Technical Appendix: A Clean Energy Bargain: More Jobs, Less Global Warming Pollution, and Greater Security for Less Than the Cost of a Postage Stamp Per Day[1]

March 2010

NEMS-NRDC:

Overview

NEMS was developed by the U.S. Department of Energy, and it is the model that the Energy Information Administration (EIA) uses to develop its Annual Energy Outlook (AEO). It is an integrated system with representations of U.S. energy supply, demand, and conversion, all within an economic framework. NRDC commissioned OnLocation Inc., a consulting group with extensive experience with NEMS for a variety of clients, to analyze the American Clean Energy and Security Act (ACES) using a modified version of this model referred to as NEMS-NRDC. OnLocation has provided NEMS model development and support to EIA for over 15 years.

Model Architecture

The time horizon of NEMS-NRDC is through 2030 (AEO 2010, which was just released, now extends to 2035). Because of the diverse nature of energy supply, demand, and conversion in the United States, NEMS-NRDC supports regional modeling and analysis in order to represent the regional differences in energy markets, to provide policy impacts at the regional level, and to portray transportation flows. The level of regional detail for the end-use demand modules is the nine Census divisions. Other regional structures include production and consumption regions specific to oil, natural gas, and coal supply and distribution, the North American Electric Reliability Council (NERC) regions and subregions for electricity, and the Petroleum Administration for Defense Districts (PADDs) for refineries.

For each fuel and consuming sector, NEMS-NRDC balances the energy supply and demand, accounting for the economic competition between the various energy fuels and sources. NEMS-NRDC is organized and implemented as a modular system. The modules represent each of the fuel supply markets, conversion sectors, and end-use consumption sectors of the energy system. NEMS-NRDC also includes a macroeconomic and an

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[1] Additional details can be found at http://docs.nrdc.org/globalWarming/files/glo_09101501a.pdf,, which provides additional information given to the House Energy and Commerce Committee in response to questions regarding modeling assumptions.

international module. The primary flows of information between each of these modules are the delivered prices of energy to the end user and the quantities consumed by product, region, and sector. The delivered prices of fuel encompass all the activities necessary to produce, import, and transport fuels to the end user. The information flows also include other data such as economic activity, domestic production, and international petroleum supply availability.

The integrating module of NEMS-NRDC controls the execution of each of the component modules. To facilitate modularity, the components do not pass information to each other directly but communicate through a central data storage location. This modular design provides the capability to execute modules individually, thus allowing decentralized development of the system and independent analysis and testing of individual modules. This modularity allows use of the methodology and level of detail most appropriate for each energy sector. NEMS-NRDC solves by calling each supply, conversion, and end-use demand module in sequence until the delivered prices of energy and the quantities demanded have converged within tolerance, thus achieving an economic equilibrium of supply and demand in the consuming sectors. Solution is reached annually through the projection horizon. Other variables are also evaluated for convergence such as petroleum product imports, crude oil imports, and several macroeconomic indicators.

NEMS-NRDC reports results on an annual basis through 2030.

Much of the information in this section was taken directly from EIA’s “Assumptions to the Annual Energy Outlook 2009,” which contains more detailed information on the version of NEMS that EIA used for its AEO2009 projections, and it is available at: http://www.eia.doe.gov/oiaf/aeo/assumption/index.html. Please note that unless explicitly stated in this report, we did not change the embedded assumptions in the version of NEMS used for the March AEO2009 Published Release.

NEMS-NRDC: REPRESENTING BUSINESS-AS-USUAL

Overview

Business-as-usual (BAU) is the March AEO2009 Published Release which we modified to reflect the extended renewable tax credits specified in the Stimulus Bill. The April AEO2009 Updated Release with the Stimulus Bill included an updated economic forecast (reflecting the growing recession), updated (higher) world oil prices, and other changes to reflect some of the provisions of the Stimulus Bill. Because we did not attempt to replicate the changes made between the March and April releases of the AEO2009 in developing our BAU case, there are differences between our BAU case and the April AEO2009 Updated Release with the Stimulus Bill. For example, our BAU case forecasts slightly higher total primary energy consumption and energy-related carbon dioxide (CO_2) emissions in 2030 relative to the AEO2009 Updated Release by 2.0 percent and 3.5 percent, respectively.

Description of Key BAU Assumptions (in both NEMS-NRDC and AEO2009)

The following section on capital costs, learning rates, capacity constraints, and transportation assumptions provide insight into how each of those topics are handled in AEO2009. For our BAU case in NEMS-NRDC, we did not modify any of these assumptions, so they are identical to those in AEO2009. As mentioned in the previous paragraph, the only difference between our BAU and the AEO2009 is how we chose to modify the March AEO2009 Published Release to reflect the Stimulus Bill.

