ELECTRIC POWER RESEARCH INSTITUTE

The Power to Reduce CO_2 Emissions

The Full Portfolio

2009 Technical Report

The Power to Reduce CO_2 Emissions: The Full Portfolio

2009 Technical Report

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INTRODUCTION

In 2007 EPRI released its first Prism and MERGE analyses [EPRI 2007], providing a technically and economically feasible roadmap for the electricity sector as it seeks to reduce its greenhouse gas emissions. The Prism analysis provided a comprehensive assessment of potential CO_2 reductions in key technology areas of the electricity sector. The MERGE analysis identified the optimum economic technology portfolio in response to a given CO_2 emissions constraint.

The 2009 update reflects economic and technological changes that have the potential to affect projected emissions and the technologies to address them. This update also includes new technologies and analysis features.

The Prism analysis determined that the sector can potentially meet the challenges that confront each technology option and deploy "The Full Portfolio" of technologies to achieve substantial emissions reductions. The full Prism builds from the top down. The top line of the graph represents the estimated U.S. Energy Information Agency's (EIA) 2009 Annual Energy Outlook [EIA 2009] base case for CO_2 emissions from the U.S. electricity sector. Each color represents the additional reduction in emissions based on assumption of technically feasible levels of technology performance and deployment. The Prism illustrates the overall reductions achievable using the Full Portfolio of technologies.

The MERGE analysis estimates the most economic deployment of technologies over time to meet a specified CO_2 emissions constraint. Based on current and projected technology costs, consideration of fuel costs and reserves, and competition for resources with other parts of the economy, MERGE projects several quantities: the electricity generation through 2050 for different technologies, CO_2 prices, electricity costs, and the overall cost to the U.S. economy of implementing CO_2 emissions reductions.

This report summarizes results initially released at the 2009 EPRI Summer Seminar [EPRI/SS 2009] from both analyses as well as providing a more detailed discussion of key factors, technical assumptions, and methods used in each analysis.

2
2009 PRISM ANALYSIS

The 2009 Prism analysis estimates that the technical potential exists for the U.S. electricity sector to reduce 2030 annual CO_2 emissions from the U.S. electric sector by:

- 41% relative to 2005 emissions, based on assumption of increased performance and deployment of eight different electric sector technologies;
- 58% relative to 2005 emissions, if reductions due to increased deployment of electro-technologies and electric transportation are included; and

Compared to the 2030 base case projection in the EIA 2009 Annual Energy Outlook, the calculated emissions in 2030 from the Prism analysis are 62% lower.

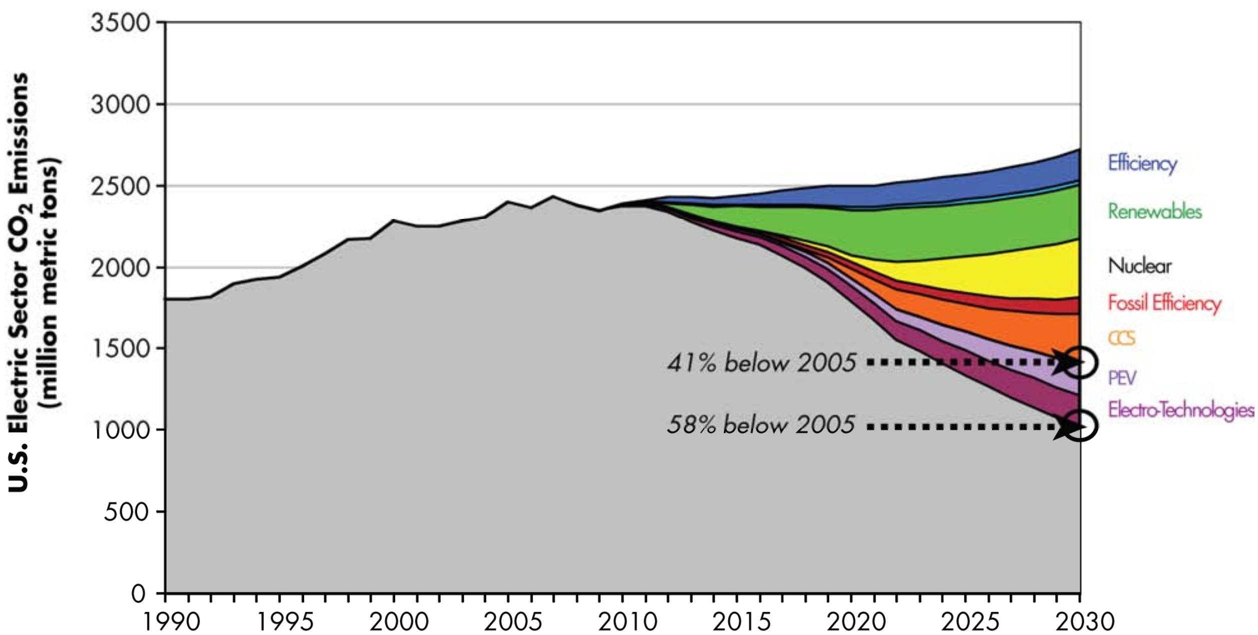

Figure 2-1
2009 Prism

The Prism analysis projects that by 2030, 60% of the total U.S. generation mix would consist of low- or non-CO_2 emitting generation—provided that the required research, development and technology demonstrations can be realized and the technical assumptions can be met.

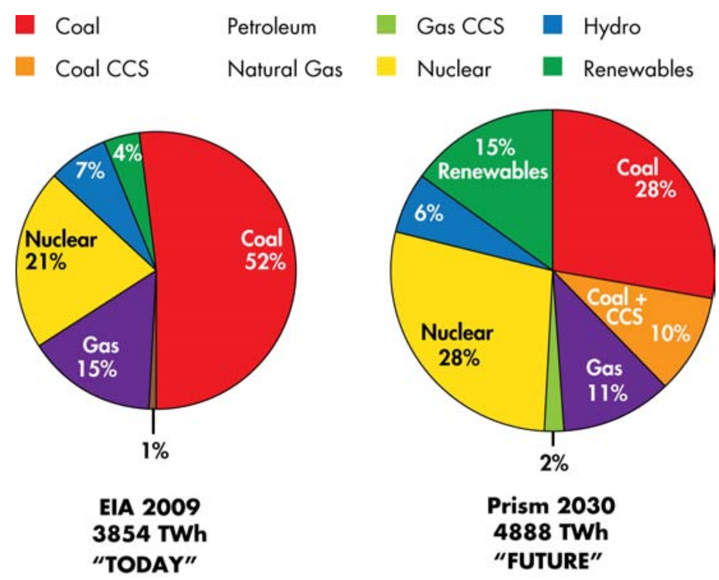

Figure 2-2
Comparison of Current to Future U.S. Electricity Generation Based on 2009 Prism

The emissions reduction potential for each technology area discussed below is expressed as a percent reduction relative to the EIA 2009 Annual Energy Outlook base case. A more detailed discussion of the 2009 Prism Analysis can be found in Appendix A.

End-Use Energy Efficiency

The 2009 analysis estimates a potential CO_2 emissions reduction in 2030 of 6.5% as a result of gains in energy efficiency.

A 2009 EPRI study [EPRI 2009] assessed the potential to reduce demand growth and electricity consumption based on different levels of success and penetration of energy efficiency technologies and programs. The study compared effects of different efficiency assumptions relative to the 2008 EIA Annual Energy Outlook [EIA 2008] base case (the most current assessment at that time.)

2009 Prism analysis assumption:

- Achieve “maximum achievable potential” as calculated in the 2009 EPRI efficiency study, resulting in a 2030 net consumption reduction of 8%.

Transmission & Distribution Efficiency

The 2009 analysis estimates a potential CO_2 emissions reduction in 2030 of 0.9% as a result of efficiency gains in the U.S. transmission and distribution system.

A key aspect of the "smart grid" will be a more efficient transmission system. Research in advance conductors, corona and insulation losses, and optimum system voltage will improve transmission capacity, optimize use of existing generation capacity, and reduce transmission and distribution losses.

Efficiency gains also may be realized through more effective system planning and operation, including voltage control and optimal network designs.

2009 Prism analysis assumption:

- 20% reduction in transmission & distribution losses by 2030.

Renewable Energy Resources

The 2009 analysis estimates a potential CO_2 emissions reduction in 2030 of 13% as a result of substantially increased deployment of renewable generation.

The 2009 Prism assumes the penetration of diverse renewable generation resources, based on consideration of existing and potential state and federal programs, cost and performance improvements, and grid integration challenges.

2009 Prism analysis assumptions:

- By 2030, 15% of total U.S. electricity generation comes from non-hydro renewables.
- The above assumption corresponds to 135 gigawatts (GW) by 2030, consisting of ~100 GW new wind; ~20 GW new biomass; ~15 GW other technologies, including solar.

Nuclear Power

The 2009 analysis estimates a potential CO_2 emissions reduction in 2030 of 11% as a result of substantially increased deployment of advanced nuclear power plants.

The fundamental components of the 2009 Prism assumption regarding nuclear power's expected contribution to emissions reductions are based on several factors:

- Existing fleet continues to operate safely at high capacity factors;
- Ongoing efforts to extend the service of existing plants beyond 60 years;
- Approximately 30 applications for new nuclear plant construction licenses; and
- Sites for nearly all new capacity expected by 2030 are on existing nuclear plant locations.

2009 Prism analysis assumption:

- Construction of 10 GW of advanced reactors by 2020, and ultimately 64 GW by 2030.

Fossil Efficiency

The 2009 analysis estimates a potential CO_2 emissions reduction in 2030 of 3.7% as a result of increasing the efficiency of new and existing fossil-fueled generation.

Economic analysis indicates that a subset of existing 300- to 500-megawatt coal units could remain competitive as baseload during the transition to new plant designs – and contribute to an overall carbon reduction strategy.

