Technical and Economic Analysis of Various Power Generation Resources Coupled with CAES Systems

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FINAL REPORT

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NETL Contact:

Ryan Egidi

Technical Project Monitor

National Energy Technology Laboratory

www.netl.doe.gov

Prepared by:

Energy Sector Planning and Analysis (ESPA)

Jovan Ilic
Booz Allen Hamilton, Inc.

Marija Prica
Booz Allen Hamilton, Inc.

Shawn Rabiei
Booz Allen Hamilton, Inc.

Jesse Goellner
Booz Allen Hamilton, Inc.

David Wilson
Booz Allen Hamilton, Inc.

Chungyan Shih
Booz Allen Hamilton, Inc.

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Acronyms and Abbreviations

CAES	Compressed Air Energy Storage
GIS	Geographic Information System
ISO	Independent system operator
kWh	Kilowatt-hour
MW	Megawatts
MWh	Megawatt-hour
MMBtu/MWh	Million British thermal units per megawatt-hour
NETL	National Energy Technology Laboratory
NPV	Net Present Value
NYSEG	New York State Electric and Gas
NYSERDA	New York State Energy Research and Development Authority
PJM	PJM Interconnection, LLC
RTO	Regional transmission organization
$/MWh	Dollars per megawatt hour
$/MMBtu	Dollars per million British thermal units

Executive Summary

Compressed air energy storage (CAES) is an energy storage application with the potential to supplement intermittent power sources, such as wind and solar generators, and to enable better load following for more constant power sources such as coal combustion generators. Electricity generated during low-demand periods can be stored by using a compressor to pressurize and store air in a containment space. During times of higher demand, the compressed air can be used to drive a turbine to generate electricity, which can be delivered back into the grid.

To better understand CAES's potential to provide practical energy storage for intermittent and constant-output power sources in the U.S., we analyzed three practical considerations important to CAES planning and operations:

1. Siting decisions
2. Development of optimal charge-discharge strategies
3. Design and operating factors that affect efficiency

These three analyses form the major sections of this study.

Siting Decisions: To identify geographic regions that might be good candidates for hybrid CAES/wind generation, we applied the methodology used by New York State Electric and Gas (NYSERDA, 2009) and extended it to analyze the entire land area of the continental United States. The infrastructure factors we used as primary criteria were:

- Proximity to natural gas lines, needed for reheating air prior to expansion in a turbine
- Proximity to high-voltage transmission for delivery of power to and from the grid
- Proximity to a market for wholesale electric power, in the form of an independent system operator (ISO) or regional transmission organization (RTO).

For sites meeting these criteria, we examined whether they had suitable geology and wind resources. For sites where salt-solution mining would likely be used, we further examined the availability of water and brine disposal sites.

Using geographic information system (GIS) methods, we identified regions within the U.S. that met these requirements. Suitable sites included areas in the upper Midwest, Great Plains states, Texas coast, Great Lakes coast, and upper Appalachian states. We also present detailed results of the analysis for the state of West Virginia.

Development of optimal charge-discharge strategies*:* To get practical insight into how a profit-maximizing CAES operating strategy might be developed, we created a simple dynamic programming model that takes forecasts of electricity prices, wind resources, coal generation costs, and natural gas prices as inputs. The model provides a profit-optimizing strategy of air reservoir charge and discharge, using a range of alternatives for site and grid power purchases and sales. As a part of this forward-looking approach, the model also takes into account key

technical parameters including storage power capacity, energy capacity, ramp-up and ramp-down rates, and start-up and shut-down times.

We used the model to derive profit-maximizing operating strategies for hypothetical CAES/wind, CAES/wind/coal and CAES/wind/natural gas plants. While the actual control strategies and profit levels will depend on the technical and economic parameters of the particular installation, our approach demonstrates that profit-maximizing control involves complex interactions among current and forecast prices, demand, and supply, rather than a pre-scheduled charge-discharge schedule based upon heuristics.

To demonstrate the approach in detail, we developed profit estimates for the CAES operations alone, generation systems alone, and combined CAES/generation systems. We derived separate profit estimates using two different sets of CAES technical data, corresponding to the existing plants in Huntorf, Germany, and McIntosh, Alabama. For configurations that included coal generation, we developed separate profit estimates using a lower ($10/MWh) and higher ($25/MWh) average cost of generation. Summary of the result is given in Exhibit ES – 1.

Exhibit ES – 1 Optimal Weekly Profits for Different Plant Configurations

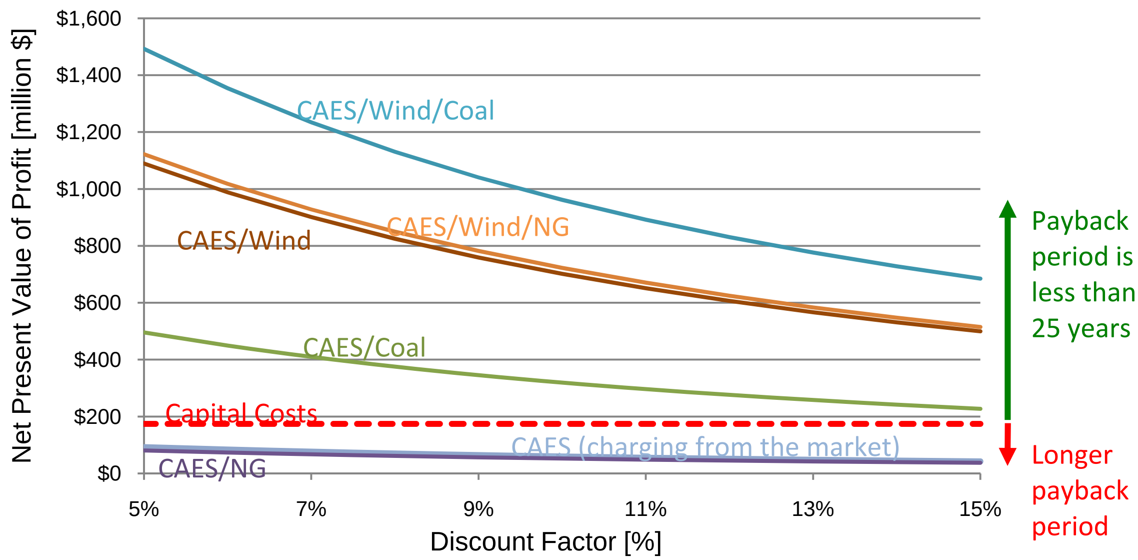
Plant configuration		Huntorf weekly profit [$K]	McIntosh weekly profit [$K]
CAES only		$40	$82
Wind only		$161	$161
Coal only	Coal generation cost $10/MWh	$277	$277
	Coal generation cost $25/MWh	$59	$59
Natural Gas only		$5	$5
CAES/Wind		$201	$243
CAES/Coal	Coal generation cost $10/MWh	$317	$358
	Coal generation cost $25/MWh	$ 94	$139
CAES/Natural Gas		$35	$84
CAES/Wind/Coal	Coal generation cost $10/MWh	$478	$519
	Coal generation cost $25/MWh	$258	$302
CAES/Wind/Natural Gas		$203	$248

The hypothetical hybrid CAES/wind plant showed a significant increase in weekly operating profit over hypothetical plants operating with wind alone or CAES alone. That is, the hybrid system can capture the profits that the CAES system would have generated operating with grid power, while using locally generated renewable wind power. The results for the other hybrid systems — CAES/coal systems, CAES/Gas systems, CAES/Wind/Coal, and CAES/Wind/Gas— showed a similar increase in profitability for the hybrid plant compared to each individual system operating by itself.

Our demonstration model assumed that the CAES would only be charged by the on-site generator and not by the grid in times of low prices. We included this constraint because we were studying the use of CAES to make wind power more dispatchable, and coal power more load-following. This constraint kept the hybrid plants' profits at or below the sum of the separate wind and CAES plant profits. If this constraint were lifted, we would anticipate synergies that would make the profit at or higher than the sum of the two plants operating separately.

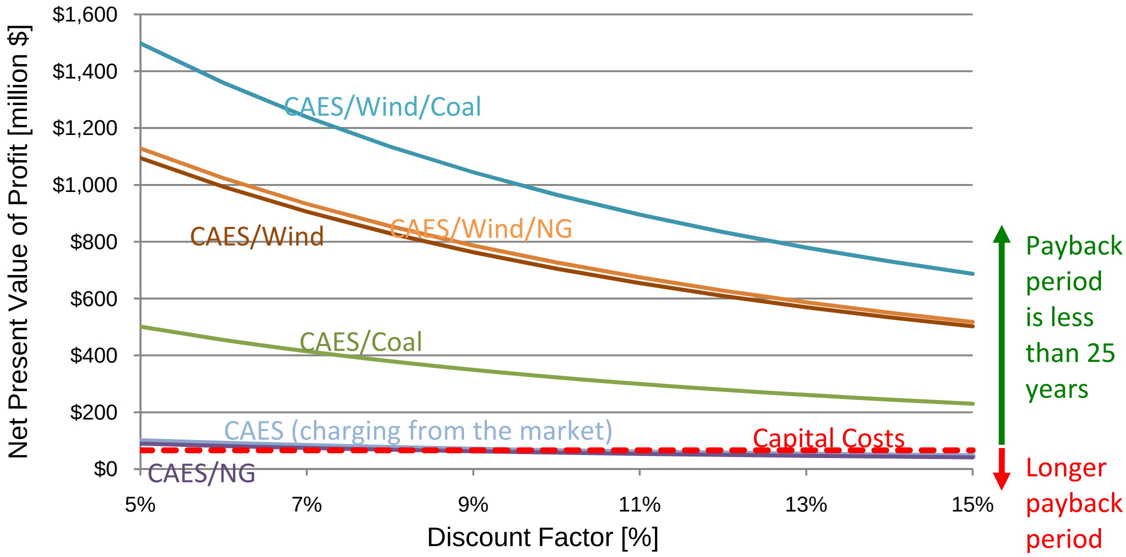
We used a simple net present value (NPV) analysis to determine whether the operating profit for each hybrid configuration would be enough to recover the capital costs for the CAES storage subsystem over an assumed 25-year commercial lifetime. Exhibit ES -2 and Exhibit ES -3 show the estimated NPV of 25-year operating profit as a function of discount rate, with the capital costs shown for comparison.

Exhibit ES-2: Net Present Value of Operating Profit (Huntorf)



For the Huntorf design, the NPV of operating profit for the non-hybrid CAES and hybrid CAES/NG configurations was not sufficient to cover CAES capital costs under a wide range of discount rates; in other words, the payback period for these configurations was beyond the 25-year lifetime of the plant. This is seen in Exhibit ES-2, where the NPV lines for CAES and CAES/NG are completely below the Capital Cost line. For the McIntosh design (Exhibit ES-3), these same two configurations had payback periods of less than 25 years using discount rates below about 10 percent, but payback periods of more than 25 years at higher discount rates. For all other configurations, the NPV of operating profit exceeded the CAES capital costs for all discount rates less than 15 percent; that is, the payback period was less than 25 years.

Exhibit ES – 3: Net Present Value of Operating Profit (McIntosh)



Design and operating factors that affect efficiency. We used detailed process modeling to better understand some of the design and operating parameters that can affect CAES efficiency. In agreement with common practice, we first categorized CAES plant designs based upon the method of managing heat from compression and expansion of the air. These categories are:

1. ***Adiabatic***, in which: heat of compression is stored in a solid or fluid and returned to the air during expansion;
2. ***Diabatic***, in which heat of compression is removed and dissipated during compression, and the air is re-heated during expansion using a burner;
3. ***Isothermal***, in which compression and expansion are done slowly enough to keep the air at approximately a constant temperature through energy exchanges with the environment.

We reviewed the literature to investigate different ways to calculate the efficiencies of these different designs. We also identified other efficiency-relevant design factors, such as the use of recuperators and humidification cycles. Using the results of this literature review, we developed models using the Aspen Plus® process modeling tool to investigate the effects of different operating parameters on efficiency through the compression and expansion cycles. Our modeling focused on adiabatic and diabatic design, leaving the isothermal category for further research.

We modeled an adiabatic design that uses Thermalane-800 as the heat storage medium, with some heat loss during underground storage of the compressed air. Overall system efficiency was approximately 75 percent, limited by the physicochemical properties of the heat storage fluid, which degrades at the higher temperatures. We used this model to show the relationships between expander exhaust temperature and thermal reservoir temperature, and between expander exhaust temperature and plant and storage efficiency.

We extended this model to a diabatic design, and showed quantitatively how plant efficiency decreases as the expander exhaust temperature increases. The model also shows the thermal reservoir temperatures for which icing may occur at the expander under realistic conditions for a diabatic design in the absence of additional heat input, such as through a burner.

These investigations provide insight into some of the more practical aspects of CAES design and operation. In addition to the insights themselves, they demonstrated the value of quantitative modeling in investigating planning and operations for CAES. We recommend that agencies and firms use similar modeling in their own investigations.

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1 Identification of Potential United States CAES Sites

The following preliminary analysis to identify underground CAES sites in the United States adopted the criteria used in a 2009 study prepared for the New York State Energy Research and Development Authority (NYSERDA, 2009) by the New York State Electric and Gas (NYSEG). NYSEG conducted a thorough analysis of the criteria required for compressed air energy storage (CAES) in the State of New York. Their report discussed the characteristics of the wind resources, infrastructure, and physical geography characteristics that would favor a CAES siting. The NYSEG report focused on three main aspects: (1) location; (2) CAES structural condition requirements; and (3) means of brine disposal. The results presented here are limited to the 48 conterminous states and based on the same criteria as the NYSEG study, albeit the issue of brine disposal was deferred, and the best available data source was used in lieu of empirical information.

1.1 CAES Development Requirement

1.1.1 Location

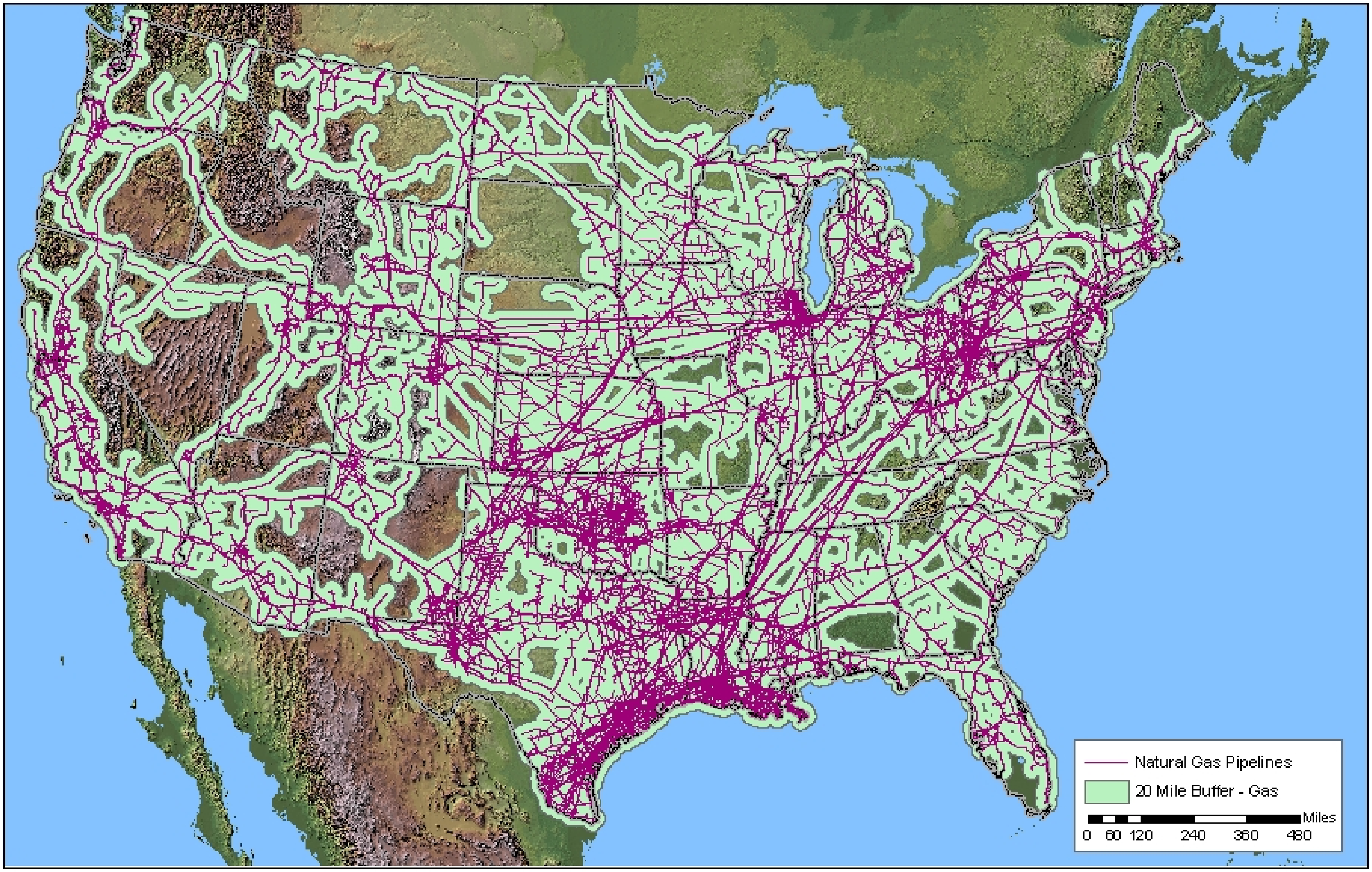
A suitable site for CAES must meet three proximity conditions:

- Proximity to natural gas transmission lines
- Access to high voltage electrical transmission assets
- Access to the wholesale power market (*i.e.*, ISOs and RTOs).

If any of the infrastructure assets required are not available within about 20 miles away from the potential site, the cost to construct extensions may become too high to be considered (NYSERDA, 2009).

Proximity to natural gas transmission lines with greater than 124 psi pressure is illustrated in Exhibit 1.