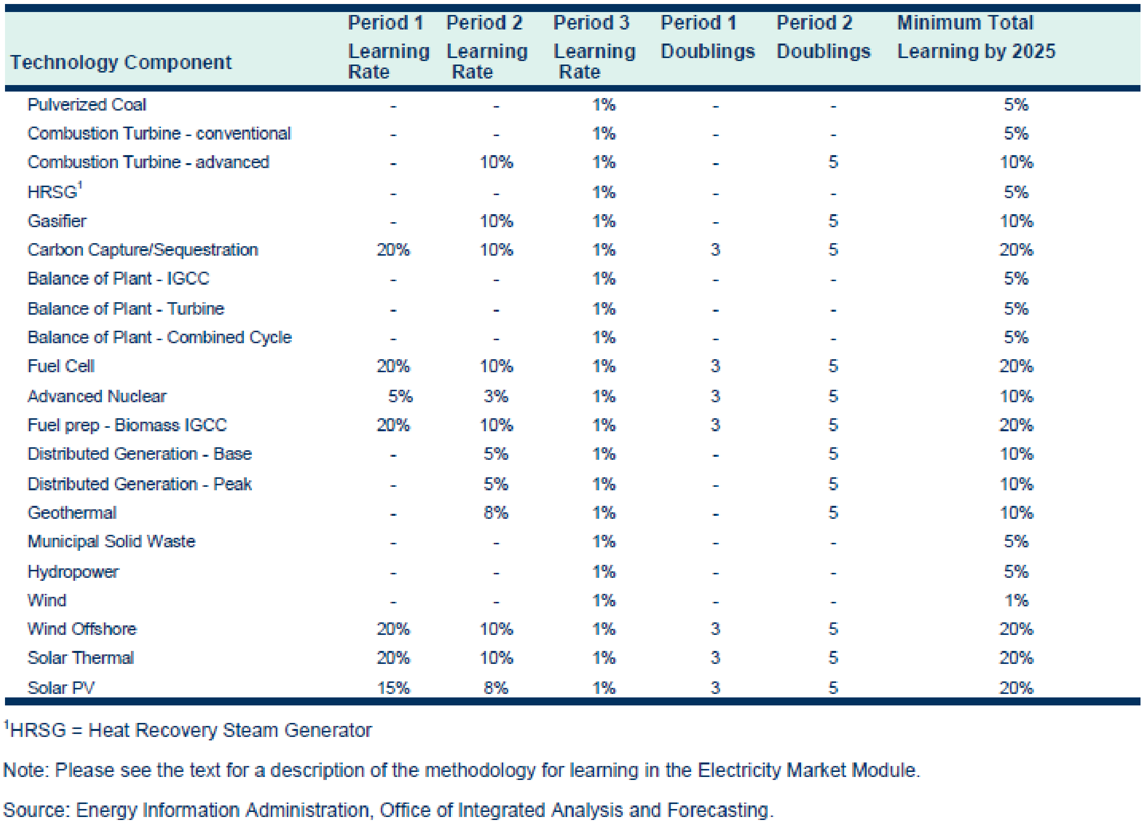
Capital Costs and Learning Rates

We did not change the overnight capital and O&M costs of electricity generating technologies from the levels used in the March AEO2009 Published Release. Overnight capital costs for selected technologies are presented further below in Table A-2. Variable and fixed O&M costs can be found on Page 89 of the AEO2009 Assumptions document, which is available at: http://www.eia.doe.gov/oiaf/aeo/assumption/pdf/0554(2009).pdf.

Furthermore, we did not alter the learning parameters in the model from those used in AEO2009. In AEO2009, learning parameters specify how much technology costs can go down over time. Costs are assumed to decline relative to how much capacity has been built, to reflect the tendency for costs to decline more sharply in the early phase of a technology's development than later when the technology becomes more mature. To capture this, "progress ratios" are applied to a technology's cost over time according to how much has been built. Progress ratios indicate how much costs are assumed to decline for a given doubling in installed capacity. For example, if total installed capacity for a particular technology doubles and there is a progress ratio of 90%, the technology will cost 90% of what it originally cost. AEO2009 further refines learning by breaking down a generation technology into its components, with some components achieving cost reductions faster than others. For example, for IGCC with CCS, the cost of its combustion turbine component declines faster than the cost of its heat recovery steam generator component. (For more information, see pages 90 and 91 of the following: http://www.eia.doe.gov/oiaf/aeo/assumption/pdf/0554(2009).pdf).

In the NEMS-NRDC reference and policy cases, we follow EIA's NEMS assumptions, which classify progress ratios into three general stages, and though the progress ratios in each stage vary across technologies, they tend to be ~80% in Stage 1, ~90%-95% in Stage 2, and 99% in Stage 3. Each technology component is designated into one of three technology types, each moving through one or more learning stages. To cite an example, the cost of a very new technology component would be designated as "revolutionary" and would start in Stage 1, declining to ~50% (~80%^3) of its original cost after its total installed capacity has doubled 3 times (i.e., if the original cost is $1,000/kW, then after three doublings of total installed capacity, the cost will now be $512/kW, assuming an 80% learning rate). The technology would then enter Stage 2 and continue to improve up to a maximum progress ratio through 2030 that varies by technology type. The declining cost curve over time is also referred to as "learning," with "learning rates" being the inverse of the progress ratio (a progress ratio of 80%, for example, would have a corresponding learning rate of 20%). Revolutionary technologies are limited to 50% learning overall (so in the previous example cited, its cost could only lower to $500/kW); evolutionary technologies are limited to 30% learning rates (i.e., 70% progress ratio) and conventional technologies are limited to 10% learning. Learning rates for each stage are shown below in Table A-1.

Table A-1. Learning parameters for new generating technology components, taken from Page 90 of the AEO2009 Assumptions document



Technology Component	Period 1 Learning Rate	Period 2 Learning Rate	Period 3 Learning Rate	Period 1 Doublings	Period 2 Doublings	Minimum Total Learning by 2025
Pulverized Coal	-	-	1%	-	-	5%
Combustion Turbine - conventional	-	-	1%	-	-	5%
Combustion Turbine - advanced	-	10%	1%	-	5	10%
HRSG[1]	-	-	1%	-	-	5%
Gasifier	-	10%	1%	-	5	10%
Carbon Capture/Sequestration	20%	10%	1%	3	5	20%
Balance of Plant - IGCC	-	-	1%	-	-	5%
Balance of Plant - Turbine	-	-	1%	-	-	5%
Balance of Plant - Combined Cycle	-	-	1%	-	-	5%
Fuel Cell	20%	10%	1%	3	5	20%
Advanced Nuclear	5%	3%	1%	3	5	10%
Fuel prep - Biomass IGCC	20%	10%	1%	3	5	20%
Distributed Generation - Base	-	5%	1%	-	5	10%
Distributed Generation - Peak	-	5%	1%	-	5	10%
Geothermal	-	8%	1%	-	5	10%
Municipal Solid Waste	-	-	1%	-	-	5%
Hydropower	-	-	1%	-	-	5%
Wind	-	-	1%	-	-	1%
Wind Offshore	20%	10%	1%	3	5	20%
Solar Thermal	20%	10%	1%	3	5	20%
Solar PV	15%	8%	1%	3	5	20%

[1] HRSG = Heat Recovery Steam Generator

Note: Please see the text for a description of the methodology for learning in the Electricity Market Module.

Source: Energy Information Administration, Office of Integrated Analysis and Forecasting.

Capacity Constraints

Capacity constraints on generation technologies are identical to the constraints in AEO2009. AEO2009 does not establish "hard limits" on the adoption of technologies, though it does ratchet up the cost of those technologies at various points (which effectively serves as a "soft limit"). More specifically, the model looks at the amount of capacity that has been added in every year over the last ten years (and it does this every year, so the ten-year period is constantly shifting forward). In particular it is looking for the greatest amount of capacity that has been added in a single year over the last ten years – for the purposes of this explanation, we will refer to that amount of capacity as the "base amount." So in any given year, it will allow up to 120% of that "base amount" to be added at the reported overnight capital cost. If between 120% and 200% of that "base amount" is added, then the cost goes up by 40% (e.g., from $1,000/kW to $1,400/kW) for the capacity that is added after the 120% threshold; and if between 200% and 300% of the "base amount" is added, then the cost goes up 130% relative to the original cost (e.g., from $1,000/kW to $2,300/kW) for the capacity that is added after the 200% threshold.

Transportation[i]

Regarding light-duty vehicles (LDVs), fuel economy standards reflect current law through model year 2010. For model years 2011 through 2015, fuel economy standards reflect NHTSA's recently proposed standards. For model years 2016 through 2020, the standards reflect EIA's assumed increases that ensure a light vehicle combined fuel economy of 35 mpg is achieved by model year 2020. For model years 2021 though 2030, fuel economy standards are held constant at model year 2020 levels, although fuel economy continues to improve at a slower pace, reaching 38 mpg by 2030.

