The Impact of Electricity Storage on Energy Sector Emissions

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May 2011

Masters project submitted in partial fulfillment of the requirements for the Master of Environmental Management degree in the Nicholas School of the Environment of Duke University.

2011

Abstract

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The composition of the U.S. electrical power system reflects competing objectives, as investments are driven by ratepayers who demand access to electricity that is both low cost and reliable. Maintaining generation ready for fluctuations in demand currently requires the inefficient use of generation assets, driving up total energy system costs. During the night, low demand for electricity can force the underutilization of wind farms and baseload coal-fired plants. During the day, load-following natural gas-fired plants are often operated at partial capacity so they can be ramped up to track changing demand. One means to address these two issues is electricity storage. Electricity storage technologies are capable of shifting surplus low cost nighttime electricity to times of higher daytime demand. Whether time-shifting electricity storage technologies may enable lower energy system costs depends upon the parameters of these technologies and future conditions. In this study, a least-cost optimization energy model (MARKAL) managed by U.S. EPA is used to explore the potential future role of electricity storage under varying conditions. Scenarios model a stricter national renewable portfolio standard (RPS), varying natural gas prices, and a national limit on CO_2 emissions from the energy system. Scenario results are analyzed to discern the impact of electricity storage on generation output and on the associated energy sector emissions of CO_2, SO_2, NO_x, and PM10. Four trends emerge when examining the impacts of time-shifting electricity storage on the national energy system. First, electricity storage enables an increasing utilization of baseload generation and a corresponding decreasing reliance on daytime load-following generation. Second, and to a lesser degree, nighttime natural gas-fired generation increases, making use of existing capacity. Third, the overall decreasing natural gas use by load-following generation leads to the increasing use of natural gas in the industrial sector. Fourth, the use of time-shifting electricity storage does not result in net increases of electricity output from renewable power sources. The impacts of these four trends on generation investments and emissions vary by the future conditions modeled. In many instances the use of electricity storage results in a less expensive energy system with higher emissions of CO_2, SO_2, NO_x, and PM10.

Acknowledgements

I would like to thank my master's project advisor Dr. Timothy Johnson for his advice and many hours of assistance throughout this project. I would also like to thank the Energy and Climate Assessment Team at the United States Environmental Protection Agency for their invaluable support.

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List of Acronyms

CAES	Compressed Air Energy Storage
CCS	Carbon Capture and Sequestration
ECAT	Energy and Climate Assessment Team (U.S. EPA)
GW	Gigawatt
GWh	Gigawatt Hour
KTonnes	Thousand Metric Tons
kW	Kilowatt
MARKAL	MARKet ALlocation energy systems model
MW	Megawatt
MWh	Megawatt Hour
NaS	Sodium-Sulfur Battery
NEMS	National Energy Modeling System
NREL	National Renewable Energy Laboratory
PHS	Pumped Hydroelectric Storage
PJ	Petajoule
ReEDS	Regional Energy Deployment System
RPS	Renewable Portfolio Standard
U.S. EPA	United States Environmental Protection Agency
VRB	Vanadium Redox Battery

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1 Introduction

1.1 Purpose of Research

Historically, the composition of the U.S. electrical power system reflects competing objectives, driven by ratepayers who demand access to electricity that is both low cost and reliable. In a delicate balancing act, system operators dispatch the least-cost generation resources which are capable of tracking fluctuations in demand.

Baseload plants, which include nuclear and coal-fired facilities, typically provide the most cost-effective output of electricity. However, for technical and economic reasons, these baseload plants are generally limited to operating continuously at levels of high utilization. Supplementing baseload generators are load-following plants which may cycle up and down to meet fluctuations in demand, with combined-cycle and single-cycle natural gas plants providing most load-following services. Beyond generation which meets demand, all power systems require varying levels of reserve capacity that is capable of responding rapidly to unanticipated shortfalls in supply. A leading method of providing this rapid response capacity is the partial utilization of natural gas-fired power plants, a practice which decreases efficiency and increases the overall electric power system costs. In the absence of affordable means to store electricity on the grid, the practice of partially utilizing generation will likely continue.

The challenge of efficiently balancing reliability and cost is further complicated as intermittent renewable power technologies increase in use. In particular, wind power is increasingly providing electricity to power systems during overnight hours of low demand. As overnight demand is typically met by inflexible baseload generation, large influxes of wind energy can threaten to imbalance grid operations. In the absence of affordable means to store this surplus electricity, it can be necessary to either waste electricity from wind power or to inefficiently ramp down baseload coal-fired generation.

Driven to ensure the reliable and low-cost delivery of electricity, there is growing interest within the electric power sector in technologies which will enable a more efficient utilization of generation assets. In particular, grid-scale electricity storage technologies have attracted growing attention in recent years, with significant investments focused on decreasing the costs of technologies which may store and shift surplus electricity from periods of low nighttime demand to periods of higher daytime demand. Such technologies hold potential to not only make better use of surplus energy from nighttime generation, but also to provide load-following services. This could allow a smaller capacity of load-following natural gas plants to meet demand while operating at higher efficiencies.

The future role and penetration of time-shifting electricity storage will certainly depend in part on the investment and operational costs of the storage technologies. So too will the future use of time-shifting electricity storage be shaped by market and policy conditions that affect the competitiveness of generation technologies. For instance, if current natural gas prices rise due to stricter environmental regulations, this may incentivize the use of time-shifting electricity storage. Alternatively, a significant increase in the development of wind power capacity may provide an excess of electricity overnight which storage technologies would be well suited to shift to periods of higher demand. Such an increase in wind power capacity might be driven either by mandates for renewable power or incentivized under a national greenhouse gas limit. Moreover, it is currently difficult to discern the potential impacts of time-shifting electricity storage on air quality and greenhouse gas levels. In order to better understand the potential future impact of these technologies on emissions, it will be necessary to investigate the role of electricity storage under varying future conditions.

1.1.1 Research Questions Addressed

Over the past decade there has been extensive research led by the U.S. Department of Energy into the field of grid-scale time-shifting electricity storage. Much of the resulting literature details the technical parameters of emerging energy storage technologies. The most comprehensive review of such energy storage technologies to date is the *EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications* (EPRI-DOE, 2003). Amongst other parameters, this report provides estimates for technology efficiencies, lifetimes, startup times, capital cost, and operating costs. Since this report was published in 2004, there exists great variation in subsequent estimation of electricity storage technology costs, with the debate largely conceptual due to a dearth of commercial development.

Building upon technology reviews, Sandia National Laboratories conducted a high-level assessment of the benefits of electricity storage in a study entitled *Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide* (Sandia National Laboratories, 2010). This analysis focused on identifying multiple market applications which electricity storage technologies may serve simultaneously. The quantitative estimates for electricity storage market potential were limited to a ten-year horizon which stretched to 2020. This analysis was based on a future with business as usual conditions, and did not model energy system changes outside of the electric power sector.

However, other research has begun to investigate the impact of electricity storage on generation technologies. For instance, the National Renewable Energy Laboratory (NREL) recently published a report entitled *Modeling the Benefits of Storage Technologies to Wind Power* (National Renewable Energy Labatory, 2008). This study utilized the ReEDS model which is rich in wind generation detail to assess the role of pumped hydroelectric storage, CAES, and sodium-sulfur (NaS) batteries. Scenario analysis was conducted for varying future conditions, including business as usual, and a generation mix with 20% of its output provided by wind power by 2030. These future conditions were modeled with and without electricity storage. The study only examined the electric power sector, focused on the relation of electricity storage to wind power.

These three reports are illustrative of our current knowledge of energy storage technologies and understanding of its potential impacts. Lacking recent experience in the construction and operation grid-scale electricity storage facilities, there remains significant uncertainty regarding the cost of such technologies. When studies have examined the applications of energy storage technologies, much of the focus has been upon short-term benefits to the electric power systems of narrow geographic markets. A counterexample to this trend is found in the 2010 NREL study, but even this study was narrowly focused on the electric power sector. Missing from analysis is a broad long-term energy system perspective.

Recognizing the need to better understand the impact of time-shifting electricity storage in a broad energy system context, this report examines the potential impacts of such storage on electric power sector investments and energy system emissions out to 2055 under varying future conditions. The layering of future system-level factors helps identify conditions which may draw more heavily on time-shifting electricity storage, and how the impacts of electricity storage are context dependent.

1.1.2 Conditions Evaluated

The penetration and impact of time-shifting electricity storage on the national energy system was hypothesized to differ depending upon the composition and use of the future electricity generation mix. As the future mix of generation is uncertain, it is necessary to explore the role of storage under varying market and policy conditions. This report focused on a selection of conditions to be modeled in scenario analysis. Following is an overview of the conditions hypothesized to significantly impact the generation mix, and consequently, the use time-shifting electricity storage.

First, the increased adoption of intermittent renewable power was hypothesized to significantly impact the generation mix. This may be the case if a surplus of nighttime wind energy reduces future use of baseload generation, instead increasing reliance upon load-following natural gas plants.

Second, the existence of a national cap on CO_2 emissions was hypothesized to significantly impact the future generation mix. This was expected as a cap on emissions likely will force changes in the generation mix towards baseload and load-following technologies with lower CO_2 emissions. The use of time-shifting electricity will likely depend upon the particular composition of this generation mix.

Third, the least-cost route to meeting a national CO_2 emission limit may rely upon the use of carbon capture and sequestration (CCS) technologies. Should these technologies be unable to compete in the market, either due to cost or technical limitations, it was hypothesized that this may significantly impact the composition of the future generation mix. In the absence of CCS technologies, a CO_2 limit may significantly reduce the use of both coal and natural gas, altering both baseload and load-following technologies.

Fourth, higher or lower natural gas prices were hypothesized to impact the use of natural gas for load-following services. Recent advances in the economic recovery of natural gas locked within shale formations has resulted in projections of low future natural gas prices, sparking significant investments in new natural gas combined cycle plants. Should natural gas prices fall further, an increased reliance on load-following natural gas may diminish the role of baseload technologies. In contrast, rising natural gas prices may increase the role of baseload generation. Furthermore, the impact of natural gas prices may ripple through other sectors of the economy which are capable of fuel switching, impacting air quality and greenhouse gas levels.

Fifth, the investment costs of time-shifting electricity storage technologies were hypothesized to impact their penetration in the market. This is reflected in the findings of a recent NREL report which found that "the value of energy arbitrage alone does not appear to justify the deployment of energy storage at current technology cost and electricity prices (National Renewable Energy Laboratory, 2010)." Decreases in the investment costs of these time-shifting (price arbitrage) storage technologies may justify their use in a least-cost solution which meets energy system demands.

1.2 MARKAL & ECAT's Databases

1.2.1 Energy Systems Modeling at U.S. EPA

The U.S. Environmental Protection Agency is tasked with crafting air pollution regulations that address anthropogenic air pollution detrimental to human and environmental health. A primary focus of U.S. EPA's regulatory attention is the electric power sector, as its combustion of fossil fuels contributes significantly to currently high levels of many regulated air pollutants. Consequently, over the coming years U.S. EPA is staged to issue a combination of new regulations and stricter revisions to existing regulations that will affect emissions from electric power generators. In an effort to help inform the development of these regulations, U.S. EPA's Office of Research and Development (ORD) is devoting time and resources from its Energy and Climate Assessment Team (ECAT). ECAT is a part of the Atmospheric Protection Branch, which is within ORD's National Risk Management Research Laboratory. ECAT is responsible for conducting forward looking energy system analysis enabled by MARKAL, a data-driven energy systems economic optimization model (U.S. EPA, 2008).

1.2.2 Overview of MARKAL

The MARKAL (MARKet ALlocation) model is a technology explicit partial equilibrium model which represents the entire energy system of the United States (Loulou, Goldstein, & Noble, 2004). The model's objective is to minimize the total cost of the nation's energy system over the planning horizon while meeting demand and complying with constraints. It was developed by Brookhaven National

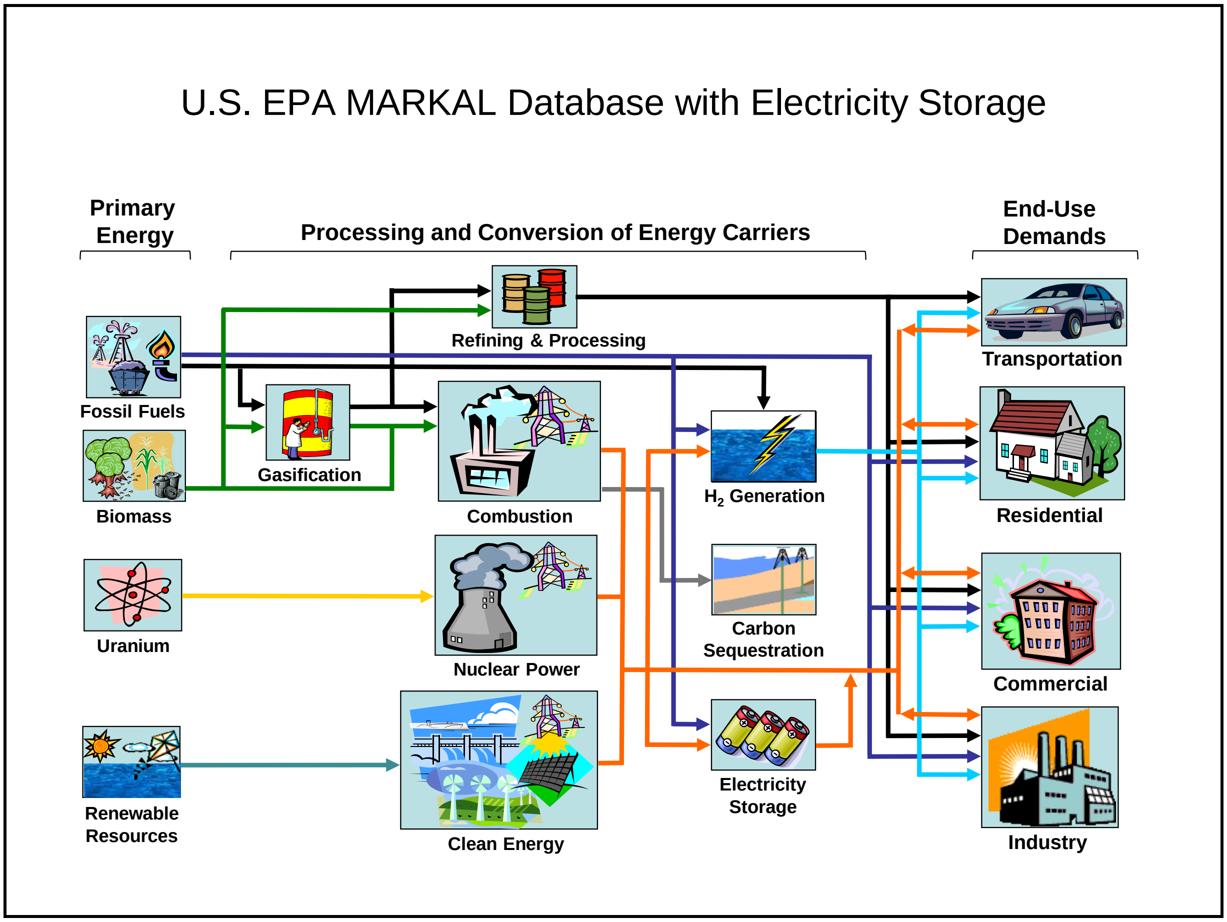
Laboratory in the late 1970s, and is currently in use by more than 40 countries for research and energy planning purposes (U.S. EPA, 2008).

MARKAL is an intertemporal partial equilibrium model of energy markets, meaning that prices and quantities are in equilibrium in each time period, with production exactly meeting demand (Loulou, Goldstein, & Noble, 2004). This balance is struck at all levels of the energy system, including primary resources, secondary fuels, final energy, and energy services (Loulou, Goldstein, & Noble, 2004). The markets represented in MARKAL are competitive, and energy commodity prices equal their own marginal values in the overall system (Loulou, Goldstein, & Noble, 2004). With perfect foresight, MARKAL seeks to maximize social surplus, which is the sum of consumer surplus and producer surplus. Thus, the model's investment decisions are optimal over the whole time horizon (Loulou, Goldstein, & Noble, 2004).

1.2.3 MARKAL Databases

The MARKAL database characterizes the energy system structure to be modeled. This representation includes resource supplies, energy conversion technologies, and end use demands. The database includes the necessary information to characterize each of the energy conversion technologies, with parameters including fixed costs, variable costs, technology availability and performance, and pollutant emissions. Figure 1 reflects the U.S. EPA's MARKAL Database representation on the national energy system, including time-shifting electricity storage.

Figure 1: U.S. EPA MARKAL Database with Electricity Storage



This figure is an adaptation of a diagram from Dr. Dan Loughlin, U.S. EPA.

U.S. EPA's ECAT maintains two MARKAL databases, with one representing the U.S. by the nine census divisions (EPAUS9r), and one representing the nation as a single region (EPANMD). Each database includes the same energy technologies and end use demands, including transportation, residential, commercial and industrial sectors. Both databases are also configured for MARKAL model runs spanning the time period of 2005 to 2055 at five-year intervals. Each year within a five-year interval is identical. However, within each year MARKAL recognizes three seasons (winter, summer, intermediate) and four time of day periods (day a.m., day p.m., peak, night). The peak time of day is a narrow time segment representing the period of highest demand for electricity, when high cost marginal generating units are typically brought online to meet demand. With each season containing the four time of day periods, there are total of twelve time slices in MARKAL within each five-year period. The first period in each of ECAT's MARKAL models is 2005, representing historical investments and activity in the energy sector. The last period to be optimized in each of ECAT's MARKAL models is 2055.

1.2.4 Electric Power Sector Representation in ECAT's MARKAL Databases

The electric power sector of MARKAL is optimized over twelve time slices in each period, with demand for electricity being specified in each time slice. Similarly, the availability of electricity generation technologies may be characterized by time slice. This is especially important for renewable energy generation technologies which are predictably limited by the time of day, such as is the case with solar power. This is distinctly different from characterizing the variability of electrical generation technologies which may be dispatched at any time. MARKAL is not configured to model technology availability on a temporal resolution narrower than the twelve time slices. In addition, MARKAL represents availability of generation technologies with discrete values for each of the twelve time slices, values which hold true for at least one five-year period. This is in contrast to other models which more thoroughly characterize the uncertainty in renewable energy resources.

