing the most significant changes since the passage of the original Clean Air Act. The potential for regulatory change is driven by the following: national emissions caps, similar to the current SO_2 cap, under a multi-pollutant control strategy such as Clear Skies; control of mercury and other hazardous air pollutants under Title III of the Clean Air Act Amendments; water-quality and use issues associated with power production, including air pollutant loading to surface water, constraints in water availability, and cooling water intake structure regulations; and solid residue and byproduct issues, including increased volumes and related impacts associated with more stringent regulatory requirements.

Projects are underway for advanced environmental control technology and ancillary systems in the following areas: A) advanced NO_x emissions control, B) mercury emissions control, C) particulate-matter emission control, D) coal utilization by-products, E) air quality research, and F) energy-water interface. Field demonstrations (utilizing up to 600 MW scale plants) are being carried out in the areas of innovative NO_x, mercury and particulate control technologies as well as exploring opportunities for by-product utilization. Laboratory testing and modeling projects support these demonstration and other existing plant initiatives. Advances in the above areas will aid current systems, as well as providing the foundation for lower cost systems for new plants.

Clean Coal Technology Roadmap
Destinations and Critical Technology Needs

Advanced Combustion

Destinations

- Fuel flexible combustion (2005)
- Ultra-low NO_x combustion (2005)
- Supercritical steam – 1200°F (2010)
- Ultra-supercritical steam – 1400°F (2020)
- Nitrogen-free combustion (sequestration-ready) (2020)

Technology Needs

- Cofiring, CFB (circulating fluid-bed) scale-up, advanced boiler tube & steam turbine materials, coal-oxygen combustion, oxygen "carriers," sensors & controls

Combustion technology needs are focused on three areas: advances that allow the effective use of existing plant assets (e.g., use of expert system techniques to improve emissions control; repowering technology to increase plant capacity, increase efficiency, and meet environmental requirements), advances to current plant concepts that will bridge to future plants, (e.g., ultra-supercritical steam to achieve higher efficiency), and future plant designs that have near-zero emissions including CO_2. Fuel flexibility and ultra-low NO_x combustion are near-term objectives to enhance existing plant capability and performance. The capability to achieve operation with ultra-supercritical steam allows for increased plant efficiency. This capability will benefit plants built in 2010 and be available for integration in future near-zero emission plant concepts. Nitrogen-free combustion includes innovative concepts that include oxygen combustion and concepts that utilize chemical oxygen carriers. Projects have been initiated in each of these areas.

Clean Coal Technology Roadmap
Destinations and Critical Technology Needs

Advanced Gasifier System

Destinations

- Lower cost, increased efficiency, higher availability (2010, 2020)
- Advanced, low-cost air separation 2010)
- Dry solids feed/fuel flexible (2010)

Technology Needs

- More efficient, lower cost gasifier designs (transport & others), improved refractory materials, air separation, more efficient & reliable feed systems

Integrated gasification combined cycle (IGCC) plants are the cleanest coal-based power systems available today and represents an effective means of capturing carbon dioxide for sequestration. The capital cost and reliability, availability and maintainability (RAM) of gasification processes are two key drivers in determining the commercial deployment of gasification technology.

Gasifier concepts are being investigated to lower the plant capital cost. Higher throughput designs; improved refractory life; the development of low-cost, reliable dry feed technology; and increased carbon conversion (98% target) are projected to contribute approximately 10% reduction in plant cost and approximately 5 percentage point increase in plant efficiency. Advanced air separation technology is projected to contribute a 5-7% reduction in the capital cost. The next generation air separation technologies require efficient thermal integration with the gasifier and the energy conversion technology (e.g., gas turbine).

Projects are being carried out in each of these areas. The low-temperature transport gasifier development at the Power Systems Development Facility in Wilsonville, AL illustrates one new gasifier concept. Partial gasification technology is being pursued including hybrid gasification/combustion concepts. Air separation membrane technologies under development promise to reduce capital costs and improve plant efficiency.