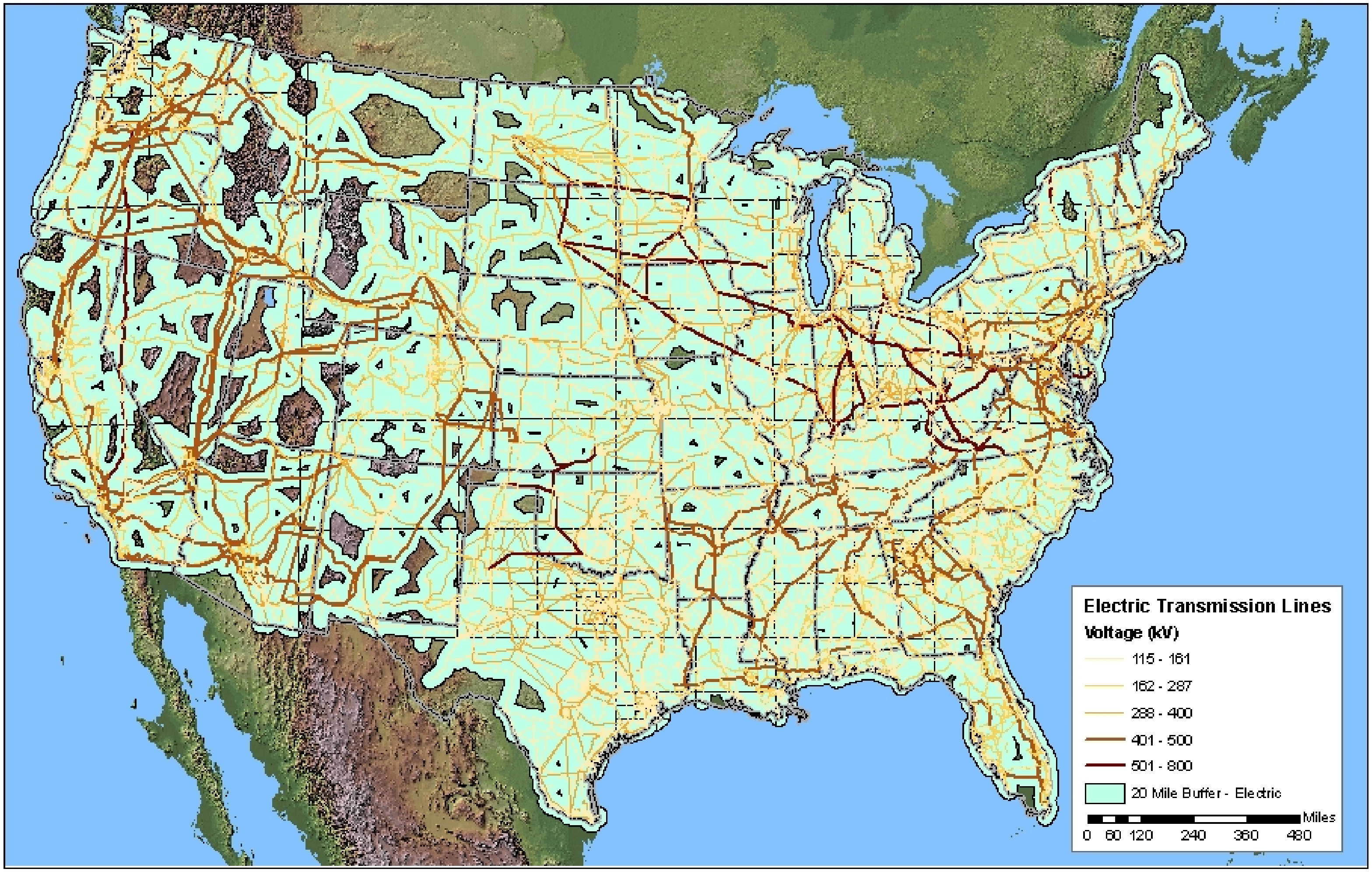
Exhibit 1 Natural Gas Transmission Lines with 20 Mile Buffer



Source: (Ventyx, 2010)

Proximity to high-voltage electric transmission lines (115 kV or above) is illustrated in Exhibit 2.

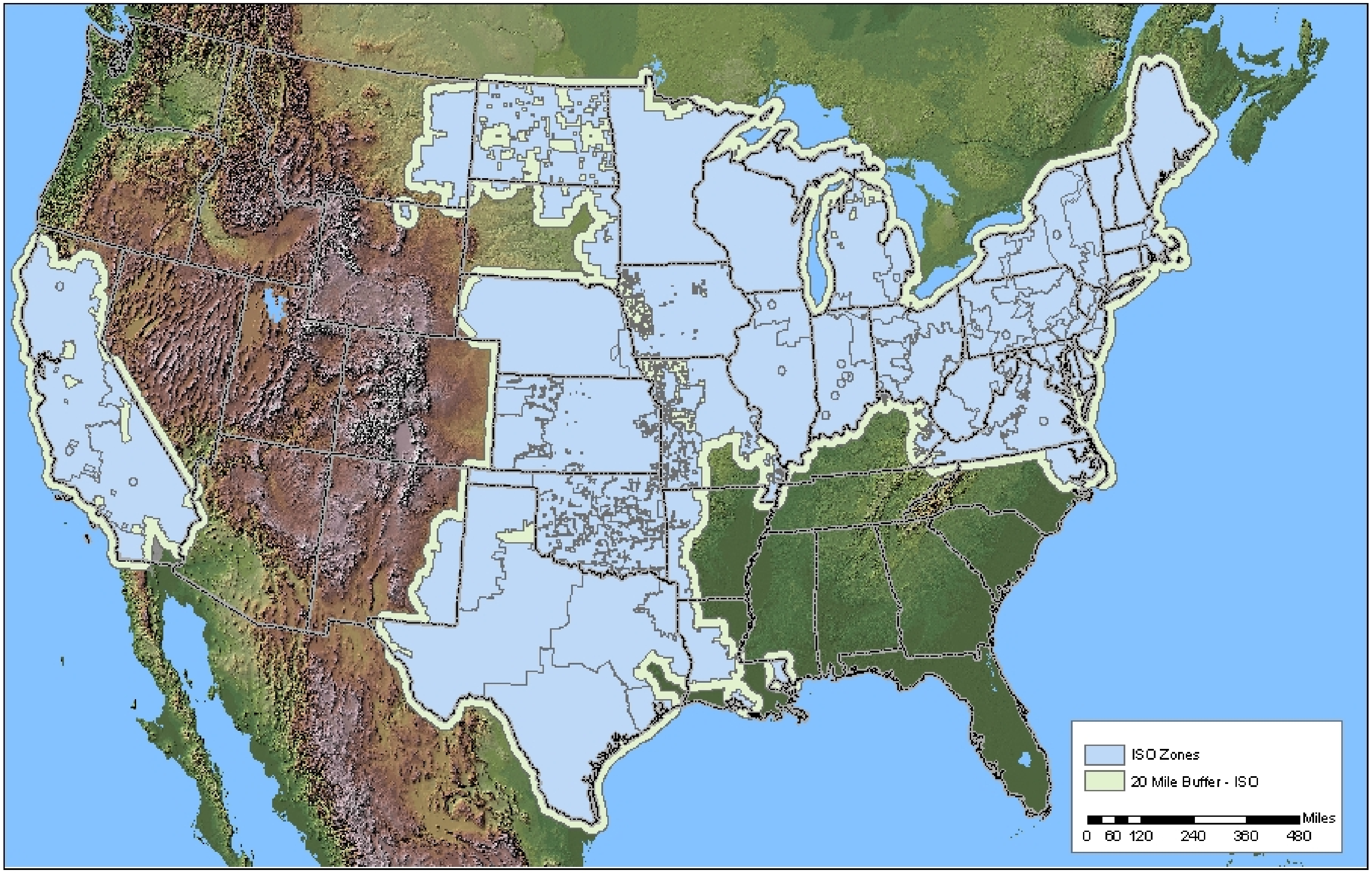
Exhibit 2 Electric Transmission Lines with 20 Mile Buffer



Source: (Ventyx, 2010)

Market proximity, i.e., proximity to an ISO zone, is shown in Exhibit 3.

Exhibit 3 ISO Zones in the US



Source: (Ventyx, 2010)

1.1.2 Structural Condition Requirements

Sites with larger potential air storage volume will allow a higher return on investment since the volume determines the length of time that the air is available for electricity generation. In order to ensure the quality of the potential sites for CAES, the following structural condition requirements for potential sites should also be considered (NYSERDA, 2009):

- Volume
- Porosity and permeability
- Containment
- Pressure and depth

Various types of geologies may satisfy these requirements, including domal salt formations, bedded salt formations, aquifers, hard rock formations, and abandoned coal mines. However, the capital investment cost is different for each type (Allen, 1985; Mehta, 1992; Succar & Williams, 2008). The estimated capital costs of converting different formations into air storage are listed in Exhibit 4. Domal salt formation might be the most feasible geology for CAES development since the formation can be solution-mined with fresh water and can be large and airtight (NYSERDA, 2009). The capital expenditure requirements for converting domal salt formation into air storage facilities are also relatively low compared to other geologies. However, Succar (Succar & Williams, 2008) provided a caveat regarding the use of salt bed formations in that they tend to contain more impurities than other geologies, which can affect the structural integrity of the reservoir.

In this analysis, domal salt formation, bedded salt formation, and aquifers were considered.

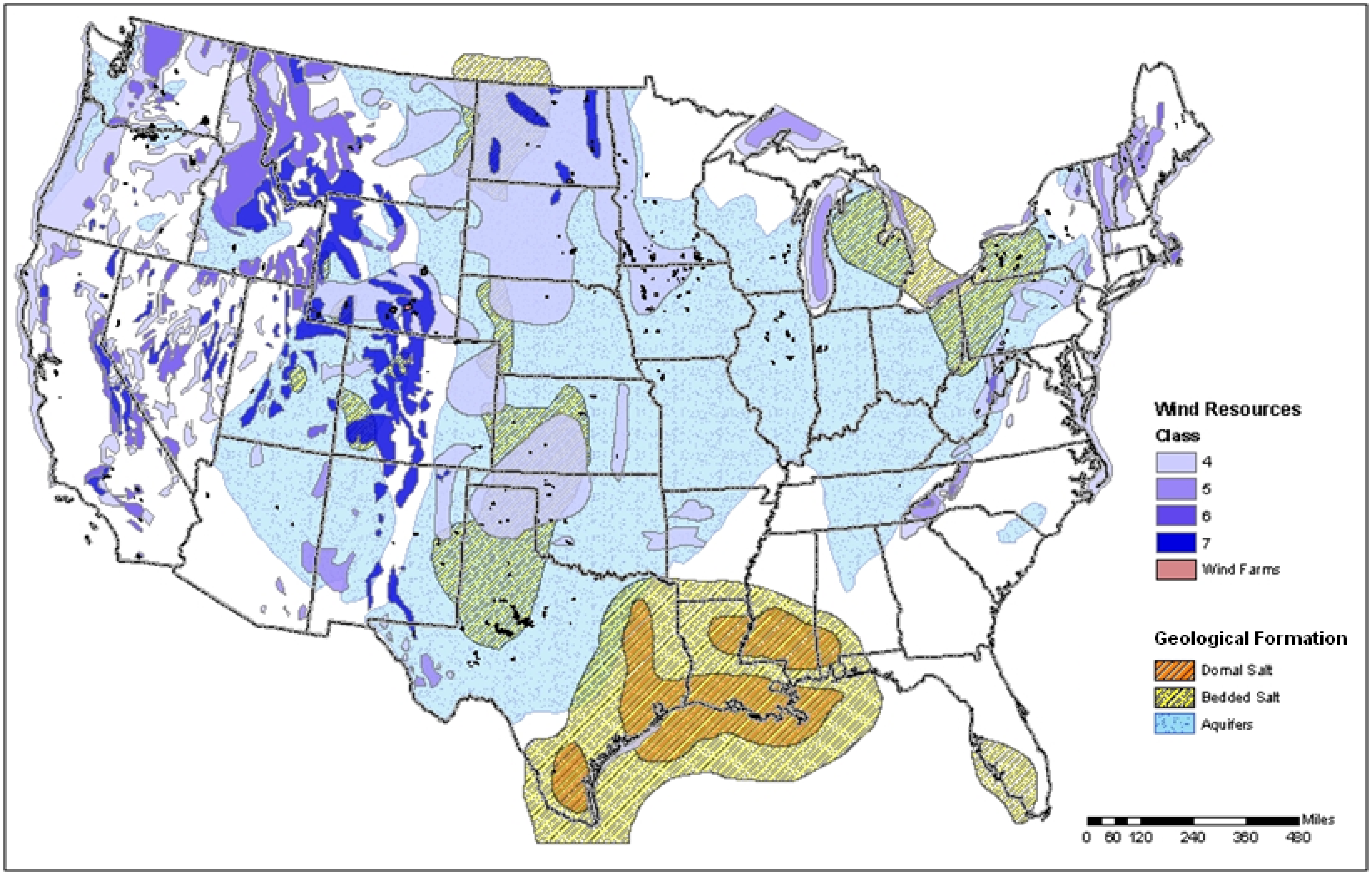
Exhibit 4 Estimated Capital Costs for Varying Geologies

Geology	Capital Cost of Energy Storage Component
Salt Cavern / Solution Mined	$1/kWh
Salt Cavern / Dry Mined	$10/kWh
Hard Rock / Excavated & Existing Mines	$30/kWh
Porous Rock / Aquifer	$0.10/kWh
Abandoned Limestone or Coalmines	$10/kWh

Source: (EPRI-DOE, 2003).

Exhibit 5 shows the wind resources and potential geologies for CAES. The wind resource in this analysis adopted the United States' annual average wind power from the *Wind Energy Resource Atlas of the United States* (Elliott, 1986). Class 4+ wind resources are defined as having a wind power density of greater than 400 W/m^2 at 50 m (average annual wind speeds greater than ~7.0 m/s). Succar (Succar & Williams, 2008) suggested that wind resources of class 4 and above are viable and economical. Thus, only class 4+ winds were used in this analysis.

Exhibit 5 Wind Resources and Geologies for CAES



Data adapted from: Elliott, Holladay, Barchet, Foote, & Sandusky, 1986; Succar & Williams, 2008

In the Great Plains and Midwest states, class 4+ winds are abundant. However, these states are sparsely populated. CAES systems will allow wind farms to bring electricity cost-effectively from the Great Plains to major urban electricity demand centers (Succar & Williams, 2008). As shown in the figure, although domal salt formation might be the most feasible geology for CAES development, there are not many class 4+ wind resources in areas where such formations are abundant. Geology availability (e.g., competition from natural gas and prime olefin storage) and development cost should be further investigated as part of the planning process for CAES projects.

1.1.3 Means of Brine Disposal

An important aspect in choosing potential CAES sites is finding ways for brine disposal. For salt solution-mined caverns, brine will be generated during the leaching process. In this leaching process, operators must have (1) a source of freshwater for leaching the cavern, and (2) a suitable location and/or process for disposal of brine from the leaching process. However, this detail was deferred until the consideration of specific potential CAES project and was not part of this study.

1.2 Siting Procedure

The procedure adopted in this investigation as the criteria for CAES development is outlined below.

1.2.1 Data Collection and Mapping

The following data relevant to siting potential CAES locations were collected, with the data source identified in parentheses next to the data element:

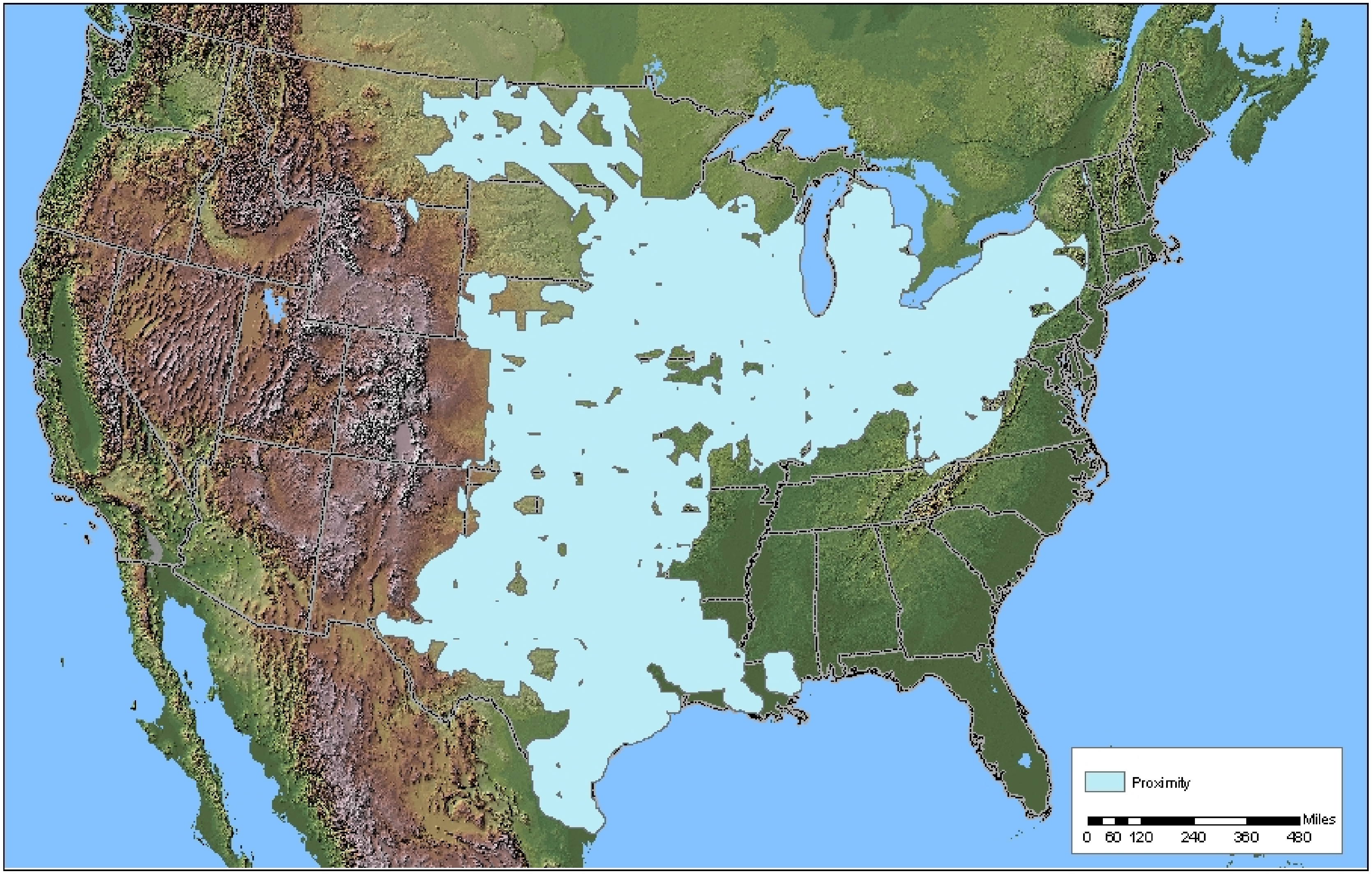
a. ISO zones (Ventyx, 2010)
b. Electric transmission lines (Ventyx, 2010)
c. Natural gas transmission lines (Ventyx, 2010)
d. Wind resources (Elliott, 1986)
e. Domal salt formations (Succar & Williams, 2008)
f. Bedded salt formations (Succar & Williams, 2008)
g. Aquifers (Succar & Williams, 2008); (Ventyx, 2010)

1.2.2 Data Processing

Data were processed after the collection phase to eliminate unnecessary information and to create distance buffers based on natural gas and electric transmission lines to ensure the proximity requirements were met.