NEMS-NRDC: REPRESENTING THE AMERICAN CLEAN ENERGY AND SECURITY ACT

Overview

To model the impact of the American Clean Energy and Security Act (ACES), we reflect emission limits, renewable electricity standards, carbon capture and sequestration incentives, energy efficiency provisions, CAFE standards for light-duty vehicles, offsets, banking, allowance allocations toward different purposes, and a tightening of the renewable fuel standards for transportation fuels. Unless otherwise stated, the assumptions described under BAU are the same in the policy case.

Emissions Limits

In accordance with the version of the bill that passed the House of Representatives, we imposed emissions limits of 3% below 2005 levels by 2012, 17% below 2005 levels by 2020 and 42% by 2030, with the limits for interim years determined by a linear interpolation between those years. Furthermore, those limits were applied to sectors of the economy that represented 86 percent of total emissions: all energy-related CO_2 emissions; methane from coal mining, stationary combustion and mobile sources; nitrous oxides from stationary combustion, mobile sources, and industrial processes; and all fluorinated gases except hydrofluorocarbons. The bill's phase-in of certain industrial and natural gas sources was not represented in the model.

Renewable Electricity Standards

ACES requires retail electricity distributors to meet a rising fraction of demand with renewable energy sources and improved efficiency, starting with 6 percent in 2012 and rising to 20 percent in 2020, then remaining at that level thereafter. At least three-quarters of that amount must come from renewable resources. However, the Federal Energy Regulatory Commission (FERC) may, on a governor's petition, lower the renewable component to three-fifths of a utility's obligation, with the remainder to come from efficiency. Because of that ability for energy efficiency to meet part of the requirement, we assume that the "effective" RES level is at 75% of the stated standard (i.e., 15% in 2020, as opposed to 20%). In order to represent the additional energy efficiency that may occur due to the EERS, we used the EIA AEO 2009 High Technology case assumptions and assumed that energy efficiency would make up the gap between 15 percent renewables and 20 percent total requirement (for more details, please see below under "Energy Efficiency Provisions").

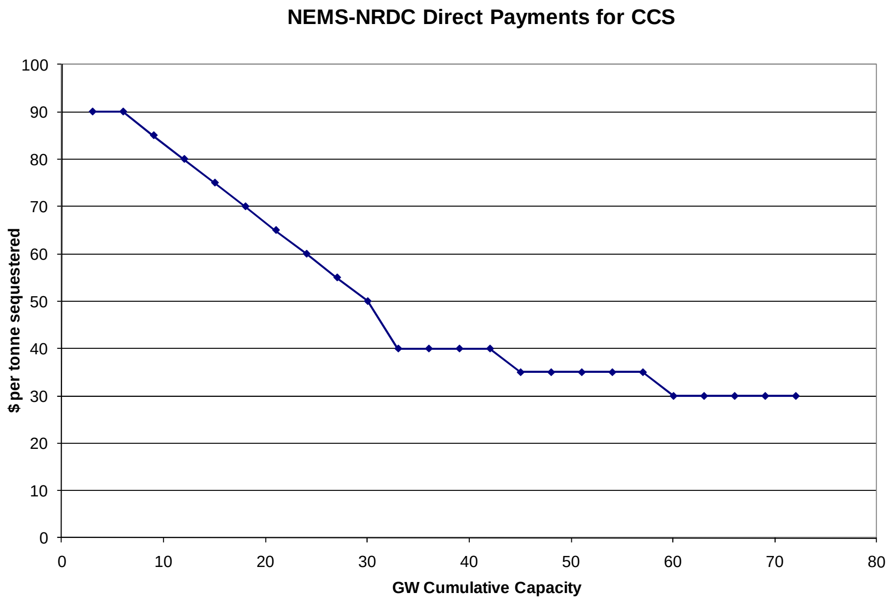
We also modeled an RES triple credit through the year 2030 for distributed generation.

Carbon Capture and Sequestration Incentives

Regarding CCS, ACES has provisions that provide incentives for the successful deployment of carbon capture and sequestration (CCS). Those provisions were modeled as incentive payments per ton of CO_2 captured that decline as a function of cumulative installed capacity. Payments to eligible facilities are paid annually over a 10-year period.

The incentive payments are available to the first 72 GW of CCS capacity built, both IGCC coal and natural gas combined cycle with CCS, beginning at $90 per ton (in 2008 dollars) for the first 6 GW and declining thereafter according to the schedule shown below in Figure A-1.

Figure A-1. Incentive payments for the deployment of CCS, which decline according to the cumulative amount of installed capacity.



Energy Efficiency Provisions

In order to approximate the effects of energy efficiency provisions and programs designed to remove barriers to cost-effective energy efficiency measures in ACES, we did the following:

i) The High Technology Case assumptions from the AEO2009 Published Release (March) were adopted in place of the Reference Case assumptions for the residential and commercial sectors in our core run of ACES.

The High Technology Case assumes that more efficient devices come onto the market faster than in the Reference Case. More information on the High Technology Case can be found in the AEO2009 documentation, available at: http://www.eia.doe.gov/oiaf/aeo/pdf/0383(2009).pdf.

To provide a sense of the magnitude of these changes between the Reference Case and the High Technology Case, here is an excerpt describing its impact on the residential sector (from page 63 of the previously-linked AEO2009 Assumptions document): *"The high technology case assumes lower costs, higher efficiencies, and earlier availability of some advanced equipment. In the reference case, residential energy use per capita is projected to fall below the 2006 level (the lowest since 1990) after 2012. In the high technology case, delivered energy use per capita in the residential sector falls below the 2006 level after 2011, reaching a 2030 level that is 5 percent below the reference case projection."*

ii) In order to test an alternative way of modeling the effect of the energy efficiency provisions in NEMS-NRDC, we also ran a sensitivity case in which we assumed 10 percent of allowance value would be used to subsidize

> ***residential and commercial consumers' purchases of more efficient devices in space heating, space cooling, water heating, and commercial lighting.***
>
> The resulting decrease in total consumption was fairly similar to that in our core run of ACES, which leads us to believe that using the High Technology case is a fair approximation of the effect of the energy efficiency provisions.

Note that EIA's AEO2009 reference case assumptions for the industrial sector were used without modification.