Electricity storage on the grid is permitted in MARKAL. Prior to this project, the databases of ECAT contained one electricity storage technology, being existing pumped hydroelectric storage, a technology which is described elsewhere in this report. MARKAL enables electricity storage through the use of STG technologies, a category defined as being those plants which have the same commodity as both input and output. The operation of STG technologies for electricity storage is restricted, as STG technologies may only charge at nighttime. The logic behind this rule is based upon electricity prices, as electricity prices are typically lower at nighttime when demand is low. The stored electricity in STG technologies is released optimally to meet demand in any of the remaining time of day periods (day a.m., day p.m., peak). The daytime usage determines the amount of electricity to be stored during the nigh-time period. As all days within a season have equal energy demand, this perfect knowledge enables optimum electricity storage charging and discharging. Such uniformity in demand does not reflect real world uncertainty.

1.2.5 Comparison of MARKAL to Other Energy Models

The strengths of MARKAL lie in its broad technology-rich representation of the nation's energy systems, allowing the examination of impacts of market or policy changes which can ripple through sectors affecting investments and emissions. Two similar, but distinctly different models are the National Energy Modeling System (NEMS) and the Regional Energy Deployment System (ReEDS).

The Energy Information Administration's National Energy Modeling System (NEMS) is a multiregional partial equilibrium model used for forecasting. Unlike MARKAL, NEMS includes a macroeconomic component, and reaches results via an iterative process. With a time horizon of 25 years, NEMS projects the production, imports, conversion, consumption, and prices of energy (U.S. Energy Information Administration, 2009). The model represents the broad U.S. energy system, often at a narrower level of detail than in MARKAL. With a more complex representation of the U.S. energy system, NEMS generally takes longer to run than MARKAL.

Developed by the National Renewable Energy Laboratory, the Regional Energy Deployment System (ReEDS) is a multiregional optimization model used to represent the U.S. electric power sector out to 2050 (National Renewable Energy Laboratory, 2009). More specifically, ReEDS is a geographic information systems (GIS) linear programming model used to examine least-cost capacity expansion within the United States electric power sector (National Renewable Energy Laboratory, 2009). Two key aspects of ReEDS are its robust representations of renewable resources and electrical transmission access. The model is particularly well suited to examine the impact of intermittent renewable power technologies on electric power system reliability. Similar to MARKAL, the model allows electricity storage capacity to be built and utilized for load shifting. Pumped hydroelectric storage, compressed air energy storage, and battery technologies may be represented. In contrast to MARKAL, ReEDS allows electricity storage capacity to provide ancillary services, capturing market benefits beyond the price differential available in time-shifting electricity. ReEDS results reflect similar parameters as MARKAL, including generation capacity, output, and associated emissions.

1.3 Electricity Storage Technology Overview

In this report the terms electricity storage and energy storage are used interchangeably. While the storage devices of interest actually store energy, rather than electricity, the term electricity storage is often used to better represent the role of these technologies which both import and export electricity as part of electric power systems.

It is important to differentiate power from energy in the context of electricity storage technologies. Whereas energy reflects the ability of a storage device to do work, power reflects the rate at which the device can convert energy to electricity.

The storage of electricity may be accomplished by a wide array of technologies relying upon chemical, kinetic, or potential energy. As electricity storage technologies vary, so do the needs which they may serve. The National Renewable Energy Laboratory (NREL) classifies electricity storage technologies into three categories as summarized in Table 1.

Table 1: Electricity Storage Class Descriptions from National Renewable Energy Laboratory, 2010

Electricity Storage Class	Example Applications	Discharge Time Required	Electricity Storage Technologies within Class
Power Quality	Transient Stability, Frequency Regulation	Seconds to Minutes	capacitors, flywheels, superconducting magnetic energy storage
Bridging Power	Contingency Reserves, Ramping	Minutes to ~ 1 hr	lead-acid batteries, nickel-cadmium batteries, nickel-metal hydrides batteries, and lithium-ion batteries
Energy Management	Load Leveling, Firm Capacity, Transmission & Distribution Deferral	Hours	pumped hydroelectric storage, compressed air, thermal energy storage, sodium-sulfur batteries, flow batteries

Analysis in this study was focused on the electricity storage class of energy management, as it is this category which may time-shift large amounts of electricity, potentially enabling broad energy system changes that can be examined in MARKAL. Within the electricity storage class of energy management, attention was focused on the technologies which were furthest along in development and lowest in cost. These included pumped hydroelectric storage (PHS), compressed air energy storage (CAES), sodium-sulfur batteries (NaS), and vanadium redox batteries (VRB). Operational parameters and costs for these six technologies are summarized in Table 2.

Table 2: Time-Shifting Electricity Storage Technology Parameters and Costs

	CAES, Over Ground, Small Reservoir	CAES, Over Ground, Large Reservoir	CAES, Underground, Large Reservoir	Pumped Hydroelectric Storage	Sodium-Sulfur Batteries	Vanadium Redox Batteries
Maximum Hours of Storage (daily)	3	10	10	10	10	10
Maximum Days of Use per Year	60	250	250	346	250	250
Date Technology is Available for Use	2015	2015	2020	2020	2015	2015
Lifetime (years)	20	20	30	30	15	10
Investment Cost (2005$/kW)	701	1058	574	5056	2410	2786
Fixed O&M Costs (2005$/kW-yr)	8.50	8.50	4.25	11.78	6.24	3.15
Variable O&M Costs (million 2005$/PJ)	1.48	1.48	0.89	0.00	1.58	0.83
Electricity Output per Unit of Electricity Input	1.33	1.33	1.33	0.75	0.77	0.72
Natural Gas Heat Rate (Btu/kWh)	4200	4200	4100	-	-	-

Data References: *Energy Information Administration: Office of Energy Analysis, 2010; EPRI-DOE, 2003; Sandia National Laboratories, 2003.*

These operational values and costs were obtained from federal agencies and national laboratories (Energy Information Administration: Office of Energy Analysis, 2010; EPRI-DOE, 2003; Sandia National Laboratories, 2003). There is a fair degree of uncertainty in many of these values, as there is a lack of recent experience building these technologies at grid-scale.

There are currently 21.8 GW of pumped hydroelectric storage (PHS) in the United States, representing nearly all of the domestic time-shifting electricity storage technology capacity built to date (Energy Information Administration, 2010). Recent years have seen minimal new PHS construction on existing waterways, largely due to opposition on environmental grounds. However, there is renewed interest in PHS, with 35.9 GW of preliminary permits currently filed with the Federal Energy Regulatory Commission for possible new facilities (Federal Energy Regulatory Commission, 2011). The proposals for new PHS facilities often are designed so as to not obstruct waterways, instead using a constructed reservoir at a higher elevation than a water source or second reservoir. However, the cost of PHS facilities is relatively high, with the Energy Information Administration estimating an overnight capital cost of $5,595/kW. This is more than twice the estimated overnight capital cost of onshore wind capacity, and five times greater than the estimated cost of advanced natural gas combined cycle capacity (Energy Information Administration: Office of Energy Analysis, 2010).

A second, and less mature, energy management technology is compressed air energy storage (CAES). A CAES plant operates by using off-peak electricity to compress air either in a storage vessel or in an underground reservoir. In periods of higher electricity demand, this compressed air is released to spin a turbine. While escaping air can spin a turbine, greater efficiencies are reached when natural gas is introduced and combusted to expand the air. This requires significantly less natural gas than a natural gas combined cycle plant. There is currently only one such CAES facility in the U.S., located in McIntosh, Alabama (EPRI-DOE, 2003). In commercial operation since 1991, this 110 MW plants uses an underground reservoir for 26 hours of storage (EPRI-DOE, 2003). CAES facilities must be paired with appropriate geologic formations, with suitable formations including porous rock, depleted natural gas/oil fields, and caverns in salt or rock (California Public Utilities Commission, 2009). Smaller CAES facilities may rely on above ground storage reservoirs, but this is generally regarded as a more expensive option less well suited for price-arbitrage.

Unlike PHS and CAES, battery technologies are not limited by geography. While there are many evolving battery technologies potentially scalable for time-shifting grid applications, this study incorporated two battery technologies which are well studied and are relatively commercialized. These two battery technologies are sodium-sulfur (NaS) batteries, and vanadium redox batteries (VRB).

Amongst the battery technologies, sodium-sulfur (NaS) batteries are fairly efficient at approximately 75% round-trip efficiency. These batteries contain two molten electrodes, and operate at temperatures near 300° C. Being produced in a modular design by Tokyo Electric Power Company, over 100 MW have been produced to date for grid applications. However, the high price of the batteries has limited the application of the technology to peak shaving and power quality applications, with price-arbitrage alone proving unprofitable.

In contrast to the modular sodium-sulfur batteries, there is a growing push in battery research and development in the area of flow batteries. Flow battery systems consist of electrolytes which are stored separately from the electrodes, being circulated through only when a chemical reaction is desired. There are potential advantages to this configuration, wherein battery systems may be more easily scalable and have lower costs per MWh stored. Vanadium redox batteries are one example of a flow battery, being similar in efficiency and lifetime to sodium-sulfur batteries (EPRI-DOE, 2003). However, the estimated price of vanadium redox batteries varies by more than a factor of two, potentially making it much more expensive than sodium-sulfur batteries. Much of this price volatility depends upon the market commodity price of vanadium, an essential battery input which is also used in the production of steel.

2 Methods

As with all MARKAL-based analysis, the modeling of electricity storage is dependent on how the technologies are characterized in the MARKAL database. ECAT's nine-region model (EPAUS9r) was updated in 2010 and forms the basis for this study's analysis. Prior to this project, ECAT's MARKAL database did have one electricity storage technology characterized, being pumped hydroelectric storage. This technology was characterized as a residual technology, meaning that the technology could only represent 20.36 GW of existing capacity, and could not be drawn upon by the model in future construction of storage capacity.

Seeking to model the use of time-shifting electricity storage going forward, six such technologies were identified and represented in an updated EPAUS9r database. These six technologies included pumped hydroelectric storage, three types of compressed air energy storage, sodium-sulfur batteries, and vanadium redox batteries. Table 3 summarizes the data required to fully characterize each electricity storage technology for use in MARKAL.

Table 3: Required Values to Represent Time-Shifting Electricity Storage Technologies in MARKAL

Costs	Units
Fixed Operations and Maintenance	Year 2005 $ in Millions / GW of Capacity
Variable Operations and Maintenance	Year 2005 $ in Millions / PJ of Capacity
Investment Costs	Year 2005 $ in Millions / GW of Capacity
Facility Characteristics	Units
Date That Facilities Could Begin Operations	Calendar Year
Expected Lifetime of a Facility	Years
Availability Factor: by season and time of day	0 - 1 value
Electricity Efficiency Ratio	(units input) / (units output)
Natural Gas Efficiency Ratio (if applicable)	(units input) / (units output)

A literature review was conducted examining the six time-shifting electricity storage technologies. Key technology attribute values from this literature review are found in Table 2. As guided by EPA policy, wherever possible, data was drawn from the U.S. Department of Energy's *Annual Energy Outlook* (AEO) and its underlying modeling data. However, the AEO only contained sufficient data for pumped hydroelectric storage, the most mature time-shifting electricity storage technology. For the remaining technologies, operational parameters and costs were obtained from the 2003 EPRI-DOE study titled

Handbook of Energy Storage for Transmission and Distribution, and the 2003 Sandia study titled *Long-vs. Short-Term Energy Storage Technology Analysis: A Life Cycle Cost Study.* While more recent data would have been preferable, the breadth of analysis and detail far exceeds that found in other literature that was reviewed. Importantly, MARKAL may be used for prescriptive modeling even under the current cost uncertainties, with the model's representation of energy storage technologies enabling future scenario analysis of energy system impacts.

2.1 Enhancements to U.S. EPA's 9-Region National Database

The representation of time-shifting electricity storage technologies in MARKAL must include the specification of technology availability during each of the three seasons and four times of day. This required four assumptions.

First, the storage technologies were not modeled to be available for use every day of a year. In order to reflect necessary system downtime, estimated values from the literature review were utilized. All technologies except for two were modeled with an availability of 250 days per year (EPRI-DOE, 2003). Pumped hydroelectric storage was modeled with an availability of 346 days per year, and small above ground CAES was modeled with an availability of 60 days per year (EPRI-DOE, 2003).

Second, the technologies were limited to operating only in daily cycles, wherein nighttime charging would enable daytime discharge of electricity. The shifting of electricity across seasons was not permitted.

Third, each technology was limited to time-shifting a specific amount of energy each day. As reflected in Table 2, all technologies except for small above ground CAES were modeled to have a maximum discharge of 10 hours at their full rated capacity. Small above ground CAES was modeled to have a maximum discharge of 3 hours at its full capacity. For example, a 10 MW small above ground CAES plant would be able to discharge 10 MW for 3 hours, totaling 30 MWh per daily cycle.

Fourth, it was necessary to specify the time periods in which each storage technology was permitted to discharge its electricity in order to ensure that the technologies in MARKAL did not discharge more electricity than was stored. The availability of each storage technology varied both by the time of day and season, with this being based upon storage capacity, annual downtime, and the price of electricity. The time of day availability for the discharge of electricity was prioritized based upon price, with storage first allocating its discharge in the following order: peak; day p.m.; day a.m. The system downtime for storage technologies was modeled to be split equally between the winter and intermediate time period, with the higher electricity prices during the summer incentivizing greater utilization.

2.2 Scenario Construction

The impact of time-shifting electricity storage on the national energy system was hypothesized to differ depending upon five market conditions. Preliminarily analysis and model runs narrowed the focus of this report to three market conditions, eliminating two. While foreshadowing results, it is important to explain why two hypothesized drivers of change in electricity storage adoption were dropped from this analysis.

The role of carbon capture and sequestration (CCS) technologies on electricity storage use is not examined in this study. Preliminary MARKAL runs which prohibited the use of CCS resulted in an electric power sector composed primarily of wind power. This heavy reliance on wind could not be modeled with confidence as it was not possible to adequately represent the potential variability in wind resources and necessary grid integration costs.

In addition, the role of electricity storage investment costs was not examined in this study. Preliminary MARKAL model runs illustrated that at current costs, as reflected in Table 2, no new storage technologies are built as part of a least-cost solution. Furthermore, subsequent runs with storage costs reduced by up to 50% did not result in new storage being constructed as part of a MARKAL least-cost solution. There are likely two reasons for this. First, MARKAL does not reflect ancillary service benefits provided by electricity storage, meaning that based upon price-arbitrage alone the technologies are modeled as being less competitive than they are in reality. Second, price-arbitrage benefits stem from the daily electricity price cycles in a region. If these prices reflect a narrower difference between high and low prices, then price-arbitrage will provide less value to the energy system. Calibrating these daily price cycles in the MARKAL EPAUS9r database was beyond the scope of this study. Combined, these two factors diminish confidence in any price threshold which may be identified by model runs.

The three market conditions which were examined in the MARKAL analysis included: the penetration of intermittent renewable power; changing natural gas prices; and the imposition of a national limit on CO_2 emissions from the energy system. Furthermore, the interactive nature of natural gas prices and a CO_2 limit was examined. Scenarios were constructed to represent varied natural gas prices with and without the imposition of a national CO_2 limit on the energy system. Following is an overview of the MARKAL scenarios which were constructed to examine the impact of these market conditions on energy sector investments and emissions. In order to identify the impact of electricity storage technologies under each future scenario, it was necessary to set up the model runs in pairs. These paired scenario runs have identical conditions except that one allows the use of new electricity storage, and one prohibits such use. Similar scenarios are grouped within sets by the future market conditions which they characterize.

2.2.1 Scenario Set #1: Base Case Conditions

Scenario 1: Base Case Conditions without New Electricity Storage

The ECAT team maintains an EPAUS9r base case scenario which serves as a stable reference point for subsequent scenario analysis. This base case is calibrated to closely match the Energy Information Administration's Annual Energy Outlook. This model run reflects Clean Air Interstate Rule (CAIR) emission limits, but does not contain a national limit on greenhouse gas emissions. The only electricity storage represented is 20.36 GW of existing pumped hydroelectric storage capacity. All subsequent scenarios are built upon this scenario, with all differences noted.

Scenario 2: Base Case Conditions with the Use of Current Electricity Storage Technologies Allowed

This scenario mirrored Scenario 1 except that it allowed the new construction and use of six time-shifting electricity storage technologies. The storage technologies included: small above ground CAES; large above ground CAES; large below ground CAES; pumped hydroelectric storage, sodium-sulfur batteries, and vanadium redox batteries. The cost and performance parameters for these six technologies matched the values in Table 2. These values were based upon government and peer-reviewed literature, and were processed to match the MARKAL database import formats.

Scenario 3: Base Case Conditions with the Use of a Hypothetical Electricity Storage Technology Allowed

This scenario resembled Scenario 2 except with regard to the electricity storage technologies permitted. In contrast to Scenario 2, the single electricity storage technology available in this scenario was a hypothetical battery technology with a low cost and high efficiency. This battery was named Battery Technology X, and was modeled as having the following parameters.

Table 4: Battery Technology X Parameters and Values

Parameter	Value
Round Trip Efficiency	85%
Lifetime (years)	15
Maximum Hours of Storage (daily)	10
Maximum Days of Use per Year	250
Investment Cost ($/kW)	200
Fixed O&M (million $ / GW)	1
Variable O&M (million $ / PJ)	1

All subsequent scenarios which allow the use of electricity storage only permit the use of Battery Technology X. The operational and cost values associated with Battery Technology X were uniform across scenarios.

2.2.2 Scenario Set #2: A Stricter National Renewable Portfolio Standard (RPS)

Scenario 4: A Stricter National RPS without Electricity Storage

This scenario represented a modification of Scenario 1 wherein the representation of current renewable portfolio standards was strengthened. As with Scenario 1, the construction of new electricity storage was not permitted. Scenario 1 included the EPAUS9r representation of current renewable portfolio standards, with such standards being aggregated by the nine census divisions. In Scenario 4, a strengthened renewable portfolio standard is set at the national level. This required a national increase in renewable energy output beyond the base case trajectory beginning in 2025. A 20% increase over the base case state RPS levels was required in 2025, increasing to 40% in 2030, 60% in 2035, 80% in 2040, and 100% for 2045 through 2055. These percent increases were in comparison to existing RPS requirements, ultimately doubling the RPS targets by 2045. New electricity storage was not permitted in this scenario.

Scenario 5: A Stricter National RPS with Electricity Storage

This scenario mirrored Scenario 4 in all regards except for electricity storage. The construction and use of new electricity storage was allowed in this scenario, with the single option being the hypothetical Battery Technology X.