Areas where potential CAES facilities could access natural gas and electric transmission lines, ISO zones, and geologies were identified as shown in Exhibit 6.

Exhibit 6 Areas That Meet All Proximity Requirements



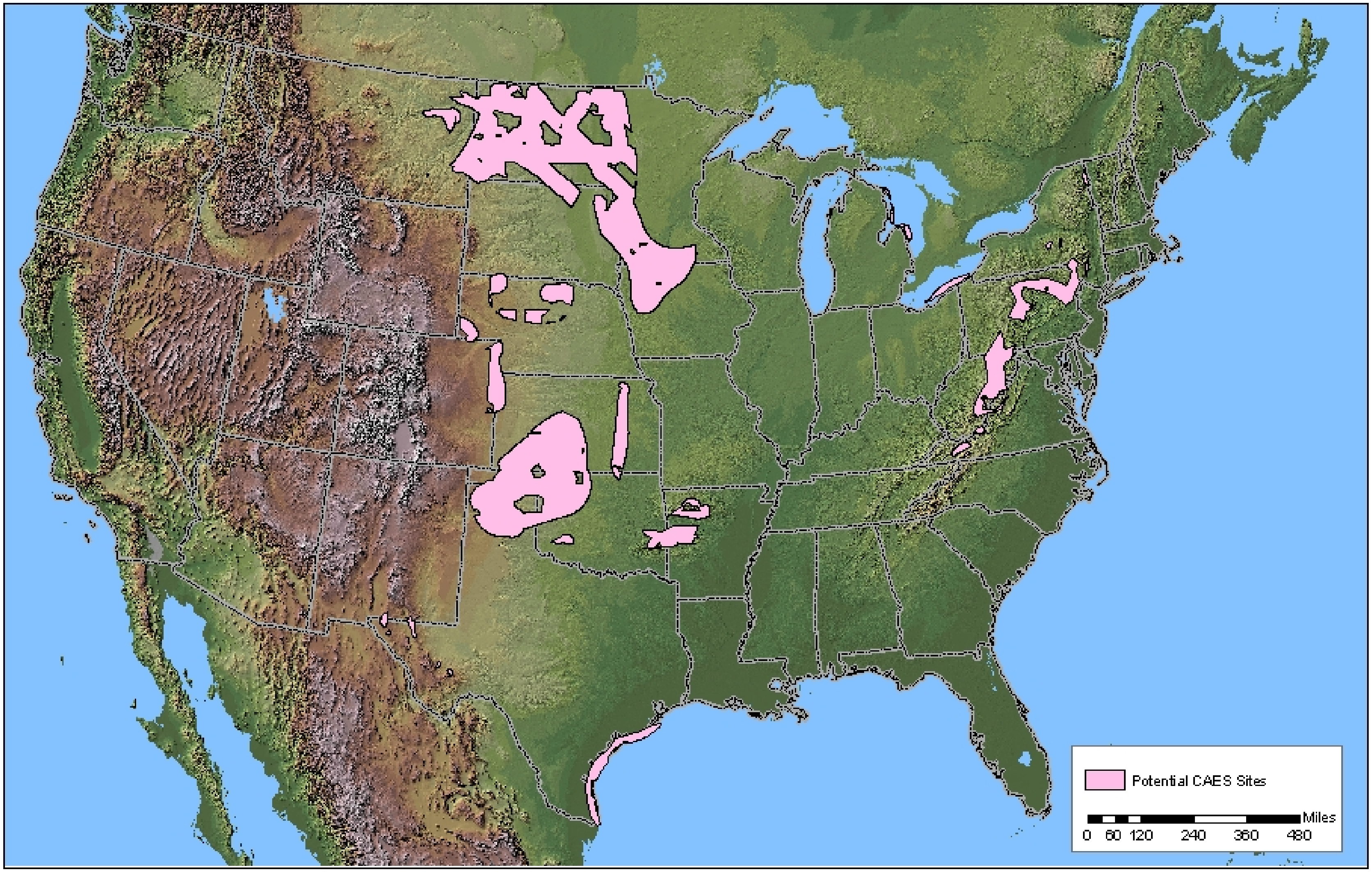
Data source: (Ventyx, 2010)

1.2.3 Data Analysis

Spatial queries on the data sets were executed to locate potential sites for CAES development based on wind resources, various geologies, and proximity requirement buffers to locate potential sites. For example, some locations might have abundant wind resources but might not meet the requirements and the querying process would eliminate such areas.

As shown in Exhibit 7, in some states, areas that can serve as potential CAES sites can be as large as the entire state while in other regions the potential sites are sparsely scattered.

Exhibit 7 Potential CAES Sites Identified by This Study



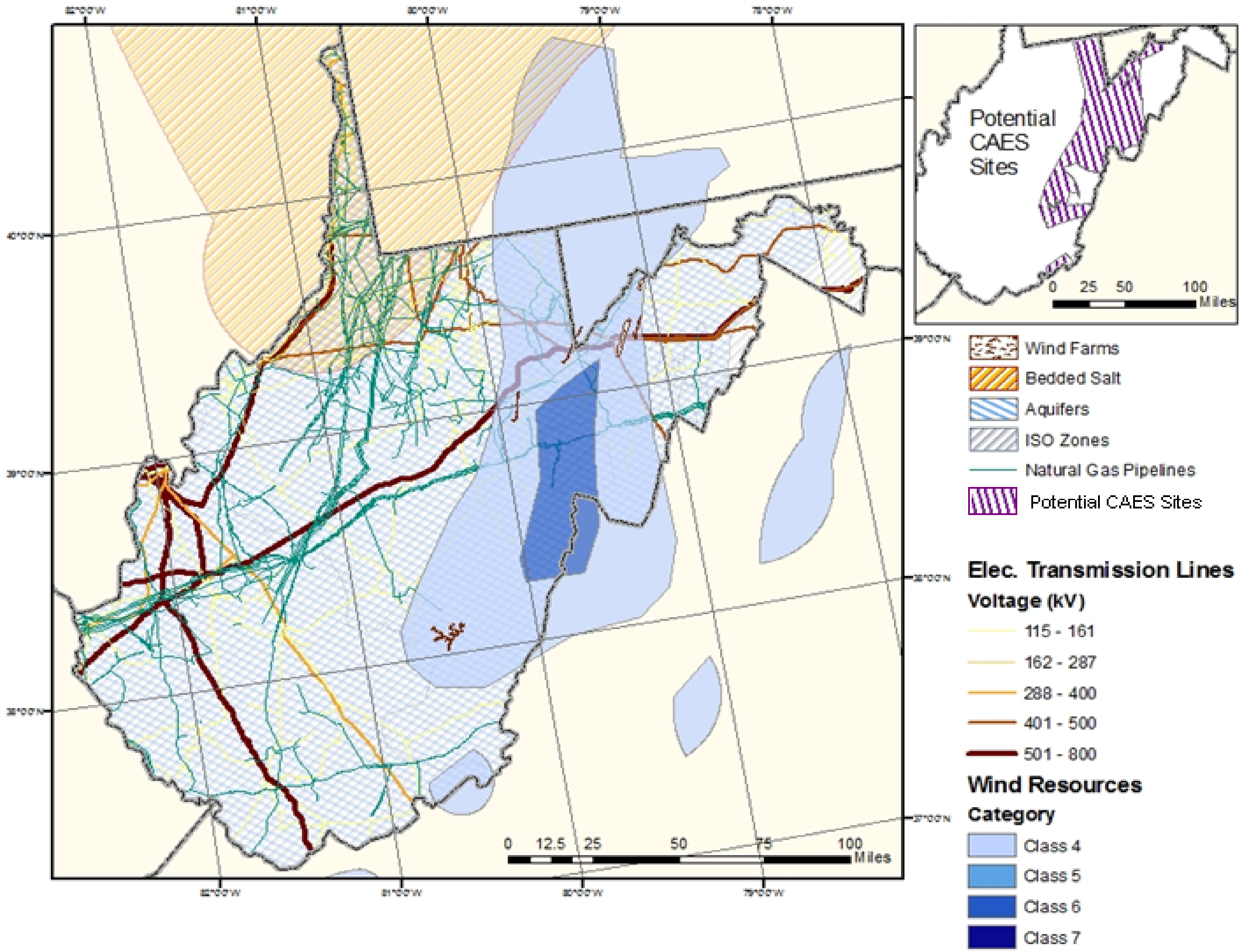
Data source: (Ventyx, 2010)

It is interesting to note that this evaluation using the NYSEG criteria did not locate a potential site in New York State. It is important to note the NYSEG study was focused on finding the best sites in New York under the constraint that the New York renewable portfolio standard will be enforceable and wind generation will be a significant part of meeting that standard. Hence, the NYSEG study was targeting the best potential use and location of wind-CAES in New York and not whether New York was an optimal choice for locating wind-CAES technology. Also, NYSEG study used class 3+ wind as a requirement, not class 4+ as was used in this study.

Information can be drilled down to analyze requirements and resources at various levels (e.g., state, county, etc). For example, the evaluation shows that almost the entire state of West Virginia is covered by ISO zones and potential aquifer zones (Exhibit 8). Natural gas and electric transmission lines are also accessible in West Virginia. Moreover, existing wind farms in West Virginia are located in potential CAES regions. Since class 4+ winds are abundant in the state, CAES can be a good option to utilize renewable energy sources.

However, besides resource availability, siting analysis at the project level requires further consideration of capital requirements, operating costs, and risk as well. If the analysis is desired for a specific state or facility, more detailed resource information and further investigation are required.

Exhibit 8 West Virginia CAES Siting Analysis



Data source: (Ventyx, 2010)

1.3 Summary

This preliminary analysis extended the methodology developed by New York State Electric and Gas (NYSERDA, 2009) to identify geographic regions that might be good candidates for CAES economically and technically in the United States. The results presented here are based on the best available data sources at the time of analysis. Three infrastructure criteria were used: proximity to natural gas lines (for use in reheating gas prior to expansion in the turbine); proximity to high-voltage transmission lines (for delivery of power to and from the grid); and proximity to a market for wholesale electric power, in the form of an independent system operator (ISO) or regional transmission organization (RTO). Areas meeting these criteria were further evaluated for availability and cost of appropriate geologies; quantity of wind resources; and, where salt-solution mining would be used, the availability of water and brine disposal sites.

NYSEG focused on mapping geologies and proximity to infrastructures in New York State for CAES siting. The mapping process in this analysis included the wind resource as well as geologies and proximity to infrastructures. Therefore, the result generated by this analysis might be slightly different from the NYSEG (NYSERDA, 2009) research. Past research (Succar & Williams, 2008) suggested that wind resources of class 4 and above are viable and economical. Thus, only class 4+ winds were used in the geospatial analysis to identify potential regions for wind resource and CAES development. Using geographic information system (GIS) methods to spatially join the criteria, we identified regions within the U.S. that met all these requirements. Suitable locations meeting all criteria included sites in the upper Midwest, Great Plains states, Texas coast, Great Lakes coast, and upper Appalachian states.

While this preliminary analysis provides useful resource matching information for siting, a more detailed analysis would be appropriate to further investigate a specific site. The wind resource data used in the analysis is suitable for analysis at a state or higher level, and is not appropriate for specific wind farm economics.

2 NETL's Proposed CAES Operational Guidance Model

2.1 Need for Operational Guidance Model

Based on an investigation of current CAES modeling capabilities, the Department of Energy's National Energy Technology Laboratory (NETL) is proposing an operational guidance model for CAES, CAES/wind, CAES/wind/coal or CAES/wind/natural gas operations. The proposed model could be used as a decision making tool by generator owners. This generator owner prospective is a different prospective than system prospective of previously developed models and methodologies.

Several models and methodologies (DYNATRAN, HOMER, Ridge Energy Model, PROMOD, and ReEDS) have previously been developed to analyze CAES and Wind-CAES operations. However, as can be expected, given the nascent state of CAES technology, these currently available tools are focused on planning issues such as quantifying the economic benefit of the technologies and how technology choices affect the operating curve and maximize return on investment. While these models handle the temporal fluctuations in CAES operating parameters in sophisticated ways, their focus is on understanding the impact of CAES technology, CAES added-value, and the risk associated with the technology.

As CAES technology moves from its research and development stage with a few benchmark applications to early adopter demonstration plants[1] toward general usage[2], new tools are needed for optimized short-term operations. Specifically, tools beyond planning models are necessary for day-to-day operations. Operational guidance and optimization tools are required to properly use and dispatch CAES assets once they are operational. Furthermore, these short-term optimization tools can be integrated with the planning process, providing more accurate and reliable predictions of different planning scenarios.

DYNATRAN, HOMER, Ridge Energy Model, PROMOD, and ReEDS have been fundamental methodologies for planning analysis and quantifying potential economic benefits of hybrid storage/ generation systems. While being useful for specific analytical purposes, each of these tools has some shortcomings. For example:

- Unit commitment in DYNATRAN is based on a heuristic approach that will give suboptimal solutions for charge/discharge CAES profiles and does not take into account wind forecast.

[1] There are two commercially operational CAES power plants in the world: Huntorf in Germany, build in 1978, and McIntosh commissioned by the Alabama Electric Cooperative and completed in 1991 (Energy Sector Planning and Analysis, 2010).

[2] The U.S. government, through its Recovery Act Funding, has funded different energy storage projects including three CAES projects. The significance of these projects is that they are employing new CAES designs and ideas (Energy Sector Planning and Analysis, 2010).

- Ridge Energy shapes the wind generation output without optimizing the air compression-decompression schedule.

- PROMOD dispatches energy units on hour-by-hour basis. Storage device is charged during weeknights and weekends and discharged during weekdays.

- ReEDS uses common CAES pattern charging overnight and discharging during the day, and it is not explicitly coordinated with wind behavior or price.

These limited methodologies cannot provide optimal operational guidance for CAES, or hybrid CAES/generation facilities. All of these models use system approaches, not element approaches. For example:

- DYNATRAN calculates the charging/discharging CAES profile according to predefined threshold prices. However, charging and discharging based on the comparison between the energy price and generation cost does not mean that the charging/discharging profile is optimal or that it maximizes profit.

- PROMOD focuses on system economics and is primarily limited by the lack of daytime charging logic.

- ReEDS optimizes generation and transmission capacity so that system-wide cost is minimized, and demand, reserve requirements, and emission constraints are satisfied at the same time. This approach is appropriate for regulated industries.

A system wide optimization approach is not appropriate in a restructured industry, except for independent system operators or regional transmission operators. Generator owners are for-profit companies that are looking into investments in a free market environment (Mazer, 2007). The decision to build a CAES or hybrid CAES/generation plant and its operational scheme is an economically driven decision.

Existing CAES and/or hybrid CAES/generator models mostly focus on the planning aspects of specific CAES applications (e.g., quantifying potential benefits). Consequently, they do not optimize hourly CAES/wind operations. The proposed CAES Operational Guidance is a model for optimal CAES, CAES/wind, CAES/coal and CAES/natural gas operation that includes investment cost, operations and maintenance cost, and technical constraints (storage power capacity, energy capacity, ramp-up and ramp-down rates, start-up and shut-down times). This model goes beyond traditional generation operation planning by addressing the complexity of the CAES charging/discharging schedule. In addition, the CAES/wind charging/discharging model that provides operational guidance on scheduling should incorporate forecasted wind power generation and locational marginal price.

The proposed model can schedule CAES charging during the weekdays and discharging during weeknights which is different than prescheduled charging/discharging profile used in existing models and methodologies. The generally accepted CAES charging/discharging heuristic is to charge CAES overnight and discharge over the day or partially charge/discharge over the week and fully charge over the weekend. Following such a pattern allows the CAES owner to profit from the price arbitrage ($/MWh of power) created by the temporal dependence of the locational marginal price of electricity and the ability to store energy. However, following such heuristics is not the same as optimizing CAES scheduling and provides limited operational guidance, thus limiting the economic benefit derived from a CAES asset. For example, CAES may have the same charging/discharging profile for the whole week regardless of electricity price volatility or wind power.

Coal power generation can also be used for charging CAES. Coal, similar to wind, has low marginal generation cost, and it is suitable to be used with CAES. In addition, a coal power plant could be better utilized if it is used in combination with CAES. Better coal power plant utilization is achieved by charging CAES from the coal power plant during hours when it is not profitable to sell power to the market. This situation happens when the marginal generation cost of coal power plant is higher than the locational marginal price.

Natural gas power generation can also be used for charging CAES, and its profitability depends on natural gas prices.