The EPRI/Coal Utilization Research Council Technology Roadmap [CURC/EPRI] establishes aggressive but achievable technological advances that could result in new levels of efficiency in key fossil technologies. The 2009 Prism assumptions for new fossil plant performance also assume these advances are achieved.

2009 Prism analysis assumptions:

- An increase of 3% in thermodynamic efficiency for 75 GW of existing coal generation fleet;
- Higher efficiencies for new ultra-supercritical coal and integrated gasification combined-cycle (IGCC) plants: 42% efficiency by 2020, 49% by 2030; and

Combined-cycle plants achieve 60% efficiency by 2020 and 70% by 2030; combustion turbines achieve 45% by 2030.

Carbon Capture and Storage

The 2009 analysis estimates a potential CO_2 emissions reduction in 2030 of 11% as a result of bringing into service technologies that (1) capture CO_2 emissions from fossil-fueled generation, (2) transport the CO_2 and (3) securely sequester it.

The 2009 Prism bases these estimates on assumptions that new units coming on line post-2020 will be equipped with CCS and that 20% of the existing fleet (60 GW) could be retrofitted with CCS. It assumes that existing coal units of >500 megawatts (MW) capacity and <12,000 Btu/kWh heat rate, with all installed environmental controls, and placed in service after 1970, are viable candidates for CCS retrofit.

2009 Prism analysis assumptions:

- 90% CO_2 capture for all new coal and natural gas combined-cycle plants built after 2020; and
- CCS retrofit for 60 GW of existing coal generation at 90% capture efficiency.

Plug-in Electric Vehicles

The 2009 analysis estimates a potential CO_2 emissions reduction in 2030 of 9.3% as a result of electricity displacing gasoline and diesel to fuel a substantial portion of the vehicle fleet.

The 2009 Prism bases this estimate on the assumption that plug-in electric vehicles (PEVs) are introduced to the market in 2010, consistent with product plans of many automakers, and the rapid growth of market share to almost half of new vehicle sales within 15 years.

Net emissions reduction estimates from the increasing market share of PEVs are based on research by EPRI and others, [EPRI/NRDC 2007] factoring vehicle miles traveled, carbon savings from gasoline not burned, and the trend for the electric system to become “cleaner” – i.e. for an increasing share of power generation to emit less or no CO_2.

2009 Prism analysis assumptions:

- 100 million PEVs in the fleet by 2030; and
- Fraction of non-road transportation applications (e.g. forklifts) represents three times the current share by 2030.

Electro-Technologies

The 2009 analysis estimates a potential CO_2 emissions reduction in 2030 of 6.5% as a result of electric technologies displacing traditional use of primary energy consumption for certain commercial and industrial applications.

Electro-technology research [EPRI/ELEC 2009] indicates that there are applications through which net reductions in CO_2 emissions can be achieved. This projection is based on replacing significant use of direct fossil-fueled primary energy with relatively de-carbonized electricity for a range of possible applications, e.g. heat pumps, water heaters, ovens, induction melting, and arc furnaces.

2009 Prism analysis assumptions:

- 4.5% of primary energy supplied by fossil fuels is replaced by electricity by 2030.

3
2009 ENERGY-ECONOMIC (MERGE) ANALYSIS

The 2009 MERGE analysis estimates the economically optimum portfolio of electric sector technologies that will meet a CO_2 emissions constraint comparable to those currently proposed in draft legislation and policies. MERGE (Model for Estimating the Regional and Global Effects of Greenhouse Gas Reductions) analyzes the economy-wide impacts of climate policy[1] in a global context. Under assumptions regarding CO_2 emissions constraints and technology costs and availability, MERGE compares economic consequences of different technology scenarios.

The 2009 MERGE analysis compares two technology scenarios: "limited portfolio" and "full portfolio." These two contrasting scenarios allow an assessment of the value of investing in RD&D. The limited portfolio assumes that CCS and PEVs are not successfully deployed, and that there is no expansion or replacement of the nuclear fleet. The full portfolio assumes availability of CCS, advanced nuclear, significant improvement in costs of renewables, availability of PEVs, and accelerated improvements in end-use efficiency. The 2009 analysis adds several features to previous EPRI analyses:

- Emissions constraints reflecting current U.S. and international policy proposals (83% below 2005 levels for developed countries by 2050);
- Updated technology costs based on EPRI's Technical Assessment Guide research program;
- Unconventional resources such as shale gas included in the natural gas supply;
- CCS retrofit limited to 60 GW of existing coal plants in the full portfolio scenario;
- Grid integration costs considered for high levels of variable output generation from renewables;
- Higher biomass feedstock costs for large-scale biofuels and/or biomass electricity production; and
- Potential nuclear expansion in the full portfolio scenario reflects existing uranium supply, assuming a once-through fuel cycle.

[1] Climate policy is evolving rapidly as it goes through the legislative process, so the current scenarios analyzed with MERGE are likely to be somewhat different than the ultimate final form of the policy.

MERGE Technology Results

Under CO_2 emissions constraints representative of current proposals, MERGE projects that the optimum economic technology portfolio consists of substantial amounts of renewable electricity generation, significant electricity production from coal with CCS and nuclear, as well as large reductions in electricity consumption. Retrofit of CO_2 capture and storage for existing coal plants plays an important transitional role between 2010 and 2030. The sharp growth of new coal with CCS after 2030 will be driven by continually tightening emissions constraints, retirement of coal units with CCS retrofit, the need to reduce emissions from natural gas without CCS, and anticipation that much of existing uranium supplies for nuclear plants are consumed (based on the once-through fuel cycle).

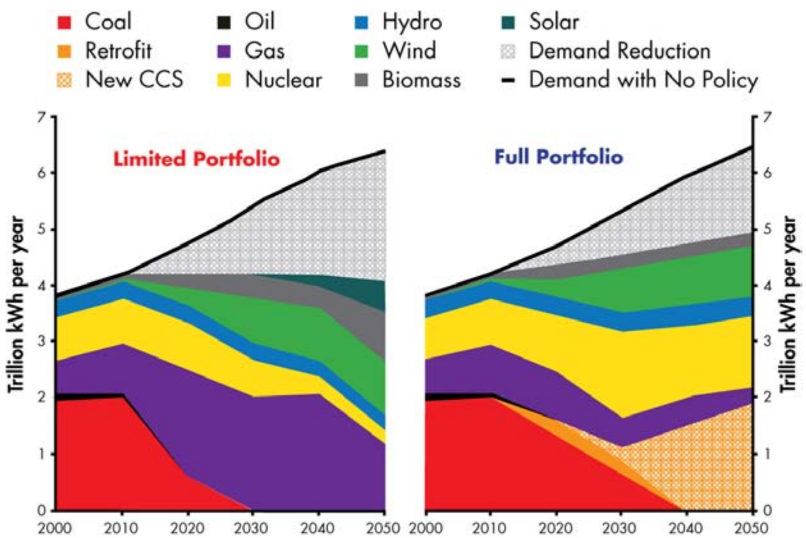

Figure 3-1
U.S. Electricity Generation Based on 2009 MERGE Analysis

Role of Demand Reduction

MERGE estimates substantial demand reduction between reference cases without CO_2 emissions constraints and scenarios with constraints. Demand reduction is complex and cannot be explained without taking an economy-wide perspective. Much of the electricity demand reduction observed under an emissions constraint results from price-induced efficiency: as prices rise, existing technologies that improve load management and demand response become more attractive. At the same time, electrification (substituting electricity for carbon-based fuels in other sectors) will limit the drop in electricity demand. Reductions in consumption also result from new technologies, such as the smart grid, which creates the platform for deploying smart technologies that improve load management and demand response.

Technology Insights

The MERGE analysis yields several valuable insights regarding future technology needs and the consequences of choosing different technology strategies to produce electricity under an economy-wide CO_2 emissions constraint:

- Demand reduction plays a very large role in meeting CO_2 emissions constraints compared to an economy with no constraints in either the limited or full portfolio scenarios. The magnitude of demand reduction (1500-2000 TWh) implies that substantial consumption reduction via end-use efficiency will be economic under CO_2 emissions constraints. Note that demand reduction in the limited portfolio scenario is more than 50% larger than in the full portfolio. It is therefore important to enable widespread deployment of end-use efficiency technologies, e.g. via development of the smart grid.
- Renewables (particularly wind and biomass) will ultimately be economic at large scales under CO_2 emissions constraints, even without subsidies. Non-hydro renewables represent more than 20% of total electricity generation by 2050 in the full portfolio. In the limited portfolio, they represent more than 50% of generation by 2050. Due to their high electricity production cost, solar technologies only appear in the limited portfolio where they are economically attractive due to the combination of limited technology options and unacceptability of CO_2 emissions from natural gas in outlying years. These conclusions indicate that it will be important to enhance the transmission system such that large amounts of variable output generation can be accepted and coordinated within the grid.
- If advanced coal with CO_2 capture and storage (CCS) and the ability to expand the nuclear fleet are not available, tremendous demand will be placed on natural gas to meet electricity production under CO_2 emissions constraints. In the limited portfolio, where neither advanced coal nor nuclear is available, natural gas consumption for electricity production increases 275% from 2010 to 2050. If advanced coal with CCS and nuclear expansion are available options, the combination of coal and nuclear will consistently represent 60% or more of electricity generation in an economically optimum portfolio. RD&D enabling the availability of these options is therefore vital.

MERGE Economic Results

The analysis confirms that while the cost of achieving major CO_2 emissions reductions is substantial, development and deployment of a "full portfolio" of technologies will reduce the cost to the U.S. economy by more than $1 trillion, compared to the "limited portfolio" case.