2.2.3 Scenario Set #3: Higher Natural Gas Prices

Scenario 6: Higher Natural Gas Prices without Electricity Storage

This scenario represented a modification of Scenario 1 wherein the price of natural gas was increased by 100% beginning in the 2015 time period. As the natural gas supply curve was represented in steps, each step's respective price was increased by 100%. This applied to both domestic production and imports. As with Scenario 1, the construction of new electricity storage was not allowed.

Scenario 7: Higher Natural Gas Prices with Electricity Storage

This scenario matched Scenario 6 in all regards except for electricity storage. The construction and use of new electricity storage was permitted in this scenario, with the single option being the hypothetical Battery Technology X.

2.2.4 Scenario Set #4: Lower Natural Gas Prices

Scenario 8: Lower Natural Gas Prices without Electricity Storage

This scenario represented a modification of Scenario 1 wherein the price of natural gas was decreased by 50% beginning in the 2015 time period. As the natural gas supply curve was represented in steps, each step's respective price was decreased by 50%. This applies to both domestic production and imports. As with Scenario 1, the construction of new electricity storage was not allowed.

Scenario 9: Lower Natural Gas Prices with Electricity Storage

This scenario mirrored Scenario 8 in all regards except for electricity storage. The construction and use of new electricity storage was allowed in this scenario, with the single option being the hypothetical Battery Technology X.

2.2.5 Scenario Set #5: Carbon Dioxide (CO_2) Limit

Scenario 10: Carbon Dioxide (CO_2) Limit without Electricity Storage

This scenario matched Scenario 1 in all regards except for the inclusion of a limit on the total energy system's emissions of carbon dioxide (CO_2). The CO_2 emission limit was national in scope, and gradually increased in stringency through 2055. The limit imposed in this scenario required that CO_2 emissions be stabilized by 2015, and then be reduced by an additional 8% every five years. By 2055, the CO_2 emission limit represented a 42.0% reduction in comparison to 2010 levels, and a 45.5% in comparison to 2005 levels. Importantly, the percent reductions required in this emission limit are in relation to the CO_2 emission levels associated with the base case conditions of Scenario 1. Offsets were not allowed and end-use demands for energy was fixed. As with Scenario 1, the construction of new electricity storage was not permitted.

Scenario 11: Carbon Dioxide (CO_2) Limit with Electricity Storage

This scenario mirrored Scenario 10 in all regards except for electricity storage. The construction and use of new electricity storage was permitted in this scenario, with the single option being the hypothetical Battery Technology X.

2.2.6 Scenario Set #6: Carbon Dioxide (CO_2) Limit and Higher Natural Gas Prices

Scenario 12: Carbon Dioxide (CO_2) Limit and Higher Natural Gas Prices without Electricity Storage

This scenario was built upon Scenario 10 which imposed a national CO_2 limit and did not permit the construction of new electricity storage. In this scenario, the price of natural gas is increased by 100% beginning in 2015. As the natural gas supply curve was represented in steps, each step's respective price was increased by 100%. This applied to both domestic production and imports.

Scenario 13: Carbon Dioxide (CO_2) Limit and Higher Natural Gas Prices with Electricity Storage

This scenario mirrored Scenario 12 in all regards except for electricity storage. The construction and use of new electricity storage was allowed in this scenario, with the single option being the hypothetical Battery Technology X.

2.2.7 Scenario Set #7: Carbon Dioxide (CO_2) Limit and Lower Natural Gas Prices

Scenario 14: Carbon Dioxide (CO_2) Limit and Lower Natural Gas Prices without Electricity Storage

This scenario was based on Scenario 10 which imposed a national CO_2 limit and did not permit the construction of new electricity storage. In this scenario, the price of natural gas was decreased by 50% beginning in the 2015 time period. As the natural gas supply curve was represented in steps, each step's respective price was decreased by 50%. This applied to both domestic production and imports.

Scenario 15: Carbon Dioxide (CO_2) Limit and Lower Natural Gas Prices with Electricity Storage

This scenario mirrored Scenario 14 in all regards except for electricity storage. The construction and use of new electricity storage was permitted in this scenario, with the single option being the hypothetical Battery Technology X.

3 Results

3.1 Scenario Results

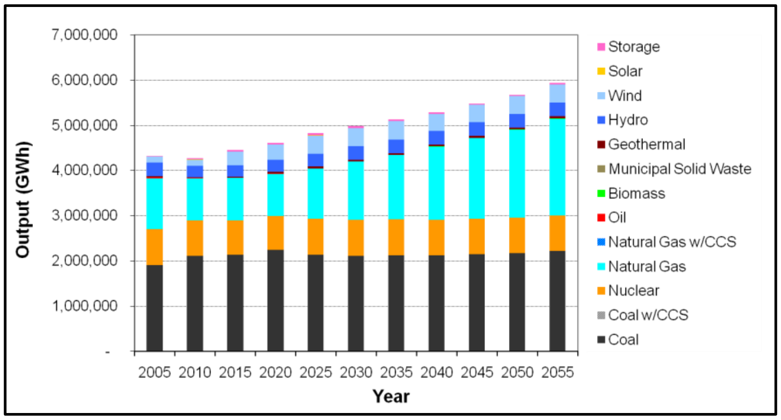
All fifteen scenarios were run in MARKAL, with the results representing prescriptive least-cost energy system solutions under the modeling assumptions. Following are selections from the model run results which reflect the composition of generation output and the associated energy sector emissions. The energy system emissions tracked and examined included CO_2, sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter of 10 micrometers or less (PM10). In examining scenario results it is necessary to isolate the impact of electricity storage from other scenario conditions. Therefore, first, base case conditions are examined to provide a baseline for subsequent scenario results. Second, scenarios which do not permit the use of storage are compared to the base case in order to discern the impacts of varying future conditions. Third, scenarios which allow the use of new electricity storage are compared to their counterpart scenarios which prohibit new storage. This final step isolates the impact of electricity storage on generation output and emissions, enabling analysis.

3.1.1 Scenario Set #1: Base Case Conditions

Scenario 1: Base Case Conditions without Electricity Storage

In this scenario, base case conditions were modeled out to 2055, with the only electricity storage being 20.36 GW of existing pumped hydroelectric storage capacity. Total U.S. electricity output is represented in Figure 2, apportioned by generation technology.

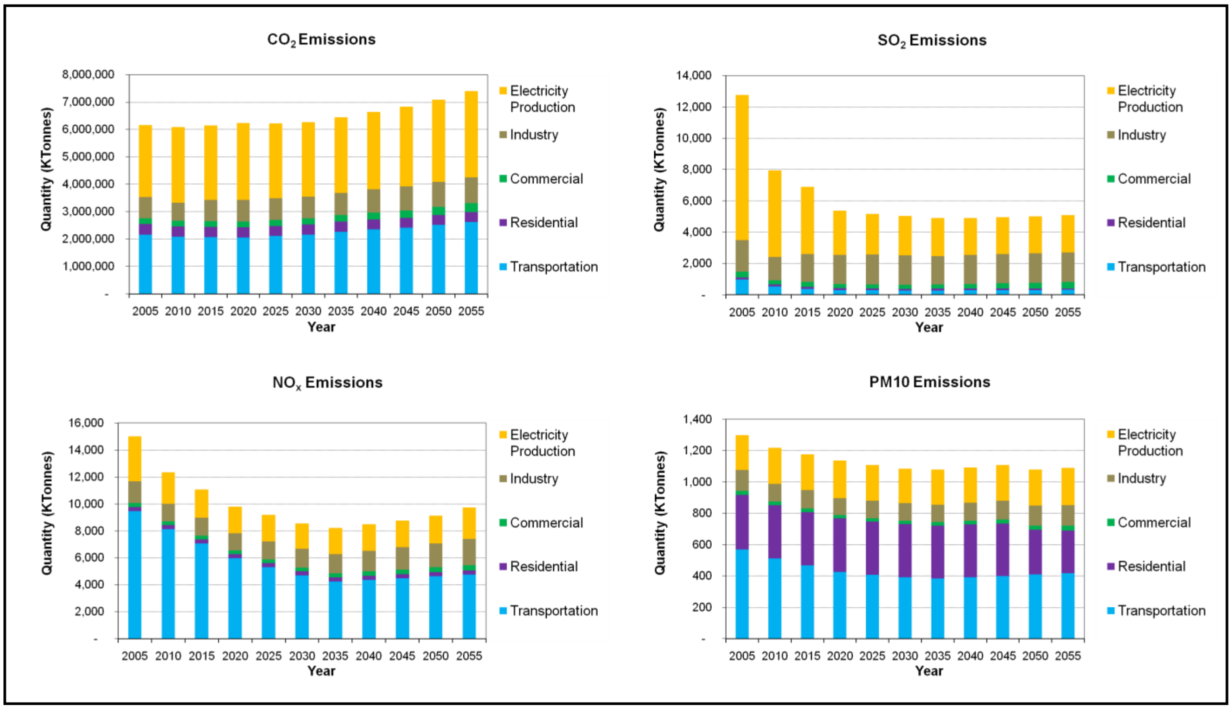
Figure 2: Total U.S. Electricity Output - Base Case Conditions without Electricity Storage



Under base case conditions, the least-cost generation mix relies increasingly upon natural gas combustion. In contrast, the use of coal-fired, nuclear, and hydroelectric power plants remains relatively constant. Increases in the use of renewable power are driven by state renewable portfolio standards. Wind power is used to satisfy RPS requirements, and there is no significant use of solar power.

Total U.S. emissions of CO_2, SO_2, NO_x, and PM10 are represented in Figure 3, apportioned by the emitting sectors.

Figure 3: Total U.S. Emissions by Sector - Base Case Conditions without Electricity Storage



Total CO_2 emissions rise throughout the timeframe driven by increases in the electric power sector (20%), transportation sector (20%), and industrial sector (23%). Electric sector CO_2 emission increases reflect rising demand and a generation pool which increases the combustion of natural gas without proportionate decreases in the use of coal. SO_2 emissions fall sharply in the electric power sector, largely attributed to a coal-fired generation fleet which maintains current output while decreasing emissions. Similarly, NO_x emissions from the electric power sector decline by 30% due to declining NO_x emission rates from the coal-fired generation fleet. PM10 emissions from the electric power sector remain relatively constant, with system reductions attributable to the transportation and residential sectors.

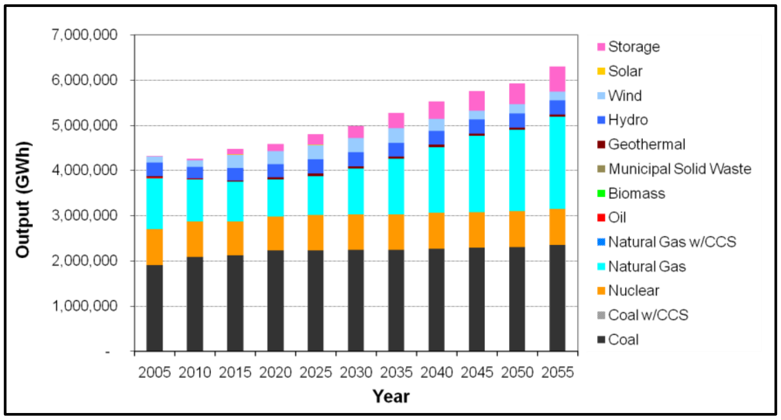
Scenario 2: Base Case Conditions with the Use of Current Electricity Storage Technologies Allowed

The conditions of this scenario mirror Scenario 1 except that it allows the new construction and use of six time-shifting electricity storage technologies. The storage technologies include: small above ground CAES; large above ground CAES; large below ground CAES; pumped hydroelectric storage, sodium-sulfur batteries, and vanadium redox batteries. Having costs which proved too high, no new storage technologies were constructed. Therefore, the results from Scenario 2 are identical to those from Scenario 1.

Scenario 3: Base Case Conditions with the Use of a Hypothetical Electricity Storage Technology Allowed

The conditions of this scenario mirrored Scenario 2 except that the single electricity storage option available is Battery Technology X, a hypothetical low-cost technology. Total U.S. electricity output is represented in Figure 4, apportioned by generation technology.

Figure 4: Total U.S. Electricity Output - Base Case Conditions with Electricity Storage

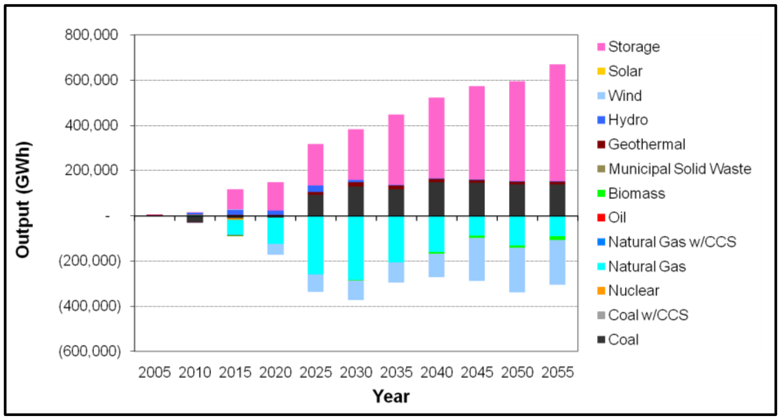


Time-shifting electricity storage is used in this least-cost solution, with its output being represented by the pink segments at the top of each bar in Figure 4. It is important to note that this does not indicate additional generation by electricity storage, but rather a visual representation of the electricity which was stored and discharged, accounting for storage efficiency losses. The use of time-shifting electricity storage increases over time in this model run, rising to approximately 550,000 GWh annually by 2055. This requires a minimum electricity storage capacity of 220 GW.

The Impact of Time-Shifting Electricity Storage under Base Case Conditions: Generation Output

In order to illustrate the impact of electricity storage use on generation under base case conditions, the generation from Scenario 1 was subtracted from Scenario 3. The differences in generation output by technology are represented in Figure 5.

Figure 5: Impact of Electricity Storage on Total U.S. Generation Output under Base Case Conditions

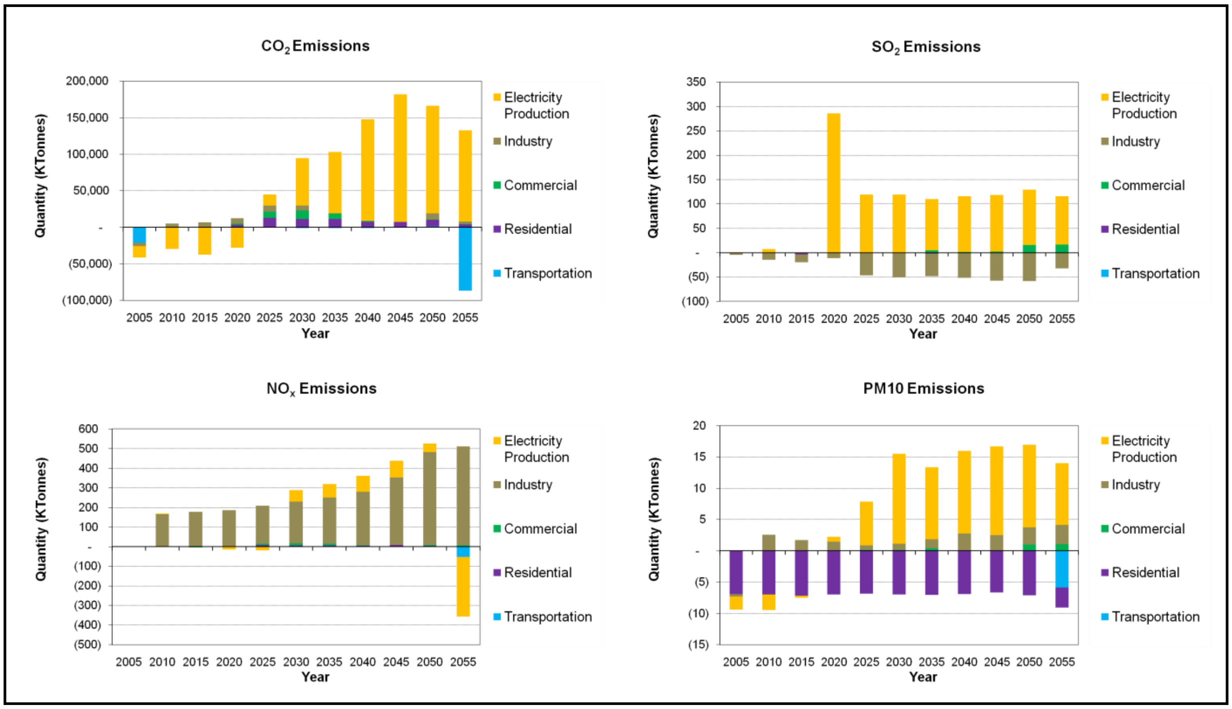


The availability of time-shifting electricity storage enables a sustained increase in coal-fired generation output. Beginning in 2025, output from coal-fired generators increases during winter and intermediate seasons. There is no change in generation output during the summer, with this increase in output being due to the greater utilization of coal-fired generation capacity. There is also an increase in the use of available natural gas-fired generation at night. Counter to these trends, daytime output from natural gas plants decreases 2015 onwards. This decrease in generation output is found during all daytime periods. There is also a significant decrease in electricity output from wind farms, with declining output across all seasons and times of day. Whereas increases in coal generation were attributable to increased utilization, the decline in wind power output is attributable to a lower installed capacity.

The Impact of Time-Shifting Electricity Storage under Base Case Conditions: Emissions

In order to illustrate the impact of electricity storage use on emissions under base case conditions, emissions from Scenario 1 were subtracted from Scenario 3. The differences in emissions by sector are represented in Figure 6.

Figure 6: Impact of Electricity Storage on Total U.S. Emissions under Base Case Conditions



The availability of time-shifting electricity storage increases emissions of all four pollutants examined. Energy system CO_2 emissions increase beginning in 2025, reaching emission levels up to 2.5% higher.

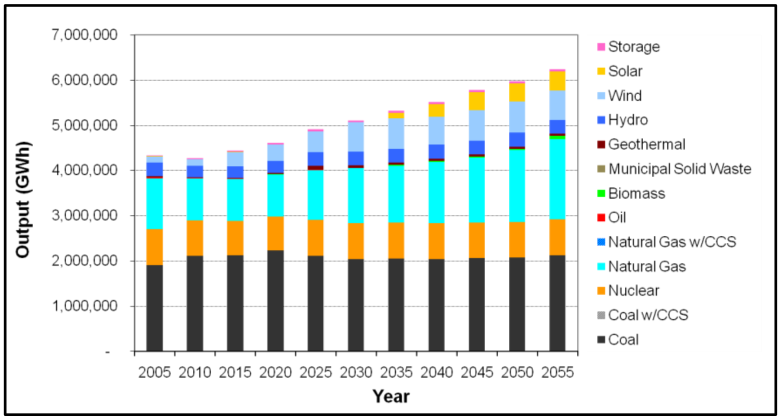
These CO_2 emission increases are largely driven by the shift towards the greater use of coal in the electric power sector. Similarly, system increases in SO_2 and PM10 emissions are due to the increased use of coal. Total energy system SO_2 emission levels increase by up to 4%. In contrast, energy system NO_x emission increases are largely due to the industrial sector's increased use of natural gas, reaching emission levels up to 5% higher.