2.2 Description of the NETL CAES Operational Guidance Model

The main objective of NETL's proposed CAES Operational Guidance and Optimization model is profit maximization. The profit function used in the model is defined as the total revenue from selling power, minus operating cost and the capital cost over a week:

$$\max \ \text{Profit} = \sum_{t=1}^{168} \text{Revenue}(t) - \sum_{t=1}^{168} OperatingCost(t) - C_{CapitalCost}^{perWeek} \qquad (1)$$

While capital recovery is irrelevant to operational guidance once a capital asset exists, the NETL model incorporates capital recovery so that it can readily be used for both operations (hour-to-hour decision making after a plant is built) and planning analysis (deciding whether a project merits investment).

CAES/Wind Revenue and Operating Cost

The revenues and operating costs depend upon the availability of wind for CAES/wind operation.

CAES operation consists of two main modes, charging and discharging. CAES can be charged by using the plant's wind power, power from the electric grid (network power), or both. For simplicity, we assume that the operating costs for the hybrid CAES/wind plant are primarily those for buying power from the grid during charging, and heating gas during expansion, and that other operating costs can be ignored. In charging mode, we assume that the CAES is always charged at the maximum rate. This power will be bought from the grid if wind power available is less than the maximum charging power of the CAES. In this case, the revenue equals zero, and the operating costs are equal to the cost of buying power from the market. If available wind power is greater than the maximum charging power of the CAES, excess wind power will be sold back to the market. Revenue in this mode is equal to the profit of selling excess wind power to the market, and operating costs are zero.

During CAES discharge, both power derived from discharging the stored compressed air and power generated directly from the wind are sold, and the revenue is equal to the sales of power derived from discharging the CAES and power derived from wind. The operating CAES costs are essentially the cost of natural gas used to heat the stored air being expanded for power generation.[3] The revenues and operating costs for two different modes are

$$\text{Revenue}(t) = \begin{cases} 0 & \text{charging, } P_{ch}(t) > P_{wind}(t) \\ (-P_{ch}(t) + P_{wind}(t)) \cdot \lambda(t) & \text{charging, } P_{ch}(t) < P_{wind}(t) \\ (P_{disch}(t) + P_{wind}(t)) \cdot \lambda(t) & \text{discharging} \end{cases} \qquad (2)$$

[3] Air cools considerably as it expands. Consequently, air being expanded from storage must be heated to avoid creating severe operational issues such as icing which could lead to catastrophic equipment damage.

$$\text{OperatingCost}(t) = \begin{cases} (P_{ch}(t) - P_{wind}(t)) \cdot \lambda(t) & \text{charging, } P_{ch}(t) > P_{wind}(t) \\ 0 & \text{charging, } P_{ch}(t) < P_{wind}(t) \\ c_{NG}(P_{disch}) & \text{discharging} \end{cases} \tag{3}$$

where $\lambda(t)$ is real-time locational marginal price, $P_{ch}(t)$ is charging power, $P_{disch}(t)$ is discharging power, $P_{wind}(t)$ is wind power, and $c_{NG}\left(P_{disch}\right)$ is cost of natural gas used during discharge. Input data for wind power and natural gas price are weekly forecasts. The optimal solution will depend on how accurate they are.

CAES/Coal Revenue and Operating Cost

The revenue from selling power, as well as the operating cost, depends on the locational marginal price and the cost of coal-fired generation. We assume that the coal power plant capacity is larger than the maximum CAES charging power and that in charging mode the CAES is charged by using only power from the coal power plant, not from the grid. If the electricity price is greater than the coal generation cost, excess coal power will be sold to the market. Revenue during charging is equal to the sales of excess coal power to the market.

During CAES discharge, both power derived from discharging the stored compressed air and power generated from the coal are sold, and the revenue is equal to the total sales of power derived from both sources. The revenues from selling power and the operating costs for the two different modes are as follows:

$$\text{Revenue}(t) = \begin{cases} 0 & \text{charging, } \lambda(t) < C_{coal} \\ (-P_{ch}(t) + P_{coal}(t)) \cdot \lambda(t) & \text{charging, } \lambda(t) \geq C_{coal} \\ (P_{disch}(t) + P_{coal}(t)) \cdot \lambda(t) & \text{discharging, } \lambda(t) < C_{coal} \\ P_{disch}(t) \cdot \lambda(t) & \text{discharging, } \lambda(t) \geq C_{coal} \end{cases} \tag{4}$$

$$\text{OperatingCost}(t) = \begin{cases} P_{ch}(t) \cdot C_{coal} & \text{charging, } \lambda(t) < C_{coal} \\ P_{coal}(t) \cdot C_{coal} & \text{charging, } \lambda(t) \geq C_{coal} \\ c_{NG}(P_{disch}) & \text{discharging, } \lambda(t) < C_{coal} \\ c_{NG}(P_{disch}) + P_{coal}(t) \cdot C_{coal} & \text{discharging, } \lambda(t) \geq C_{coal} \end{cases} \tag{5}$$

where $\lambda(t)$ is real-time locational marginal price, $P_{ch}(t)$ is charging power, $P_{disch}(t)$ is discharging power, C_{coal} is coal marginal generation costs and $c_{NG}(P_{disch})$ is the cost of the natural gas used for discharge.

CAES/Natural Gas Revenue and Operating Cost

CAES/natural gas revenue and operating cost depend on locational marginal price and natural gas generation cost. Having the same assumptions as for the CAES/coal case, the revenue and operating cost may be calculated by substituting the natural gas power plant generation cost and output for the coal power plant generation cost and output in equations (4) and (5).

CAES can go from zero to full capacity within 14 minutes (Robb, 2010). Consequently, if operational guidance is provided on an hourly basis, as we assume in the current analysis, there is no need to include ramp-up and ramp-down constraints in the model. However, if operational guidance is required on a shorter time scale, then the following constraints should be included in the decision process

$$P_{ch}(t) - P_{ch}(t-1) \leq P_{ramp-up} \tag{6}$$

$$P_{disch}(t-1) - P_{disch}(t) \leq P_{ramp-down} \tag{7}$$

Additional constraints can be imposed for charging/discharging energy, and minimum and maximum energy limits. Charging energy is calculated as:

$$\Delta E_{ch}(t) = P_{ch}(t) \cdot t \cdot \eta_{compressor} \tag{8}$$

where $\eta_{compressor}$ refers to compressor efficiency. The dynamic equation governing the stored quantity is:

$$E_{stored}(t) = E_{stored}(t-1) + \Delta E_{ch}(t) - \Delta E_{disch}(t) \tag{9}$$

This construction requires that the economic dispatch calculation cannot be done as one point at a given time. A proper calculation methodology must account for what happens before a given time and what will happen in the future. Dynamic programming can be used to solve a problem with this structure (Bertsekas, 2000). Previous models, predominantly aimed at project planning and technology investment decisions rather than dynamic operational guidance, did not address this construct. The discrete dynamic programming approach divides a complex problem into a sequence of decision steps over time and accounts for what happened before and what will happen in the future.

2.3 Illustration of the Model Using Real CAES Plant Parameters

The NETL CAES Operational Guidance and Optimization model is illustrated by evaluating the McIntosh, Alabama, and Huntorf, Germany, CAES power plants with wind and coal power plants and wind and natural gas power plants. The data for these power plants are summarized in Exhibit 9.

Two types of planning horizon were used in the analysis. In Section 2.3.1 the optimal performance of CAES, wind, coal and natural gas power plants over a one week period is analyzed. This analysis is used to take a closer look at the CAES charging and discharging profile. In section 2.3.2 the planning horizon is expanded to one year. The analysis is used to estimate a payback period to cover capital investments for CAES.

Exhibit 9 McIntosh and Huntorf Power Plants Data

	Huntorf	McIntosh
Max. Charging Power [MW]	60	50
Max. Discharging Power [MW]	290	110
Max. Energy [MWh]	480	2000
Min. Energy [MWh]	0	200
Charging Time [h]	8	40
Discharging Time	3	26
Compressor Efficiency	0.8	0.8
Power Plant Efficiency	0.42	0.54
Energy Balance[a]	(0.83 $kWh_{electrical}$ +1.56 kWh_{fossil}) * 0.42 =1$kWh_{electrical}$	(0.69 $kWh_{electrical}$ +1.17 kWh_{fossil}) * 0.54 =1$kWh_{electrical}$

[a] *The McIntosh power plant uses 1.17 kWh fossil energy and 0.69 kW electrical energy to produce 1kWh of electricity, while the Huntorf power plant uses 1.56 kWh fossil energy and 0.83 kWh electrical energy for the same output.*

Source: (Robb, 2010), (Crotogino, 2006)

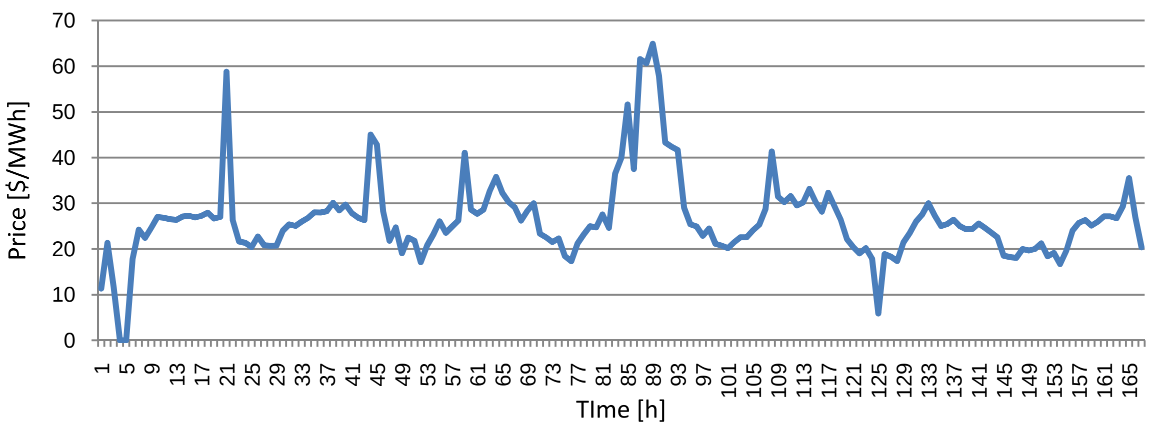
The Huntorf power plant can be charged in discrete steps of 30 MW. In other words, charging power can be 30 MW or 60 MW. If the available wind/coal or wind/natural gas power is larger than the charging power, excess power is sold to the energy market. If wind power is less than the charging power, additional power is bought from the market. At Huntorf, the maximum discharging power is 290 MW. However, the plant can be discharged in discrete steps of 72.3 MW. In other words, discharging power can be 72.3 MW, 144.6 MW, 216.9 MW and 289.2 MW. Initially, CAES-stored energy depends on how long the CAES was charged.

The McIntosh power plant can be charged in discrete steps of 25 MW and discharged in discrete steps of 36.2 MW. CAES is charged for 38 hours before optimization takes place, and the maximum energy is assumed to be 2,000 MWh. To illustrate the possibility of CAES having a lower limit, 200 MWh is assumed to be the minimum available energy.

2.3.1 One-Week Time Horizon

We modeled a restructured industry scenario where optimal operation is determined based on hourly locational marginal energy prices. When using this model for real-time operating guidance, the input data would be a wind power, locational marginal energy price, coal and natural gas power plant generation cost forecast. However, in the example below we used historical data for illustrative purposes. The real-time locational marginal price was obtained from the PJM website (PJM, 2010). Exhibit 10 illustrates the pricing data from the September 1 – September 7, 2009, period used in the analysis example.

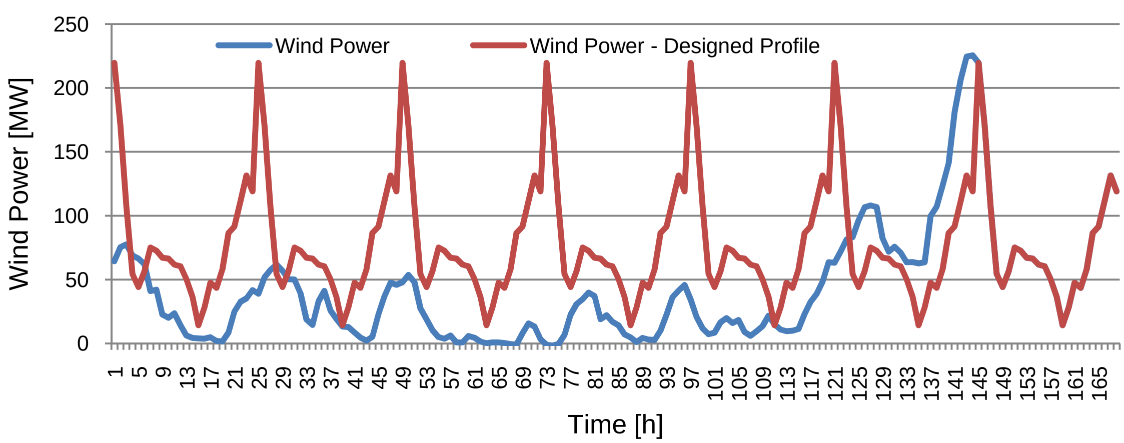
Exhibit 10 Real-Time Locational Marginal Price (PJM 9/1/2009 - 9/7/2009)



Source: (PJM, 2010)

Wind power, for the same period, was obtained from the Velocity Suite: PJM Zonal Wind generation (Ventyx, 2010). For illustrative purposes, we designed an additional wind power profile by repeating a one-day wind power profile for the whole week. This designed wind power profile is used to illustrate the impact that different wind profiles would have on optimal CAES scheduling. Both wind profiles are shown in Exhibit 11. The natural gas price for the same time period is assumed to be fixed, at $4.09/MMBtu (Energy Information Administration, 2010), over the time period analyzed since this would typically be controlled by contracts between the CAES owner and the natural gas supplier. However, the model can support spot-market natural gas pricing that is actually a stronger function of time (i.e., the pricing changes during the period of evaluation).

Exhibit 11 Wind Power (PJM East 9/1/2009-9/7/2009)



Source: (Ventyx, 2010)

Both the coal power and natural gas plants are assumed to have 100 MW capacities. Two different coal generation prices are used for the simulation: $10/MWh as a lower generation price and $25/MWh as the higher generation price. Heat rate of the natural gas plant is assumed to be 12,428 Btu/kWh (Ventyx, 2010). The marginal natural gas plant generation cost is $50/MWh for assumed $4.09/MMBtu natural generation price.

Nine different scenarios were analyzed, and a summary of results is given in Exhibit 12.

Exhibit 12 Analyzed Scenarios and Results (Weekly)

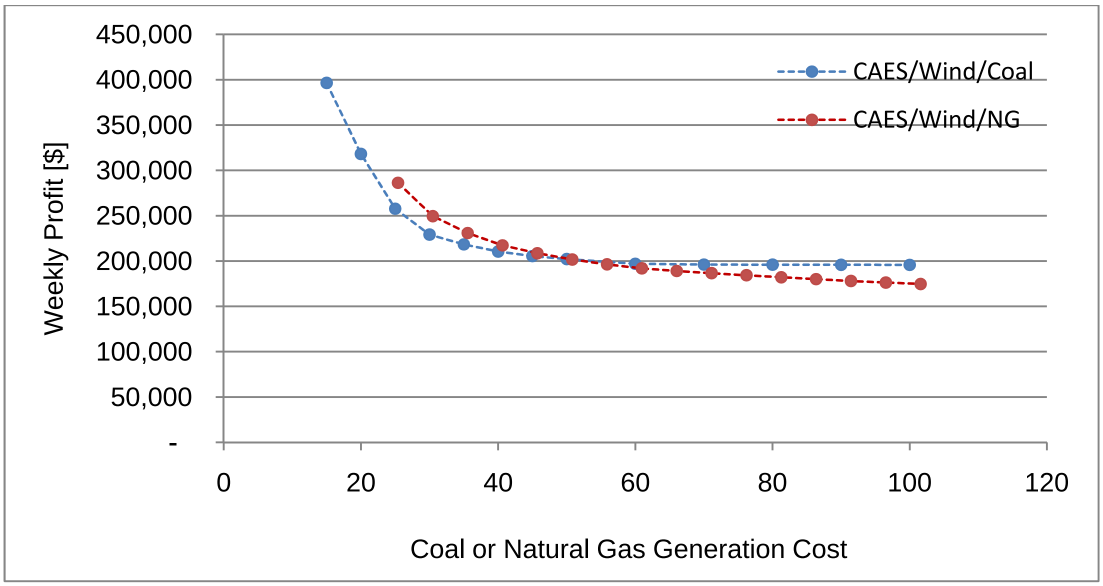
Plant configuration		Huntorf weekly profit [$]	McIntosh weekly profit [$]
CAES only		$40,391	$82,048
Wind only		$160,664	$160,664
Coal only	Coal generation cost $10/MWh	$276,726	$276,726
	Coal generation cost $25/MWh	$59,024	$59,024
Natural Gas only		$5,064	$5,064
CAES/Wind		$201,056	$242,712
CAES/Coal	Coal generation cost $10/MWh	$316,763	$357,933
	Coal generation cost $25/MWh	$ 94,175	$139,195
CAES/Natural Gas		$34,676	$84,192
CAES/Wind/Coal	Coal generation cost $10/MWh	$477,782	$519,438
	Coal generation cost $25/MWh	$257,882	$301,644
CAES/Wind/Natural Gas		$203,157	$247,642

Available energy for the Huntorf power plant is about four times smaller than for the McIntosh power plant. However, the profit for the McIntosh plant is close to that of the Huntorf power plant profit when combined with other power resources due to the McIntosh plant's operating parameters. The Huntorf power plant has greater maximum charging and discharging power than the McIntosh power plant. That is, even though the Huntorf CAES plant is smaller than McIntosh CAES plant, it can be charged and discharged with much faster rate than the McIntosh plant.

Using CAES with wind may increase the profit. CAES is used to store cheap energy and sell it when the price is right. CAES in combination with a coal power plant may increase the profit especially if the coal generation cost is high. Using CAES with natural gas will slightly increase the CAES/wind profit if the CAES is charged solely from the natural gas power plant.