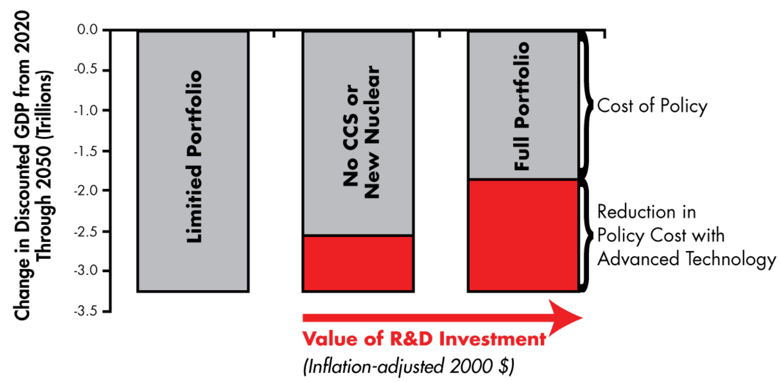

Figure 3-2
Impact of CO_2 Emissions Reduction Limits on U.S. Economy from 2009 MERGE Analysis

The benefits of investing in technology are also evident when comparing MERGE's projections of the wholesale electricity costs and CO_2 emissions allowance costs for the limited or full portfolio of technologies. By 2050, the wholesale electricity price in the full technology portfolio rises to a much lower level than in the limited portfolio. A similar divergence in future CO_2 allowance prices is also observed for these two technology cases.

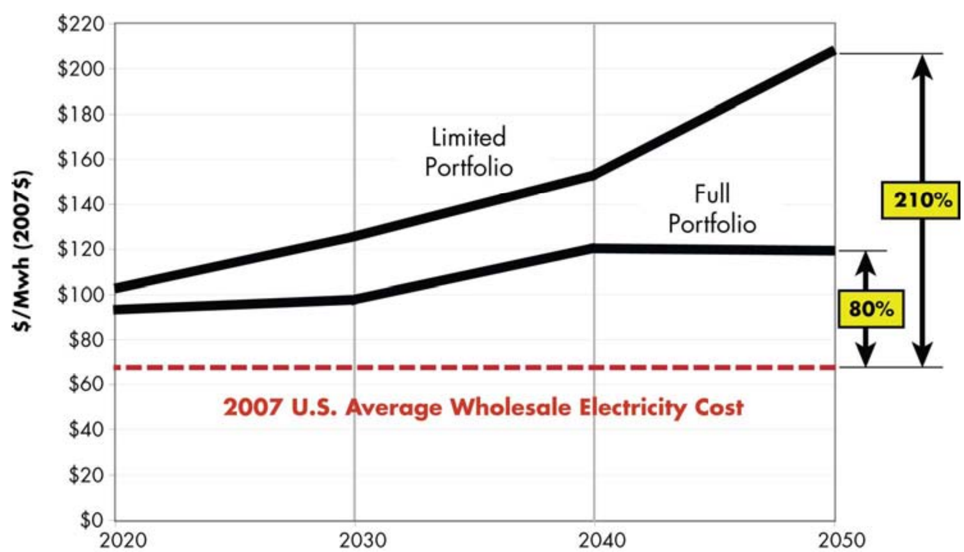

Figure 3-3
U.S. Wholesale Electricity Costs from 2009 MERGE Analysis

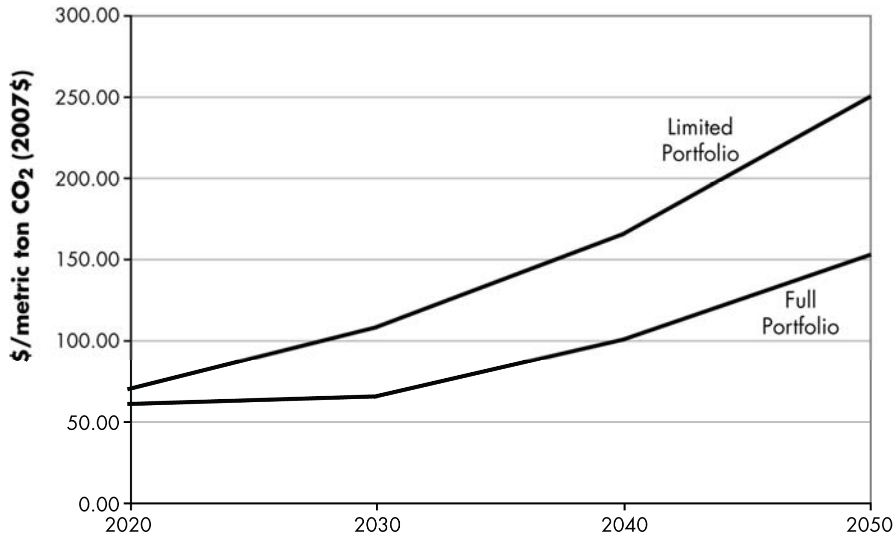

Figure 3-4
U.S. CO_2 Allowance Costs Based on 2009 MERGE Analysis

Natural gas is a pivotal fuel in the electricity generation mix, particularly between now and 2030. Assuming total U.S. natural gas reserves comprising all proven, probable, and possible reserves [PGC 2009], the MERGE analysis estimates significantly lower natural gas prices and electricity-related consumption under a full technology portfolio. Note that in the limited portfolio, annual natural gas consumption for electricity production doubles current consumption between 2020 and 2040. The projected decrease in electricity-related natural gas consumption after 2040 is driven by increasingly stringent CO_2 emissions constraints.

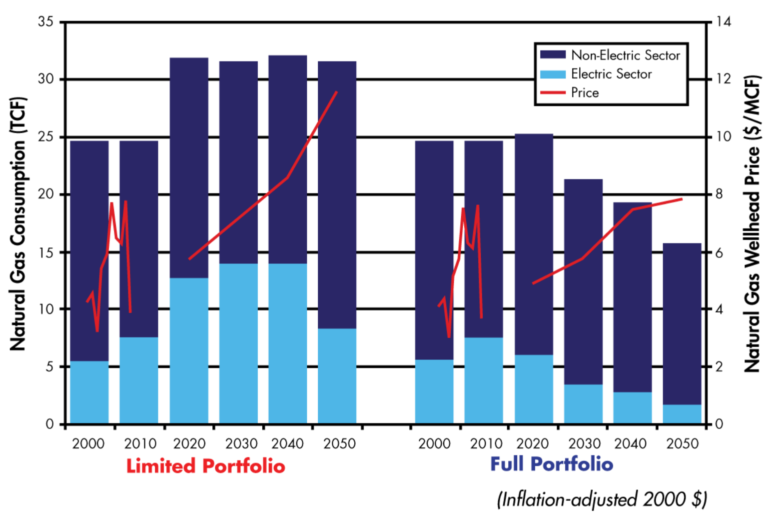

Figure 3-5
U.S. Natural Gas Consumption Based on 2009 MERGE Analysis

Impact of Offsets

A prominent aspect of discussions regarding potential CO_2 emissions reduction policies is the option to use a wide variety of offsets, that is, emissions reduction activities in uncapped sectors, to achieve compliance under the cap. For this analysis, a limited offset pool is assumed, excluding additional offsets from forestry or international activities. Because of the potentially strong effect of widespread offset use on the CO_2 price, these assumptions represent a key difference between this analysis and currently proposed legislation. This approach to offsets was chosen for several key reasons:

Significant uncertainty regarding the amount of verifiable and sustainable offsets;

- Uncertainty regarding additional costs and complexities in administrating programs necessary to manage forestry and international offsets;
- Potentially significant reduction in available international offsets due to implementation of emissions reductions policies in other countries/regions; and
- The need to illustrate implications of actually reducing emissions substantially to meet reduction targets under the cap.

EPRI is conducting additional research to assess the effects of different offsets assumptions on economic impact of emissions reduction policies.

4
TECHNOLOGY DEVELOPMENT PATHWAYS

Evaluation of the technology implications of the Prism analysis points to four key strategic technology deployment pathways that the U.S. electricity sector should follow in order to reduce CO_2 emissions significantly over the coming decades:

- Deploy smart distribution grids and communications infrastructures to enable the widespread deployment of end-use efficiency, distributed generation, and plug-in electric vehicles.
- Deploy transmission grids and associated energy storage infrastructures with the capacity and reliability to operate with 20-30% intermittent renewables in specific regions of the United States.
- Deploy new advanced light water reactors enabled by continued safe and economic operation of the existing nuclear fleet.
- Deploy commercial-scale coal-based generation units operating with 90% CO_2 capture along with associated infrastructures to transport and sequester the captured CO_2.

The specific technologies associated with each pathway are at various stages of development. However, common to all is the need for sustained, substantial RD&D to accelerate commercial deployment and to enable technology performance and deployment for 2030 comparable to levels assumed in the Prism analysis. The following sections detail the technology challenges and critical research and deployment milestones associated with each of these key technology development pathways.

Smart distribution Grids and Communications Infrastructures

The smart grid is critical for enabling widespread development and deployment of end-use energy efficiency, new electro-technologies, and plug-in electric vehicles (PEVs). These technologies will share a number of attributes. They have or will have high levels of distributed intelligence (embedded computers) built into their basic operating structure, allowing them to become "smart resources" that interact with their digital environment. Second, they will incorporate standardized communication protocols, affording high levels of interoperability with other devices. Third, they will provide for automated load management at multiple levels of aggregation, requiring communications amongst ensembles of devices and with energy management systems.

Key research and deployment milestones addressing this area will include:

- Establish standards for interoperability, and the capability for advanced metering infrastructure (AMI) to acquire and manage real-time data for dynamic energy management. Develop and deploy communication standards for AMI to ensure interoperability with the grid.
- Complete pilot projects to assess the capability of dynamic energy management based on first-generation AMI, providing real-time pricing signals and emergency demand condition signals to smart devices.
- Develop advanced on-board chargers capable of handling two-way power flow, opening the door for PEVs to become potential supply resources.
- Ensure that PEVs can be integrated into the smart distribution system and managed in aggregate to meet peak loads and emergencies, and to provide ancillary services.