3.1.2 Scenario Set #2: A Stricter National Renewable Portfolio Standard (RPS)

Scenario 4: A Stricter National RPS without Electricity Storage

This scenario represents a modification of Scenario 1 wherein the representation of renewable portfolio standard is strengthened. As with Scenario 1, the construction of new electricity storage is not allowed. A 20% increase over the base case RPS level is required in 2025, increasing to 40% in 2030, 60% in 2035, 80% in 2040, and 100% for 2045 through 2055. Total U.S. electricity output is represented in Figure 7, apportioned by generation technology.

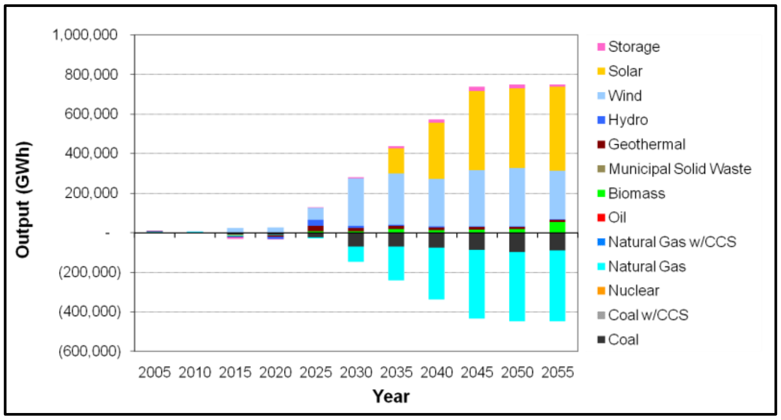
Figure 7: Total U.S. Electricity Output – A Stricter National RPS without Electricity Storage



The Impact of a Stricter National RPS: Generation Output

In order to illustrate the impact of a stricter RPS on generation output, the generation from Scenario 1 was subtracted from Scenario 4. The differences in generation output by technology are represented in Figure 8.

Figure 8: Impact of a Stricter National RPS on Total U.S. Generation Output

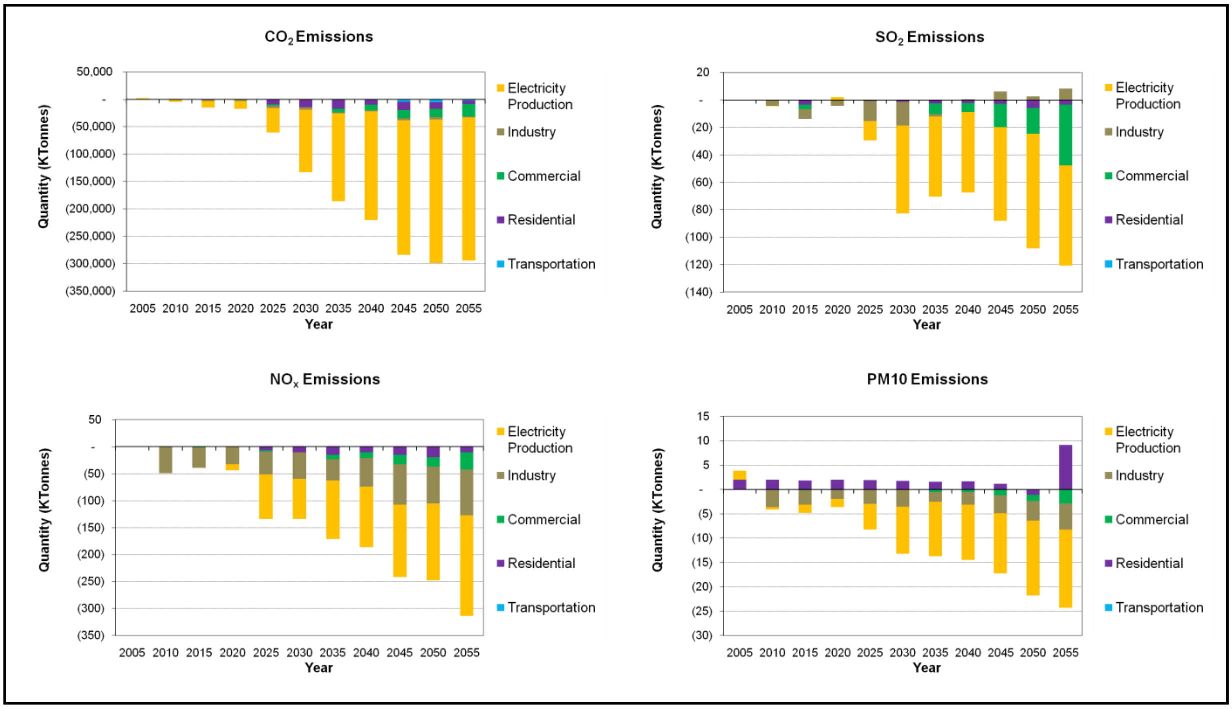


In this scenario we see that the amount of wind and solar power output has doubled in comparison to the earlier base case scenario, largely displacing a portion of the previous growth in the use natural gas. There is also a slight decrease in the use of coal-fired generation.

The Impact of a Stricter National RPS: Emissions

In order to illustrate the impact of a stricter RPS on emissions, emissions from Scenario 1 were subtracted from Scenario 4. The differences in emission by sector are represented in Figure 9.

Figure 9: Impact of a Stricter National RPS on Total U.S. Emissions under Base Case Conditions

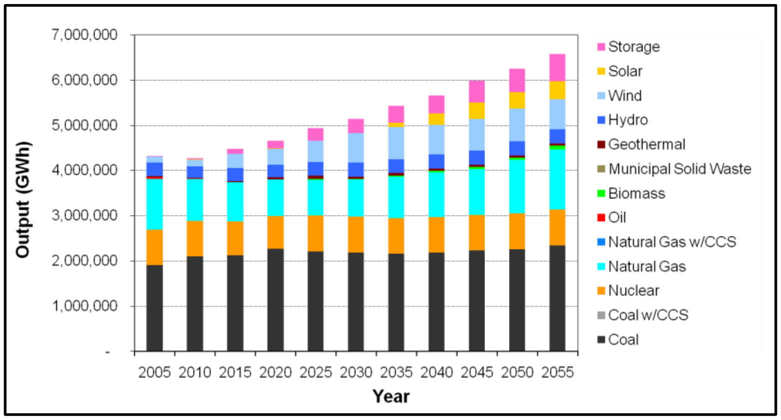


Enforcing a stricter RPS decreases emissions of all four pollutants examined. For each pollutant, declining levels are largely attributable to the decreasing use of coal and natural gas-fired generation in the electric power sector. Emission reductions from the industrial sector appear to stem from fuel switching, with a decreasing reliance on coal and an increase in the use of natural gas.

Scenario 5: A Stricter National RPS with Electricity Storage

This scenario mirrors Scenario 4 in all regards except for electricity storage. New electricity storage is permitted in this scenario, with the single option being the hypothetical Battery Technology X. Total U.S. electricity output is represented in Figure 10, apportioned by generation technology.

Figure 10: Total U.S. Electricity Output – A Stricter National RPS with Electricity Storage

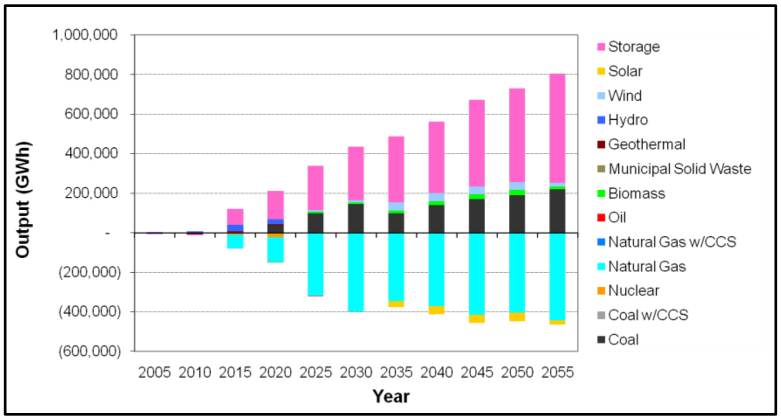


The use of time-shifting electricity storage increases over time, rising to approximately 597,000 GWh annually by 2055. This requires a minimum electricity storage capacity of 240 GW.

The Impact of Time-Shifting Electricity Storage under a Stricter National RPS: Generation Output

In order to illustrate the impact of electricity storage use on generation under a stricter RPS, the generation from Scenario 4 was subtracted from Scenario 5. The differences in generation output by technology are represented in Figure 11.

Figure 11: Impact of Electricity Storage on Total U.S. Generation Output under a Stricter National RPS



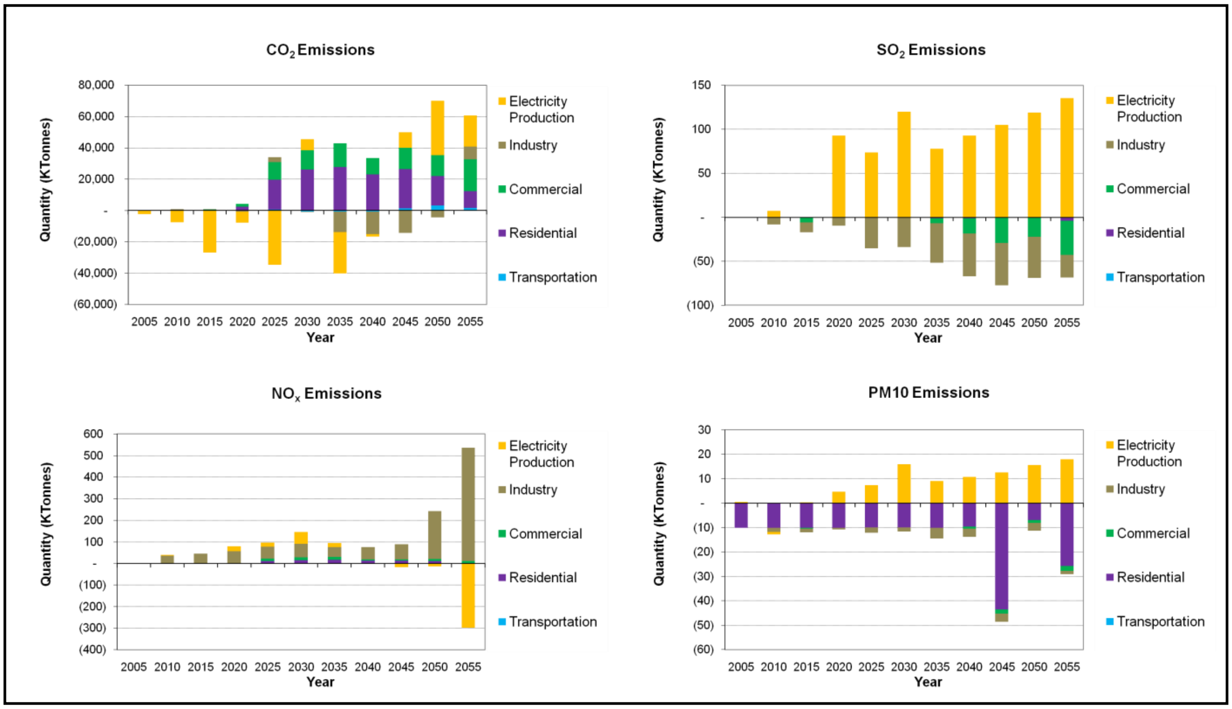
Under a stricter RPS, the availability of time-shifting electricity storage affects only marginal changes to generation from renewable power facilities. There is a small increase in the use of wind, paired with a small decrease in the use of solar. This suggests that time-shifting additional wind energy from night to day may be less costly than utilizing solar power to meet the RPS.

There are larger changes in the generation from fossil fuel technologies, with a sustained increase in the use of coal, offset by larger decreases in the use of natural gas. Electricity storage appears to allow greater use of coal at night. Beginning in 2020, output from coal-fired generators increases during winter and intermediate seasons. There is no change in generation output during the summer, with the increased output from coal-plants coming from greater utilization rather than new capacity construction. There is also an increase in the use of available natural gas-fired generation at night. In contrast, daytime output from natural gas plants decreases beginning in 2015.

The Impact of Time-Shifting Electricity Storage under a Stricter National RPS: Emissions

In order to illustrate the impact of electricity storage use on emissions under a stricter RPS, emissions from Scenario 4 were subtracted from Scenario 5. The differences in emissions by sector are represented in Figure 12.

Figure 12: Impact of Electricity Storage on Total U.S. Emissions under a Stricter National RPS


CO_2 Emissions

SO_2 Emissions

NO_x Emissions

PM10 Emissions

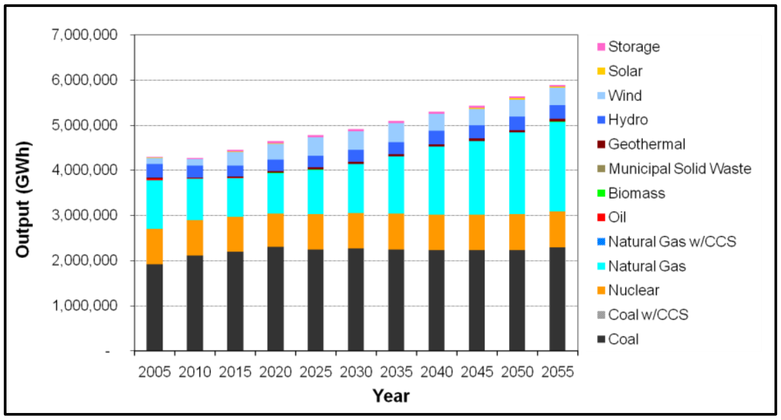
The availability of time-shifting electricity storage leads to broad energy system emission increases in CO_2, SO_2, and NO_x. Changes within the electric power sector ripple through the commercial and residential sectors, resulting in minor increases in CO_2 emissions. More specifically, residential and commercial sector energy demand is satisfied to a greater degree by natural gas, displacing electricity. However, the total change in CO_2 emissions is relatively small, representing at most a 1% increase. In contrast to CO_2 emissions, we see a clear upward trend in electric power sector SO_2 emissions enabled by electricity storage. SO_2 emission increases in the electric power sector are due to its increased use of coal, while decreases in industrial sector SO_2 emissions are due to its declining use of coal. For context, the net impact of electricity storage in these conditions leads to at most a 2% increase in national emissions of SO_2. Total system NO_X emissions increase by up to 2.5%. NO_x emission increases within the industrial sector may be attributable to the sector's increased natural gas use. Increases in electric power sector PM10 are likely due to the increased use of coal-fired generation.

3.1.3 Scenario Set #3: Higher Natural Gas Prices

Scenario 6: Higher Natural Gas Prices without Electricity Storage

This scenario represents a modification of Scenario 1 wherein the price of natural gas is increased by 100% beginning in the 2015 time period. As with Scenario 1, the construction of new electricity storage is not allowed. Total U.S. electricity output is represented in Figure 13, apportioned by generation technology.

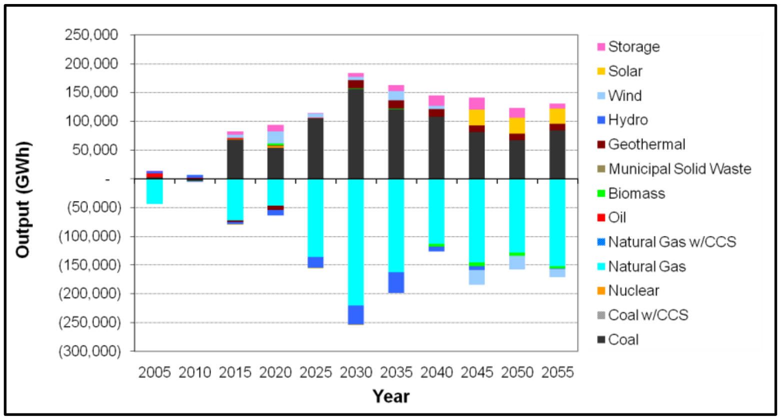
Figure 13: Total U.S. Electricity Output – Higher Natural Gas Prices without Electricity Storage



The Impact of Higher Natural Gas Prices: Generation Output

In order to illustrate the impact of higher natural gas prices on generation output, the generation from Scenario 1 was subtracted from Scenario 6. The differences in generation output by technology are represented in Figure 14.

Figure 14: Impact of Higher Natural Gas Prices on Total U.S. Generation Output

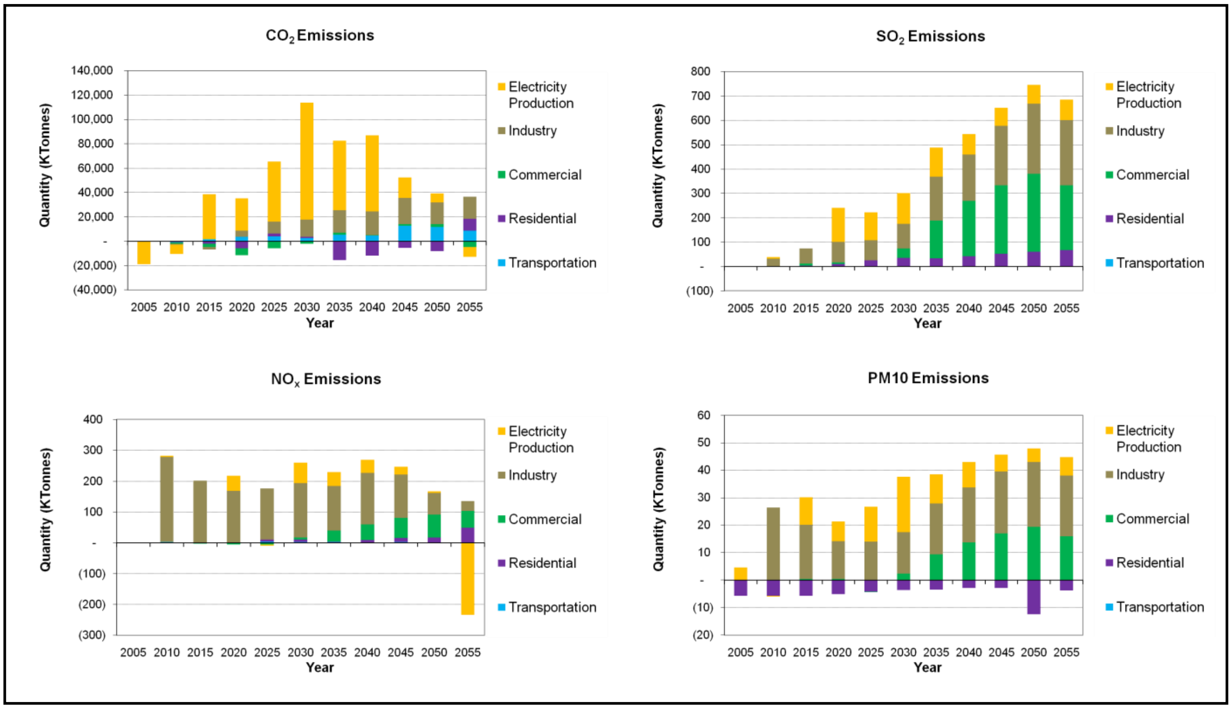


In this scenario we see that generation from natural gas-fired generators declines beginning in 2015, coinciding with the introduction of higher natural gas prices. This is offset by a sustained increase in output from coal-fired generation. The change in storage reflected in Figure 14 is limited to changes in the use of existing pumped hydroelectric storage as the construction of new storage is not permitted in Scenario 6.