A given profit depends on coal and natural gas prices. Exhibit 13 illustrates that the Huntorf profit changes as a function of the costs of coal power plant generation and natural gas power plant generation for two plant configurations: CAES/Wind/Coal and CAES/Wind/Natural Gas. The blue line is calculated for the CAES/Wind/Coal configuration by changing the coal generation cost from \$15/MWh to \$100/MWh[4] and keeping price of natural gas (necessary for CAES discharging)[5] at \$4.09/MMBtu. Similar results are obtained for a CAES/Wind/Natural Gas plant configuration if the natural gas generation cost, used for charging CAES, is changed from \$25/MWh to \$100/MWh[6] and the natural gas price used for CAES discharging is kept constant at \$4.09/MMBtu. The red curve is calculated for CAES/Wind/Natural Gas plant configurations by changing the natural gas price from 2 – 8 \$/MMBtu[7] for both charging and discharging modes. This natural gas price range corresponds to a cost range of \$25/MWh to \$100/MWh for a natural gas power plant in charging mode and a range of \$11/MWh to \$44/MWh in discharging mode. The portion of CAES that uses natural gas during discharging mode has a 5.32 MMBtu/MWh heat rate.

Exhibit 13 Profit as a Function of Coal or Natural Gas Generation Cost



The profit will decline until coal or natural gas generation costs are mostly larger than the real-time electricity price. When the generation cost is close to the real-time electricity price, the profit becomes constant because it is achieved by discharging CAES without recharging it again.

[4] Coal power plant total marginal generation costs are from \$15/MWh to \$121/MWh in PJM area. However, less than 1 percent of coal power plants have total marginal generation price larger than \$100/MWh.

[5] Natural gas is used for preheating the air. Air being expanded from storage must be heated to avoid creating severe operational issues such as icing which could lead to catastrophic equipment damage.

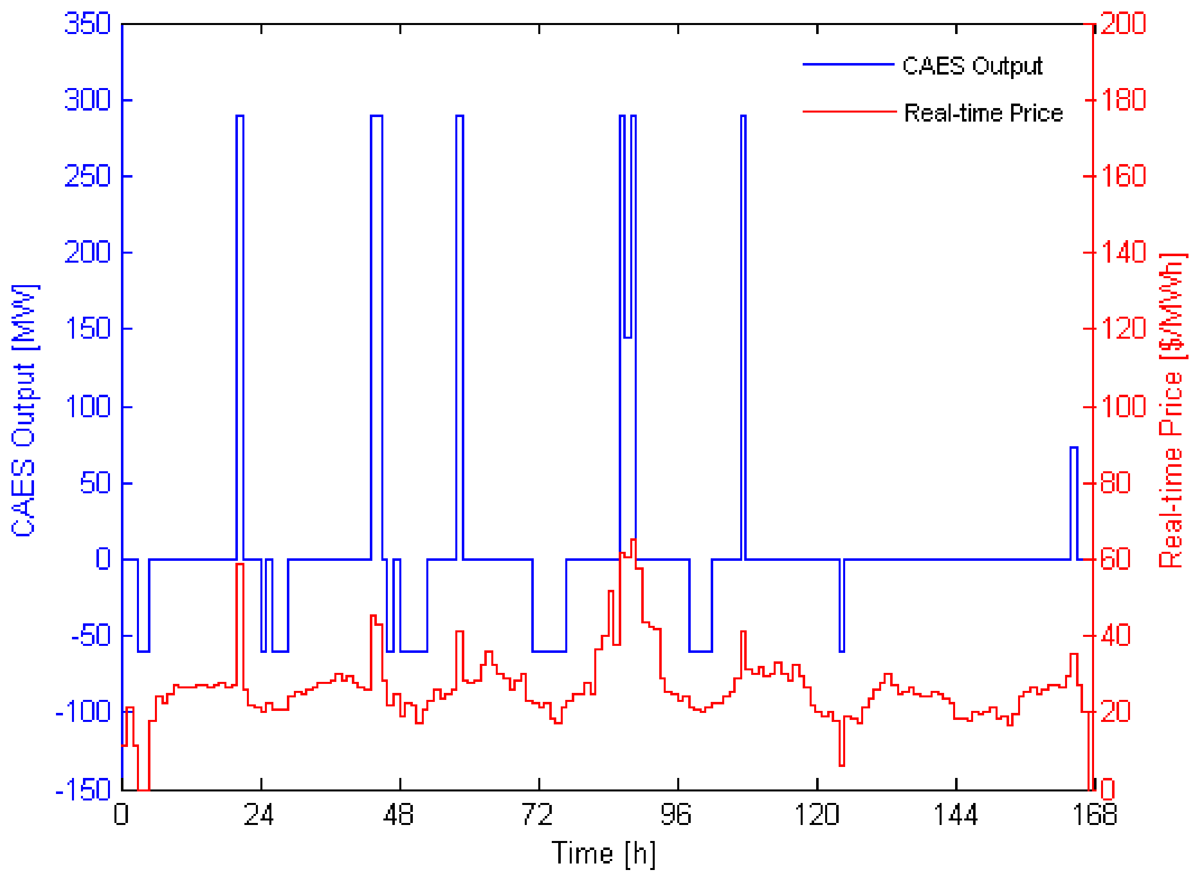
[6] The \$25/MWh to \$100/MWh price range corresponds to a natural gas price range of 2 – 8 \$/MMBtu for a natural gas power plant heat rate of 12,428 Btu/kWh.

[7] Natural gas price during one year period (September 2009 – August 2010) was varying between \$3.98/thousand cubic feet and \$6.97/thousand cubic feet, which correspond to \$3.88/MMBtu – \$6.79/MMBtu. 2 – 8 \$/MMBtu natural gas price interval is chosen such that the natural gas prices are inside the last year natural gas price interval ± ~\$1.5/MMBtu to provide insight if natural gas prices increase/decrease in the future.

The following exhibits illustrate some of the cases summarized in Exhibit 12 in more detail. All the cases analyzed are given in Appendix A and Appendix B.

Exhibit 14 and Exhibit 15 illustrate the Huntorf power plant's optimal scheduling without wind during one week (168 hours).The first exhibit illustrates CAES power output (blue line) and real-time locational marginal price (red line) while the second exhibit illustrates available CAES energy (blue line) and real-time locational marginal price (red line). Exhibit 14 shows that CAES has negative power output (-60 MW) during charging mode and positive power output (72 MW, 145 MW and 290 MW) during discharging mode. The exhibit also illustrates that CAES is charged with its maximum power of 60 MW, while during discharge the output level may vary. For example between the 72nd and the 96th hour of a given week, CAES will be discharged with 290 MW if the real-time locational marginal price is ~$62/MWh, then it will be discharged with 145 MW when the real-time locational marginal price decrease to $60/MWh and CAES will be again discharged with 290 MW when the real-time locational marginal price increases to ~$65/MWh.

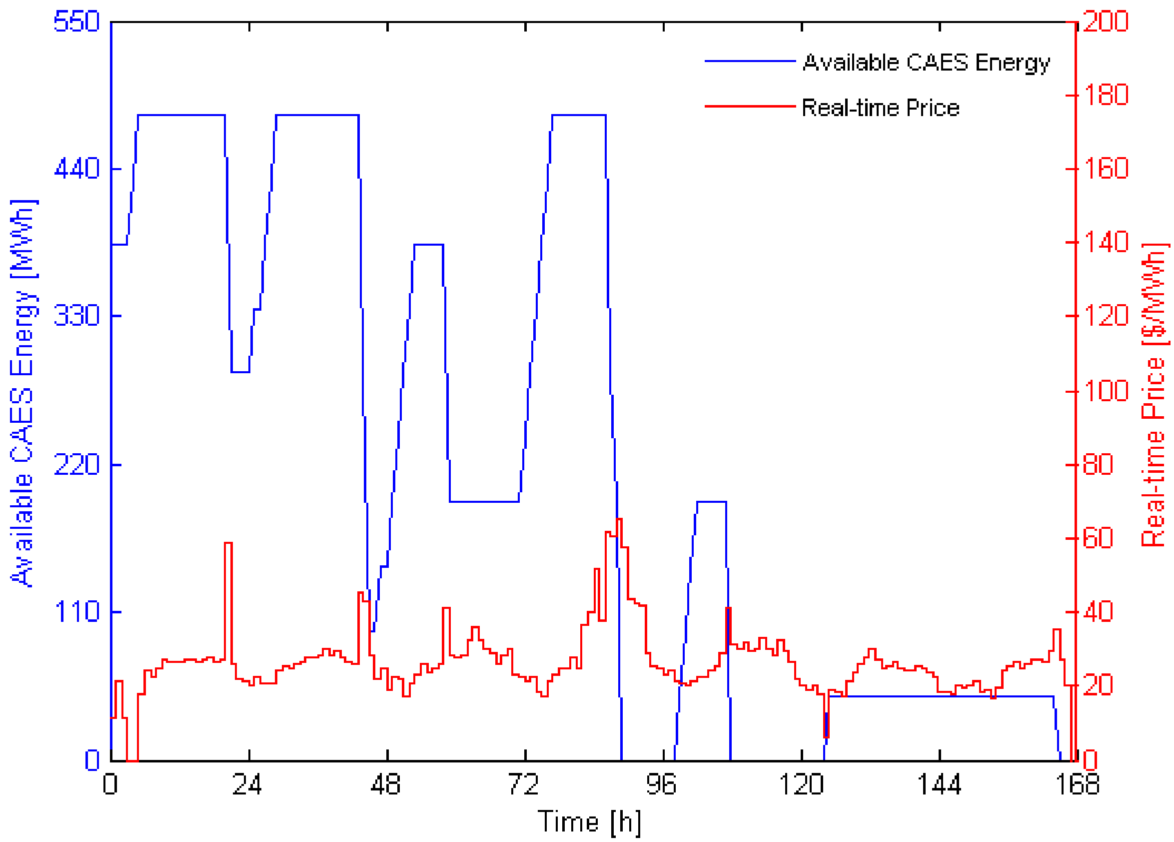
Exhibit 14 Huntorf Power Plant Optimal Schedule without Wind (CAES Power Output)



CAES will not be charged at all if the market price is low and non-volatile. For example between the 144th and 168th hour of a given week, CAES will not be charged since the real-time locational marginal price is ~$20/MWh during the night and ~$35/MWh during the day. For CAES to be profitable, the difference between charging and discharging price should be more than $22/MWh because cost of discharging CAES is at least $22/MWh.[8] Total profit for the week is $40,391.

Exhibit 15 shows available CAES energy during one week that corresponds to charging/discharging profile shown in Exhibit 14. The available energy would show more periodic behavior if previously developed models, such as PROMOD, are used because they charges CAES during weeknight and discharged during weekdays. The proposed model does not follow the same predefined pattern. The model increases profit by charging/discharging CAES regardless of time of day.

Exhibit 15 Huntorf Power Plant Optimal Schedule Without Wind (Energy)



The CAES optimal schedule is the same for the case with wind (Exhibit 16 and Exhibit 17). Exhibit 16 shows CAES power output (blue line), wind power plant power output (dotted blue line) and real-time locational marginal price (red line) while Exhibit 17 illustrates available CAES energy (blue line) and real-time locational marginal price (red line). Without wind, the

[8] Huntorf power plant uses 1.56 kWh of fossil energy to produce 1 kWh. If natural gas price is $4.09/MMBtu, CAES discharging cost is 1.56 kWh*$4.09/MMBtu÷293 MMBtu/kWh per kWh = $0.021/kWh or $21.7 /MWh.

total profit is $40,391 per week, while the CAES/wind profit is $201,056 per week. The increasing profit is due to charging CAES with low-cost power[9] and selling excess wind-generated power to the energy market. It is interesting to notice that CAES will not be charged during the period of low and non-volatile real-time locational marginal energy prices regardless of wind power. For example, between the 144th and 168th hour of the given example week, the wind power is very high. However, the CAES is not charged during these hours. Such CAES behavior has a very simple explanation. The CAES discharging cost is not equal to zero since natural gas is used during the discharging mode. The CAES cost of producing 1 MW of electricity is around $22/MWh. For the given example, this means that CAES owner should decide if he will sell around 220 MW of wind power for ~$20/MWh or if he will store 50 MW of wind power and sell it later. However, if the owner chooses the latter scenario, he will lose money because 220MW*$20/MWh = $4,400 is higher than 170MW*$20/MWh+50MW*($36/MWh-$22/MWh) = $4,100. From the 144th hour, the maximal locational marginal price is around $36/MWh and operator's profit is only $14/MWh because the CAES dispatching costs are $22/MWh. Wind power plant will be used to charge CAES only if it can get larger on-peak energy revenue through a CAES. CAES will be charged only if locational marginal off-peak price is less than future locational marginal price minus $22/MWh. In this example when off peak price is ~$20/MWh (time between the 144th and 168th hour), CAES will be charged only if any future locational marginal price is higher than $42/MWh. This simple calculation shows the reason for using a dynamic programming approach. If the CAES operator takes into consideration only the present generation cost and market energy price, he may decide to charge CAES during high wind. However, a proper calculation methodology must account for what will happen in the future by considering the likely wind availability and locational marginal price value.

[9] Since the main idea of the examples is to show CAES profitability when it is used with different technologies, it is assumed that wind power plant already paid off its capital cost, its operating (fuel) costs are very low and the wind power plant owner is a price taker. Deciding if it is profitable to build a wind power plant or developing a business case for a wind power plant is not a subject of this report.

Exhibit 16 Huntorf Power Plant Optimal Schedule with Wind (Power)

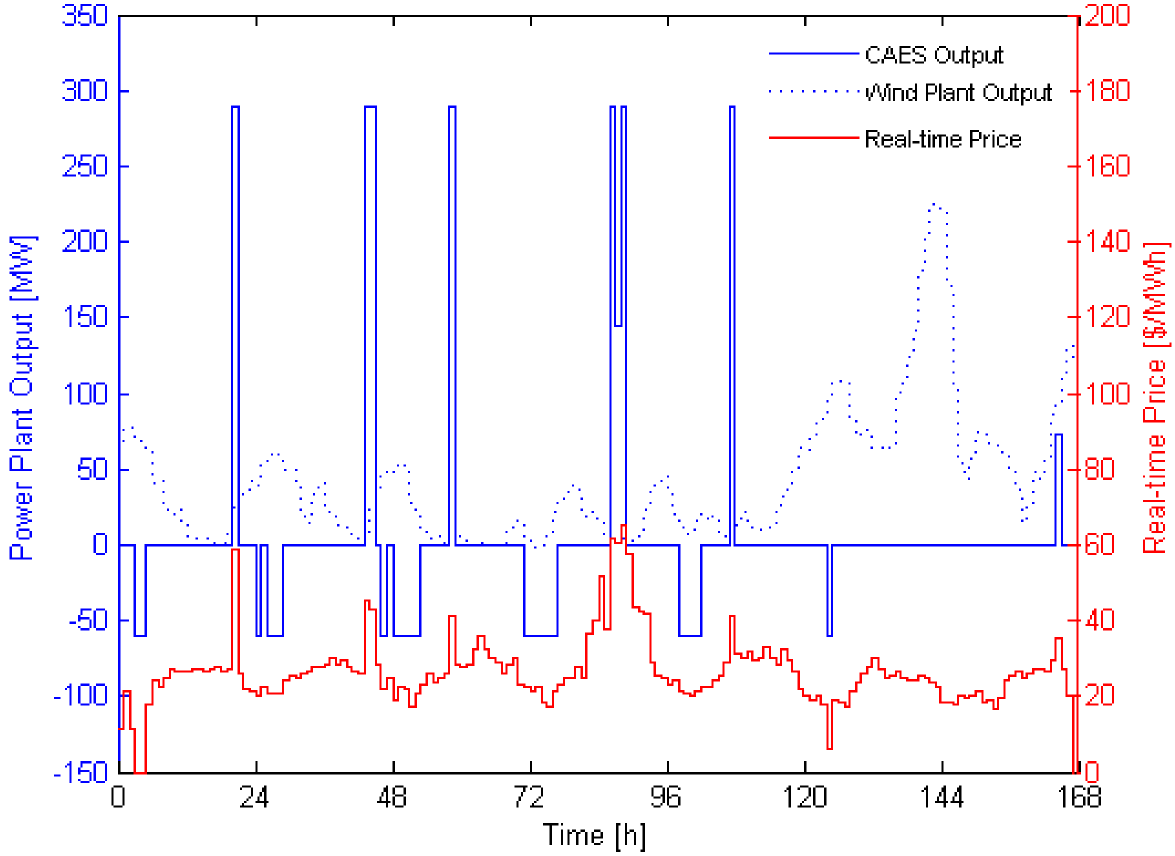


Exhibit 17 Huntorf Power Plant Optimal Schedule with Wind (Energy)

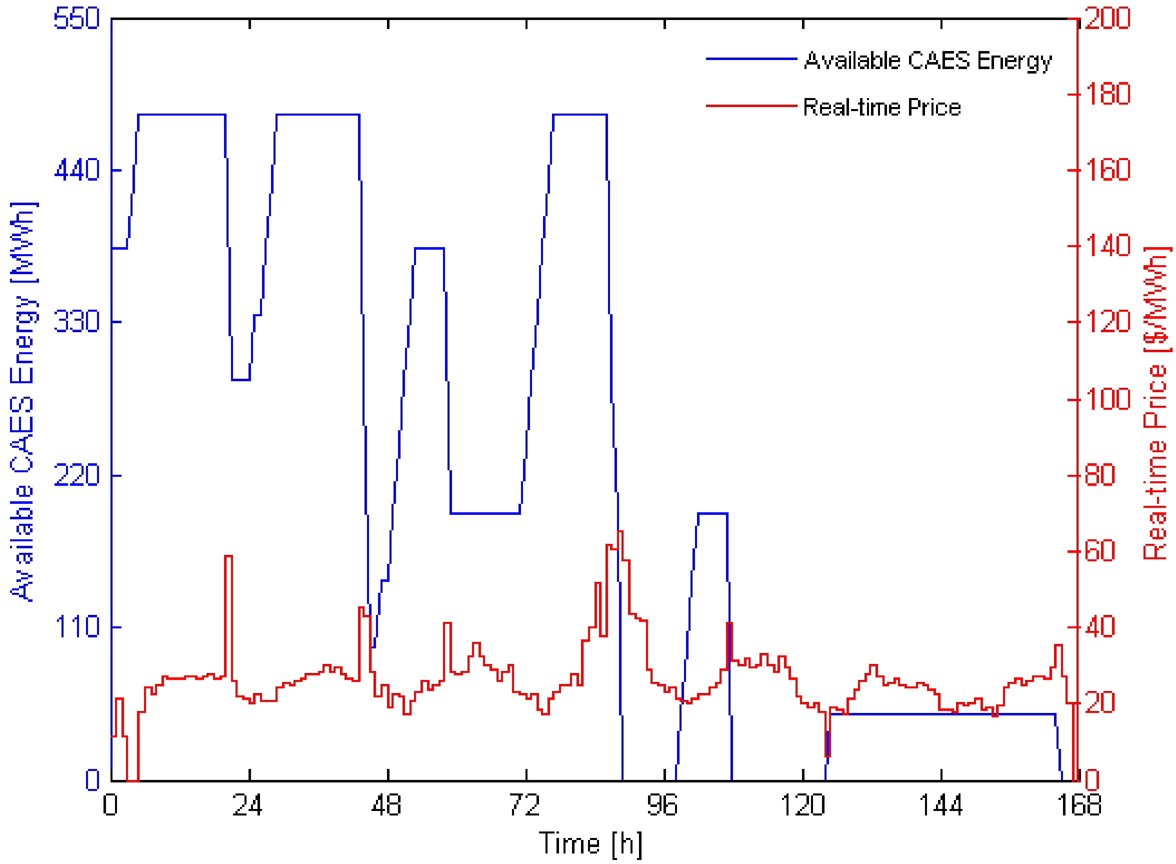


Exhibit 18 shows the impact of wind power on the CAES optimal schedule. The optimal scheduling is the same as in Exhibit 16 regardless of higher wind power. The maximum charging power (60 MW) limits the CAES to being charged faster during hours with high wind. The maximum charging power is a technical constraint that limits the speed of CAES charging/discharging because it limits the maximum power that can be used during charging/discharging process. This technical limit together with maximum capacity of the CAES volume determines how long it will take CAES to be fully charged/discharged. In addition, the low and non-volatile locational marginal power price also impacts the CAES charging/discharging profile. The profit in this case is $365,154.