Clean Coal Technology Roadmap
Destinations and Critical Technology Needs

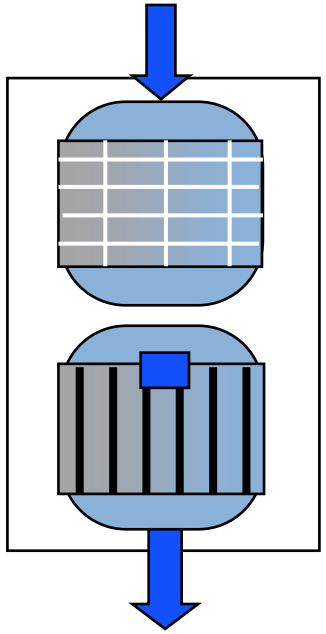
Gas Cleaning

Destination

- Systems to meet environmental & process requirements at optimal temperature & pressure for oxidizing & reducing environments (2010)

Technology Needs

- Multi-pollutant control, filter materials & systems, regenerable sorbents, sensors & instrumentation



Gas cleaning requirements are driven by environmental and process considerations. The process requirements for future coal-fired plants are generally far more stringent than what is needed to meet environmental regulations*. Gas cleaning removes gas-phase contaminants and particulates to avoid corrosion, erosion or deposition in downstream energy conversion equipment. This equipment can include combustion turbines, fuel cells, catalytic reactors to convert syngas to fuels, separations technologies for capturing CO_2 or separating H_2, and heat transfer equipment. The design of the gas cleaning system must also consider process control and operability issues – e.g. compatibility in operating temperature and pressure transients during turndown, start-up or shut-down. The approach for gaseous contaminant control is usually to employ sorbents. Sorbent performance, cost, regenerability and attrition resistance are common barriers. One of the challenges is how to design a system to meet the multi-pollutant control needs that is simple, low cost and reliable.

*Specific process gas cleaning requirements will depend on the downstream unit operations selected for the plant design. The requirements will differ for reliable operation of membrane separation technology, fuel cells, turbines, and other component designs. Representative requirements for fuels or chemicals production include total sulfur <60 ppb, total halide < 10 ppb, NO_x < 100 ppb as well as specifications for other trace chemicals.

Clean Coal Technology Roadmap
Destinations and Critical Technology Needs

Syngas Utilization for Power and Fuels

Destinations

- Clean fuels production from syngas (2010)
- Increased power, fuels conversion efficiency (2010)
- Reduced emissions for syngas combustion (2010)
- Co-production of electricity & hydrogen (2020)
- Hydrogen/air & natural gas/oxygen turbines (2020)
- Solid oxide fuel cell (SOFC), affordable @100 MW scale (2020)
- Advanced hydrogen separation (2020)

Technology Needs

- Fuels synthesis reactors, syngas combustion, fuel cells, fuel-flexible turbines, hybrid fuel cell-turbine systems, hydrogen combustion, air separation, hydrogen separation

The destinations for the coal program roadmap are coal-based energy plants. Gasification based plants produce a synthesis gas (syngas) that can be used to produce power, liquid fuels, hydrogen, chemicals or process heat. In order to achieve the overall energy plant efficiency and cost targets, advances are required beyond the currently available technology for producing these products. The roadmap defines programs to develop gas separation technologies (e.g. hydrogen) and power generation technologies (e.g. solid oxide fuel cells, hydrogen turbines, oxygen-fired gas turbines). Programs are also defined to build integrated co-production plants.

A specific integrated co-production plant program is FutureGen[9]. FutureGen is an integrated CO_2 capture and sequestration and hydrogen research initiative to design, build and operate a nearly emission-free, coal-fired electric power and hydrogen production plant. The plant will be based on gasification technology which produces a synthesis gas. The syngas will be used to produce hydrogen and electric power. The plant will test new syngas utilization technology as well as other advanced plant components.

[9]FutureGen – A Sequestration and Hydrogen Research Initiative, DOE FE Techline, February 2003.