The Impact of Higher Natural Gas Prices: Emissions

In order to illustrate the impact of higher natural gas prices on emissions, emissions from Scenario 1 were subtracted from Scenario 6. The differences in emission by sector are represented in Figure 15.

Figure 15: Impact of Higher Natural Gas Prices on Total U.S. Emissions

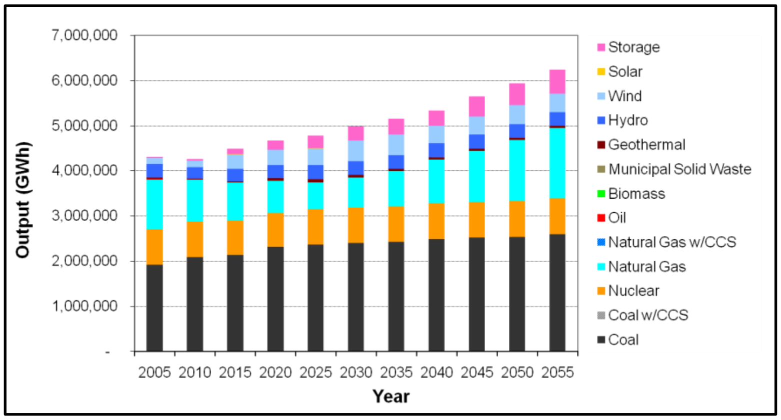


Higher natural gas prices result in higher emissions of all four pollutants examined. There is a decrease in the use of natural gas in all sectors, with increasingly less gas used over time. In contrast, there is an increase in the use of coal in the electric power and industrial sectors. Due to the higher emission rates of coal combustion, increases in pollution from the electric power and industrial sectors are largely attributable to fuel switching from natural gas to coal.

Scenario 7: Higher Natural Gas Prices with Electricity Storage

This scenario mirrors Scenario 6 in all regards except for electricity storage. New electricity storage is permitted in this scenario, with the single option being the hypothetical Battery Technology X. Total U.S. electricity output is represented in Figure 16, apportioned by generation technology.

Figure 16: Total U.S. Electricity Output - Higher Natural Gas Prices with Electricity Storage

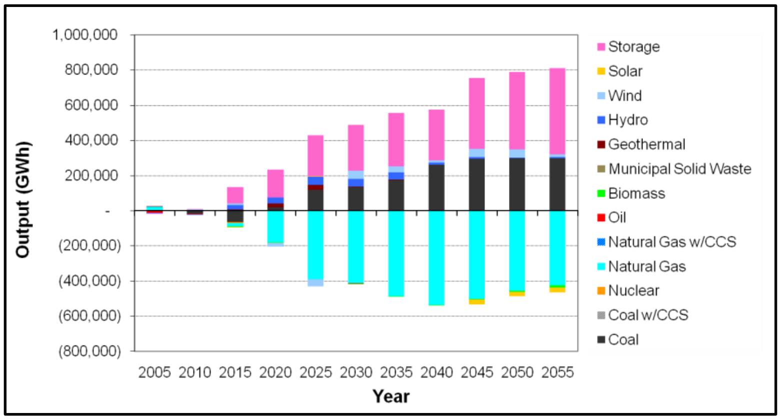


The use of time-shifting electricity storage increases over time, rising to approximately 530,000 GWh annually by 2055. This requires a minimum electricity storage capacity of 212 GW.

The Impact of Time-Shifting Electricity Storage under Higher Natural Gas Prices: Generation Output

In order to illustrate the impact of electricity storage on the use of generation under higher natural gas prices, the generation output from Scenario 6 was subtracted from Scenario 7. The differences in generation output by technology are represented in Figure 17.

Figure 17: Impact of Electricity Storage on Total U.S. Generation Output under Higher Natural Gas Prices



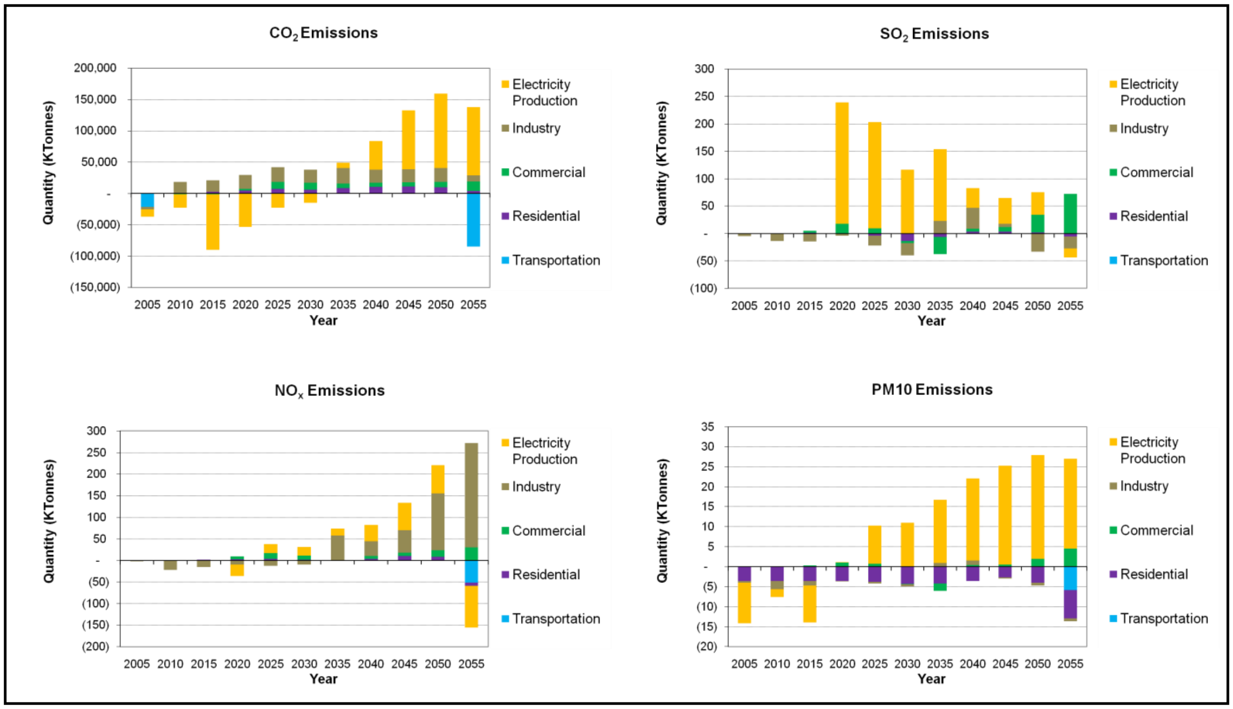
Under higher natural gas prices, the availability of time-shifting electricity storage affects small changes to generation from renewable power facilities. There is a small increase in the use of wind power, paired with a small decrease in the use of solar power. This suggests that even under existing renewable portfolio standards it may be less costly to time-shift additional nighttime wind energy.

There are larger changes in the generation from fossil fuel technologies, with a sustained increase in the use of coal, offset by larger decreases in the use of natural gas. Electricity storage allows the greater use of coal-fired generation capacity at night during winter and intermediate seasons, allowing baseload capacity to run at higher levels. Most of the increased output from coal-plants is due to increased utilization rather than the construction of new capacity. Decreases in natural gas-fired generation are seen during all daytime periods, with a slight increase seen during nighttime across most seasons.

The Impact of Time-Shifting Electricity Storage under Higher Natural Gas Prices: Emissions

In order to illustrate the impact of electricity storage use on emissions under higher natural gas prices, emissions from Scenario 6 were subtracted from Scenario 7. The differences in emissions by sector are represented in Figure 18.

Figure 18: Impact of Electricity Storage on Total U.S. Emissions under Higher Natural Gas Prices



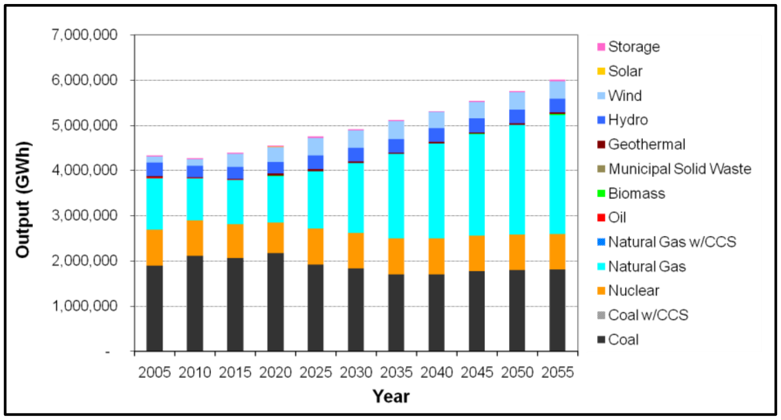
The availability of time-shifting electricity storage leads to emission increases in all pollutants examined. Total energy system emissions of CO_2, NO_x, and PM10 all rise by up to 2%, with emissions of SO_2 rising by up to 4%. The combustion of coal in the electric power sector increases, driving the emission increases in SO_2 and PM10. Contrary to this trend, coal use declines in the industrial sector, being replaced by natural gas. Natural gas use also increases in the residential and commercial sectors. NO_x emissions increases within the industrial sector may be attributable to the sector's increased natural gas use.

3.1.4 Scenario Set #4: Lower Natural Gas Prices

Scenario 8: Lower Natural Gas Prices without Electricity Storage

This scenario represents a modification of Scenario 1 wherein the price of natural gas is decreased by 50% beginning in the 2015 time period. As with Scenario 1, the construction of new electricity storage is not allowed. Total U.S. electricity output is represented in Figure 19, apportioned by generation technology.

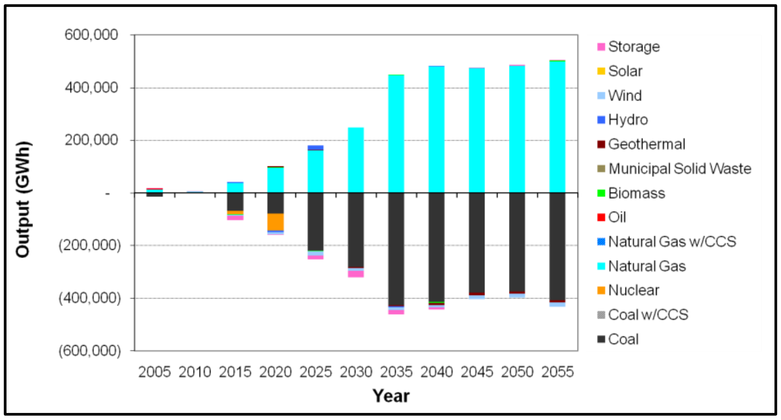
Figure 19: Total U.S. Electricity Output – Lower Natural Gas Prices without Electricity Storage



The Impact of Lower Natural Gas Prices: Generation Output

In order to illustrate the impact of lower natural gas prices on generation output, the generation output from Scenario 1 was subtracted from Scenario 8. The differences in generation output by technology are represented in Figure 20.

Figure 20: Impact of Lower Natural Gas Prices on Total U.S. Generation Output

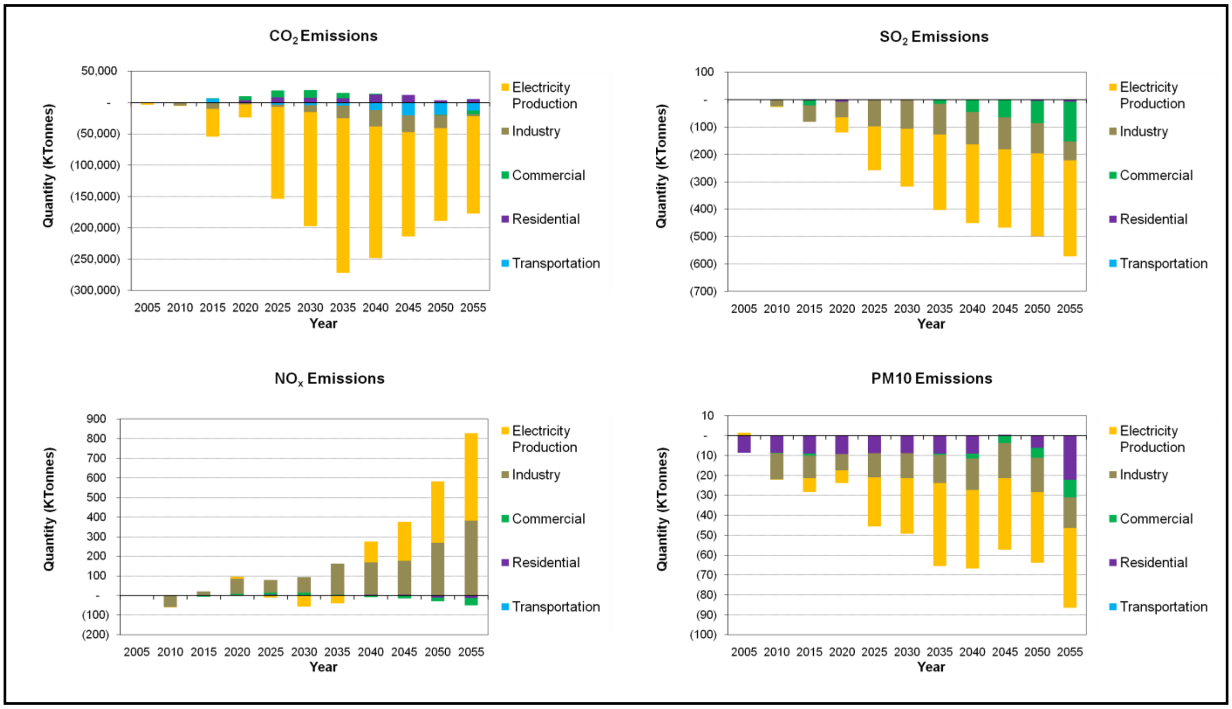


In this scenario we see that generation from natural gas-fired generators increases beginning in 2015, coinciding with the introduction of lower natural gas prices. This is offset by a sustained decrease in output from coal-fired generation.

The Impact of Lower Natural Gas Prices: Emissions

In order to illustrate the impact of lower natural gas prices on emissions, emissions from Scenario 1 were subtracted from Scenario 8. The differences in emission by sector are represented in Figure 21.

Figure 21: Impact of Lower Natural Gas Prices on Total U.S. Emissions

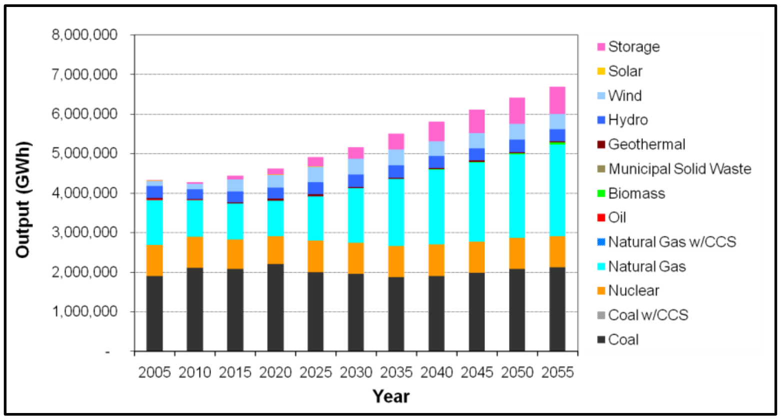


Lower natural gas prices result in lower emissions of CO_2, SO_2 and PM10. There is an increase in the use of natural gas in all sectors, a trend which grows over time and is most pronounced in the electric power sector. Coal use declines in the electric power and industrial sectors. Declines in CO_2, SO_2 and PM10 from the electric power and industrial sectors are largely attributable to this fuel switching from coal to natural gas. However, the increase in NO_x emissions in the electric power and industrial sector may also be due to increased use of natural gas. This may be the case if natural gas generation displaces the use of coal-fired generators with better NO_x controls.

Scenario 9: Lower Natural Gas Prices with Electricity Storage

This scenario mirrors Scenario 8 in all regards except for electricity storage. New electricity storage is permitted in this scenario, with the single option being the hypothetical Battery Technology X. Total U.S. electricity output is represented in Figure 22, apportioned by generation technology.

Figure 22: Total U.S. Electricity Output – Lower Natural Gas Prices with Electricity Storage

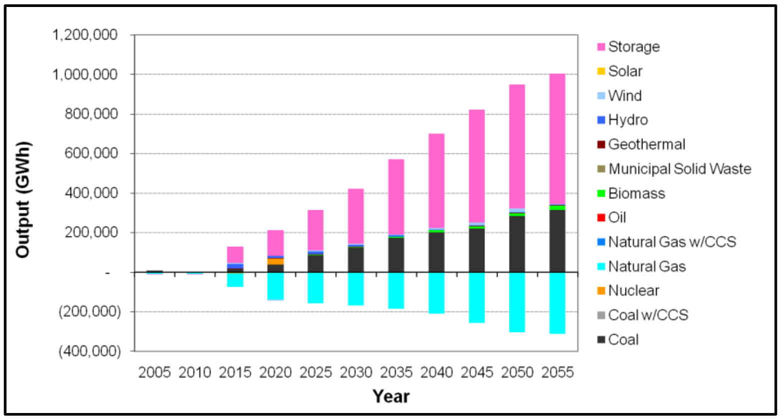


The use of time-shifting electricity storage increases over time, rising to approximately 692,000 GWh annually by 2055. This requires a minimum electricity storage capacity of 277 GW.