Exhibit 18 Huntorf Power Plant Optimal Schedule with Hypothetical Wind (Power)

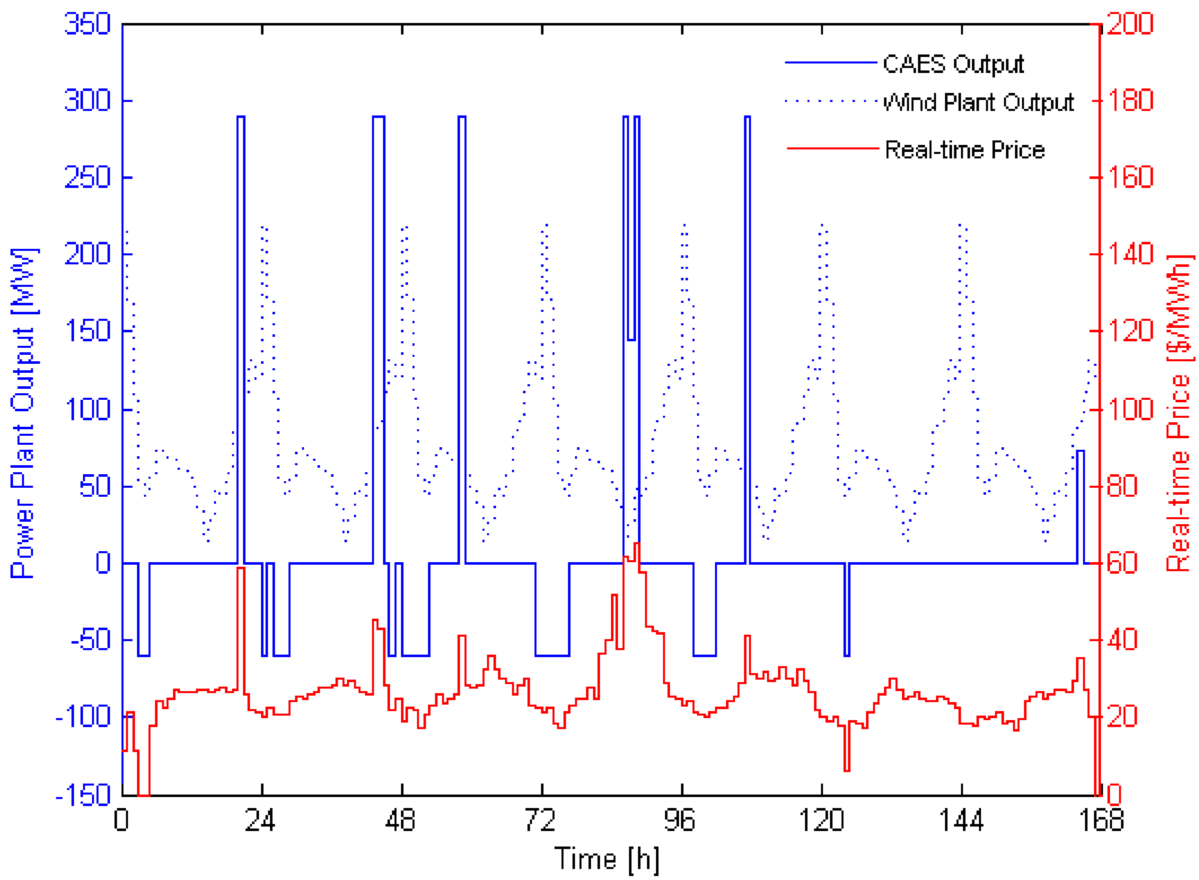
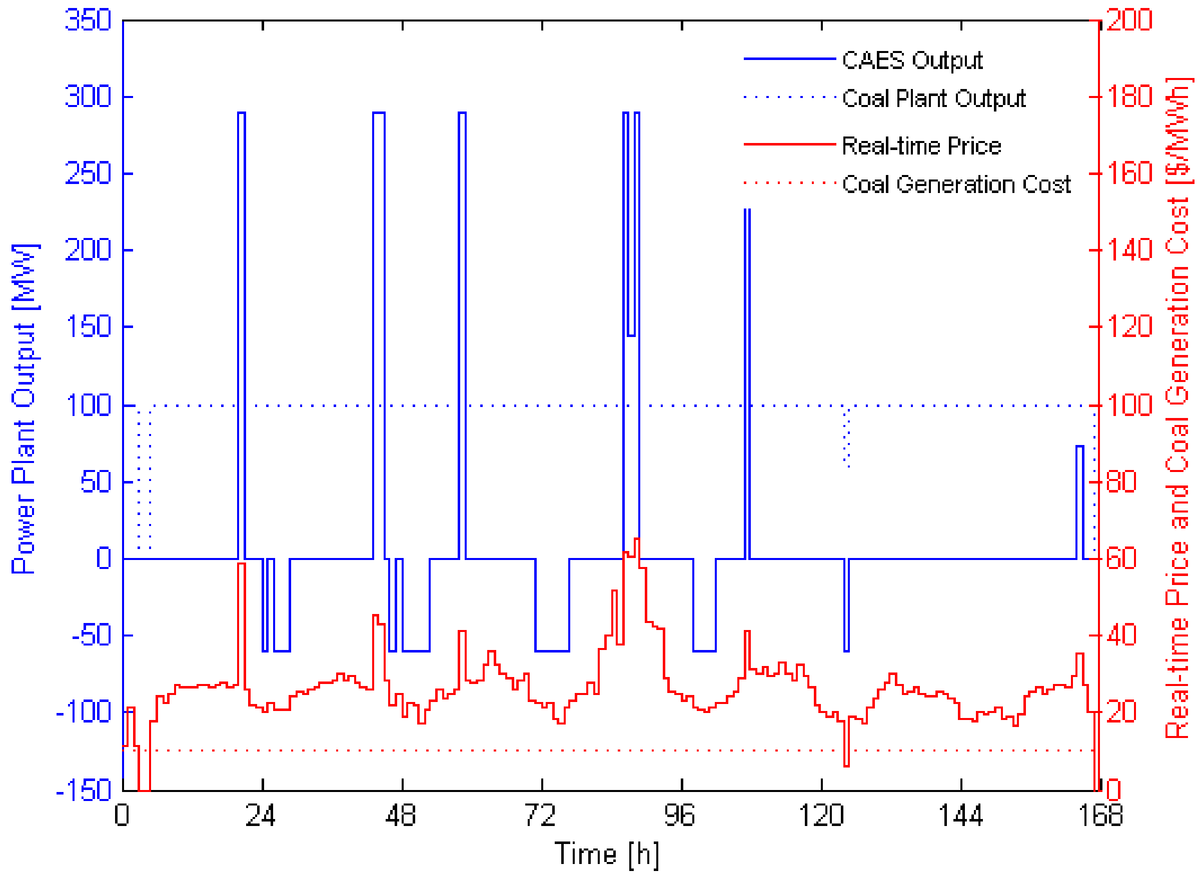


Exhibit 19 illustrates the optimal CAES/coal scheduling scenario. The scheduling profile is similar to the CAES/wind scheduling profile, in part because the low coal generation cost of $10/MWh. However, the optimal weekly profit is $316,763. The coal generation cost (dashed red line) is almost always lower than the locational marginal price (red line), and the coal power plant works at full capacity (dashed blue line) almost all the time. This analysis assumes that coal power plants will have 100 MW, 60 MW, 30 MW, or 0 MW outputs, depending on the market clearing price. If the coal generation cost is lower than or equal to the locational marginal price, the coal power plant will work with full capacity (100 MW). The coal power plant will produce 60 MW or 30 MW if the coal generation price is higher than the locational marginal price but it is profitable to charge CAES and sell the stored energy during peak hours. The coal power plant will produce 0 MW if the coal generation cost is higher than the locational marginal price and the cost of charging CAES cannot be returned by selling the stored energy at a higher price. 100 MW, 60 MW, and 0 MW coal power plant outputs are shown in Exhibit 19.

Exhibit 19 Optimal CAES Scheduling with Coal Power Plant (Coal Cost = $10/MWh)



If the coal generation cost is $25/MWh, the maximum weekly profit is $94,175. The scheduling profile is given in Exhibit 20. If the coal plant generation costs are higher than the locational marginal price, the coal power plant will be used to charge CAES if it is profitable, and the stored energy can be sold during peak hours.

Exhibit 20 Optimal CAES Scheduling with Coal Power Plant (Coal Cost = $25/MWh)

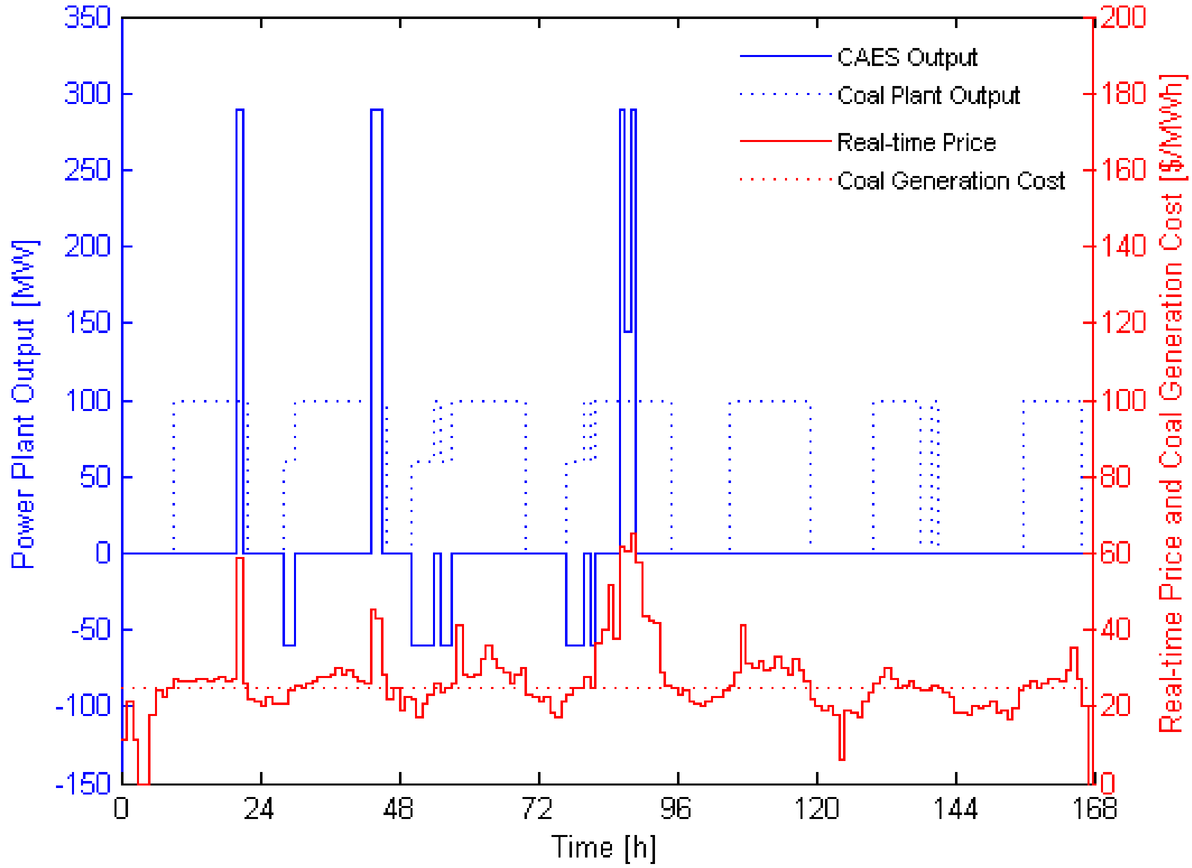


Exhibit 21 illustrates the optimal coal power plant scheduling when the coal generation cost is $25/MWh and there is no CAES. The total profit is $59,024. Comparing Exhibit 20 and Exhibit 21, it can be concluded that the coal power plant is better utilized if CAES is used.

Exhibit 21 Optimal Coal Power Plant Scheduling (Coal Cost = $25/MWh)

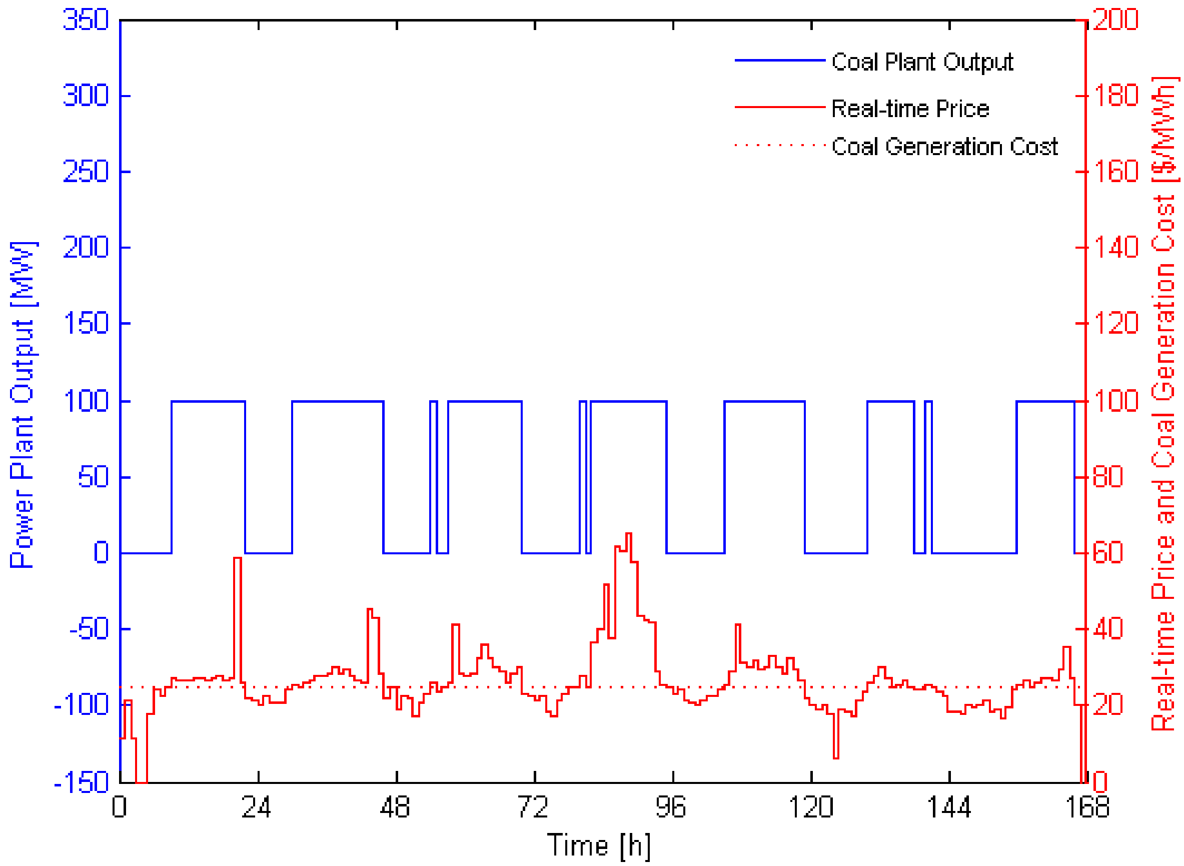
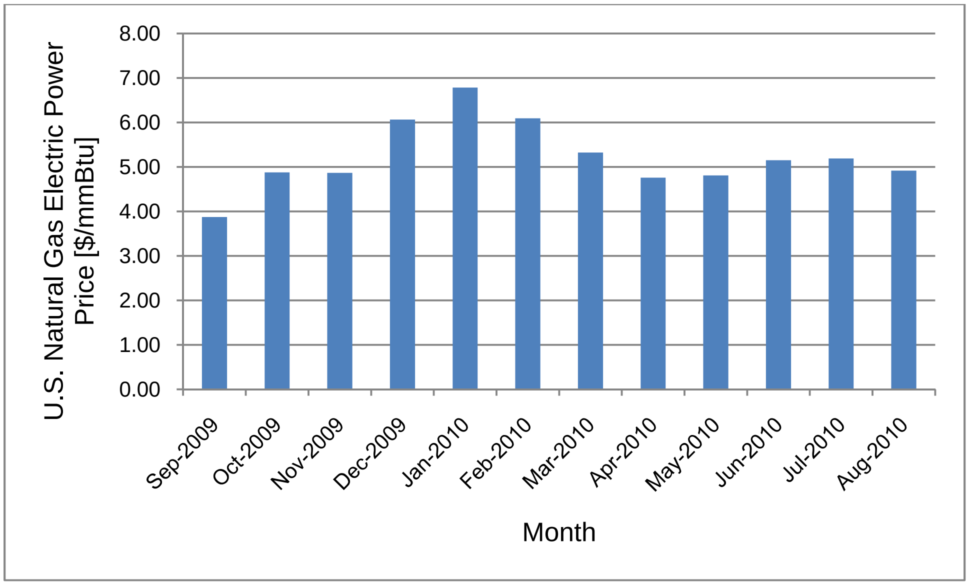


Exhibit 21 illustrates that when the locational marginal price is lower than the coal generation cost, the coal power plant will produce 0 MW. However, if the coal power plant is accompanied with the CAES and CAES can be charged only from the coal power plant (without using power from the grid), the coal power plant scheduling will be different because it will be used to charge CAES during hours when it would otherwise be shut down.