Clean Coal Technology Roadmap
Destinations and Critical Technology Needs

CO_2 Capture & Sequestration

Destinations

- MW-scale capture demonstrations (2010)
- Field sequestration demonstrations (2010)
- Integrated capture/sequestration meeting program cost goal (2020)

Technology Needs

- Solid sorbents, CO_2 hydrates, membranes, liquid move between absorption, O_2 combustion
- Direct & indirect sequestration concepts; value-added concepts; geologic, ocean, soil eco-system performance & modeling capability

The cost of CO_2 capture using current technology is too high. This is the result of current power generation technology that uses air-fired combustion resulting in a dilute CO_2 stream and the high cost of currently available CO_2 capture technology. The coal program roadmap is focused on developing fossil fuel energy conversion processes for new plants that exhaust CO_2 in a more concentrated form, making it easier to capture CO_2 and carrying out research to develop new capture technology to reduce the cost of CO_2 capture. This approach will significantly reduce the capital and energy penalty cost for CO_2 capture. The MW – scale capture demonstrations will utilize new CO_2 capture technology and will apply the technology on gas streams representative of the new fossil fuel energy conversion technology being developed.

Sequestration encompasses all forms of carbon storage, including storage in terrestrial ecosystems, geologic formations, and perhaps oceans. The goals of the sequestration program are to expand the number and type of carbon sequestration opportunities, lower the cost, and develop practices to achieve permanence (minimize seepage and develop monitoring and verification technology). Examples of specific objectives for the field sequestration demonstrations by 2010 include demonstration in unmineable coal seams and injection into saline formations using horizontal or multilateral wells.

Clean Coal Technology Roadmap Benefits
Key Assumptions

- Costs & benefits in constant 2002 dollars
- No credit taken for prior DOE investments in technology currently in use (e.g., FGD)
- Cost savings relative to state-of-art coal plant
- Benefits to 2010 primarily from existing plants
- Benefits 2010- 2020 primarily from new plants
- Added capacity in 2020 includes replacement of >60-year old plants (53 GW) plus new capacity (31-64 GW)
- Benefits from emissions trading cost credits not considered

The Basis for This Projection

Cost savings are estimated by quantifying the economic and environmental advantages gained by advanced technology relative to a reference coal plant without the benefit of the DOE supported technology. The gains are calculated by assuming the 2010 and 2020 performance and cost targets previously identified are achieved and technology is deployed that uses advanced technology. Specific assumptions are made with regard to the new plant capacity that benefits from the technology (e.g. for 2010, no existing plants are retired and the new plant capacity is the EIA projected coal plant growth), increased capacity and fuel savings from existing plants, emissions reductions achieved beyond the reference regulations, forecast cost of conventional technology, etc. The assumptions include consideration of market penetration and time delays to fully implement new technology.

Projecting Benefits – Prior Studies

There are different approaches used to evaluate benefits from technology research and development. The National Academy issued a report in 2001[10] that was an evaluation of the benefits from the R&D conducted since 1978 in DOE's energy efficiency and fossil energy programs. Economic, environmental and security benefits were considered. Evaluation of selected technologies and programs (case studies) was the approach used in this evaluation. EPRI carried out a study[11] to estimate the value of coal R&D to electricity consumers and generators using the real option valuation methodology. Estimated benefits of coal R&D for the period 2007-2050 range from $0.3 to 1.3 trillion. An evaluation[12] of the economic benefit of the fossil energy program using the advanced technology assumptions in the Energy Information Administration Annual Energy Outlook (EIA AEO) 2002 document projected over $100 billion cumulative savings in electricity costs through 2020. This analysis included natural gas fired technology but did not represent the more aggressive performance targets represented in this coal program roadmap. DOE is carrying out additional studies projecting benefits using the National Energy Modeling System (NEMS). This approach looks at the economic benefit due to the reduced cost of electricity for different technology scenarios including performance targets in the coal program roadmap. Initial results project the same order of economic benefit as estimated with this approach.

[10] Energy Research at DOE – Was it Worth It?, National Academy Press, 2001.
[11] Market-Based Valuation of Coal Generation and Coal R & D in the U.S., EPRI, May 2002.
[12] Foresting the Benefits of DOE Programs for Advanced Fossil Fuel, Electricity Technologies: The EIA High Fossil Electricity Technology Case, F. Shaffer and M. Chan, U.S. DOE, NETL, October 2002.