CAFE Standards and Other Policies for Light-Duty Vehicles

Near-term increases in the corporate average fuel economy (CAFE) standards pursuant to the 2007 energy bill (EISA) are included in the reference case for NEMS-NRDC (reaching 35 mpg by 2020). However, in the policy case we assumed higher efficiency standards in the ACES runs because: 1) The national program for passenger vehicle efficiency announced by President Obama in May 2009 moves up the schedule for reaching 35 mpg to 2016 instead of 2020, and these have not been incorporated into the AEO yet, and 2) ACES has incentives to promote continued improvements in vehicle efficiency. ACES adds $25 billion to the EISA efficient vehicle manufacturer loan guarantees and also allocates another $28 billion in allowance value for automaker clean vehicle technology programs. These investments in clean, efficient vehicles pave the way for higher standards beyond those currently included in the reference case, even though such higher standards are not explicitly required in ACES. We assumed vehicle efficiency standards of 42 mpg in 2020 and 55 mpg in 2030. It is important to note, however, that these standards are not fully achieved in NEMS-NRDC. Given the vehicle cost and performance assumptions in the model, NEMS-NRDC finds that it would be cheaper for vehicle manufacturers to pay non-compliance fines than fully meet the standard. As a result, vehicle efficiency reaches 40 mpg in 2020 and 48 mpg in 2030 in NEMS-NRDC.

The plug-in hybrid (PHEV) subsidy provided by ARRA (up to $7,500 per vehicle, depending on battery size) was also included in the policy case. In order to simulate a momentum effect, the credit was modeled as continuing indefinitely rather than allowing PHEV sales to fall once the credit expires.

Renewable Fuel Standards

The EIA AEO2009 assumes that the EISA targets for biofuels under the Renewable Fuel Standards (RFS) are not achievable by 2022 due to limits on how quickly the new technologies can be deployed, and therefore waivers are issued. Under the ACES case, we assume more rapid expansion rates are possible for cellulosic ethanol and biomass-to-liquids in order to meet more closely the RFS targets as specified by EISA. However, waivers are still necessary in a few years, and the 36 billion gallon target with 16 billion from cellulosic sources was reached in 2023 rather than 2022.

Offsets Supply

Our assumptions for domestic offsets supply and cost are based on EPA's updated March 2009 Marginal Abatement Cost (MAC) Curves for agricultural and forestry offsets (4 out of the 5 categories of domestic offsets), estimated using the Forest and Agriculture Sector Optimization Model with Greenhouse Gases (FASOMGHG), the primary model EPA has used to estimate domestic offsets from land use and land use change, and EPA 2006 MAC curves for landfill methane offsets (this category was not updated by EPA in 2009 so these are the most recent). Our assumptions for international offsets were based on EPA's March 2009 international forest carbon sequestration MAC curves for the 3 categories of international forestry-based offsets (afforestation, avoided deforestation and forest management) and EPA 2006 MAC curves for international landfill methane offsets, international coal mine methane offsets and international fossil energy-related offsets. In our core modeling runs of ACES, we assumed that international projects in avoided deforestation and forest management would not generate international offsets until 2020. We imposed that constraint to reflect a conservative view about the amount of time that developing countries will need before being able to produce and sell tradable offsets in those categories that meet the standards of the U.S. offsets program. As a result, the only international forestry offsets assumed to be available for purchase in the U.S. from 2012-2019 are those based on afforestation. From 2020 onward, all three categories of forestry offsets are made available on the market (afforestation, avoided deforestation, and forest management). For all core runs, we maintained the ACES overall 2 billion ton annual limit on the use of offsets, split evenly between domestic and international offsets, and applied the ACES 1.25:1.00 discount factor on international offsets beginning in 2018. Throughout all international offsets are pooled so that international demand for offsets (based on the domestic emissions reduction commitments made by other countries) competes with the United States for the available supply of international offsets in any given year. Throughout the complete time horizon of the model, 59 percent of offsets used are international and the remaining domestic. Cumulatively, approximately 47 percent of the allowed 2 billion/year limit is used.

Sources for domestic offsets include reductions in methane emissions from landfills, natural gas and oil systems, agriculture and livestock, and reductions in nitrous oxide emissions from agriculture and waste management. Domestic offsets available from reductions in methane from landfills were discounted 75 percent to reflect the bill's performance standard.

Banking

Banking of allowances permits covered sources to over comply in one year to satisfy the requirements of future year reductions. In NEMS-NRDC, allowance prices escalate at 7.4 percent per year in real terms, which reflects the average cost of capital for electric power producers who are doing the majority of banking. Since the model's forecast period ends in 2030 and the bill's requirements extend to 2050, a bank balance of 5 billion tons in 2030 was assumed for this analysis for use in meeting post-2030 requirements.

Allowance Allocations

Allocations in NEMS-NRDC are modeled both directly and indirectly, depending upon the capacity of the model for a given allocation. Some allocations are treated only very generally in the macroeconomic module, while others can be modeled in both the macroeconomic module and more precisely in other modules. With respect to allowance value, NEMS-NRDC is structured as follows: First, the revenue from auctioned allowances is collected as a federal tax in the macroeconomic module. Second, the tax revenues are then allocated toward different purposes as specified by the legislation, after adjusting for revenue used to keep federal deficit levels from rising. The amount of Federal revenue collected from the tax is determined by the allowance price the model finds is needed to meet the cap.

Briefly, the major allocation tranches were modeled as follows:

- The electricity local distribution company allocations were modeled as a reduction in utility bills in the electricity module.
- CCS bonus allowances were allocated as production tax credits to new power plants built with the CCS technology in the electricity module.
- Allocations to merchant coal, home heating oil, and natural gas consumers were indirectly modeled via a personal tax reduction in the macroeconomic module.
- The Climate Change Consumer Refund was modeled as a personal tax reduction in the macroeconomic module.
- Allocations to energy-intensive firms were treated as “uncollected Federal tax revenue” in the macroeconomic module which is similar to a rebate of allowance value back to these industries.
- Allocations toward low income households were modeled as a personal tax reduction in the macroeconomic module, spread equally among all households (NEMS-NRDC does not have households disaggregated by income).
- Finally, allocations toward energy efficiency and renewable energy were modeled through a combination of Federal spending in the macroeconomic module and EIA’s High Technology assumptions in the residential and commercial demand modules.

NEMS-NRDC: TECHNOLOGY COSTS IN BAU VERSUS POLICY SCENARIOS OVER TIME

To assess the technology impacts resulting from the assumptions and policies modeled, below we provide a table of how overnight capital costs evolved over time in both the BAU and ACES cases (Table A-2). The overnight capital costs reported by NEMS-NRDC exclude transmission and distribution costs, as well as financing costs during construction.

In comparing costs between the reference and policy cases, one should keep in mind several factors: 1) Costs (and learning) are dependent on the amount of capacity built for each technology; as capacity increases, costs go down along the learning curve (as discussed previously); 2) Capital costs are affected by a “metals price index” that is calculated by the macroeconomic model. This metals index increases slightly in the policy case due to the carbon policy, causing costs to be slightly higher even if capacity builds were to remain unchanged between the reference and policy cases; and 3) Costs for site-specific renewable technologies such as wind, geothermal, hydro and landfill gas will generally increase as you build more capacity and use up the best sites, although increased wind costs are not reflected in the capital costs in Table A-2.