2.3.2 One-Year Time Horizon

To show yearly profits, the one week's data were expanded to one year's data. The real-time locational marginal price was obtained from the PJM website (PJM, 2010) for period of September 1, 2009, through August 31, 2010. Wind power data, for the same period, were obtained from the Velocity Suite: PJM Zonal Wind generation. The natural gas price for the same time period is assumed to have changed monthly (Energy Information Administration, 2010). The monthly natural gas price is shown in Exhibit 22. The coal power plant generation cost is assumed to be $10/MWh.

Exhibit 22 Natural Gas Price for 9/1/2009 – 8/31/2010



The same nine scenarios were analyzed on an annual basis, and the results are summarized in Exhibit 23. These results cannot be obtained by simply multiplying results from Exhibit 12 by 52 weeks because the real-time prices, wind profiles, and natural gas prices change over the year.

Exhibit 23 Analyzed Scenarios and Results (Annual)

Plant Configuration	Huntorf Annual Profit [$]	McIntosh Annual Profit [$]
CAES only	$6,565,227	$6,950,592
Wind only	$70,736,222	$70,736,222
Coal only (Coal generation cost: $10/MWh)	$28,631,680	$28,631,680
Natural Gas only	$2,619,610	$2,619,610
CAES/Wind	$77,301,449	$77,686,814
CAES/Coal (Coal generation cost: $10/MWh)	$35,163,588	$35,553,960
CAES/Natural Gas	$5,738,651	$6,369,764
CAES/Wind/ Coal (Coal generation cost: $10/MWh)	$105,930,389	$106,316,471
CAES/Wind/Natural Gas	$79,685,155	$80,082,257

The simplest net present value (NPV) analysis is used to determine if the profit is enough to recover investments. NPV of annual profit is calculated as

$$NPV = \sum_{t=1}^{T} \frac{CF}{(1+i)^t} \qquad (10)$$

where *NPV* is net present value of cash flow, *T* is time over which cash flow is discounted, *CF* is cash flow during time *t*, and *i* is discount rate. Assuming T = 25 years, the same annual profit for all 25 years, and CAES capital cost of $600/kW (Geschler, 2010), Exhibit 24 and Exhibit 25 show annual profit NPV for different discount factors. They also show if project will be paid off in 25 years. If the annual profit NPV is larger than the power plant capital cost, the project payback period is shorter than 25 years. Otherwise the project payback period is longer.

Exhibit 24 Net Present Value of Cumulative Annual Profit (Huntorf)

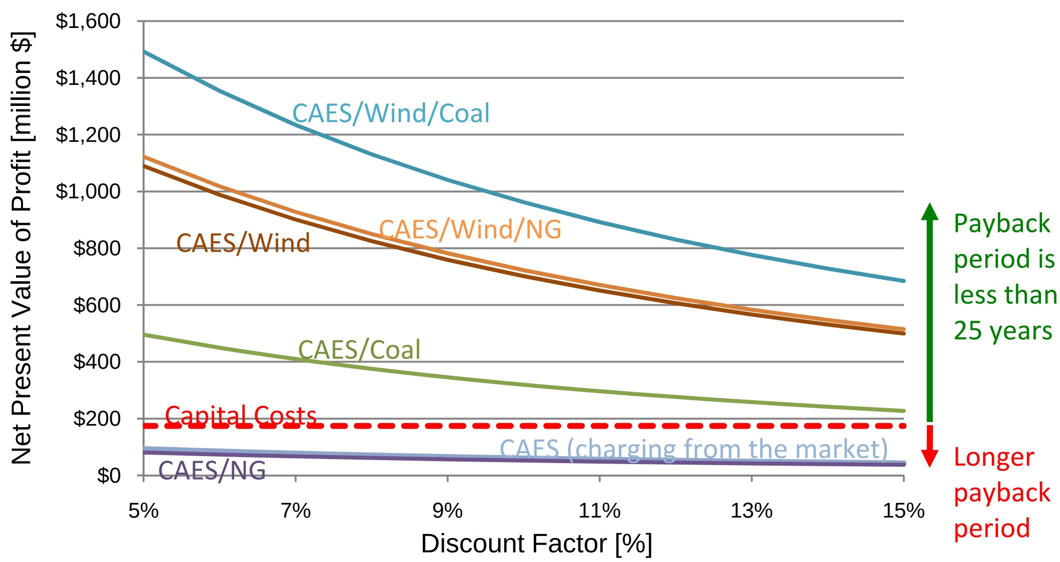
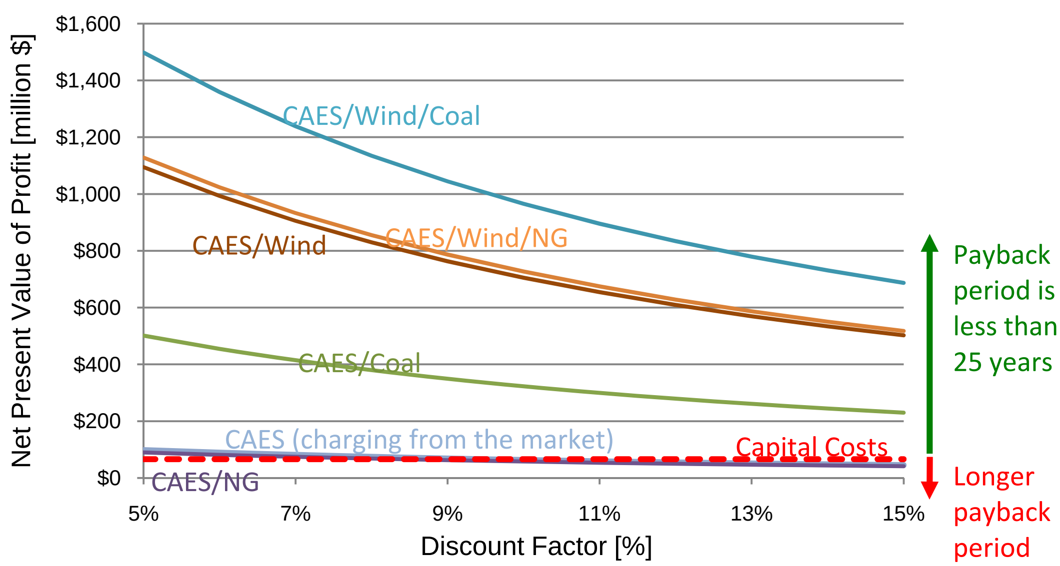


Exhibit 25 Net Present Value of Cumulative Annual Profit (McIntosh)



In both cases, CAES/NG and CAES are the combinations with the smallest profit. Depending on the discount factor, CAES/NG and CAES may have payback period less than 25 years for the McIntosh power plant, but for the Huntorf power plant payback period can be much longer. The CAES/Coal combination is the most realistically profitable for a CAES owner. For both power plants this combination has payback period less than 25 years. CAES/Wind, CAES/Wind/NG, and CAES/Wind/Coal are the combinations with the highest profits. However, these combinations depend heavily on the wind profile. For the given PJM wind profile, these combinations are highly profitable regardless of the discount factor, but in different areas with different profiles this may not be the case.

2.4 Summary

An NETL CAES Operational Guidance model was developed that determines the optimal CAES scheduling that maximizes profit and takes into consideration the technical characteristics of the power plant. The optimal schedule depends on real-time price and wind power. The real-time price and wind power are forecasted values. However, in this analysis we used historical values for simplification.

It is important to note that CAES charging during low demand (and low prices) and discharging during high demand (and high prices) is dependent on future demand and price. CAES will have a different charging/discharging profile for each day due to daily price changes. The better predictors of future wind profile and demand will improve the ability of the model to be exercised for maximum profit. The model is constructed with capital recovery costs, so this tool can also be used in planning and project financing, not just for operational guidance.

This study is a proof of concept. Different objectives and constraints can be formulated for different power plants with different parameters. Furthermore, this model can readily be adapted to incorporate the economic impact of the other services CAES can provide such as frequency regulation.

The study shows that CAES projects are profitable in combination with wind power plants and/or coal power plants. CAES in combination with natural gas may be profitable. However, it will depend on the size of CAES power plant and assumptions used in the financial analysis.

3 Simulations of Compressed Air Energy Storage Operations

The three major stages in the CAES operations (compression, storage, and generation) could be operated in different ways and using different plant configurations. The operational regimes can be classified as follows:

- Adiabatic: There is not any heat loss from the process to the ambient. The only heat loss happens in the underground heat storage.
- Diabatic: This method dissipates heat into the ambient. This approach is studied because, thus far, it is the only method commercially implemented.

3.1 CAES Efficiency

There are different points of view and therefore different methods discussed in the literature for calculating CAES efficiencies. This is partially because combining thermal and electric parameters is not straightforward. Choosing the relevant expression for efficiency ultimately depends on the application at hand and the purpose of the work (Succar & Williams, 2008). Different approaches are usually considered (NETL, 2010) to define the CAES efficiency, including the following:

- Equivalent fuel basis: The CAES plant might use more than one type of energy source, e.g., electrical from wind and thermal from natural gas. All of these energies are converted to a fuel-basis based on the heating value of the fuel and the plant performance.
- Equivalent electricity basis: Various types of energy are converted to equivalent electricity based on the fuel heating value and the plant performance.
- Adjusted equivalent electricity basis: This method adjusts the "equivalent electricity basis" by subtracting out the assumed contribution to the electrical output attributable to the fuel.

The first method is a representation of the overall electrical generation system efficiency. It is usually applied to CAES units charged by nuclear, fossil fuel plants, combined heat and power, and grid-averaged power plants (Zaugg, 1975). Arsie et al. have applied a modified version of this efficiency formulation to the wind/CAES systems (Arsie, Marano, & Nappi, 2005). An "atmospheric wind turbine efficiency" is used to convert the wind turbine electric energy to an equivalent thermal energy. This energy is then added to the thermal energy used in a turbine and the sum is used to calculate the overall efficiency. This approach has been referred to as "not optimal" (Succar & Williams, 2008) because in contrast to the fossil fuel and nuclear plants, the extraction of energy from wind does not affect the overall plant cost.

The second method above is not considered an actual representation of the efficiency since the energy input to the compressor is stored and the electrical equivalent of the turbine fuel is over-estimated.

The third method above represents a more realistic efficiency index for the compressed energy storage systems as it accounts for the fuel contribution to the electrical output. The fuel contribution can be accounted for by estimating how much electricity could be produced by the consumed fuel. The efficiency index can also be adjusted by accounting for the fuel used for compression (Denholm & Kulcinski, 2004). Depending on the fuel contribution adjustment method, the reported CAES efficiencies are in the range between 66 percent and 82 percent (Succar & Williams, 2008).

The simulations in this study allow for the calculation of any of the above discussed efficiency indices. Since this work is of exploratory nature, the following general efficiency will be used for all cases:

$$\text{Efficiency} = \frac{(\boldsymbol{Total\ Energy\ Output})}{(\boldsymbol{Total\ Energy\ Input}) - (\boldsymbol{Energy\ Remaining\ in\ Storage})} \qquad (11)$$

Since compression and electricity generation are done at different times and possibly for different time durations, the “Energy remaining in storage” is the difference between the stored energy at the beginning and the end of a charge/discharge cycle. This energy difference can be positive or negative.

Other types of efficiency can be calculated for selected plants to provide a meaningful comparison with the literature-reported efficiencies and the efficiencies reported by the stakeholders.

3.2 CAES Designs

Various CAES process configurations can yield different efficiencies and costs. The following sections discuss selected configurations to evaluate the efficiency and the costs associated with them, including but not limited to:

- Conventional CAES (occasionally referred to as the first generation CAES). The Huntorf plant built in Germany (Crotogino, Mohmeyer, & Scharf, 2001) is a good example of such a configuration. This configuration serves as the “benchmark” for evaluating other configurations.
- Economized CAES using a recuperator. The turbine waste heat is recovered to preheat air before combustion. The McIntosh plant in Alabama (Energy, 2006) is an example of such a configuration.
- CAES coupled with a combined cycle power plant;
- CAES with injection of steam into the air to increase mass flow before expansion;
- CAES with a humidification cycle to humidify the air before expansion to increase mass flow;
- Adiabatic CAES, which recovers and stores thermal energy from the compression cycle to later reheat the air during generation.

In addition to the above list, there are other plant configurations recently introduced in the literature referred to as CAES 2 (Biasi, 2009). This new generation of CAES is aimed at providing unique flexibility for load management of renewable energy, smart grid regulation, synchronous reserve, demand power, and peak shaving management.

3.3 Different Storage Configurations

3.3.1 Adiabatic CAES

Heat loss to the environment is assumed to be zero. There will not be any additional fuel required if all the “loss mechanisms” are ignored. This approach has been the subject of research because of its promise of high efficiency (Bullough, 2004). In parallel to this is the “second generation” or CAES 2 technology. It minimizes the heat transfer to the environment by using an integrated recuperator and an air expander that makes use of the exhaust heat. This approach eliminates the need for a separate gas burner, thus reducing both the fuel consumption and emission. A CAES 2 storage unit is expected to have 60 percent less consumption of fuel compared to a single cycle and 40 percent less compared to a combined cycle power plant (Narret).

3.3.2 Diabatic CAES

The heat transfer losses to the environment (except for the air storage) are neglected in the adiabatic cases. In reality, it is not possible to completely eliminate the losses and therefore the efficiency is expected to be closer to 70 percent (BINE, 2008). The loss mechanisms, the thermodynamics, and the technical issues that limit the adiabatic operation will be identified and studied for various plant configurations. By running these models in “transient mode” the relationship between the storage time and heat loss to the environment could be studied. This would lead to the relationship between efficiency, time, and the plant configuration.

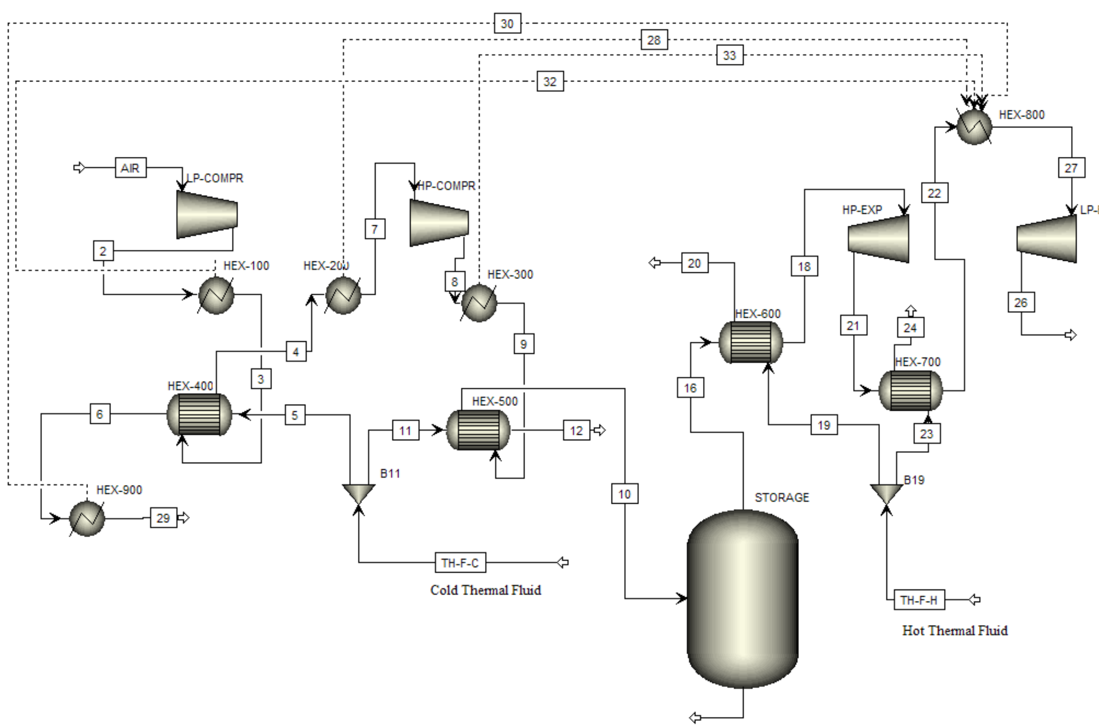
3.4 Adiabatic CAES Simulations Using Aspen

The adiabatic process was simulated in detail using the Aspen Simulation package, which is commercially available software and is capable of simulating processes in steady-state as well as time-varying (transient) mode. The advantages of using Aspen include the physicochemical properties packages for all the fluids, which are taken from the “property package” libraries, already pre-built-in. The simulator automatically and constantly checks on the energy and mass balances throughout all over the process flow diagram and thus eliminates any chance for operator mistakes in those areas. The process equipment and machinery are also simulated using the process modules existing in “equipment pallets” in Aspen. For example, the air “throttling” could be simulated by a partially open valve and this model already exists in the Aspen libraries and can be immediately used. The “Aspen Cost Estimator” could be used to develop the cost associated with each process configuration.