Clean Coal Technology Roadmap Benefits
Basis for Benefits Projections

Savings Category	Basis
Fuel Cost	Higher Efficiency
Capital Cost (New Plants)	Lower capital cost of plants using advanced technology
Control Technology Cost (Existing Plants)	Lower capital and operating cost to achieve environmental regulations
Avoided Environmental Costs	Estimated credit for avoided environmental costs (health, infrastructure, agriculture)
Technology Export	Clean coal technology will increase U.S. sales of technology abroad by 10-15%

Absence of near-zero emission coal option	**1-2 ¢/kWh increase in cost-of-electricity**

Benefits Considered

The approach for this effort was to select 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 export resulting from more competitive U. S. technology.

Actual avoided environmental costs for health, infrastructure and agriculture depends on geographic location, urban vs rural environment, and many other factors. Estimates are made based on review of available projections by EPA and Resources for the Future (July 2001).

Additional Benefits Not Included

The estimated benefits are through 2020. Benefits of the technology employed beyond 2020 are not included (e.g., repowering an existing plant to realize higher efficiency will result in fuel cost savings beyond 2020). Other benefits not included are knowledge products from the R&D (e.g., 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 (e.g., freeing natural gas use for other sectors), and potential savings if carbon dioxide regulations are enacted.

Clean Coal Technology Roadmap – Economic Benefits

Savings Categories	Cumulative Benefits ($ billions, today – 2020)
Fuel Cost	10
Capital Cost (New Plants)	12
Control Technology Cost (Existing Plants)	32
Avoided Environmental Costs	10
Technology Export	36
Total Benefit	**100**

Other Benefits

- Increased jobs from technology export – estimate 75,000 new jobs per year in 2010 increasing to 200,000 per year in 2020
- Additional $500 billion to $1 trillion savings through 2050 if loss of coal option results in 1-2 ¢/kWh increase in cost of electricity

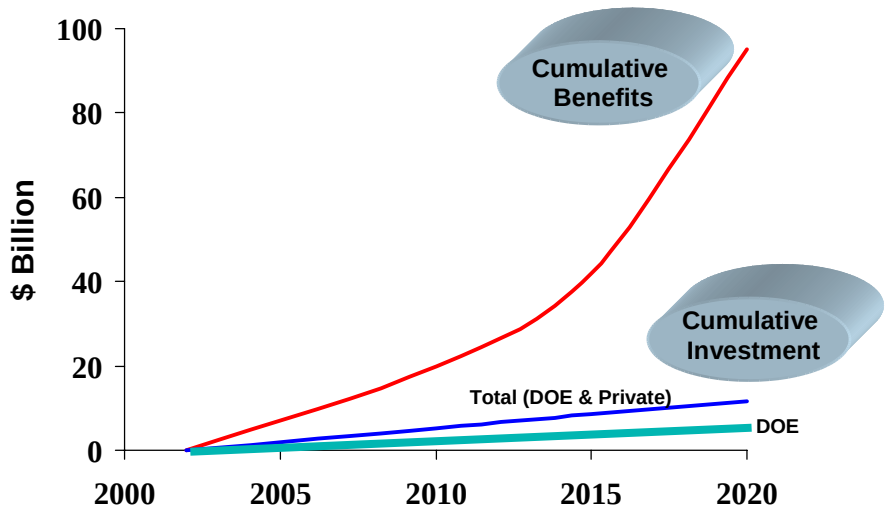
Perspective on the Projected Benefits

The projected cumulative benefits to 2020 of approximately $100 billion represent a significant return on a forecasted investment of approximately $11 billion. For perspective, the end-use price of electricity in the U. S. is greater than $230 billion/year. The fuel cost saving compares with an estimated fuel cost for U.S. coal-fired generation of $25 and 30 billion/year. The capital cost savings reflect savings of $100/kW and $200/kW for new plants built in 2010 and 2020. The savings in control technology includes savings from the lower cost of air emissions control and savings resulting from increased by-product utilization (the largest savings in later years). Avoided environmental costs were calculated on a $/ton of pollutant basis. Only SO_2 ($200/ton SO_2) and NO_x ($800/ton NO_x) were considered for these projections. Avoided costs for Hg was not included given the current uncertainty in making estimates. The estimate for increased exports is based on the current U. S. Bureau of Census estimate for power generating machinery and equipment, projections for world coal fired generating capacity, and the potential for increased market penetration for clean coal technology primarily in developing countries. The estimated current export sales are $30-35 billion/year.