Advanced Transmission Technologies

The output of principal non-hydro renewable resources (i.e., wind, solar) is variable, which will require significant enhancements to the transmission system. Currently, insufficient transmission exists to access renewable resources located in areas far from load centers. Additional transmission will also be required to address grid voltage and frequency instability due to fluctuating energy output, high ramping burdens that require added reserves, and limited reactive power control. Also, new generation resources and transmission lines change the topology and power flows on the grid, and variable generation will require power electronics for new control strategies. Assuming conditions where 20-30% of electricity generation is produced by variable output renewables, new technologies addressing these challenges will be needed.

Key research and deployment milestones addressing this area will include:

- Demonstrate a large-scale energy storage plant in support of a large wind or solar facility. Large-scale energy storage increases resource dispatchability and allows variable output resources to operate during periods of maximum efficiency, independent of load profiles.
- Develop and demonstrate new analysis tools to optimize regulation, reserves, and load-following requirements in regions with high penetration of variable generation.
- Develop data visualization tools that more accurately reflect load and demand response capabilities, enabling confidence in stable operations with higher wind penetration.
- Demonstrate increased transmission system efficiency through advanced grid management technologies, such as real-time simulation and grid security assessment tools, and wide-area monitoring.

Advanced Nuclear Plants

Nuclear power's contribution to CO_2 emissions reductions depends on the ability to efficiently build new plants and on the continued safe and economic performance of the existing fleet. A substantial siting resource already exists for fleet expansion based on existing or cancelled nuclear sites that were originally licensed to accommodate multiple nuclear units. Nuclear energy's R&D needs, therefore, span both the current fleet and new plant construction.

The near-term technology needs for nuclear energy principally relate to light water reactor (LWR) technology (used in more than 80% of the world's current reactors). The existing fleet of U.S. commercial nuclear reactors generates approximately 20% of U.S. electricity at capacity factors averaging 90%. The existing 104 U.S. nuclear units have operated for 13 to 40 years, and almost half of the current fleet received operating licenses after 1980. Electricity production from existing plants is critical to significant CO_2 reductions. To date, 54 units have been granted 20 year extensions on their operating licenses. An additional 21 units have applications for license extension under review, and applications for an additional 23 units are anticipated.

New U.S. nuclear units will be based on advanced light water reactor (ALWR) technology. Of five major commercial designs, two are certified by the U.S. Nuclear Regulatory Commission and three are under review or in the process of preparing review applications. ALWRs operate commercially and are being constructed in Japan, Korea, Taiwan, France, and Finland. The RD&D challenge is to incorporate experience in design, construction, and operations into new ALWRs to ensure high levels of safety, capacity factors, and reliability comparable to current levels in the existing fleet. To date, 32 new nuclear units are under consideration at 21 nuclear sites, representing 20 nuclear operators. Combined Operating License Applications (COLAs) have been filed for 28 new units.

Key research and deployment milestones addressing this area will include:

- Develop material and equipment life cycle management technologies enabling 80 year nuclear unit operating life.
- Expand the application of digital control technology in both safety and plant control applications.
- Develop a new generation of highly reliable, high burnup nuclear fuel, capable of longer outage cycles and significantly reduced volumes of spent fuel.
- Resolve remaining ALWR generic regulatory issues – including instrumentation and control design criteria, high-frequency seismic design criteria, quality assurance standards, and fitness for duty.
- Develop enhancements to ALWR design, construction, and operations (e.g. modular construction, advanced automated plant controls, enhanced standardization) based on successful technology transfer of construction and operating experience from the existing fleet and early ALWR deployments.

Advanced Coal with CO_2 Capture and Storage

Coal currently accounts for more than half of the electricity generated in the United States, and is projected by most energy-economic analyses to remain a significant component of U.S. electricity supply through 2050. Sustaining coal's viability in a carbon-constrained world entails increasing the efficiency and reducing the capital cost of pulverized coal (PC) and integrated gasification combined-cycle (IGCC) technologies, and making CO_2 carbon capture and storage cost-effective and commercially viable. Large-scale demonstrations will be necessary to establish confidence that commercialization is feasible. Significant efficiency gains for PC technology can be realized by increasing temperatures and pressures in the steam cycle; a 10% efficiency gain, for example, translates to a CO_2 emissions reduction of 25%. Advanced materials such as corrosion-resistant nickel alloys and new boiler and steam turbine designs will be necessary to accommodate higher temperatures and pressures. Lower-cost electricity production from IGCC plants requires development of larger gasifiers, their integration with larger, more efficient combustion turbines, and use of ion transfer membrane and other low-energy-demand oxygen supply technologies. While significant industrial experience exists, current technologies for CO_2 capture are energy intensive and costly – achieving cost-effective electricity production from coal depends on reducing the energy and cost requirements of capture. Naturally occurring CO_2 reservoirs and CO_2 injection for enhanced oil and gas recovery demonstrate several aspects of feasibility of CO_2 storage, but large-scale injection and storage of CO_2 produced from electricity generation has not been proven. Pilot-scale and large scale demonstrations of CO_2 injection from electricity production are needed.

Key research and deployment milestones addressing this area will include:

- Demonstrate efficiencies of 33-35% for advanced pulverized coal and IGCC plants with CO_2 capture.
- Conduct pilot projects demonstrating chilled ammonia and improved amine CO_2 capture technologies.
- Demonstrate commercial availability of CO_2 storage capable of supporting new coal plants capturing 90% of CO_2.
- Demonstrate ultra-supercritical pulverized coal plants operating at higher temperatures with CO_2 capture - initially 1100°F (593°C) with 25-50% CO_2 capture; then 1200-1300°F (649-704°C) with 50+% CO_2 capture.
- Develop new/improved processes and membrane contactors for post-combustion capture.
- Field test ion transfer membrane technology, leading to pre-commercial testing of IGCC with oxy-combustion; conduct multiple oxy-combustion pilot projects, leading to pre-commercial demonstration.
- Demonstrate integrated gasification fuel cell (IGFC) plants.
- Conduct at least 3-5 large-scale demonstrations of CO_2 storage (for multiple geologies) receiving captured CO_2 from coal plants; 10 or more demonstrations preferred.

5
CONCLUSIONS

De-carbonizing the electricity infrastructure under economy-wide CO_2 reduction targets while providing reliable, affordable, and environmentally responsible electricity presents a considerable challenge. The 2009 Prism analysis estimates that substantial technical potential exists for the U.S. electricity sector to reduce annual CO_2 emissions.

The MERGE analysis indicates that a technology portfolio similar to that outlined by the Prism analysis can achieve CO_2 emissions reductions at a considerably lower economic cost – more than $1 trillion in some scenarios. An important insight from the MERGE analysis is that competitive, low-carbon electricity is essential in making the transition to a low-carbon economy. The value of the full portfolio in reducing the carbon intensity of the electricity sector while minimizing the cost of reducing emissions can be seen by comparing the growth in electricity production costs to estimated electric sector CO_2 emissions intensity over time:

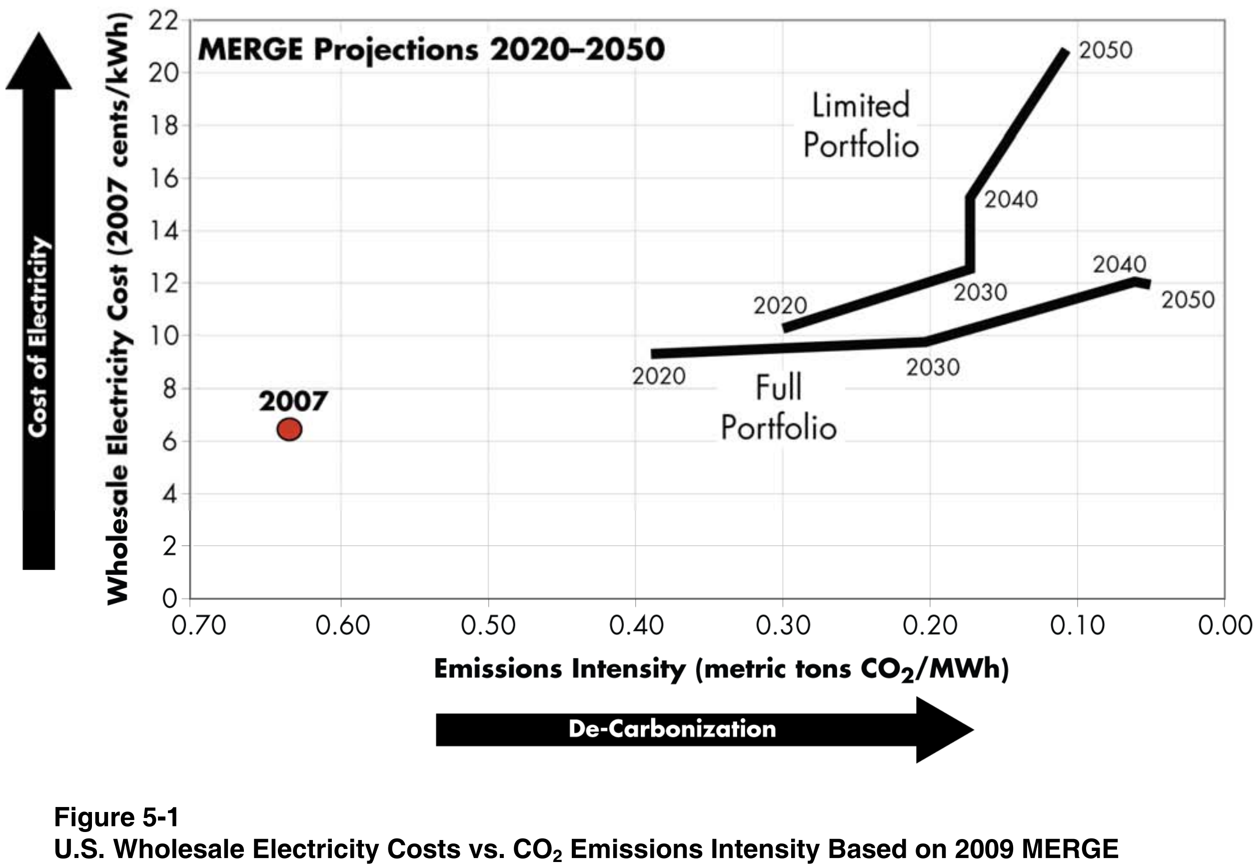

Figure 5-1
U.S. Wholesale Electricity Costs vs. CO_2 Emissions Intensity Based on 2009 MERGE Analysis