One also has to be cautious in comparing costs between technologies. A lower overnight cost does not necessarily mean the final delivered energy will be cheaper, as it does not take into account capacity factors or location. Some technologies, such as wind and solar, operate at lower capacities due to intermittency, or may be located some distance (like wind) from where the energy they produce is consumed. In addition, these reported overnight capital costs are not adjusted for differences in regional costs, which can vary materially.

Finally, since learning rates are tied to components rather than technologies, capacity built of one technology can influence the learning rate of another. For example, both IGCC with and without CCS progress at a similar rate, as most components of each plant are the same. Biomass IGCC costs also decline, due to improved efficiency of gasifiers used in IGCC.

Table A-2. Overnight costs for selected electricity generating technologies, by selected years, under BAU and in the policy case (kW, 2007$)

	BAU						**Policy Case**				
Technology	**2010**	**2015**	**2020**	**2025**	**2030**		**2010**	**2015**	**2020**	**2025**	**2030**
Coal											
Advanced w/o Sequestration		2,320	2,141	1,900	1,787			2,334	2,166	1,871	1,711
Advanced with Sequestration			3,073	2,701	2,509			0	2,705	2,317	2,143
Conventional		2,029	1,897	1,716	1,638			2,043	1,920	1,738	1,665
Combined Cycle											
Advanced w/o Sequestration		928	857	756	711			933	873	772	726
Advanced with Sequestration			1,650	1,437	1,328				1,391	1,207	1,143
Conventional		949	887	803	766			955	898	813	779
Combustion Turbine/Diesel											
Advanced	611	618	566	491	457		611	621	579	504	467
Conventional	646	661	618	559	533		646	665	625	566	542
Nuclear Power			2,950	2,562	2,349			0	2,924	2,505	2,322
Fuel Cells		5,000	4,445	3,807	3,423			5,033	4,498	3,856	3,479
Renewable Sources											
Conventional Hydropower		2,318	2,110	1,909	1,805			2,311	2,250	2,037	1,233
Geothermal	1,645	4,398	4,047	3,720	3,488		1,645	4,390	4,116	3,664	4,070
Municipal Waste	2,452	2,507	2,344	2,121	2,024		2,452	2,524	2,372	2,148	2,057
Wood and Other Biomass		3,632	3,322	2,890	2,620			3,655	3,362	2,896	2,362
Solar Thermal		4,604	3,991	3,408	3,052			4,635	4,039	3,452	3,103
Solar Photovoltaic		5,900	5,246	4,422	3,966			5,940	5,308	4,479	4,032
Wind	1,849	1,906	1,804	1,652	1,597		1,849	1,918	1,824	1,672	1,622
Offshore Wind		3,537	3,249	2,885	2,700			3,559	3,286	2,921	2,744
Distributed Generation											
Base		1,326	1,220	1,086	1,018			1,335	1,235	1,100	1,035
Peak	1,581	1,593	1,466	1,304	1,223		1,581	1,603	1,483	1,321	1,243

MARKAL

Overview

MARKAL was developed in a cooperative multinational project over a period of almost two decades by the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency. It is an integrated energy system optimization model that identifies least-cost pathways to meeting U.S. national energy system needs under a set of environmental and other policy constraints. NRDC commissioned International Resources Group, a consulting group with extensive experience with MARKAL for a variety of clients, to analyze the American Clean Energy and Security Act (ACES). The version of MARKAL used in this analysis is an expanded and updated version of EPANM-35, which is a peer-reviewed version of the model[2] developed by the Atmospheric Protection Branch of EPA's National Risk Management Research Laboratory under the Office of Research and Development

Model Architecture

The MARKAL model accepts industrial, commercial, residential, and transportation demands for energy services over the next several decades, and determines the least cost sources of energy to meet these demands – whether domestic or imported – based on the available technologies that transform primary energy into final energy that is used by end-use devices to meet the demands for energy services. The components are tied together by means of a Reference Energy System (RES), which establishes the network of energy flows and technology options encompassing the energy system. The characteristics of each technology (resource supply, process, conversion and end-use) include the investment cost, operating and maintenance costs, service life, efficiency, availability and emissions.

MARKAL then simultaneously identifies the least-cost mix of energy carriers and existing and new technologies that will satisfy the energy service demands and meet all the constraints imposed on the energy system. Common constraints include limitations on the rate of fuel switching or the penetration of new technologies, caps on various emissions (SO2, NOX, CO2, mercury, etc.), minimum requirements for renewable energy, etc.

Each energy service demand responds to price pressures by means of own-price elasticities. MARKAL also allows for learning-based cost reductions as new technologies get taken-up by the energy system. In addition, MARKAL can be used for tracking material flows, factoring in lumpy investments, and the development of hedging strategies by employing probability functions.

The expanded and updated MARKAL model used for this analysis starts with the year 2000 as the base year and employs 5-year periods out to 2050. The 2000 and 2005

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[2] EPA U.S. National MARKAL Database Documentation, U.S. Environmental Protection Agency, Office of Research and Development, Washington, DC, EPA-600/R-06/057, February 2006.

periods are calibrated to historical data from the AEO, and a Reference scenario was established that closely reflects "official" projections that constitute a business-as-usual future. In this case, it was calibrated to AEO2009.

Policy scenarios that can be analyzed with the model include measures to improve energy security, cut emissions, promote energy efficiency, reduce new technology costs, impose a cap-and-trade program, institute incentives or impose taxes. The value of the model is that the impacts of these policy scenarios can be compared in terms of the different technologies used, the different fuels consumed, the change in energy system cost, emission levels, etc.

MARKAL: REPRESENTING BUSINESS-AS-USUAL

Overview

We used the Energy Information Administration's (EIA) March Annual Energy Outlook (AEO) 2009 Published Release, with a few exceptions that are due either to the difficulty of translating data into the MARKAL format or because we concluded that the AEO assumptions do not best reflect the literature and we made adjustments to those selected assumptions in MARKAL (rationale noted, where applicable).

Key Differences from AEO2009:

- The cost, efficiency, and lifetime characteristics of residential end-use appliances are from AEO2008 (as opposed to 2009).

- Costs and supply of imported coke are from AEO2008.

- Overnight capital costs for geothermal generation technologies were increased from \$3,766/kW in AEO2009 to \$4,046/kW to better reflect the literature (all in 2007\$).