A View of the Cost Without Clean Coal

Increase in electricity cost was estimated assuming the absence of a low-cost near-zero emission coal option. Based on Energy Information Administration data for 2001, the average cost of electricity in states with high coal use (>60%) is approximately 2.7 cents/kWh less than states with <50% coal use. States with substantial hydropower were excluded. Based on these data, it was assumed the cost of electricity could increase 1-2 cents/kWh if the low cost coal option is not available. A 1-2 cents/kWh increase in the cost of electricity is equivalent to a $1-2/million Btu increase in the price of natural gas to a representative plant (e.g. capacity factor, plant heat rate). The resulting benefit of $0.5 – 1.0 trillion to 2050 is essentially the same quantitative benefit projected by the EPRI real option valuation study.

DOE Coal Program – Benefits and Investment



The cumulative benefits and investment are presented in the figure. The cumulative benefit and investment represented assumes the successful implementation of near-zero emission coal-fired power plants that are capable of removing and sequestering CO_2 if that action is taken. The investment includes funding for both R&D and the administration's Clean Coal Power Initiative (CCPI) program to demonstrate innovative, high risk, coal-based fuel processing energy systems. The assumption is that the total investment is equally shared between government and industry. The cumulative investment for R&D and the CCPI is essentially equally divided between the total investment of $10.7 billion. This investment assumes the innovation for existing plants effort (environmental control for existing plants) is completed by 2010. The fuel cell R&D program is not included in this investment.

The sequestration budget component is not included in the investment calculation since the sequestration program includes applications beyond the coal program and the benefits from this technology will be realized after 2020. An investment for CO_2 capture technology is included in the gasification budget component. Substantial benefits from the coal program are projected if CO_2 capture and sequestration are required since the targeted cost of electricity is much lower using advanced technology compared with the use of current technologies that are not economically adapted for CO_2 sequestration.

Coal Program Benefits
Security Considerations

- **Reduces dependence on imported oil**
  - Co-production of power and environmentally attractive fuels (e.g. F-T liquids, hydrogen)
- **Maintains diversity of energy resource options**
  - Avoids over reliance on gas for central station power
  - Encourages economical use of gas in other sectors
  - Reduces energy price volatility and supply uncertainty
- **Retains domestic manufacturing capabilities & U.S. energy technology leadership**
  - Enhances economic growth and security

The Clean Coal Technology Roadmap Addresses Energy Security

One of the Department of Energy strategic goals is to protect our national and economic security by promoting a diverse supply of reliable, affordable, and environmentally sound energy. This goal is accomplished by developing technologies that foster a diverse supply of affordable and environmentally sound energy, improving energy efficiency, providing for reliable delivery of energy, exploring advanced technologies that make a fundamental change in our mix of energy options, and guarding against energy emergencies.