The rapid increase in wholesale electricity cost in the limited portfolio is driven by very high reliance on natural gas and renewables – by 2050, these technologies represent 85% of electricity generation. It is clear that the full portfolio enables lower CO_2 emissions intensity at much lower cost. However, much of the required technology comprising the full portfolio is not yet available. The full portfolio comprises both supply- and demand-side technologies: end-use efficiency and plug-in electric vehicles supported by a smart grid; wind, biomass, and solar; new nuclear plants; and advanced coal plants with CO_2 capture and storage. In the full portfolio, nuclear and coal consistently represent 60% or more of total electricity generation. Substantial and sustained research, development and demonstration are required on several fronts concurrently:

- Develop advanced distribution systems capable of enabling widespread deployment of end-use efficiency technologies, new electro-technologies, and plug-in electric vehicles,
- Develop advanced transmissions systems enabling the grid to accept large-scale electricity generation from variable output renewables,
- Enable deployment of new nuclear plants and long-term operations of existing nuclear plants, and
- Develop advanced coal plants with CO_2 capture and storage.

The 2009 Prism and MERGE analyses underscore the urgency of embarking on research, development, and demonstration leading to a full portfolio of electricity sector technologies capable of achieving a low-carbon electricity future at minimum cost.

A
APPENDIX A: 2009 PRISM ANALYSIS

The EPRI Prism analysis is a bottom-up estimate of greenhouse gas (GHG) reduction potential based on the assumption of increased technology performance and deployment in several key technology areas. The EPRI Prism is not a rigorous unit-by-unit assessment, a detailed economic analysis, or a climate policy recommendation. The Prism analysis provides a basis for subsequent detailed energy-economic analysis of contrasting technology development strategies.

A more detailed discussion of the Prism analysis is presented here. Figures A-1 and A-2 below outline the Prism analysis approach. Each technology performance and deployment target and its rationale are discussed below.

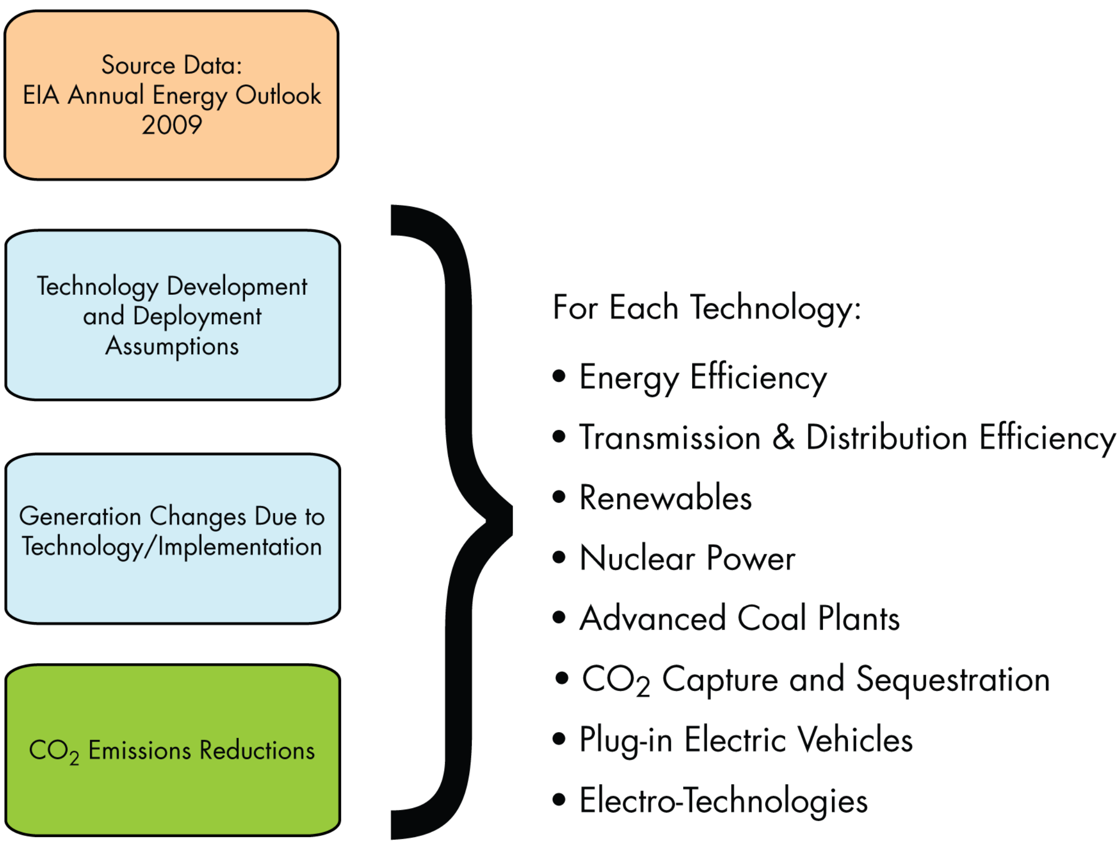

Figure A-1
Prism Methodology Overview

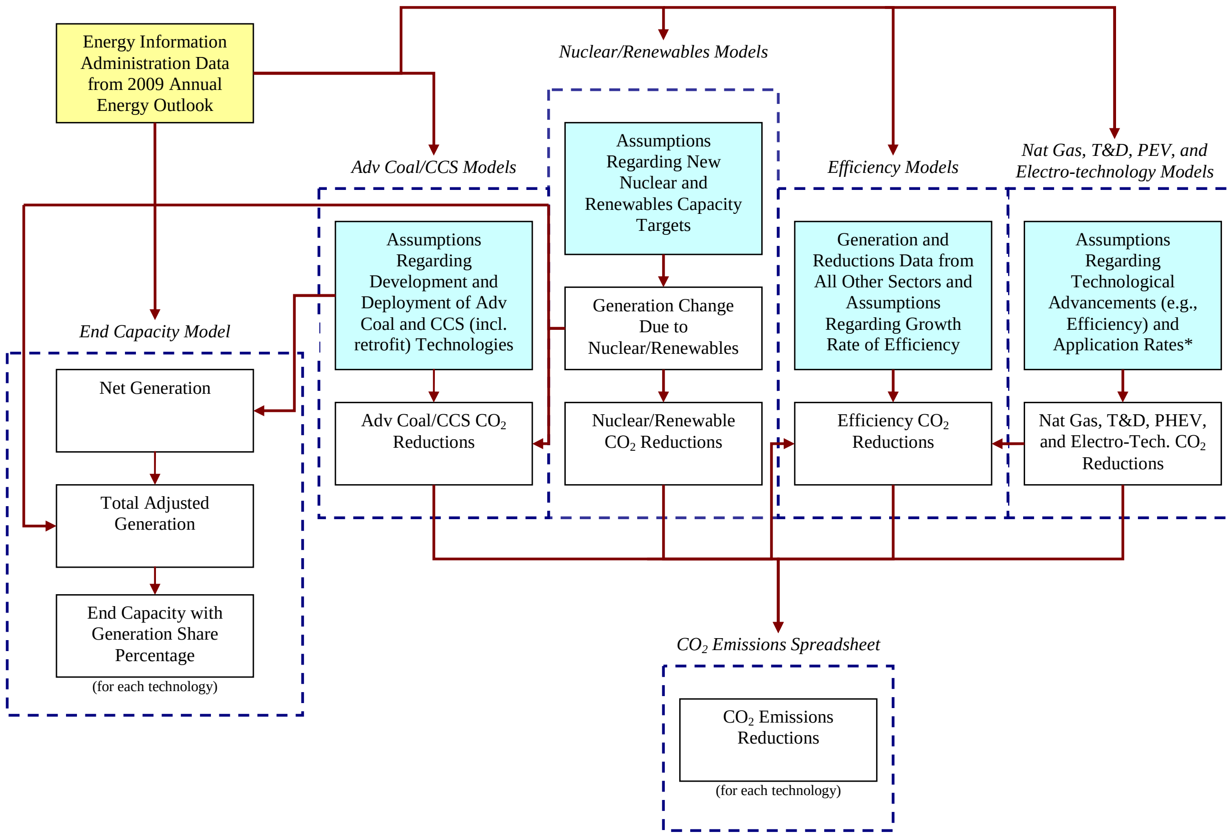

Figure A-2
Prism Analysis Flow Chart

Prism Analysis Targets

A detailed discussion of each Prism technology assumption is provided below.