The Impact of Time-Shifting Electricity Storage under Lower Natural Gas Prices: Generation Output

In order to illustrate the impact of electricity storage on the use of generation under lower natural gas prices, the generation output from Scenario 8 was subtracted from Scenario 9. The differences in generation output by technology are represented in Figure 23.

Figure 23: Impact of Electricity Storage on Total U.S. Generation Output under Lower Natural Gas Prices

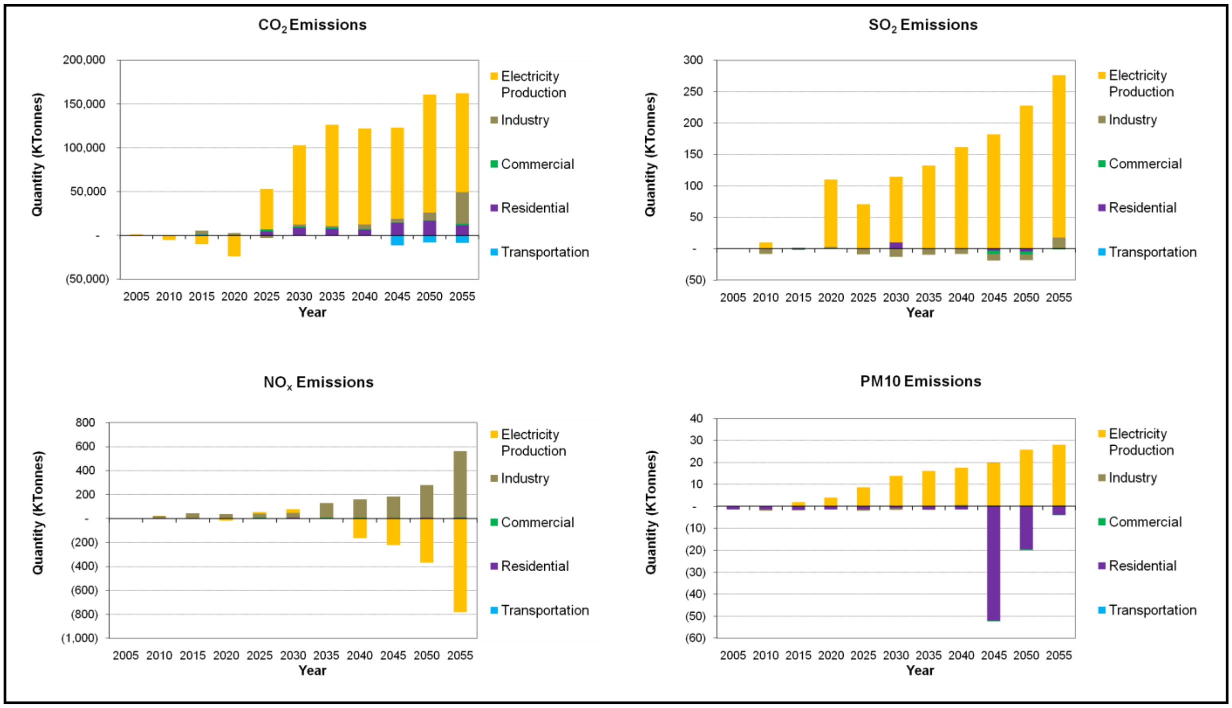


Under lower natural gas prices, the availability of time-shifting electricity storage affects a sustained increase in the use of coal, resulting in a decreased use of natural gas. More specifically, electricity storage allows the greater use of coal-fired generation capacity at night during winter and intermediate seasons, allowing baseload capacity to run at higher levels of efficiency. Decreases in natural gas-fired generation are seen during all daytime periods, with a slight increase seen during nighttime across all seasons.

The Impact of Time-Shifting Electricity Storage under Lower Natural Gas Prices: Emissions

In order to illustrate the impact of electricity storage use on emissions under lower natural gas prices, emissions from Scenario 8 were subtracted from Scenario 9. The differences in emissions by sector are represented in Figure 24.

Figure 24: Impact of Electricity Storage on Total U.S. Emissions under Lower Natural Gas Prices



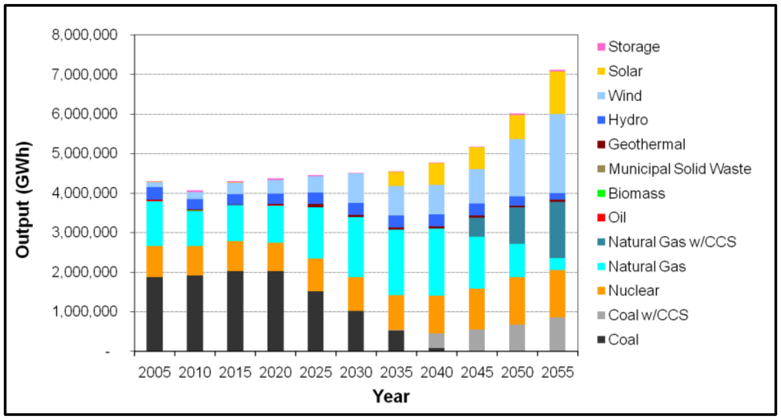
The availability of time-shifting electricity storage leads to totally system CO_2 emission increases of up to 2%. Total system emission of SO_2 increase by up to 6%, and emissions of PM10 increase by up to 2%. These trends are dominated by the increased use of coal-fired generation in the electric power sector. NO_x emissions are relatively unchanged, with decreases in the electric power sector being offset by the increases in the industrial sector. With lower natural gas prices, the industrial sector's natural gas use increases, a trend which contributes largely to the sector's increased NO_x emissions.

3.1.5 Scenario Set #5: Carbon Dioxide (CO_2) Limit

Scenario 10: Carbon Dioxide (CO_2) Limit without Electricity Storage

This scenario mirrors Scenario 1 in all regards except for the inclusion of a limit on the emissions of carbon dioxide (CO_2). The CO_2 emission limit is national in scope, gradually increasing in stringency through 2055. By 2055, the CO_2 limit represents a 42.0% reduction in comparison to 2010 levels, and 45.5% in comparison to 2005 levels. As with Scenario 1, the construction of new electricity storage is not allowed. Total U.S. electricity output is represented in Figure 25, apportioned by generation technology.

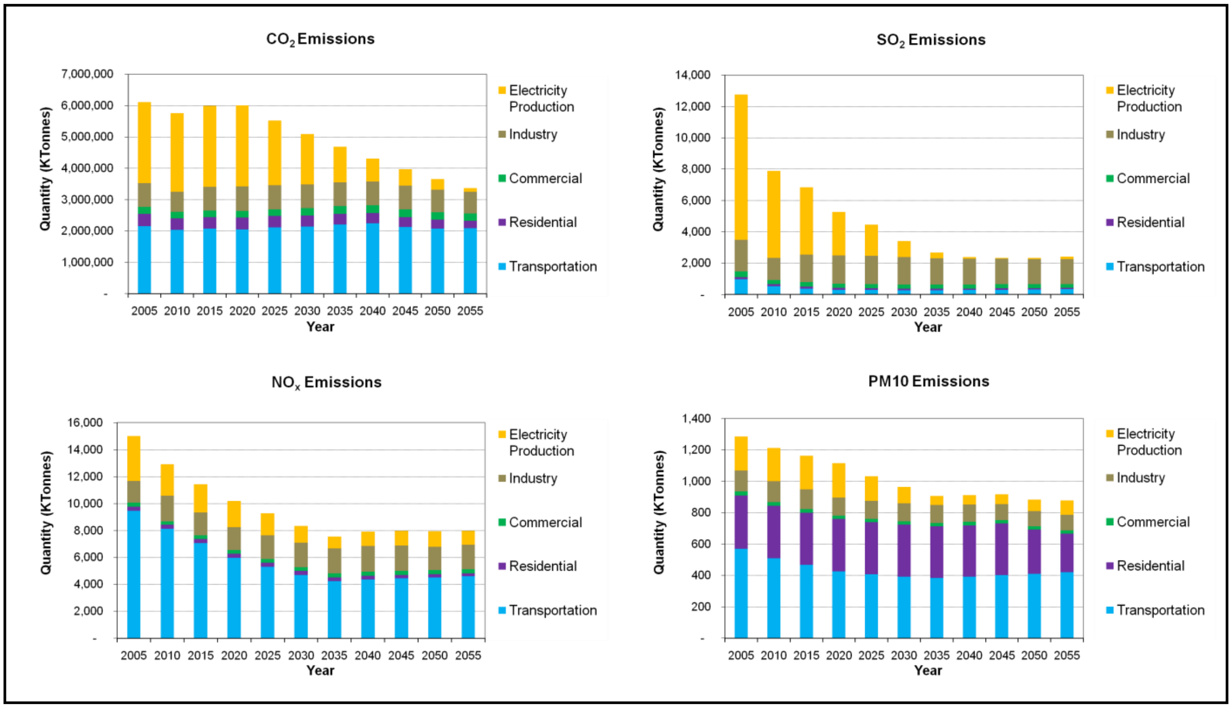
Figure 25: Total U.S. Electricity Output – CO_2 Limit without Electricity Storage



Under the CO_2 limit modeled, the least-cost generation output differs distinctly from previous scenarios. In order to reduce national energy system CO_2 emissions it is necessary to decrease the use of traditional coal and natural gas based generation. As the CO_2 limit tightens, there is an increase in the use of carbon capture and sequestration technologies, both with coal and natural gas based generation. Demand is also increasingly met by generation from wind, solar, and nuclear power.

Total U.S. emissions of CO_2, SO_2, NO_x, and PM10 are represented in Figure 26, apportioned by the emitting sectors.

Figure 26: Impact of a CO_2 Limit on Total U.S. Emissions

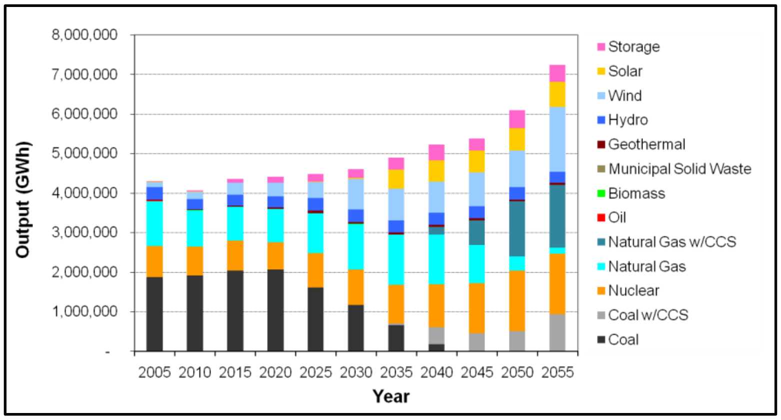


National energy system CO_2 emissions fall throughout the timeframe, ratcheted down to comply with the required CO_2 limit. These CO_2 reductions are seen primarily in the electric power sector, with emissions from other sectors remaining relatively unchanged. SO_2 emissions also fall sharply in the electric power sector, largely attributed to the retirement of all traditional coal-fired generators. Smaller decreases in NO_x and PM10 emissions from the electric power sector are also attributable to the shift from older higher-polluting fossil fuel generation.

Scenario 11: Carbon Dioxide (CO_2) Limit with Electricity Storage

This scenario mirrors Scenario 10 in all regards except for electricity storage. New electricity storage is permitted in this scenario, with the single option being the hypothetical Battery Technology X. Total U.S. electricity output is represented in Figure 27, apportioned by generation technology.

Figure 27: Total U.S. Electricity Output – CO_2 Limit with Electricity Storage

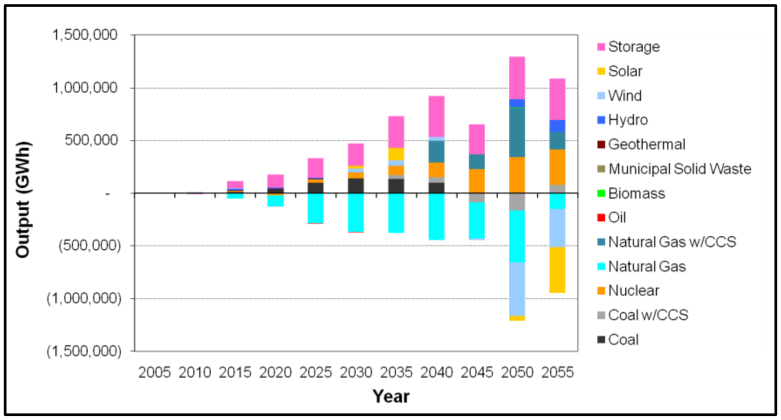


The use of time-shifting electricity generally increases over time, rising to approximately 431,000 GWh annually by 2055. This requires a minimum electricity storage capacity of 172 GW.

The Impact of Time-Shifting Electricity Storage under a CO2 Limit: Generation Output

In order to illustrate the impact of electricity storage on the use of generation under a CO_2 limit, the generation output from Scenario 10 was subtracted from Scenario 11. The differences in generation output by technology are represented in Figure 28.

Figure 28: Impact of Electricity Storage on Total U.S. Generation Output under a CO_2 Limit

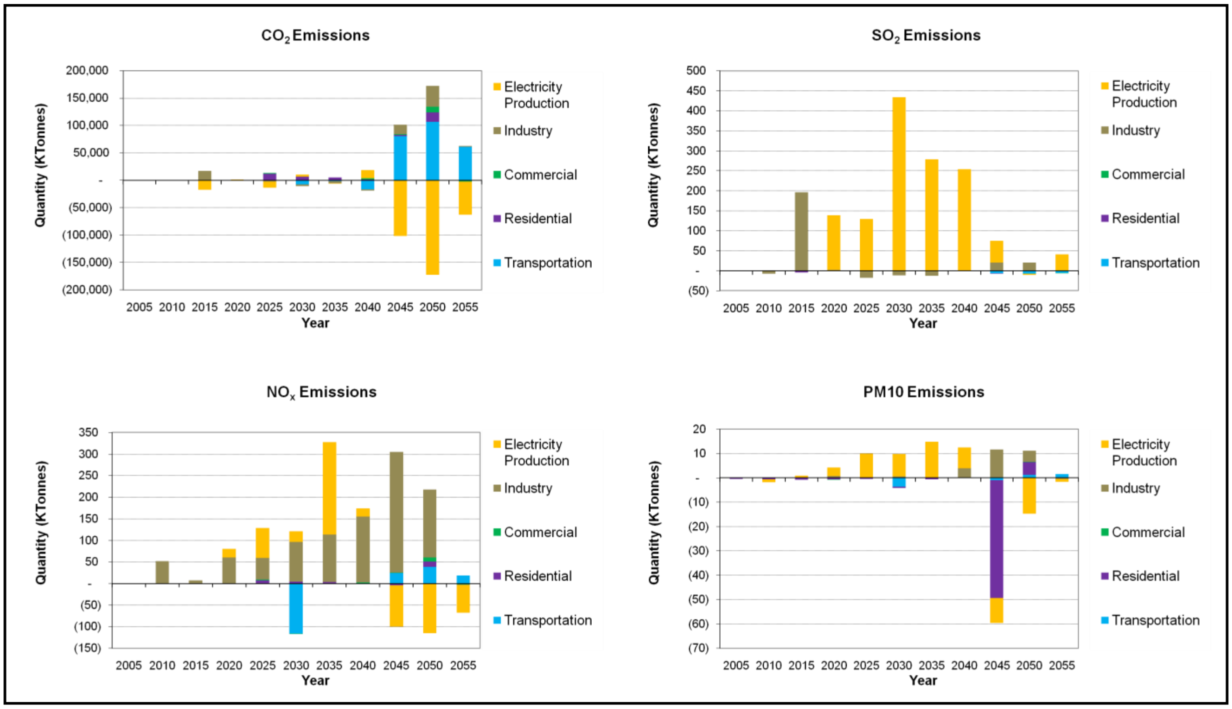


Under the CO_2 limit the availability of time-shifting electricity storage affects a short-term increase in the use of coal, followed by a more sustained increase in the use of nuclear power and natural gas with carbon capture and sequestration (CCS). The increased reliance on these three baseload technologies was offset largely by a decreased use of natural gas generation without CCS. There is also a decreased reliance on wind and solar power in later years. This is possible as nuclear and natural gas plants with CCS are very low emitters of CO_2.

The Impact of Time-Shifting Electricity Storage under a CO2 Limit: Emissions

In order to illustrate the impact of electricity storage use on emissions under a CO_2 limit, emissions from Scenario 10 were subtracted from Scenario 11. The differences in emissions by sector are represented in Figure 29.

Figure 29: Impact of Electricity Storage on Total U.S. Emissions under a CO_2 Limit



The availability of time-shifting electricity storage under the modeled CO_2 limit leads to no net change in CO_2 emissions. CO_2 emissions are reduced within the electric power sector in later years as low emitting baseload technologies replace natural gas combustion without CCS. However, in a least cost solution, CO_2 emissions reductions in the electric power sector may be offset by higher emissions in other sectors. Increases in transportation sector emissions are correlated with the reduced use of electric vehicles and the greater use of e10 (10% ethanol) and low-sulfur diesel fuel.

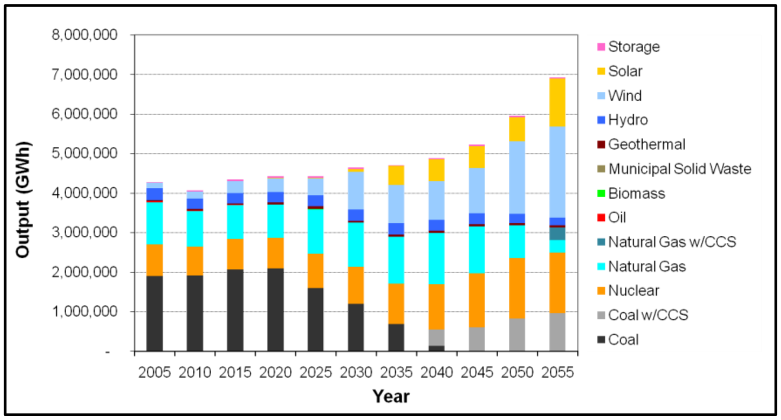
In contrast to trends in CO_2 emissions, the availability of time-shifting electricity storage leads to increases in the emissions of SO_2, NO_x, and possibly PM10. Total system emissions of SO_2 and NO_x both increase by up to 12%. Increases in SO_2 appear to be driven largely by the increasing use of coal-fired generation between 2020 and 2040. This increased coal use also may be responsible for increased PM10 emissions during the same time period. System trends in NO_x emissions are largely attributable to the industrial sector which uses less electricity, instead increasing its combustion of natural gas.