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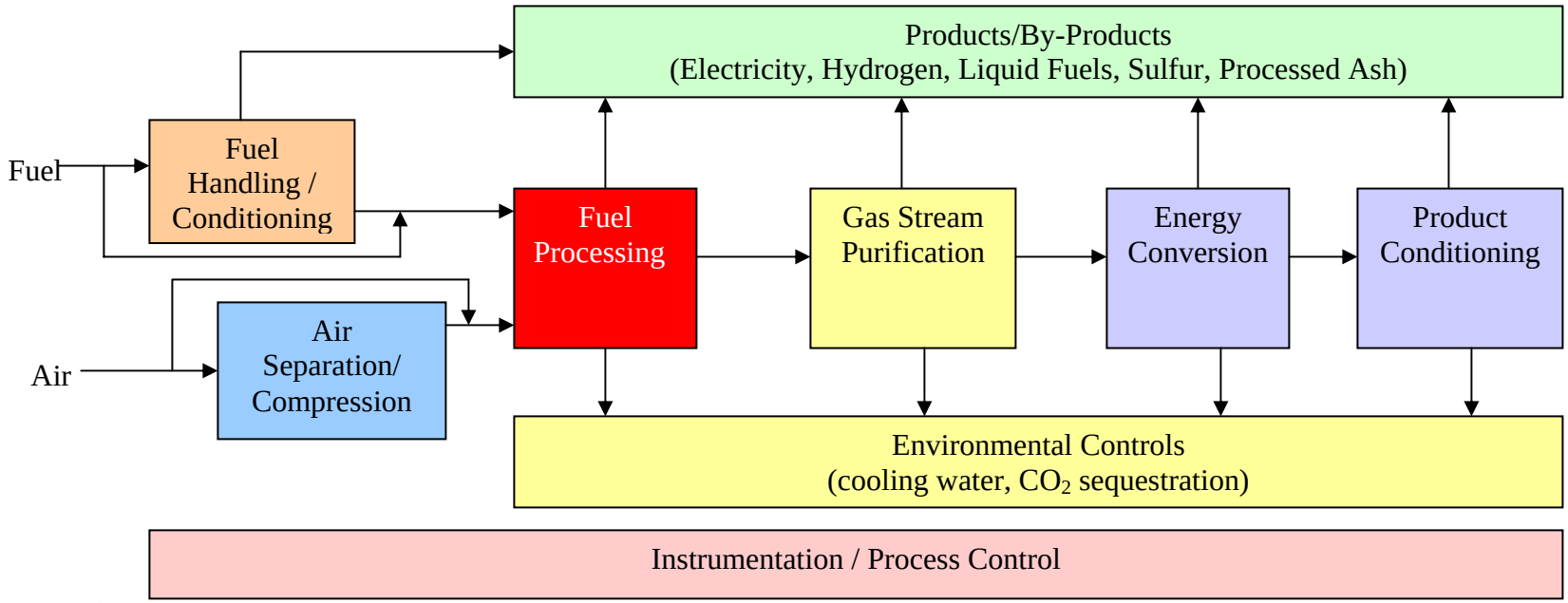