Table A-1
2009 Prism Technology Assumptions

Technology	EIA AEO Base Case	EPRI Prism Target
Efficiency	Load Growth ~ +0.95%/yr	8% Additional Consumption Reduction by 2030
T&D Efficiency	None	20% Reduction in T&D Losses by 2030
Renewables	60 GWe by 2030	135 GWe by 2030 (15% of generation)
Nuclear	12.5 GWe New Build by 2030	No Retirements; 10 GWe New Build by 2020; 64 GWe New Build by 2030
Fossil Efficiency	40% New Coal, 54% New NGCCs by 2030	+3% Efficiency for 75 GWe Existing Fleet 49% New Coal; 70% New NGCCs by 2030
CCS	None	90% Capture for All New Coal + NGCC After 2020 Retrofits for 60 GWe Existing Fleet
Electric Transportation	None	PHEVs by 2010; 40% New Vehicle Share by 2025 3x Current Non-Road Use by 2030
Electro-technologies	None	Replace ~4.5% Direct Fossil Use by 2030

End-Use Efficiency

The efficiency assumption in the 2007 analysis [EPRI 2007] was based on lower electricity demand growth, assuming lower electricity intensity in all consumption sectors due to end-use technology improvements. The 2009 analysis is based on lower demand growth assuming wide-spread deployment of end-use technologies resulting in reduced electricity consumption corresponding to the "Maximum Achievable Potential" as documented in the 2009 EPRI study on end-use efficiency [EPRI 2009]. The "maximum achievable potential" in this report was estimated to be a reduction in electricity consumption of 8% by 2030 compared to the U.S. EIA 2008 Annual Energy Outlook base case [EIA 2008], which corresponds to a 36% lower annual demand growth rate. That report evaluated potential electricity consumption savings from 2008 – 2030 based on detailed micro-economic modeling using a database of energy efficiency technologies based on input from more than 50 industry experts. Note that the EPRI 2009 efficiency study was based on increased deployment of currently available commercial efficiency technologies. The potential impact of future and emerging technologies is addressed separately in the Prism assumption related to electro-technologies. Note also that the overall growth in electricity demand resulting from all of the Prism assumptions is slightly larger than that of the EIA [EIA 2009] – 1.05%/year - because the consumption savings due to the efficiency assumption are offset by added electricity loads resulting from the PEV and electro-technology assumptions described below.

Transmission & Distribution System Efficiency

The 2009 analysis assumed a 20% reduction in the transmission & distribution (T&D) system's electricity losses and progress in transmission line and grid management technologies. Line engineering improvements would include shield wire segmentation, advanced conductors, corona / insulation losses, and voltage optimization. Grid management technology improvements would include voltage control, reactive power management, and optimal network design.

Renewables

EPRI has conducted several studies investigating the potential role of renewable electricity generation. The 2007 and 2008 energy-economic analyses [EPRI 2007, MERGE 2008] indicated that non-hydro renewables will likely play a significant role in electricity generation under an economy-wide CO_2 emissions constraint. Given widespread discussion of a potential national renewable portfolio standard, the 2009 Prism analysis assumed a 15% national renewable portfolio standard, excluding hydroelectric power. The Prism analysis assumed deployment of ~100 gigawatts electric (GWe) of new wind; ~20 GWe of new biomass; and ~15 GWe of other technologies such as concentrating solar power (CSP) and solar photovoltaics, such that by 2030, 15% of total electricity generation is provided by these resources.

Nuclear

In keeping with the Prism goal of exploring the impact of aggressive technology deployment assumptions on potential CO_2 emissions reductions from the U.S. electricity sector, the 2009 Prism analysis retained the same technology deployment assumption regarding nuclear power as in previous analyses: 10 GWe of new capacity on line by 2020, and 64 GWe of new capacity by 2030. Estimates of the U.S. nuclear fleet's capability to expand are addressed in a strategic assessment jointly developed by Idaho National Laboratory and EPRI [INEL/EPRI]. This assessment developed critical research priorities and timeframes, and discussed deployment capabilities. The Prism nuclear deployment assumption considers this strategic assessment, along with the substantial number of brownfield sites available at existing U.S. nuclear sites, and the fact that advanced light water reactor (ALWR) technology is a well-developed commercial technology that has been built several times overseas. As of February 2009, initial filings for 32 new nuclear units in the U.S. have been submitted, and current planning indicates that these units would be deployed on 21 existing sites and owned by 18 existing nuclear operators. An additional Prism assumption was that all existing nuclear plants continue to operate through 2030 based on plant life extensions to 60 years (more than half of the existing nuclear fleet has already received these extensions).

Advanced Coal Plant Efficiency Improvements

Advanced coal plants principally consist of two technologies: advanced pulverized coal combustion (PC) and integrated gasification combined-cycle (IGCC). Both technologies are addressed in a well-developed technology strategy plan jointly developed by the Coal Utilization Research Council (CURC) and EPRI [CURC/EPRI]. The EPRI/CURC roadmap lays out heat rate performance milestones extending to 2025 for both PC and IGCC technologies. Based on this, the Prism analysis targeted a thermodynamic efficiency of 43% in 2015, and 49% in 2030 for all new coal plants. It also assumed that 75 GWe of the existing coal fleet would be uprated to increase efficiency by 3%. Increased efficiencies result in lower heat rates, which become the basis for calculating avoided emissions. The Prism analysis did not differentiate between coal types or plant locations, but used average emissions intensities (metric tons CO_2 /MWh). The Prism also assumed that new combustion turbine efficiencies will increase to 42% by 2020 and to 45% by 2030. New combined-cycle plant efficiencies are assumed to increase to 60% by 2020 and to 70% by 2030.

CO_2 Capture and Storage

The CURC/EPRI technology strategy [CURC/EPRI] cited above also identifies performance targets for increasingly efficient CO_2 capture technologies. Based on this, the Prism analysis target assumed that by 2020, 90% of all new coal and natural gas combined-cycle (NGCC) plants are capturing and storing 90% of the CO_2 that they produce. The Prism assumed that partial capture demonstrations take place between 2015 and 2020, with commercial-scale of CO_2 transport and storage available beginning in 2020. Thus, for purposes of the Prism analysis, it is presumed that the large scale CO_2 storage demonstration program sponsored by the U.S. Department of Energy will be successful and on schedule. The 2009 Prism analysis added the assumption that 60 GWe of the existing coal fleet will be retrofitted with 90% CO_2 capture technology. The criteria for viable retrofit candidate plants in the existing coal fleet: >500 MW, <12,000 Btu/kWh heat rates, all environmental controls installed, and placed in service after 1970. It is assumed that these plants will be adequately efficient to be commercially viable, notwithstanding the energy penalty associated with CO_2 capture, and will have adequate physical space to add necessary CO_2 capture systems.

Plug-In Electric Vehicles (PEVs)

PEVs represent assets owned by end-users, not utility companies, and any reduction in their emissions perhaps should be accounted for in the transportation sector. The effect of PEVs was analyzed in the Prism to address questions regarding the magnitude of their potential contribution to CO_2 emissions reductions. To assess this, aggressive assumptions regarding the deployment of PEVs were based on joint research by EPRI and National Resources Defense Council [EPRI/NRDC 2007]. The Prism analysis assumed the “medium” PEV scenario from this research, which translates to ~100 million PEVs on road by 2030, and three times greater electricity use for non-road transportation applications. This research also provided assumptions for PEV performance, emissions intensity, and percentage of electric operations. The Prism's avoided emissions calculations account for additional emissions resulting from increased electricity load associated with vehicle recharging.

Electro-Technologies

Electro-technologies using decarbonized electricity can substantially reduce overall CO_2 emissions from electricity use. Electro-technologies present additional emissions reduction potential associated with the development of new end-use technologies that displace direct fossil-fueled energy consumption in favor of technologies using decarbonized electricity. The 2009 Prism assumed that electro-technologies will replace direct use of fossil fuels in commercial, industrial and residential sectors equivalent to ~4.5% of current direct use in applications such as heat pumps, water heaters, ovens, induction melting, and arc furnaces. This is equal to the technical potential calculated in EPRI research [EPRI/ELEC 2009].

B

APPENDIX B: 2009 ENERGY-ECONOMIC (MERGE) ANALYSIS

CO_2 emissions reductions policies will create a cost to the U.S. economy. Reducing CO_2 emissions will require fundamental changes in how we produce, transmit and use energy. The costs of emissions abatement will depend on how investments today are directed to ensure ample supplies of low cost, low-emitting alternatives in the future. In the interim, limited technology choices will lead to reliance on higher cost substitutes. This analysis shows the implications of different paths to achieving emissions reduction objectives.

The MERGE analysis assesses the economic impacts of different strategies to develop and deploy electric sector technologies under a specific CO_2 emissions constraint. The economic impact is estimated in terms of the change in gross domestic product (GDP); a smaller negative number corresponds to lower economic losses. MERGE [ENERGY ECONOMICS 2008, MERGE 1995, MERGE 1992] is a general equilibrium economic model that has been used for more than a decade to analyze the cost of CO_2 emissions mitigation as a function of technology cost, availability, and performance. MERGE models long time horizons to capture economic effects of potential climate change and encompasses all major greenhouse gases and all emitting sectors of the economy. Using technology descriptions and policy constraints as inputs, the model estimates energy production by technology, and the costs for wholesale electricity and carbon emissions.

The reason for using a general equilibrium model such as MERGE is that complex interactions between growth in electricity demand, division between use of non-electric and electric energy, and changes in patterns of energy use across the entire economy can exert significant effects on the overall cost of CO_2 abatement and the optimal combination of electricity technologies needed to reduce this cost over time. It is critical, therefore, to model these interactions in analyzing the impact of CO_2 emissions constraints and various strategies to develop and deploy technology.

Analysis Approach

Conceptually, MERGE estimates the least-cost combination of technologies necessary to provide the economy's energy services, both *with* and *without* a CO_2 emissions constraint. For this analysis, MERGE contrasts a "Limited Portfolio" scenario representing incremental technology deployment, and a "Full Portfolio" scenario in which many complementary technologies are effectively deployed.