3.1.6 Scenario Set #6: Carbon Dioxide (CO_2) Limit and Higher Natural Gas Prices

Scenario 12: Carbon Dioxide (CO_2) Limit and Higher Natural Gas Prices without Electricity Storage

This scenario builds upon Scenario 10 which imposes a national CO_2 limit and does not permit the construction of new electricity storage. In this scenario, the price of natural gas is increased by 100% beginning in the 2015 time period. Total U.S. electricity output is represented in Figure 30, apportioned by generation technology.

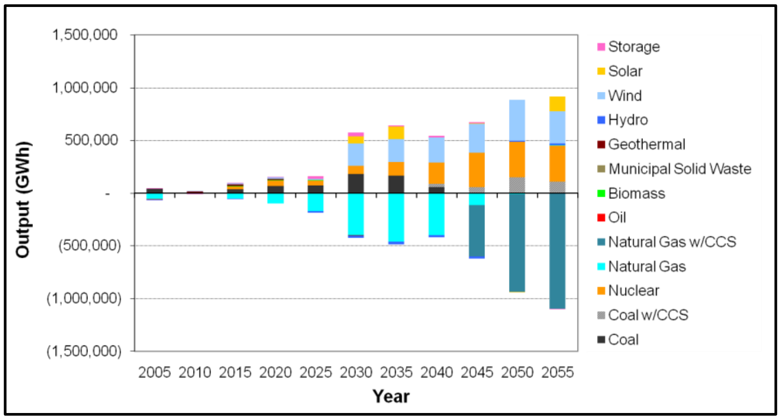
Figure 30: Total U.S. Electricity Output – CO_2 Limit and Higher Natural Gas Prices without Electricity Storage



The Impact of a CO2 Limit and Higher Natural Gas Prices: Generation Output

In order to illustrate the impact of a CO_2 limit and higher natural gas prices on generation output, the generation from Scenario 10 was subtracted from Scenario 12. The differences in generation output by technology are represented in Figure 31.

Figure 31: Impact of a CO_2 Limit and Higher Natural Gas Prices on Total U.S. Generation Output

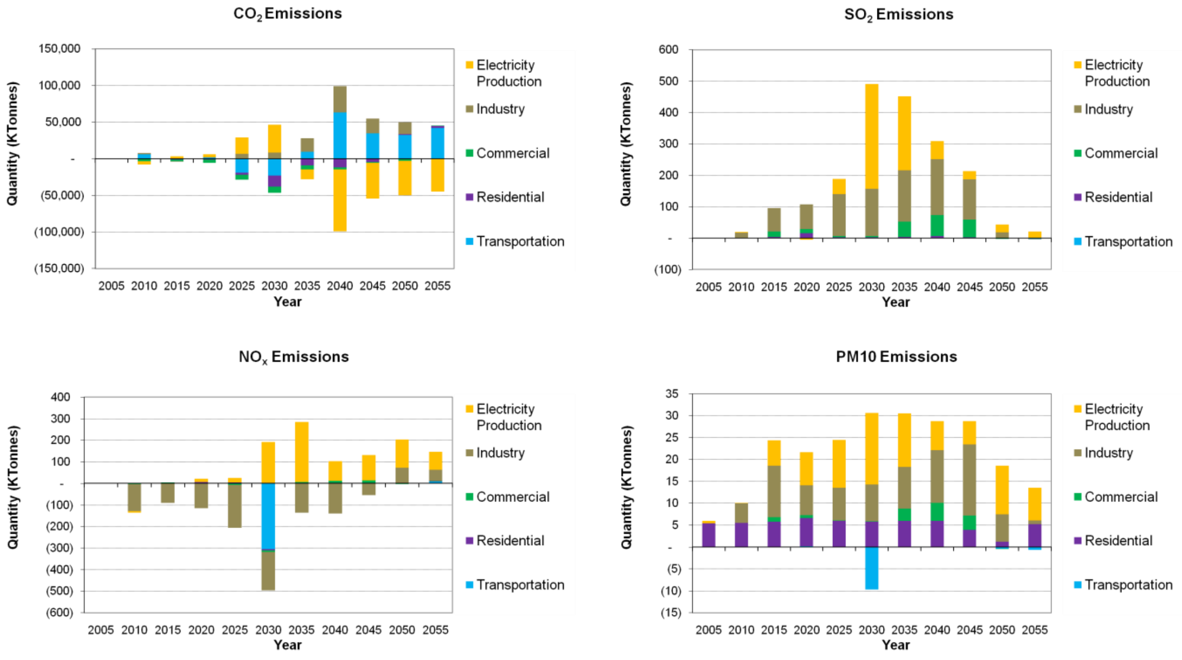


Under the modeled CO_2 limit and higher natural gas prices there is a short-term increase in the use of coal, followed by a more sustained increase in the use of nuclear and wind power. This is offset by a sustained decrease in the use of natural gas, both with and without CCS.

The Impact of a CO2 Limit and Higher Natural Gas Prices: Emissions

In order to illustrate the impact of a CO_2 limit and higher natural gas prices on emissions, emissions from Scenario 10 were subtracted from Scenario 12. The differences in emission by sector are represented in Figure 32.

Figure 32: Impact of a CO_2 Limit and Higher Natural Gas Prices on Total U.S. Emissions

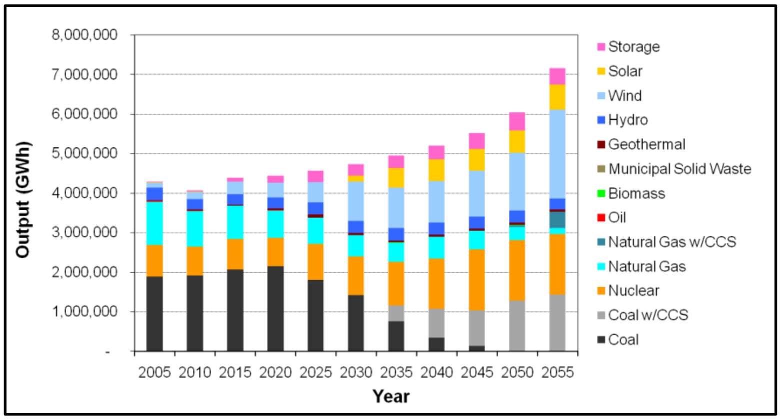


Under the CO_2 limit, higher natural gas prices cause no net change in CO_2 emissions, with reductions from the electric power sector offset by increases from other sectors. However, higher natural gas prices result in fuel switching from natural gas to coal in the electric power and industrial sectors. This results in higher emissions of SO_2 and PM10.

Scenario 13: Carbon Dioxide (CO_2) Limit and Higher Natural Gas Prices with Electricity Storage

This scenario mirrors Scenario 12 in all regards except for electricity storage. New electricity storage is permitted in this scenario, with the single option being the hypothetical Battery Technology X. Total U.S. electricity output is represented in Figure 33, apportioned by generation technology.

Figure 33: Total U.S. Electricity Output – CO_2 Limit and Higher Natural Gas Prices with Electricity Storage

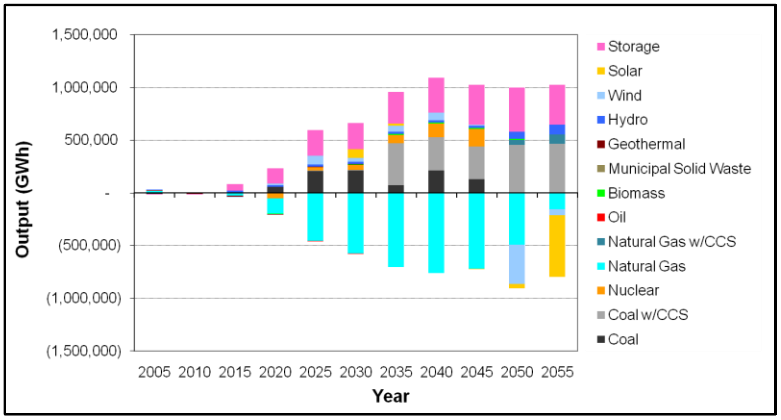


The use of time-shifting electricity generally increases over time, rising to approximately 417,000 GWh annually by 2055. This requires a minimum electricity storage capacity of 167 GW.

The Impact of Time-Shifting Electricity Storage under a CO2 Limit and Higher Natural Gas Prices: Generation Output

In order to illustrate the impact of electricity storage on the use of generation under a CO_2 limit and higher natural gas prices, the generation output from Scenario 12 was subtracted from Scenario 13. The differences in generation output by technology are represented in Figure 34.

Figure 34: Impact of Electricity Storage on Total U.S. Generation Output under a CO_2 Limit and Higher Natural Gas Prices

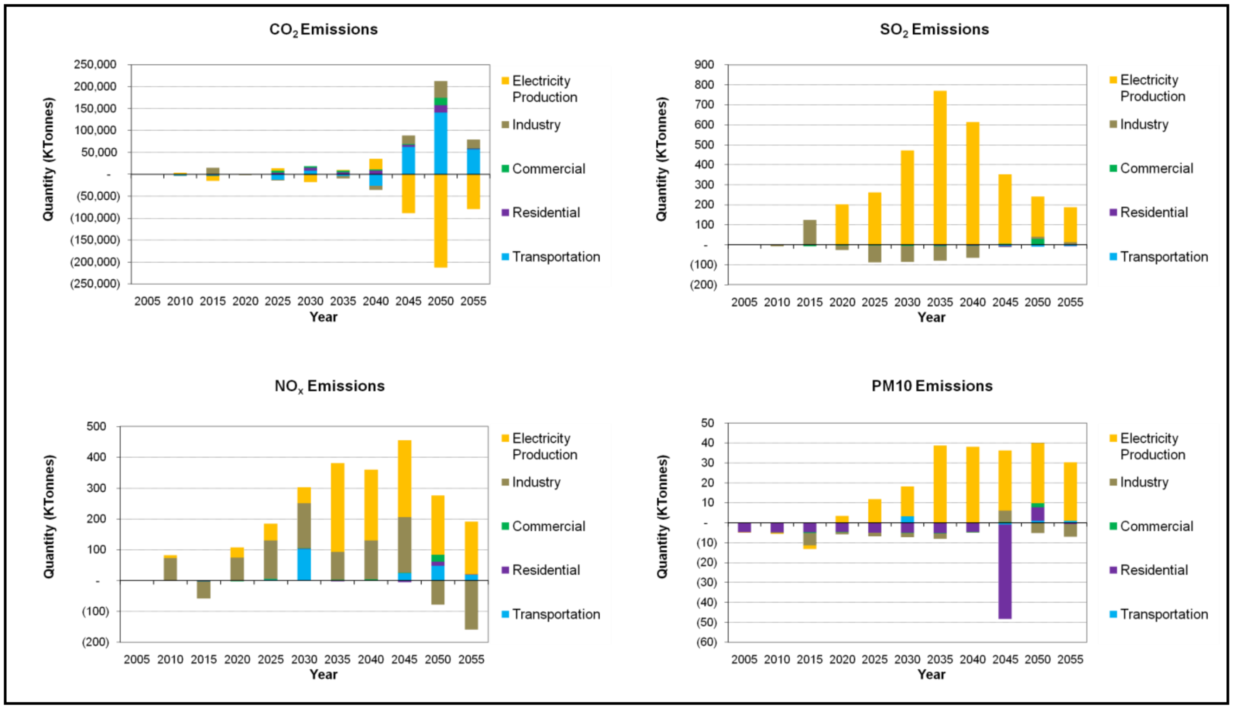


Under the modeled CO_2 limit and higher natural gas prices, the availability of time-shifting electricity storage affects a sustained increase in the use of coal-fired generation. Output from traditional coal-fired generators increases from 2020 to 2045. This is followed by larger increases in output from coal-fired generators with CCS from 2035 to 2055. The increased use of coal primarily displaces the use of natural gas generation without CCS. In later years output from wind and solar plants are also displaced by coal with CCS. Under these modeling assumptions, it appears that baseload coal with CCS provides a less costly alternative than investment in renewable power.

The Impact of Time-Shifting Electricity Storage under a CO2 Limit and Higher Natural Gas Prices: Emissions

In order to illustrate the impact of electricity storage use on generation under a CO_2 limit and higher natural gas prices, emissions from Scenario 12 were subtracted from Scenario 13. The differences in emissions by sector are represented in Figure 35.

Figure 35: Impact of Electricity Storage on Total U.S. Emissions under a CO_2 Limit and Higher Natural Gas Prices



The availability of time-shifting electricity storage under the modeled CO_2 limit and higher natural gas prices leads to increases in SO_2, NO_x, and PM10. As in scenario 11, there was no net change in CO_2 emissions. CO_2 emissions reductions in the electric power sector are offset by increases from other sectors. Total system emissions of SO_2 rise by up to 23%, with emission of PM10 increasing by up to 3%.

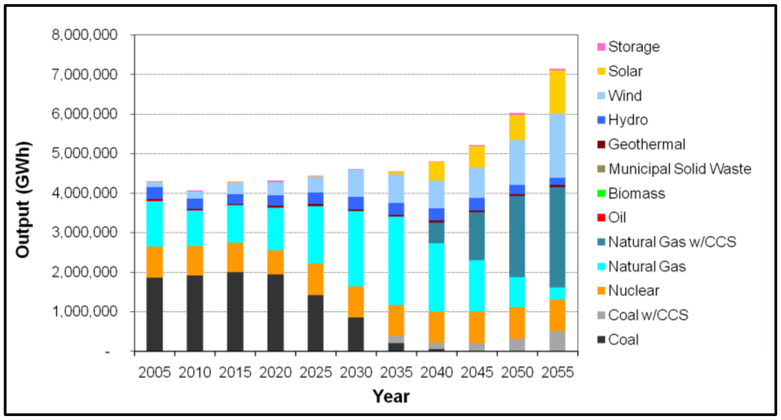
These increases in SO_2 and PM10 are driven largely by an increase in the use of coal-fired generation with CCS. Total system emissions of NO_x increase by up to 5%. The increases in NO_x emissions within the electric power sector are also likely due to the increased coal usage.

3.1.7 Scenario Set #7: Carbon Dioxide (CO_2) Limit and Lower Natural Gas Prices

Scenario 14: Carbon Dioxide (CO_2) Limit and Lower Natural Gas Prices without Electricity Storage

This scenario builds upon Scenario 10 which imposes a national CO_2 limit and does not permit the construction of new electricity storage. In this scenario, the price of natural gas is decreased by 50% beginning in the 2015 time period. Total U.S. electricity output is represented in Figure 36, apportioned by generation technology.

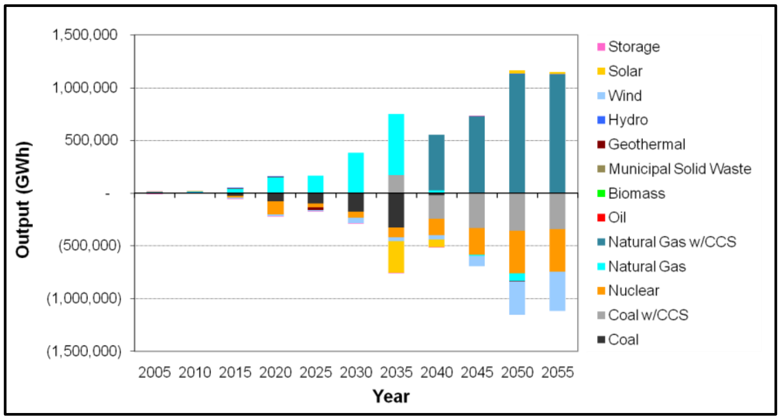
Figure 36: Total U.S. Electricity Output – CO_2 Limit and Lower Natural Gas Prices without Electricity Storage



The Impact of a CO2 Limit and Lower Natural Gas Prices: Generation Output

In order to illustrate the impact of a CO_2 limit and lower natural gas prices on generation, the generation output from Scenario 10 was subtracted from Scenario 14. The differences in generation output by technology are represented in Figure 37.

Figure 37: Impact of a CO_2 Limit and Lower Natural Gas Prices on Total U.S. Generation Output

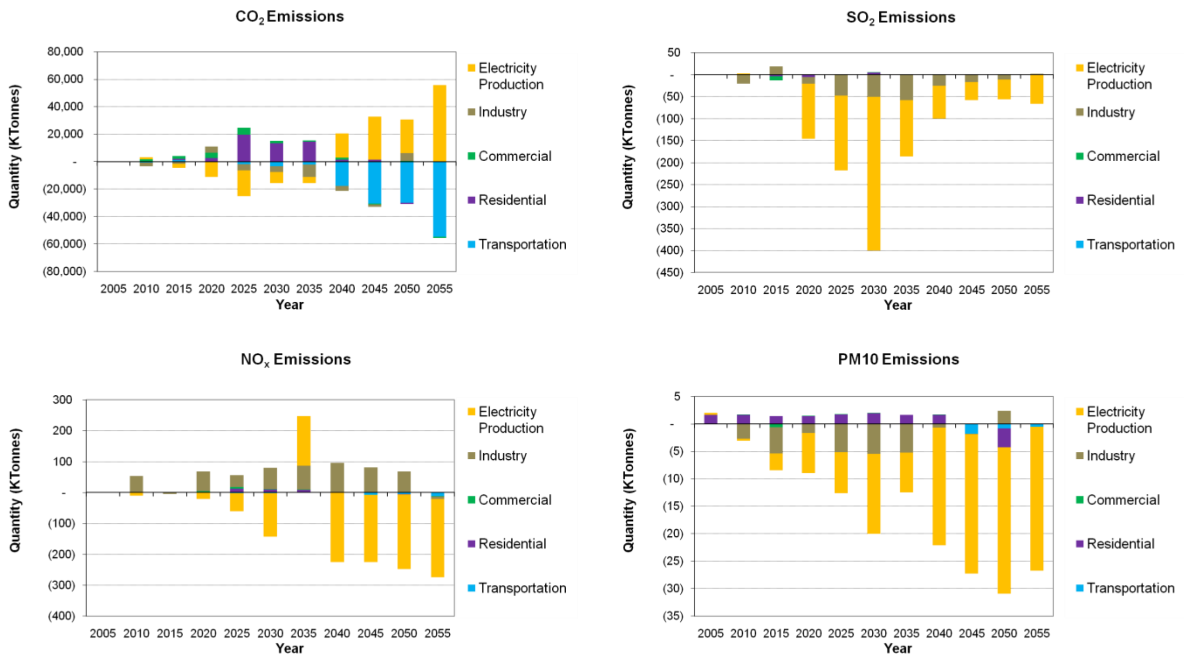


Under the modeled CO_2 limit and lower natural gas prices there is a short-term increase in the use of natural gas generation, following by an increase in the use of natural gas with CCS. This offsets declining generation output from coal-fired generators both with and without CCS. There is also decreased output from nuclear, wind, and solar power based generation.