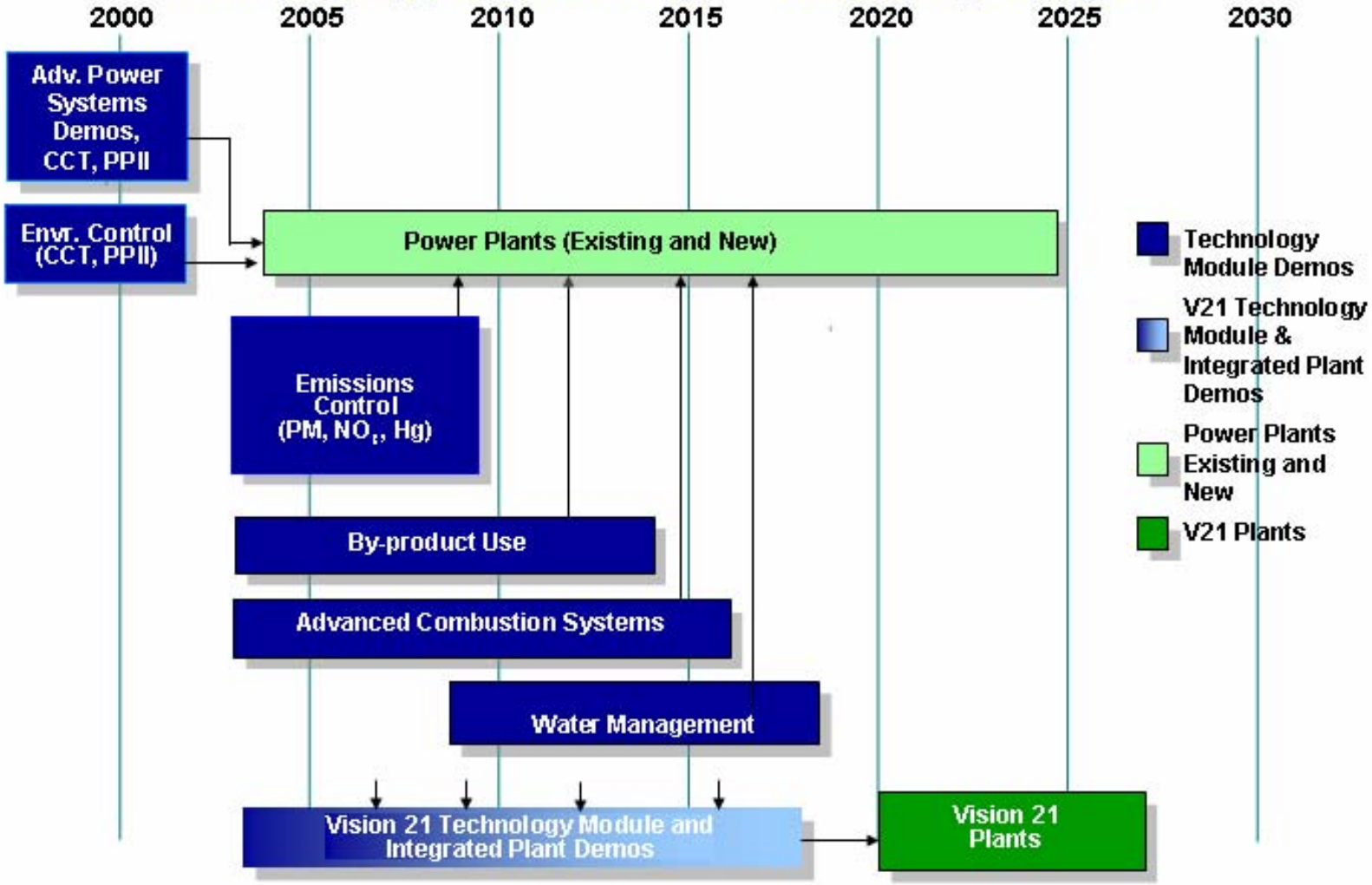
Roadmap Diagrams