- Biomass supply was adjusted, with biomass having the subcategories of woody biomass, and agricultural residues and energy crops:

    - Woody biomass supply was reduced (such that it flattens out around ~100 million dry tons, instead of AEO2009's 200 million dry tons). This change was made to account for constraints on land use that are enacted in law but not reflected in the biomass assessment. The federal RFS prohibits regulatory compliance using biomass grown on ecologically-important protected federal lands.

    - Supply of agriculture residues and energy crops was increased very slightly, reflecting two assumptions that work in opposite directions: 1) We assumed higher use of winter cover crops and crops grown on degraded lands, increasing supply; 2) On the other hand, we eliminated certain feedstocks from being eligible for compliance with the RFS due to high GHG impacts resulting from indirect land-use changes, which lowered supply.

- For the cost of more efficient light-duty vehicles, MARKAL uses AEO2009's High Technology Case assumptions (instead of the Reference Case assumptions), with the High Technology Case costs being slightly lower than those in the Reference Case, and more in-line with estimates from the Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration (NHTSA).

- We modified AEO2009 technology learning, because the version of MARKAL that we used cannot handle the three distinct stages discussed above in the NEMS-NRDC section. We also believe that NEMS-NRDC's practice of limiting learning (e.g., very new emerging technologies cannot have their prices drop more than 50% through the model time frame) is overly conservative and inconsistent with what we have seen (e.g., solar cells have experienced far more than a 50% reduction in costs in a timeframe shorter than that of NEMS-NRDC, as shown at: http://www.tf.uni-kiel.de/matwis/amat/semi_en/kap_3/illustr/i3_2_2.html), so we did not impose those maximum limits on learning in MARKAL.

  In order to figure out a way to translate the AEO2009 approach to a format that MARKAL could use, we did the following: For all stages of a given technology's capacity increase, we used a constant learning rate, such that the same cost decrease would occur as would with the NEMS algorithm. As an example, assume that in NEMS, a technology had a progress ratio of 80% for three doublings, then 90% for five doublings. In order to get the same reduction in cost for the same amount of increased capacity over 8 doublings (i.e., 80%^3*90%^5=30%), in MARKAL we would apply a constant learning ratio of 86% for each doubling (86%^8 =30%). Following AEO, for each generation technology we determined which components it was made up of, and applied the comparable progress ratios. However, there were two technologies for which we changed the calculated learning rate: 1) For solar photovoltaic, the calculated learning ratio was 89%, and we changed it to 80%; 2) For onshore wind, the calculated learning rate was 99%, and we changed it to 95%.

- In MARKAL we set maximum growth rates (capacity constraints) at which each generation technology could technologically grow (generally starting around 50% per year for emerging technologies, then ramping down to 10% for more developed technologies). These maximum growth rate constraints did not turn out to be binding in our runs. Technical experts reviewed the actual growth rates projected by MARKAL to ensure that they were reasonable.

- MARKAL included two concentrating solar thermal technologies: one without storage (derived from AEO), and one with thermal storage capacity and a 60% annual capacity factor derived from industry studies with associated cost increases compared to AEO.

- MARKAL included a remote wind technology which incorporated the cost of a dedicated 250-mile transmission interconnection.

- We also made some modifications to reflect the Stimulus Bill (since most of MARKAL's assumptions were based on the March AEO2009, which didn't yet reflect the Stimulus Bill, as described above in the NEMS-NRDC section). We reflected the following provisions of the Stimulus Bill in our MARKAL reference case:

    a. Weatherization assistance program (and $250 million to increase energy efficiency in HUD-sponsored low income housing): This was modeled in three parts: First, we assumed that 700,000 homes would be affected (which is the number of homes that our efficiency experts believe could be covered by the available funding) in 2010. Second, we divided up the funding equally to each home, with $6,500 spent on each. We divided up efficiency improvements for each home as follows (the Stimulus Bill does not explicitly allocate funding toward these three sources, but we felt they reflected good estimates of how that funding might be used). We assumed that there would be building shell improvements made to each of the 700,000 homes, at a cost of $4,000 per home. As a result, demand for space heating and space cooling would decrease, with an overall 20% reduction in household end-use energy demand. (These costs and level of savings per household from weatherization and building shell improvements are consistent with government estimates. (see Table ES.1. on Page xi of the following: http://weatherization.ornl.gov/pdf/Con-479%20May22-FINAL.pdf). $500 was applied toward purchasing more efficient refrigerators. Finally, to reflect other energy efficiency provisions, we assumed that each of 700,000 homes would have $2,000 spent toward reducing demand slightly across all end-use categories (e.g., space heating, refrigeration), assuming a resulting 15% reduction in end-use energy demand.
    b. State Energy Program: Of the $3.1 billion for the State Energy Program, we assumed that 40% would go toward residential efficiency. We applied that funding to provide $2,000 to each of 620,000 homes in 2010 to reduce demand slightly across all end-use categories (e.g., space heating, refrigeration), such that total end-use energy demand for the affected homes was decreased by 15%.
    c. Greening of General Service Administration-operated buildings: We assumed that 75% of General Service Administration-operated buildings would have their end-use energy demand decreased by 20% due to energy efficiency improvements, which would cost $700,000 per building.
    d. Removal of dollar caps in the investment tax credit for geothermal heat pumps and solar water heaters: The cost of geothermal heat pumps and solar water heaters was lowered 30% through 2020 to reflect the investment tax credit.
    e. Extension of the renewable energy production tax credit: The PTC was extended through 2012.

MARKAL: REPRESENTING THE AMERICAN CLEAN ENERGY AND SECURITY ACT

Overview

To model the impact of the American Clean Energy and Security Act (ACES), we reflect emission limits, renewable electricity standards, carbon capture and sequestration incentives, energy efficiency provisions, CAFE standards for light-duty vehicles, offsets, banking, and a tightening of the renewable fuel standards for transportation fuels. Unless otherwise stated, the assumptions described under BAU are the same in the policy case.

Emissions Limits

In accordance with the version of the bill that passed the House of Representatives, we imposed emissions limits of 3% below 2005 levels by 2012, 17% below 2005 levels by 2020, 42% by 2030, and 80% by 2050 (note that the 2050 target differs from the House bill, which specifies an 83% reduction by 2050), with the limits for interim years determined by a linear interpolation between those years. Furthermore, those limits were applied to all energy-related CO2 emissions. MARKAL does not model methane, nitrous oxides, or other industrial GHGs.

Renewable Electricity Standards

ACES requires retail electricity distributors to meet a rising fraction of demand with renewable energy sources and improved efficiency, starting with 6 percent in 2012 and rising to 20 percent in 2020, then remaining at that level thereafter. At least three-quarters of that amount must come from renewable resources. However, the Federal Energy Regulatory Commission (FERC) may, on a governor’s petition, lower the renewable component to three-fifths of a utility’s obligation, with the remainder to come from efficiency. Because of that ability for energy efficiency to meet part of the requirement, we assume that the “effective” RES level is at 75% of the stated standard (i.e., 15% in 2020, as opposed to 20%).