	Limited Portfolio	Full Portfolio
Supply-Side		
Carbon Capture and Storage (CCS)	Unavailable	Available
New Nuclear	Existing Production Levels	Production Can Expand
Renewables	Costs Decline	Costs Decline Faster
New Coal and Gas	Improvements	Improvements
Demand-Side		
Plug-in Electric Vehicles (PEVs)	Unavailable	Available
End-Use Efficiency	Improvements	Accelerated Improvements

Figure B-1
Merge Technology Scenarios

Comparing the economy-wide cost of meeting a CO_2 constraint between these two scenarios provides a basis for assessing the value of the RD&D investment in deploying a full portfolio of advanced technologies. The Limited Portfolio scenario represents modest improvement beyond the current technologies, but excludes carbon capture and storage, PEVs, nuclear power expansion. The Full Portfolio scenario represents substantial improvement in performance and costs for a range of technologies, thus allowing more widespread economical deployment of these technologies.

Consistent with post-industrial development patterns, a decline in the rate of GDP growth is assumed as an economy shifts its mix of goods and services over time. In 2010, annual GDP growth is 2.4% declining to 1.3% by 2050. Note that, on average, this is about 20% lower annual growth compared to the revised EIA 2009 Annual Energy Outlook macroeconomic assumptions issued in April 2009. Regarding projected economic growth, the analysis does not specifically model recent economic stimulus legislation, but does account for recession effects through 2010.

Discussion of Modeled CO_2 Emissions Constraint

An economy-wide CO_2 emissions constraint requiring a linearly declining level of annual emissions from 2010 is applied, such that by 2050, annual emissions levels are 83% below 2005 levels (equivalent to 80% below 1990 levels). Note that the use of this constraint in the model does not imply endorsement of any particular policies. It was selected as indicative of proposals currently being discussed by policymakers, and because it provides insight into the rate and magnitude of reductions associated with various technology choices. As noted previously, such economy-wide emissions constraints serve as inputs into MERGE. The model then allocates emissions reductions across the entire economy in a manner that minimizes the economic abatement costs. Note that the model forces compliance with the specified CO_2 emissions constraint in any scenario – the scenarios differ in terms of the economic cost of meeting the constraint as well as the pattern of technology deployment over time.

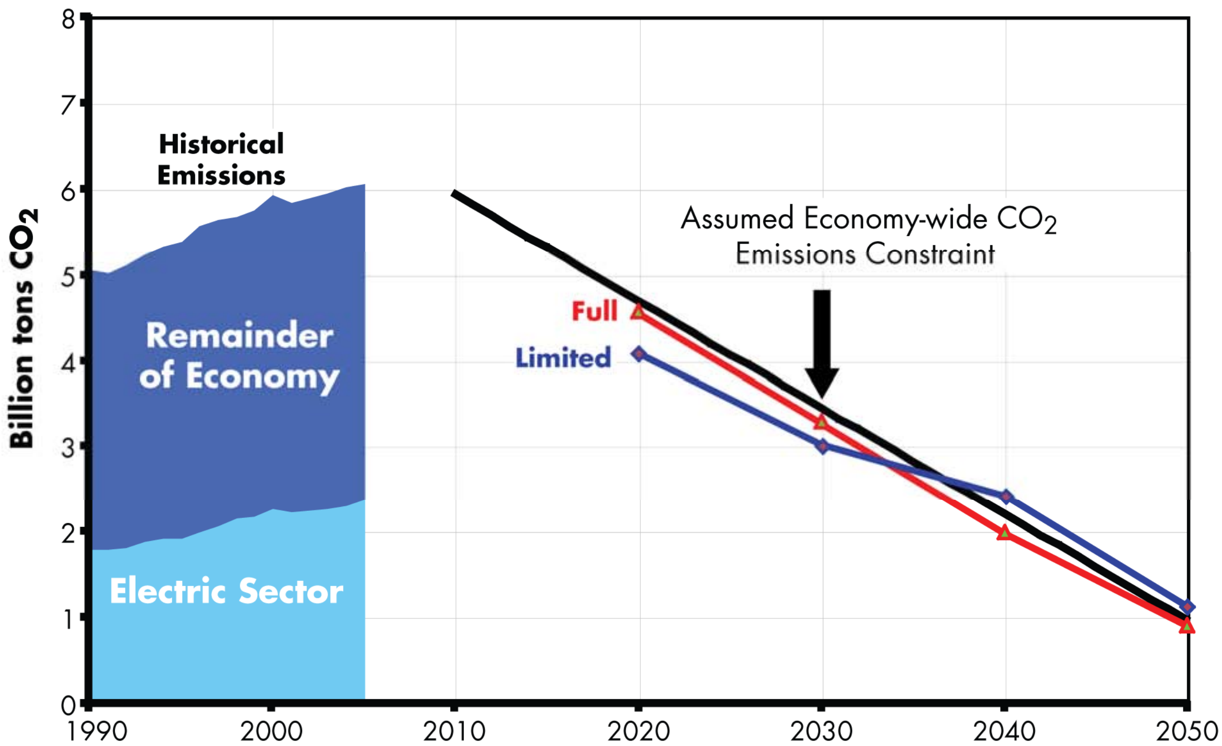

Figure B-2
U.S. CO_2 Emissions based on 2009 MERGE Analysis

The constraint was applied to all energy-related CO_2 emissions, as well as other industrial GHG sources likely to be capped by domestic regulation. A prominent feature of some legislative proposals is the ability to use a wide variety of offsets, that is, emissions reduction activities in uncapped sectors, to demonstrate compliance under the cap. In this analysis, by contrast, a limited offset pool is assumed, consisting only of domestic reductions in agricultural N_2O and CH_4. Note that these potential reductions are on the order of 200 million metric tons of CO_2/year, which is a small fraction of total required emissions. No additional offsets from forestry or international activities were included in the analysis. Because of the potentially strong effect of widespread offset use on the CO_2 price, these assumptions represent a key difference between this analysis and currently proposed legislation. This approach to offsets was chosen for several key reasons:

- Significant uncertainty regarding the amount of verifiable and sustainable offsets;
- Uncertainty regarding additional costs and complexities in administering programs necessary to manage forestry and international offsets;
- Potentially significant reduction in available international offsets due to emissions reductions policies in other countries/regions; and

The need to illustrate implications of reducing emissions substantially to meet reduction targets under the cap.

General Technology Assumptions

The 2009 MERGE analysis is based on several key technology assumptions. General assumptions, followed by a detailed description (see Table B-1) of technology cost assumptions are provided below.

- Updated technology costs are based on data from EPRI's Technology Assessment Guide (TAG) research program for 2008 and 2009. Based on cost trends between 2006 and 2008, most 2010 costs were generally projected to be approximately 10% higher than costs estimated in 2008 MERGE studies [MERGE 2008].
- $10/metric ton CO_2 transport and storage costs assumed.
- In modeling the retirement of existing coal and nuclear plants, this analysis assumes a plant life of 60 years.

No investment or production tax credits or other subsidies are assumed for any technology.

Discussion of analysis approach for specific technologies

- Assumed fuel resources
  - Natural gas reserves

    The U.S. natural gas resource base was assumed to be 1400 trillion ft^3 (TCF), which is roughly equal to the total of all proven, probable, and possible reserves as estimated by the Potential Gas Committee (PGC), a group of experts convened by the Colorado School of Mines, which issues a biennial report[PGC 2009]. The 2009 PGC report estimates that approximately 1/3 of estimated gas reserves are unconventional resources, e.g. shale. The assumed gas resource base excluded an additional 600 TCF of gas that the PGC classified as "speculative".

- Wind

  Based on current technology and assumed future improvement in technologies that would increase the potential wind resource available for development to 840 TWh in 2010, increasing by 20 TWh each decade up to 920 TWh in 2050. Note that renewables generation results from the MERGE analysis do not reach these limits until the end of the analysis period.

- Coal

  The analysis uses a constant fuel cost of $1.80/GJ (in 2000$) for coal in the U.S. This translates to $1.9/MMBtu (in 2000$) or 2.3/MMBtu (in 2008$). In some other regions coal costs range from a low of $1.3/GJ in China, India, and Russia, to a high of $2.3/GJ in parts of the European Union. New coal plants in 2020 are assigned a heat rate of 8.6 GJ/MWh in the full portfolio and 9.5 GJ/MWh in the limited portfolio. Existing coal plants were assumed to have an average heat rate of 11 GJ/MWh. This produces a U.S. fuel cost of $19.7/MWh for existing plants, and 2020 costs of $17.1/MWh for new coal in the limited portfolio, and $15.5/MWh in the full portfolio.

- Uranium reserves

  U.S. nuclear power is based on a once-through fuel cycle, in which spent fuel is not reprocessed and in which other nuclear fuels are not used (e.g. advanced fuel cycles). Given the growth of already significant nuclear energy production internationally, the 2009 MERGE analysis models a finite amount of energy equivalent to known global uranium reserves. The assumed global uranium reserve is 7,700 exajoules (EJ), based on a detailed assessment performed by Working Group III of the Intergovernmental Panel on Climate Change [IPCC 2001]. Current annual global consumption is around 30 EJ.

• CCS retrofit

Consistent with the 2009 Prism analysis, the 2009 MERGE analysis assumed that 60 GW of the existing coal fleet is viable for CCS retrofit. The basis for the 60 GW figure was technical judgment by EPRI domain experts. The following criteria were considered in forming this judgment:

- >500 MW capacity – providing for net capacity after retrofit that is large enough to retain plant's versatility as a baseload asset;
- <12,000 Btu/kWh heat rate represents a level of efficiency to keep the plant economically viable, notwithstanding the energy penalty from CCS ;
- Plants in which all other environmental controls were previously installed would not have to overcome the economic cost and hurdle of retrofitting both CCS and other environmental controls; and
- Plants placed in service after 1970 were judged more likely to have space available for retrofitted equipment.