Achieving the coal program roadmap goals for existing and future coal plants requires that the advanced technologies identified in the roadmap be demonstrated in commercial-scale operating plants. The plant schematic below shows the areas where advanced technology will be demonstrated. The figures on the following two pages present a path for demonstrating technology modules and the integration of these modules into advanced coal plants. The first figure focuses on innovations for existing plants. The second figure focuses on achieving future near-zero emission coal plants with initial plants operating in 2020. The CCPI program would be used as the primary method for implementing these demonstrations.

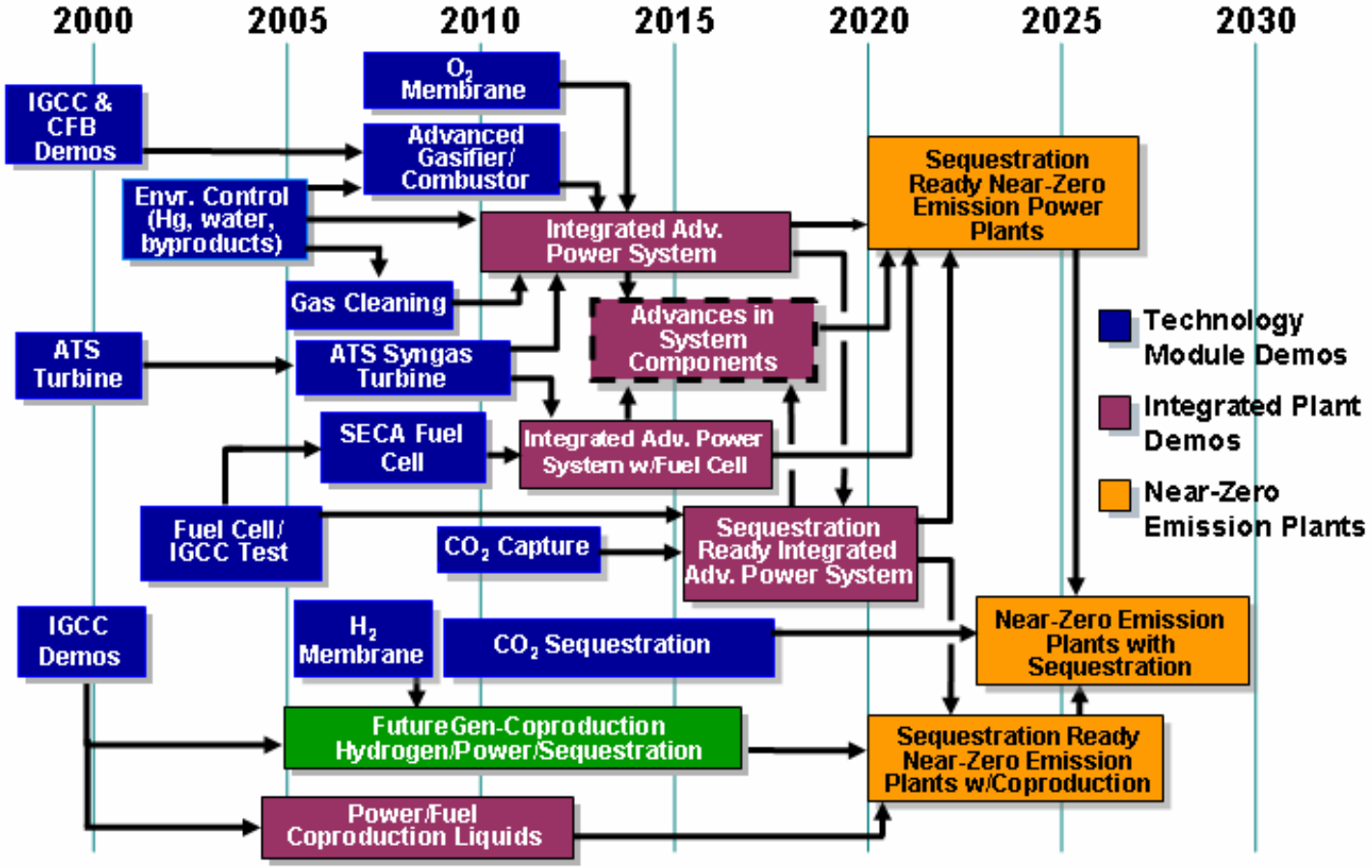
The R&D in each technology area leads to component designs that will be incorporated into these demonstrations. In many cases the technology module demonstrations will be part of an existing plant (e.g. the Wabash gasification plant is host to a demonstration of a candidate fuel cell technology). The integrated plant demonstrations would, in general, be incorporating advanced technologies that have already been tested in these technology module demonstration projects. This approach is presented to minimize the risk present when multiple new technologies are demonstrated in a first-of-a-kind plant.



Technology Roadmap – Existing Plants



Technology Roadmap – Future Energy Plants



Summary

- **Integrated Clean Coal Technology Roadmap available for first time**
  - Unified plant performance goals for DOE, industry
  - Goals consistent, quantitative, verifiable

- **Substantial benefits projected for Clean Coal Technology Program**
  - Benefit/investment ratio of 10 (through 2020) is conservative
  - Additional benefit ($0.5-1.0 trillion through 2050, ~25-50 benefit/investment) due to lower coal electricity cost

- **Major technological improvements needed to realize benefits**
  - Coal power program addresses near-term, transitional, & future (Vision 21) needs
  - Vision 21 providing innovative energy technology for use through 2050 & beyond

Conclusions

- **Coal will continue to be a valued resource with over 100 GW of new coal plants projected by 2020**
- **Advanced technology is required to meet economic and environmental goals**
- **Industry and DOE have identified critical technology needs to meet the goals**
- **Achieving cost and environmental goals requires maintaining our Nation's investment in coal R & D – both government and industry**

The benefits to the Nation include

- **Environmental Quality – near-zero emission coal-based plants**
- **Economic Savings**
  - $100 billion projected economic benefit through 2020
- **Security**
  - Reduced dependence on imported oil and natural gas
  - Maintaining diversity of energy resources
  - Retains domestic manufacturing capabilities

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