Carbon Capture and Sequestration Incentives

Regarding CCS, ACES has provisions that provide incentives for the successful deployment of carbon capture and sequestration (CCS). Those provisions were modeled as incentive payments per ton of CO_2 captured that decline as a function of cumulative installed capacity. Payments to eligible facilities are paid annually over a 10-year period.

The incentive payments are available to the first 72 GW of CCS capacity built, both IGCC coal and natural gas combined cycle with CCS, beginning at $90 per ton (in 2008 dollars) for the first 6 GW and declining thereafter according to the same schedule used in NEMS-NRDC, which is reflected in Figure A-1.

Energy Efficiency Provisions

In MARKAL, we reflected the energy efficiency measures in ACES for the residential and commercial sectors in two ways:

i) ***To approximate ACES' impact on the adoption of more efficient appliances, we assumed that end-use devices would become 5% more efficient per decade compared to baseline AEO assumptions, with 2020 being the first year affected, and no change in cost assumptions.***

The residential and commercial sectors in MARKAL have end-use energy demands for each of several end-use categories (e.g. space heating, refrigeration). The energy demand levels are taken from AEO2009. In order to meet that demand, the model must choose from various end-use devices that are available (with each device having a specified cost, efficiency, and lifetime). Those end-use devices, as well as their characteristics, are also taken from AEO (2009 for commercial and 2008 for residential). There were a few exceptions where our appliance experts told us that a certain category of appliances was near its ceiling in terms of efficiency, so in those cases, we did not assume any improvements over time.

ii) ***To reflect energy efficiency measures resulting from building codes or other provisions that would lead to building shell improvements, we lowered demand for space heating and space cooling devices in each of the residential and commercial devices.***

We modeled such improvements through lowering demand for space heating and space cooling devices in each of the residential and commercial sectors, with the assumption that such improvements could lower a household's (or business's) end-use energy consumption by 20%, for a cost of $4,000 per household and $40,000 per business. These costs and level of savings per household from weatherization and building shell improvements are consistent with government estimates. (see Table ES.1. on Page xi of the following: http://weatherization.ornl.gov/pdf/Con-479%20May22-FINAL.pdf). We assumed that 1.5 million homes would see this improvement each year (since that's the number of new homes built each year). Similarly, we assumed that 150,000 commercial buildings would see this improvement each year (since that's the number of new commercial buildings built each year).

For the industrial sector, MARKAL models potential industrial process efficiency improvements in the industry sector through investment technologies in each major industry sector that reduce their overall steam, process heat, motive power and other energy requirements. Energy requirement reductions of 15% (for feedstock needs) up to

50% (for “other” needs) are assumed to be available at a cost of $3-6 million per petajoule saved. Rebates or other incentives are not modeled.

CAFE Standards and Other Policies for Light-Duty Vehicles

Near-term increases in the corporate average fuel economy (CAFE) standards pursuant to the 2007 energy bill (EISA) are included in the reference case for MARKAL (reaching 35 mpg by 2020). However, in the policy case we assumed higher efficiency standards in the ACES runs because: 1) The national program for passenger vehicle efficiency announced by President Obama in May 2009 moves up the schedule for reaching 35 mpg to 2016 instead of 2020 and 2) ACES has incentives to promote continued improvements in vehicle efficiency. ACES adds $25 billion to the EISA efficient vehicle manufacturer loan guarantees and also allocates another $28 billion in allowance value for automaker clean vehicle technology programs. These investments in clean, efficient vehicles pave the way for higher standards beyond those currently included in the reference case, even though such higher standards are not explicitly required in ACES. We assumed vehicle efficiency standards of 42 mpg in 2020, 55 mpg in 2030, and 80 mpg in 2050. These standards were obtained, because the model assumes the constraint (as well as other constraints, e.g. emission standards, number of offsets, etc.) has to be met.

Additionally, MARKAL assumes that transportation system policies will reduce vehicle miles traveled (VMT) by 5 percent in 2020, 9 percent in 2030, and 12 percent in 2050 relative to BAU. Of this reduction in VMT, we assume that 15 percent is a shift to public transit (the shift is split 55 percent rail and 45 percent bus), and the remaining 85 percent a net reduction in VMT overall. The assumed VMT reductions are similar in magnitude to what can be achieved through smart growth and land use planning strategies, as evaluated in the July 2009 Moving Cooler report.[ii] That report estimates that smart growth could result in a 6–10 percent reduction in national light-duty VMT by 2030. Though ACES does not mandate a reduction in driving, it does provide funding for developing strategies to improve regional transportation efficiency, potentially resulting in VMT reductions. Whereas we take a conservative approach in NEMS-NRDC and do not include these impacts because they are not directly specified in ACES, our MARKAL modeling assumes that these reductions will occur.

Renewable Fuel Standards

We modeled the RFS as individual lower bounds on bioethanol, biodiesel and Fischer-Tropsch liquids.

Offsets Supply

Our assumptions for domestic offsets supply and cost are based on EPA’s updated March 2009 Marginal Abatement Cost (MAC) Curves for agricultural and forestry offsets (4 out of the 5 categories of domestic offsets), estimated using the Forest and Agriculture Sector Optimization Model with Greenhouse Gases (FASOMGHG), the primary model EPA has used to estimate domestic offsets from land use and land use change, and EPA 2006 MAC curves for landfill methane offsets (this category was not updated by EPA in 2009 so these are the most recent). Our assumptions for international offsets were based on EPA's March 2009 International forest carbon sequestration MAC curves for the 3 categories of international forestry-based offsets (afforestation, avoided deforestation and forest management) and EPA 2006 MAC curves for international landfill methane offsets, international coal mine methane offsets and international fossil energy-related offsets. In our core modeling runs of ACES, we assumed that international projects in avoided deforestation and forest management would not generate international offsets until 2020. We imposed that constraint to reflect a conservative view about the amount of time that developing countries will need before being able to produce and sell tradable offsets in those categories that meet the standards of the U.S. offsets program. As a result, the only international forestry offsets assumed to be available for purchase in the U.S. from 2012-2019 are those based on afforestation. From 2020 onward, all three categories of forestry offsets are made available on the market (afforestation, avoided deforestation, and forest management). For all core runs, we maintained the ACES overall 2 billion ton annual limit on the use of offsets, split evenly between domestic and international offsets, and applied the ACES 1.25:1.00 discount factor on international offsets beginning in 2018. Throughout, all international offsets are pooled so that international demand for offsets (based on the domestic emissions reduction commitments made by other countries) competes with the United States for the available supply of international offsets in any given year. Over the complete time horizon of the model 5 percent of offsets used are international and the remaining domestic. Cumulatively, approximately 22 percent of the allowed 2 billion/year limit is used (i.e. the constraint is non-binding).