The cost of CCS retrofit was estimated as an additional cost in dollars per megawatt-hour ($/MWh) to the average marginal electricity cost of the existing coal fleet (see Table B-1 below for data). This additional cost is based on preliminary estimates performed by EPRI. It was also assumed that implementing CCS retrofit would not extend or reduce plant operating life. The reduced plant efficiency associated with addition of CCS was considered.

- Grid integration/transmission costs for variable output renewables

  The 2009 MERGE analysis assumed that electricity production from variable output renewables (solar, wind) is limited only by levelized electricity production cost. Based on the assumption that high levels of electricity production from variable output renewables will require additional investments in generation, storage, and transmission assets to offset potential grid stability issues, a grid integration and transmission investment cost is added to the nominal, levelized cost of electricity production for variable output renewables. Beginning at zero, these added costs are gradually increased along with the share of generation provided by variable output renewables. See technology costs tabulated below.

- Increasing fuel costs for biomass

  Historical data for feedstock costs for biomass electricity production are principally based on the costs for industrial residues (e.g. wood chips). For significant levels of electricity production, dedicated production of feedstocks will be necessary. Factors such as land scarcity, competition for feedstocks from biofuels production, and transportation costs will gradually drive feedstock costs upward. Therefore, the 2009 MERGE analysis assumed increasing feedstock costs as a function of total energy demand for biofuels or biomass electricity production. See technology costs tabulated below.

Treatment of Nuclear Generation

In the limited portfolio scenario, the nuclear fleet does not expand from current levels, meaning that the existing fleet runs to retirement, with no construction of any new replacement plants. In both the limited and full portfolios, no new nuclear construction is factored prior to 2020.

Table B-1
2009 MERGE Technology Cost Data (all costs in 2008 $)

Technology	Timeframe			Notes
	2010	**2020**	**2030-2050**	
New Coal (without CCS)	$52/MWh 38% efficiency	$47/MWh 42% efficiency	$43/MWh 46% efficiency	o Average of pulverized coal, integrated gasification combined-cycle o Excludes fuel cost. o Plant life = 60 years
New Coal + CO_2 capture and storage (CCS) *(Full Portfolio only)*	Not available	$72/MWh 34% efficiency	2030: $64/MWh 37% efficiency 2040: $57/MWh 42% efficiency 2050: $57/MWh 42% efficiency	o Average of pulverized coal, integrated gasification combined-cycle. o Assumes 90% capture efficiency. o Excludes fuel cost. o Excludes CO_2 transport/storage cost. o Plant life = 60 years o This technology is never available in the Limited Portfolio case.
Existing Coal + CO_2 capture and storage (CCS) retrofit *(Full Portfolio only)*	Not available	$39/MWh 28% efficiency reduction	$39/MWh 28% efficiency reduction	o Average of pulverized coal, integrated gasification combined-cycle o Assumes 90% capture efficiency. o Excludes fuel cost. o Excludes CO_2 transport/storage cost. o Costs represent incremental cost in addition to assumed nominal dispatch cost of ~$29/MWh. o Plant life = 60 years; plant life assumed to remain unchanged by CCS retrofit. o This technology is never available in the Limited Portfolio case.
Natural Gas	$16/MWh 47% efficiency	$17/MWh 54% efficiency	$17/MWh 54% efficiency	o Excludes fuel cost o Fuel cost separately calculated by MERGE based on assumed reserves and calculated non-electric and electric gas demand.

Technology	Timeframe			Notes
	2010	**2020**	**2030-2050**	
Natural Gas + CO_2 capture and storage (CCS) *(Full Portfolio only)*	Not available	$24/MWh 39% efficiency	$22/MWh 42% efficiency	o Assumes 90% capture efficiency. o Excludes fuel cost o Fuel cost separately calculated by MERGE based on assumed reserves and calculated non-electric and electric gas demand. o This technology is never available in the Limited Portfolio case.
Nuclear				
Limited Portfolio	$84/MWh	$84/MWh	$84/MWh	o Capacity factor = 90% o Efficiency = 33% o Plant life for new, existing units = 60 years o Added non-market cost = ~$10/MWh (at current generation share for nuclear); scales up with increasing nuclear generation share. o Inclusive of fuel cost o In limited portfolio, nuclear fleet does not expand from current levels, (including no new plants to replace retiring capacity.)
Full Portfolio	$84/MWh	$74/MWh	2030: $71/MWh 2040: $69/MWh 2050: $67/MWh	
Wind				
Limited Portfolio	$105/MWh	$102/MWh	2030: $99/MWh 2040: $96/MWh 2050: $93/MWh	o 2010-2050: 32.5% capacity factor o Additional grid integration, transmission infrastructure costs are added depending on total electricity generation share (see below).
Full Portfolio	$105/MWh	$82/MWh	2030: $80/MWh 2040: $77/MWh 2050: $75/MWh	o 2010: 32.5% capacity factor o 2020-2050: 42% capacity factor o Additional grid integration, transmission infrastructure costs are added depending on total electricity generation share (see below).

Technology	Timeframe			Notes
	2010	**2020**	**2030-2050**	
Solar thermal				
Limited Portfolio	$175/MWh	$175/MWh	$175/MWh	o 34% capacity factor
Full Portfolio	$175/MWh	$175/MWh	2030: $170/MWh 2040: $165/MWh 2050: $160/MWh	
Solar photovoltaic				
Limited Portfolio	$250/MWh	$250/MWh	$250/MWh	
Full Portfolio	$250/MWh	$220/MWh	2030: $194/MWh 2040: $170/MWh 2050: $150/MWh	

Grid integration/transmission infrastructure costs for non-hydro variable output renewables (wind and solar):

- Added costs based on level of electricity generation share for sum of wind and solar.
- Added costs based on studies of large scale wind integration by DOE [DOE 2008] and LBL [LBL 2009]. Note that the maximum added transmission cost was limited to 2/3 of the LBL value based on the assumption that some new transmission would be developed independent of renewables development.
- Costs defined in two categories: grid integration (i.e. backup power/energy storage) and added transmission infrastructure.
- Costs increase more rapidly in Limited Portfolio case based on assumption that less RD&D investment leads to slower development of smart grid capabilities; the converse is true for the Full Portfolio case.
- Limited Portfolio
  - 0-5% electricity generation share: no added costs
  - 5-10% electricity generation share: add ½ of maximum costs:
    $2.50/MWh (grid integration) + $5.00/MWh (transmission) = $7.50/MWh.
  - 10-20% electricity generation share: add 75% of maximum costs:
    $3.75/MWh (grid integration) + $7.50/MWh (transmission) = $11/MWh
  - >= 20% electricity generation share: add 125% of maximum costs:
    $6.25/MWh (grid integration) + $12.50/MWh (transmission) = $19/MWh.
- Full Portfolio
  - 0-5% electricity generation share: no added costs
  - 5-10% electricity generation share: add 1/3 of maximum costs:
    ~$1.70/MWh (grid integration) + $3.33/MWh (transmission) = $5.00/MWh.
  - 10-20% electricity generation share: add 1/2 of maximum costs:
    $2.50/MWh (grid integration) + $5.00/MWh (transmission) = $7.50/MWh
  - >= 20% electricity generation share: add maximum costs:
    $5/MWh (grid integration) + $10/MWh (transmission) = $15/MWh

Technology	Timeframe			Notes
	2010	**2020**	**2030-2050**	
Biomass				
Limited Portfolio	$63/MWh	$63/MWh	$63/MWh	o 85% capacity factor o Costs at left are non-energy portion of levelized cost of electricity production. o Feedstock cost assumed to increase as combined biomass feedstock demand for biofuels and electricity production increases, fuel costs are increased to represent scarcity of land, increased transportation costs (see below). o Efficiency = 28%
Full Portfolio	$63/MWh	$50/MWh	2030: $48/MWh 2040: $47/MWh 2050: $46/MWh	

<u>Biomass feedstock costs for biofuels and electricity production</u>:

- As total feedstock consumption increases, energy cost increases due to use of different types of feedstock.
- Three feedstock types considered: non-agricultural residues (e.g. wood chips); agricultural residues, and dedicated energy crops (e.g. switchgrass).
- Non-agricultural residues
  - o feedstock cost = $2.3/mmBtu
  - o maximum energy from non-agricultural residues = 2.25 exajoules
  - o assumed available solely for electricity production
- Agricultural residues
  - o feedstock cost = $4.2/mmBtu
  - o maximum energy from agricultural residues = 4.25 exajoules
  - o assumed available for either biofuels or electricity production
- Energy crops (no limit on available energy from energy crops; assumed available for either biofuels or electricity production)
  - o Initial feedstock cost = $4.5/mmBtu
  - o For OECD, transitional economic regions, feedstock cost increases linearly at a rate of $0.64/mmBtu for each additional exajoule produced from energy crops, based on assumption of increasing land scarcity, feedstock transportation costs
  - o For developing economic regions, feedstock cost increases linearly at a rate of $0.32/mmBtu for each additional exajoule produced from energy crops
  - o Limited Portfolio –biomass heat rate remains fixed at 12,300 Btu/kWh
  - o Full Portfolio
    - ▪ Heat rate (Btu/kWh) improves over time: 12,300 (2010); 11,900 (2020); 11,500 (2030); 11,100 (2040); 10,700 (2050)

Technology	Timeframe			Notes
	2010	2020	2030-2050	
Plug-in Electric Vehicles		- $4000 price premium/ vehicle - 250 Watt-hrs/mile in electric mode - Maximum 4% vehicle fleet	2030 - 2050 - $2500 price premium/ vehicle 2030 - 220 Watt-hrs/mile in electric mode - PEV fleet can triple over 2020 deployment 2040 - 210 Watt-hrs/mile in electric mode 2050 - 200 Watt-hrs/mile in electric mode 2040-2050 - PEV fleet can double each decade	o PEV assumed to operate 50% of miles traveled in electric mode, based on 12 KWh battery.

C
APPENDIX C: REFERENCES

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