The Impact of a CO2 Limit and Lower Natural Gas Prices: Emissions

In order to illustrate the impact of a CO_2 limit and lower natural gas prices on emissions, emissions from Scenario 10 were subtracted from Scenario 14. The differences in emission by sector are represented in Figure 38.

Figure 38: Impact of a CO_2 Limit and Lower Natural Gas Prices on Total U.S. Emissions

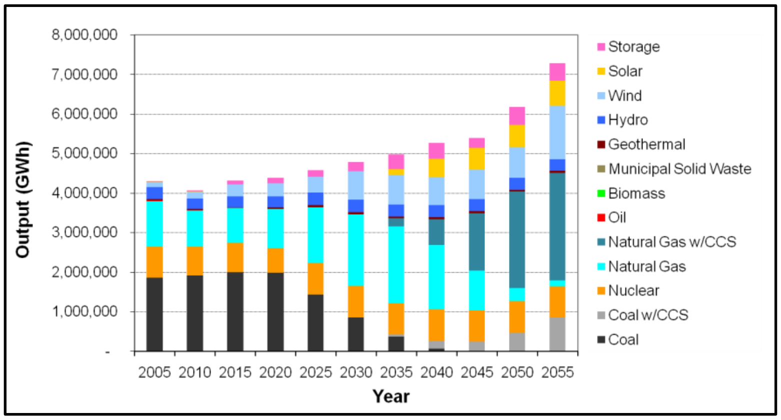


Under the CO_2 limit, lower natural gas prices cause no net change in CO_2 emissions. However, lower natural gas prices result in lower SO_2, NO_x, and PM10 emissions. These declining emissions are largely driven by reductions in the use of coal-fired generation. There is also fuel switching in the industrial sector from coal to natural gas, driving the changes in the sector's emissions.

Scenario 15: Carbon Dioxide (CO_2) Limit and Lower Natural Gas Prices with Electricity Storage

This scenario mirrors Scenario 14 in all regards except for electricity storage. New electricity storage is permitted in this scenario, with the single option being the hypothetical Battery Technology X. The differences in generation output by technology are represented in Figure 39.

Figure 39: Total U.S. Electricity Output – CO_2 Limit and Lower Natural Gas Prices with Electricity Storage

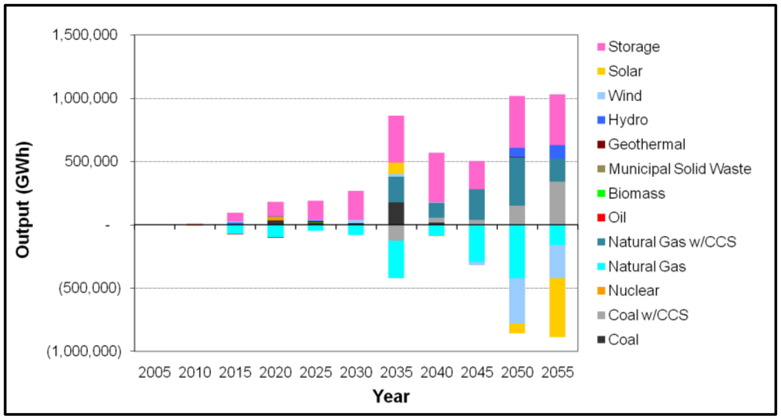


The use of time-shifting electricity generally increases over time, rising to approximately 440,000 GWh annually by 2055. This requires a minimum electricity storage capacity of 176 GW.

<u>The Impact of Time-Shifting Electricity Storage under a CO2 Limit and Lower Natural Gas Prices: Generation Output</u>

In order to illustrate the impact of electricity storage on the use of generation under a CO_2 limit and lower natural gas prices, the generation output from Scenario 14 was subtracted from Scenario 15. The differences in generation output by technology are represented in Figure 40.

Figure 40: Impact of Electricity Storage on Total U.S. Generation Output under a CO_2 Limit and Lower Natural Gas Prices

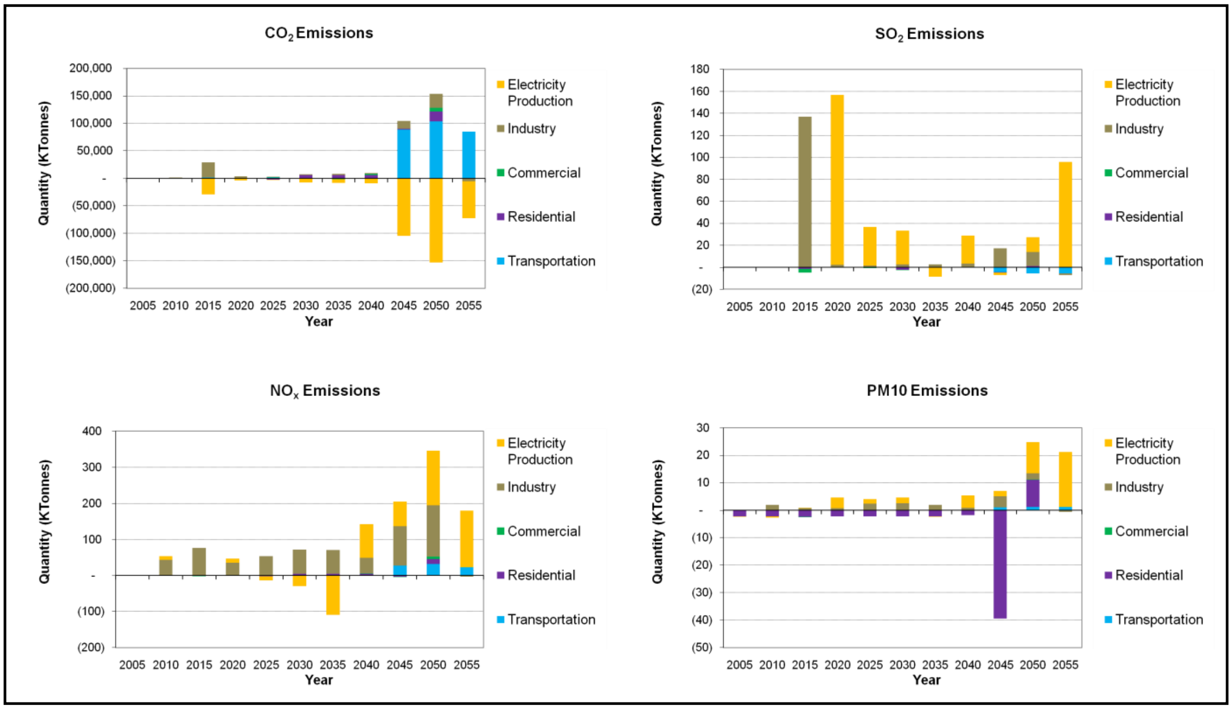


Under the modeled CO_2 limit and higher natural gas prices, the availability of time-shifting electricity storage affects a sustained increase in the use of technologies with CCS. Electricity output from natural gas-fired generators with CCS increases from 2035 to 2055. This is followed by increases in output from coal-fired generation with CCS from 2040 to 2055. Generation from natural gas plants without CCS declines over the entire timeframe. As in Scenario 14, output from wind and solar plants declines in later years. Under these modeling assumptions, it appears that baseload technologies with CCS provide a less costly alternative than investment in renewable power.

The Impact of Time-Shifting Electricity Storage under a CO2 Limit and Lower Natural Gas Prices: Emissions

In order to illustrate the impact of electricity storage use on generation under a CO_2 limit and lower natural gas prices, emissions from Scenario 14 were subtracted from Scenario 15. The differences in emissions by sector are represented in Figure 41.

Figure 41: Impact of Electricity Storage on Total U.S. Emissions under a CO_2 Limit and Lower Natural Gas Prices



The availability of time-shifting electricity storage under the modeled CO_2 limit and higher natural gas prices leads to increases in SO_2 and NO_x emissions. As in earlier scenarios, there was no net change in CO_2 emissions, with CO_2 emissions reductions in the electric power sector being offset by increases in other sectors. Total system emissions of SO_2 increase by up to 1%. This increase in SO_2 emissions is largely driven by an increase in the combustion of coal in the electric power sector. Total system emissions of NO_X increase by up to 4%. The increase in NO_x emissions from the industrial sector is largely attributable to an increase in its combustion of natural gas, biomass, and coal, offsetting a declining use of electricity.

4 Discussion and Conclusions

4.1 Trends in the Effects of Time-Shifting Electricity Storage

The seven scenario sets represent distinctly different possible futures for the U.S. electric power sector and broader energy system. Varying future conditions impact the composition and utilization of the future electric power generation mix, driving trends in its emissions. When the impacts of time-shifting electricity storage are examined, four related trends emerge.

Trend #1: Increased Baseload Generation, Decreased Daytime Load-Following Generation
First, and most prominently, the introduction of time-shifting electricity storage technologies enable the greater utilization of baseload generation. This is the case in all seven scenario sets. The time-shifting of baseload generation from nighttime to periods of higher demand in the day provides two benefits. First, storage technologies allow low cost nighttime baseload generation to meet demand during the daytime. Second, operating baseload plants at higher levels during the night allows the same plants to maintain high levels of operation during the daytime, providing additional low cost electricity during periods of high demand. It is important to note that the availability of time-shifting electricity storage does not typically prompt the building of new baseload capacity. Instead, it is underutilized baseload generation assets which are more highly utilized, especially during winter and intermediate seasons when such plants are not already operating at full capacity.

In most scenario sets the increase in baseload generation is provided by coal-fired plants without CCS. When coal-fired generation output increases it causes emissions to rise as well. In all scenarios the increased use of coal-fired generation results in higher emissions of SO_2 in both the electric power sector and total energy system. Similarly, in most scenarios, increased combustion of coal for electric power increases sector and total system emissions of PM10. When there is no CO_2 limit, the increased use of coal-fired generation also results in higher electric power sector and total system emissions of CO_2. Furthermore, it is important to consider the vintage of coal fired-plants which are being greater utilized. If electricity storage disproportionately enables the greater use of old coal-fired plants which are less efficient, the resulting emissions may increase more than is found in this study’s results.

The role of storage is similar under the modeled CO_2 limit, enabling the greater use of baseload technologies. However, the CO_2 limiting scenarios forced significant transformations of the generation mix, with nuclear plants and CCS equipped technologies providing baseload power, rather than traditional coal-fired generation. Consequently, the impact of the greater utilization of these baseload technologies differed from scenarios without the CO_2 limit. When the CO_2 limit is modeled, time-shifting electricity storage enables lower CO_2 emissions from the electric power sector. However, given the nature of a national CO_2 emission limit, other sectors increase their emissions of CO_2 until the maximum emission level is reached.

In all of these scenarios, with and without a CO_2 limit, the increased use of baseload generation largely offsets load-following natural gas-fired generators. This is true even when the price of natural gas is modeled to fall by 50%. Electric power sector emissions increased largely due to the displacement of natural gas-fired generators which have lower emission rates than coal-fired generators. However, the reduction in the daytime use of natural gas-fired generation does not fully reflect the commodity's future use.

Trend #2: Increased Nighttime Utilization of Natural Gas-Fired Generation

In many scenarios the availability of electricity storage results in increasing use of natural-gas fired electric power generators during the night. This nighttime increase in the use of natural gas is much smaller than the decreased daytime use by load-following natural gas plants. Nonetheless, natural gas-fired generation is greater utilized overnight when time-shifting electricity storage is available. This trend is most pronounced in scenarios without a CO_2 limit, as the presence of such a limit leads to less natural gas fired-generation without CCS. The impact of increasing natural gas-fired generation at night on emissions is difficult to determine. This depends upon the technology which this natural gas-fired generation displaces, which was not discernable.

Trend #3: Fuel Switching to Natural Gas in the Industrial Sector

The third trend arises in tandem with the two. As the availability of electricity storage leads to decreasing natural gas use in the electric power sector, the industrial sector increases its own use of natural gas. This holds true in all seven scenario set conditions. This reflects the fuel switching availability of some industrial processes, and the lower total-system costs achieved by this fuel switching. In most cases, increasing natural gas use in the industrial sector displaces either coal or electricity. The increased combustion of natural gas in the industrial sector leads to increases in the sector's NO_x emissions in all seven scenario sets. Furthermore, in six of these scenario sets the increased NO_x emission from the industrial sector led to overall total system NO_x emission increases.

Trend #4: No Increase in Net Renewable Energy Output

The availability and use of time-shifting electricity storage did not increase net renewable generation output in any of the scenarios examined. Instead, when electricity storage affected the use of renewable generation, one of two patterns is seen.

First, as is the case with a stricter renewable portfolio standard (RPS), the availability of time-shifting electricity storage enables an increase in nighttime wind generation which reduces the need for daytime solar power generation. By time-shifting wind power to periods of higher daytime demand, the RPS is satisfied at a lower systems cost. The emission impact of this trend was not examined, but it is likely negligible given that the operation of wind and solar power plants do not emit any of the four pollutants examined in this study.

A second pattern is also seen in the scenario results with a CO_2 limit wherein renewable generation decreases. In all three scenario sets with a CO_2 limit, the increased use of baseload generation displaced generation otherwise provided by wind and solar power. Driven by a CO_2 limit, the nuclear and CCS equipped fossil fuel generation meet demand at a lower total system cost. The emission impacts of switching from wind and solar power to baseload generation was not isolated from overall scenario emission trends. However, it is clear that coal and natural gas plants with CCS emit higher levels of all four examined pollutants than wind and solar plants. The specific emission rates of these CCS equipped generators will depend on their pollution controls.

4.2 Variation in the Total Use of Electricity Storage

While the impacts of electricity storage vary by future conditions, the maximum amount of electricity time-shifted in each scenario does not differ drastically. In the scenarios which were permitted to build the low cost Battery Technology X, the smallest maximum amount of electricity time-shifted in a scenario is approximately 417,000 GWh. In contrast, the largest amount of electricity time-shifted is roughly 692,000 GWh. These values should not be viewed as predictions, but rather as what society should do to maximize societal surplus under the modeling assumptions.

Interestingly, when reviewing the scenarios there is one clear trend in the amount of electricity time-shifted. There is a distinct difference in the amount of storage use depending upon the existence of the national CO_2 limit on energy sector emissions. Under base case conditions with Battery Technology X, approximately 550,000 GWh of storage is used by 2055. This increases to an average of 592,250 GWh for scenarios which do not include a CO_2 limit. In contrast, scenarios which include a CO_2 limit time-shift an average of 429,333 GWh, 27% less electricity. The reason for this disparity in the use of time-shifting electricity storage is not clear. This trend may be due to differences in the composition of electric power sector generation fleets. Alternatively, this may be due to the CO_2 limited scenarios having smaller swings in daily electricity prices, reducing the value of time-shifting electricity storage. This may also be caused by the CO_2 limit constraining the use of fossil fuel-fired generation technologies to charge electricity storage.

4.3 Scale of Electricity Storage Impacts on Emissions

As detailed in the results section, increases in emissions due to the use of electricity storage vary by scenario. Most emission increases are largely caused by an increasing use of coal in the electric power sector, and the increasing use of natural gas in the industrial sector. In order to provide perspective for these emission increases, it is useful to review the variation of maximum emission increases amongst the scenarios.

Under scenarios without a CO_2 limit, the maximum increases in total system CO_2 emissions range from 1% to 2.5%. Total system SO_2 emissions vary to a greater degree with maximum increase in emissions ranging from 2% to 6%. The total system emissions of NO_x vary similarly, with three scenarios having maximum increases in emissions ranging from 2% to 5%, and one scenario reflecting no change. Total system emission of PM10 exhibit a similar trend, with three scenarios having maximum increases in emissions ranging from 2% to 5%, and one scenario reflecting no change.

Changes in the maximum increases to total system emissions reflected different trends in scenarios with the CO_2 limit modeled. Restrained by the CO_2 limit, total system emissions of CO_2 do not change. There was however significant variation in other pollutants. Maximum increases in total system SO_2 emissions range from 1% to 23%. The total system emissions of NO_x vary to a lesser degree, with maximum increases in emissions ranging from 4% to 12%. Changes in the emissions of PM10 were minimal, with only one scenario reflecting an increase in emissions of up to 3%.

4.4 Study Limitations & Future Research Needs

This study relied upon a single energy system model, and consequently, reflects its limitations. The impacts of time-shifting electricity storage should be examined carefully in light of MARKAL's limitations.

First, time-shifting electricity storage is found to enable the greater use of baseload generation. Baseload generation technologies in MARKAL are represented as being incapable of varying their generation within a day. Their generation may vary by season, with each year in a five-year period being identical. This reflects nuclear generation well, and coal-fired generation to a lesser degree. Coal-fired generation is capable of slowly ramping output up or down, a capability not captured in MARKAL. It is possible that in the absence of this constraint, MARKAL would have arrived at a least cost solution which utilized less time-shifting electricity storage. Representing coal-fired generation in similar analyses with load-following capabilities would likely lead to a better understanding of benefits which electricity storage provide to coal-fired generators.

As noted earlier in this report, MARKAL is not a dispatch model. Rather, MARKAL is a least-cost optimization model which reflects what society should do if the overall goal is to minimize the cost of supplying and using energy. Whereas MARKAL's solution finds that electricity storage benefits baseload generation at night, this may not fully account for electric power market operations. Many scenarios did not result in a large penetration of wind power capacity. However, if in the future such capacity exists, it will have a marginal cost of generation that is lower than baseload coal-fired generators. Consequently, in times of high wind power generation, coal-fired generation may be displaced. A dispatch model is necessary to better understand the conditions when time-shifting electricity storage may benefit wind power rather than baseload generation.

There are also scenario results which warrant further examination, as they may indicate limitations in the MARKAL runs. More specifically, some scenarios with electricity storage produce less electricity than their counterpart scenarios without electricity storage. It may be that less electricity is necessary as other sectors increase their consumption of natural gas. Alternatively, the use of electricity storage may require less electricity trade between the nine regions, transactions which incur transmission efficiency losses in MARKAL. Further research could help determine the relative contributions of these two factors towards the decreased use of electricity in some scenarios.

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