Note that, in MARKAL, methane from landfills was modeled as an energy source (not an offset supply), and the resource supply estimates include a 75% capture ratio assumption.

Banking

MARKAL incorporates the banking and borrowing provisions of the bill by allowing the annual cap in each period to be exceeded by a maximum of 550 million MT of CO2, while requiring that the model meet the cumulative CO2 cap from 2012 through 2050. Without such a limit placed on inter-period allowance banking, the model would purchase inexpensive international allowances in the 2015-2025 period and hold them until the 2045-2050 period. This amounts to assuming investors are willing to hold allowances for 30 years at a 5 percent annual return. The annual limit imposed results in a more reasonable rate of return on banked allowances (allowance prices increase by almost 12% per year from 2045 to 2050), and forces the model to make investments in long-lived low-carbon infrastructure (especially power plants) toward the end of the model horizon.

Allowance Allocations

MARKAL is not a macroeconomic model, so the full value of allowance allocations are not represented. Allocations were modeled only insofar as ACES allocated spending toward specific technologies (e.g. toward CCS, PTCs, etc.). These allocations were assumed to be available for said purposes, and spent toward them. Note that households and government are not explicitly represented in MARKAL, so there would be no way to represent allocations other than in those cases where they influence technology choices and costs.

MARKAL: TECHNOLOGY COST IN BAU VERSUS POLICY SCENARIOS OVER TIME

To assess the technology impacts resulting from the assumptions and policies modeled, below we provide a table of how capital costs evolved over time in both the BAU and ACES cases (Tables A-3 and A-4). The NEMS-NRDC model reports overnight capital costs, but MARKAL reports the total investment cost which includes financing costs during construction as well as the grid transmission and distribution costs. Thus, reported capital costs are not directly comparable between the two models in how they are measured. Additionally, because the models are different in structure and objective, one cannot assume costs would be the same even if given in the same metric.

When comparing of how technology costs evolve over time between the reference and policy cases, one should keep in mind that the capital costs for advanced technologies are being driven primarily by learning effects, which are dependent on the amount of capacity built for each technology and its learning rate; as capacity increases, costs go down along the learning curve (as discussed above). Mature technologies, such as natural gas combined cycle and hydropower, are not modeled as learning technologies and thus have constant capital costs over time.

One also has to be cautious in comparing costs between technologies. A lower capital cost does not necessarily mean the final delivered energy will be cheaper, as it does not take into account fuel and emission costs. Some power plant technologies, such as natural gas and coal, consume expensive fuels or have high emissions.

In MARKAL, learning rates are tied to technology clusters, where the capacity built of the core technology in each cluster controls learning rate of all the technologies in the cluster. For example, all plants using IGCC technology (coal and biomass) benefit from IGCC capacity additions, and all plants using CCS technologies (coal, natural gas and biomass) benefit from capacity additions of CCS technology.

A-3. Overnight costs for selected electricity generating technologies, by selected years, under BAU (kW; 2007$)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Coal IGCC	2,702	2,702	2,590	2,149	1,994	1,922	1,878	1,818	1,772
Coal IGCC with CCS		4,422	4,422	4,422	4,422	4,422	4,422	4,422	4,422
Petroleum	786	786	786	786	786	786	786	786	786
Natural Gas Combined Cycle	1,278	1,278	1,278	1,278	1,278	1,278	1,278	1,278	1,278
NGCC with CCS		3,252	3,252	3,252	3,252	3,252	3,252	3,252	3,252
Advanced Nuclear Power			6,061	6,061	6,061	6,061	6,061	6,061	6,061
Hydropower	2,730	2,730	2,730	2,730	2,730	2,730	2,730	2,730	2,730
Pumped Storage	4,543	4,543	4,543	4,543	4,543	4,543	4,543	4,543	4,543
Solar PV	5,986	5,986	4,102	3,753	3,404	3,397	3,380	3,344	2,424
Concentrating Solar	4,430	4,430	4,430	4,430	4,430	4,430	4,430	4,430	3,901
Wind – Onshore	2,165	2,165	2,165	2,165	2,165	2,066	2,058	2,058	2,058
Wind – Offshore	3,827	3,827	3,493	3,292	3,145	3,004	2,949	2,834	2,834
Biomass Gasification CC	4,851	4,505	4,273	4,139	4,139	4,139	4,139	4,139	4,139
Geothermal	4,046	4,046	4,046	4,046	4,046	4,046	4,046	4,046	4,046
CHP & DG	912	1,132	1,019	971	903	947	1,085	1,007	921

Table A-4. Overnight costs for selected electricity generating technologies, by selected years, policy case (kW; 2007$)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Coal IGCC	2,702	2,702	2,702	2,702	2,702	2,702	2,702	2,702	2,702
Coal IGCC with CCS		3,935	3,231	2,829	2,737	2,624	2,461	2,385	2,362
Petroleum	786	786	786	786	786	786	786	786	786
Natural Gas Combined Cycle	1,278	1,278	1,278	1,278	1,278	1,278	1,278	1,278	1,278
NGCC with CCS		3,252	3,252	3,252	3,252	3,252	3,252	3,252	3,252
Advanced Nuclear Power			6,061	6,061	6,061	6,061	6,061	6,061	6,061
Hydropower	2,730	2,730	2,730	2,730	2,730	2,730	2,730	2,730	2,730
Pumped Storage	4,543	4,543	4,543	4,543	4,543	4,543	4,543	4,543	4,543
Solar PV	5,712	4,630	4,267	3,724	3,436	2,926	2,893	2,860	2,552
Concentrating Solar	4,204	4,204	4,010	3,433	3,168	2,920	2,840	2,740	2,740
Wind - Onshore	2,165	2,165	2,086	2,058	2,048	1,960	1,960	1,960	1,960
Wind - Offshore	3,827	3,094	3,015	2,987	2,977	2,889	2,889	2,889	2,889
Biomass Gasification CC	4,851	4,505	4,271	4,139	4,139	4,139	4,139	4,139	4,002
Geothermal	4,046	4,046	4,046	4,046	4,046	4,046	4,046	4,046	4,046
CHP & DG	1,066	1,148	1,026	1,023	1,133	1,122	966	1,115	1,090

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[i] This section was taken directly from EIA's "Assumptions to the Annual Energy Outlook 2009", which contains more detailed information on the version of NEMS that EIA used for its AEO2009 projections, and it is available at: http://www.eia.doe.gov/oiaf/aeo/assumption/index.html.

[ii] Moving Cooler, "Moving Cooler: Analysis of Transportation for Reducing Greenhouse Gas Emissions," July 2009, at http://movingcooler.info/.