3.5 Simulating Air Compression and Expansion Using Aspen Plus

Exhibit 26 shows the process flow diagram of an air compression/expansion process that is simulated in Aspen Plus. The proprietary package includes the Peng-Robinson equation of state and the chemical components include oxygen, nitrogen, and Thermalane-800. The latter is a heat transfer fluid that circulates in the process to recover heat from the compressor and to return the heat to the air going through the expander. Excluding the underground air storage (shown by "Storage"), this process is set up to be completely adiabatic, meaning that there is no ambient heat transfer . This process does not consume natural gas (NG) to generate power; it simply compresses the air (LP and HP COMPR in Exhibit 26), stores it underground (STORAGE), and expands it again (HP and LP EXP) to generate power when needed. Heat exchangers (HEX-100 through HEX-300) adjust the temperature of the air as it goes through the two stages of compression and heat exchange with the heat transfer fluid. Heat exchangers, HEX-400 through 800, remove the heat from the air before going to the underground storage and transfer it back to the air before expansion. The results of this simulation are in agreement with the literature (NETL, Compressed Air Energy Storage-Technology Overview, 2010). In reality the CAES air compressor and expander will most likely not operate simultaneously to compress the air during off-peak and generate power when needed. Simulating this process therefore, would be the most realistic in the transient mode and Aspen Dynamics would be a suitable tool for this transient analysis, if available. However, Aspen Plus was used to perform the steady state simulations discussed in this section. It must be emphasized that the goal of these simulations is to show the trends and behaviors of the system rather than exact numerical values. The results are still valuable as they shed light on some critical characteristics and operational considerations as will be discussed in the following.

Exhibit 26 Adiabatic Air Compression/Expansion



The "storage" is a representation of the underground air storage and is not considered adiabatic as this would not be likely in a real CAES scenario. The material and energy balance for the entire process is shown in Exhibit 27.

Exhibit 27 Material and Energy Balance for Process Illustrated in Exhibit 26

Stream	2	7	8	18	21	26	27
Temperature C	358.3	75	366.5	257.0	4.5	94.2	309.2
Pressure bar	11.5	11.5	90	75	7	1	7
Vapor Frac	1	1	1	1	1	1	1
Mole Flow kmol/hr	18717.2	18717.2	18717.2	18717.2	18717.2	18717.2	18717.2
Mass Flow kg/hr	539999	539999	539999	539999	539999	539999	539999
Volume Flow cum/hr	85772.8	47050.9	11391.3	11260.4	61402.0	571671.4	129765.3
Enthalpy MMBtu/hr	176.1	24.8	180.6	120.0	-11.7	35.8	149.5
O_2, kmol/hr	3930.6	3930.6	3930.6	3930.6	3930.6	3930.6	3930.6
N_2, kmol/hr	14786	14786	14786	14786	14786	14786	14786
THERM-01, kmol/hr	0	0	0	0	0	0	0

An overall efficiency may be defined for the adiabatic process explained above and shown in Exhibit 26 as:

$$\text{Efficiency, \%} = \frac{Total\ Work\ from\ Air\ Expansion}{Total\ Work\ Required\ for\ Air\ Compression} * 100 \qquad (12)$$

Investigating this model reveals that assuming an adiabatic operation would yield an overall plant efficiency of about 75 percent from the above formula and process. The process performance depends on the thermal capabilities of the thermal fluid and the operating temperature of the thermal reservoir. Exhibit 28 shows a typical relationship between the expander exhaust temperature and the thermal reservoir temperature. For the sake of comparison this figure considers the well-head pressure equal in all cases at 65 bars. The exhaust temperature is directly related to the efficiency of the expander and therefore the entire plant. This relationship is shown in Exhibit 29. The thermal reservoir temperature is assumed to be constant at 330 C and the well-head pressure is changed from 45 to 75 bars. Exhibit 29 also shows how the storage efficiency is changing with temperature. The storage efficiency is defined as the following:

$$\text{Storage Efficiency} = \left[\mathbf{1} - \frac{(\boldsymbol{Storage\ Heat\ Loss})}{(\boldsymbol{Compression\ Work})}\right] * \mathbf{100} \tag{13}$$

It is shown that the heat loss increases with increased expander exhaust temperature and decreased well-head pressures as expected. Exhibit 28 shows that it is crucial to properly manage the time-schedule on which the storage is charged and discharged. From the point of view of heat loss to the ground, it is desired to have the lowest pressure in the storage. However, to operate the plant efficiently, it is crucial to have the highest pressure. The reservoir charge and discharge should follow these guidelines. These concerns hold true for diabatic plants as well.

Exhibit 28 Expander Exhaust vs. Thermal Reservoir Temperature

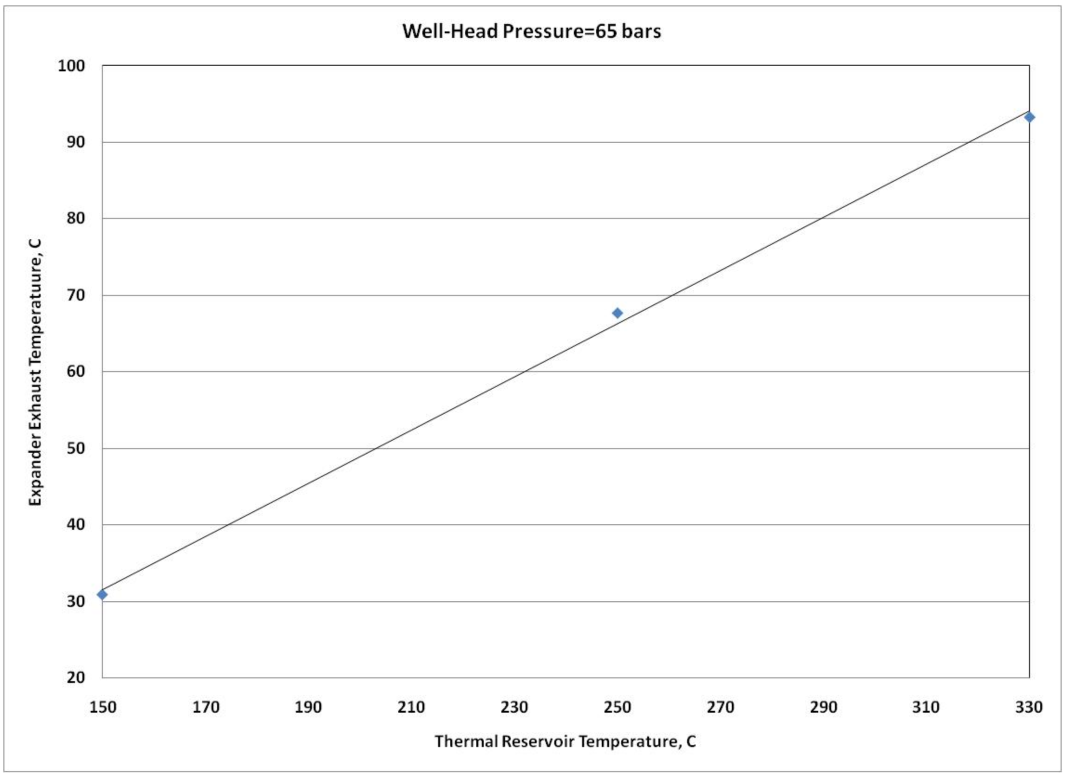


Exhibit 29 Plant and Storage Efficiency vs. Exhaust Temperature

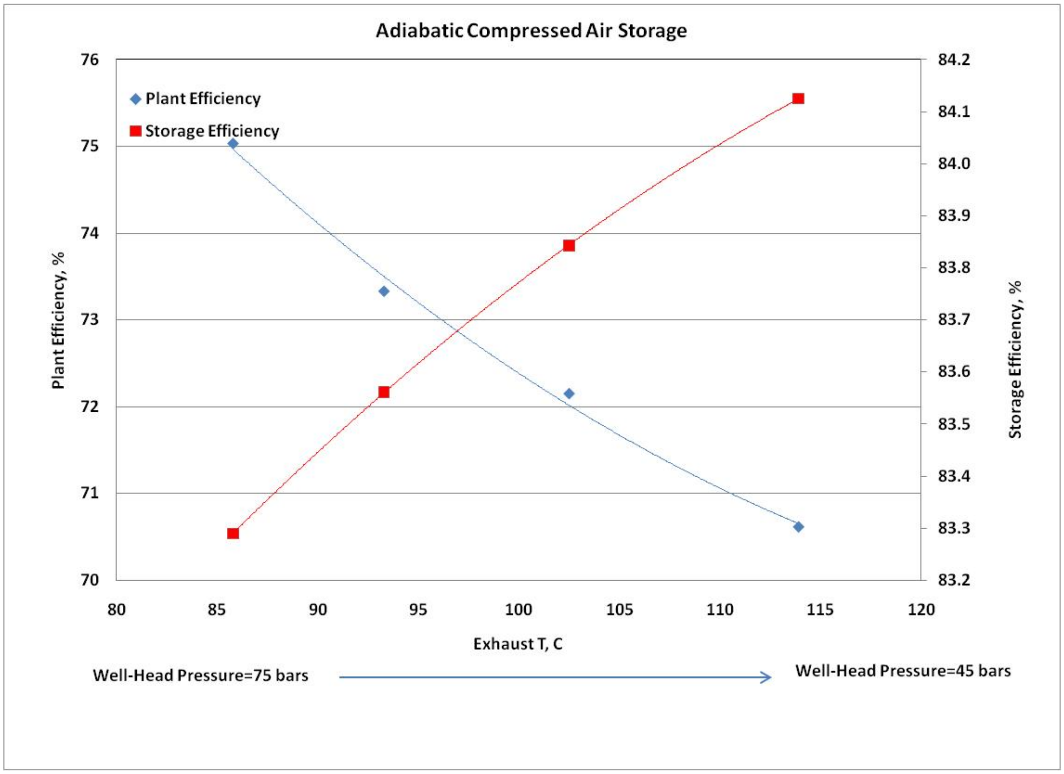


Exhibit 26 through Exhibit 29 assume an adiabatic process. However, in reality there is always some heat transfer reducing the efficiency. This would especially be true in a plant the size of CAES as the process is constantly exposed to ambient conditions. For this reason, the non-adiabatic model would be a better representation of reality. An illustration of such a plant's process is generated by removing the heat integration (dotted) lines in Exhibit 26 and connecting the stream 22 (Exhibit 26) directly to the low pressure one. This means that only part of the thermal energy stored in the gas is returned to the expander. The performance of the process would be different under these circumstances as lower energy would be available to maintain the temperature or to do efficient work. Exhibit 30 shows the efficiency of this non-adiabatic process vs. the exhaust temperature. Comparing Exhibit 29 to Exhibit 30 shows lower exhaust temperatures in the expander and lower overall process efficiency for the same operating range of the cavern pressure and the same thermal reservoir temperature, as expected.

In addition to the trends in the plant performance parameters such as efficiency, studying the plant under diabatic conditions reveals other practical limitations such as the possibility of ice-formation in the expander. In reality, such an event could cause serious damage to the machinery. Exhibit 31 shows the relationship between the expander exhaust and the thermal reservoir temperature. Similar to Exhibit 28, these cases are generated under the identical storage pressure of 65 bars. This figure demonstrates the possibility of freezing and ice-formations under more realistic, non-adiabatic conditions. Burning natural gas and inlet air heating are practical methods to adjust the temperature and to prevent the hazards of ice-formation. The concerns associated with freezing are mentioned in the literature. Exhibit 32 shows the exhaust temperature as a function of thermal storage capacity. According to this figure, if the compressed air is reheated using recycled heat from the compressor instead of natural gas, the thermal storage efficiency should be at least 90 percent to prevent freezing problems.

Exhibit 30 Plant Efficiency vs. Exhaust Temperature (Diabatic Process)

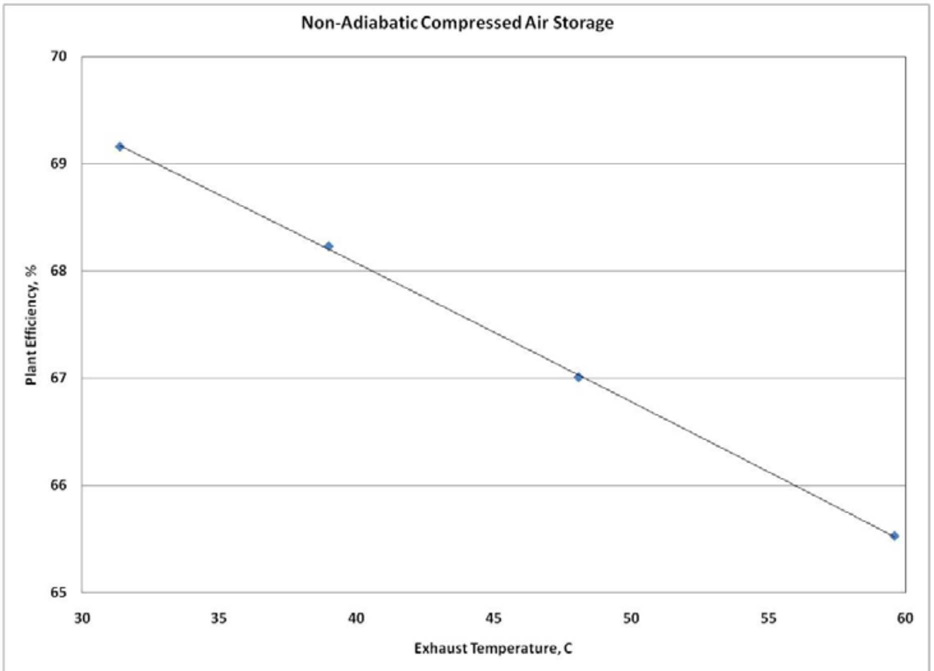


Exhibit 31 Freezing Could Easily Happen Under Realistic Conditions

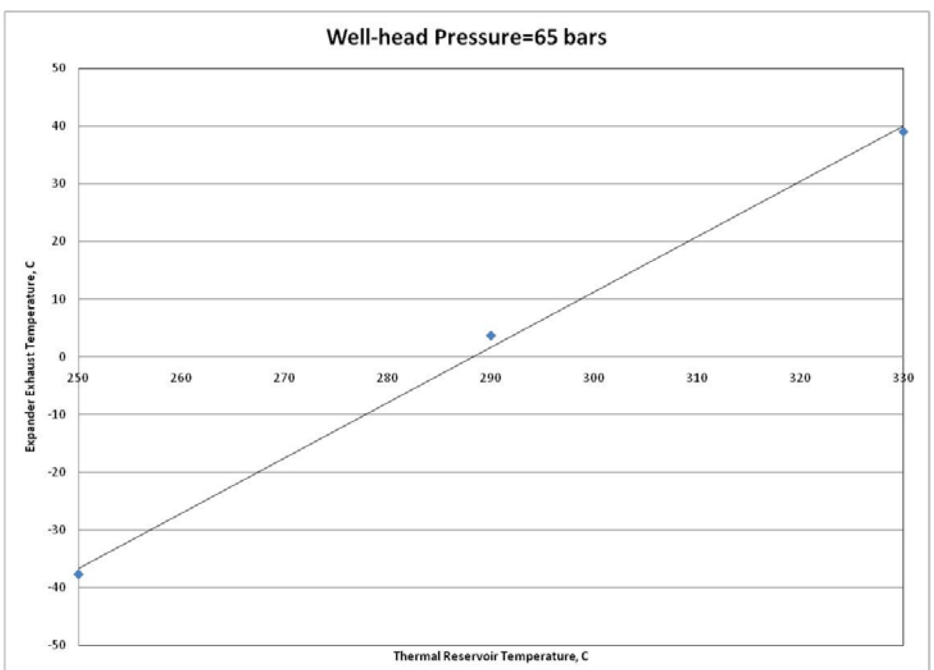
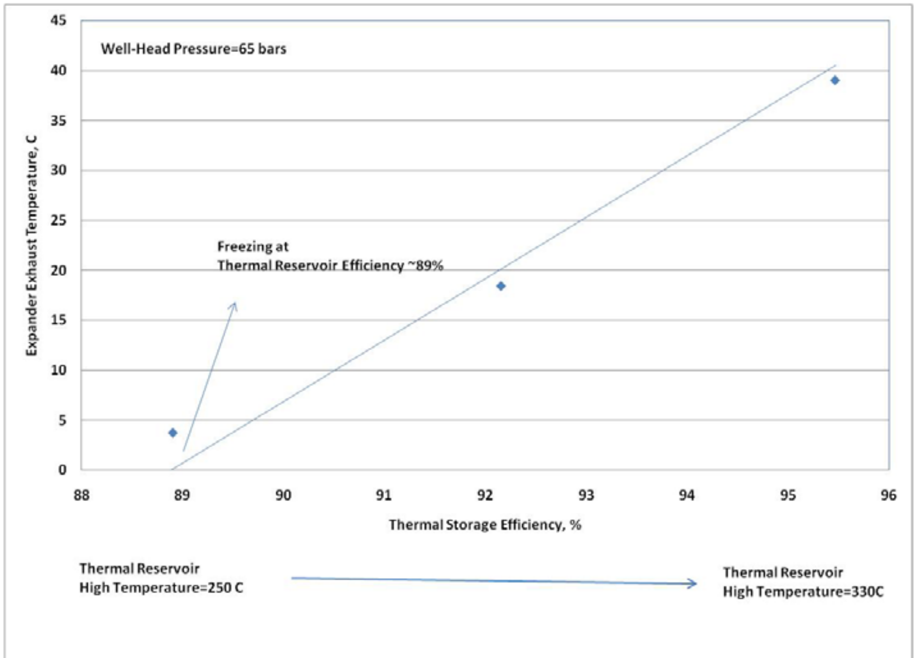


Exhibit 32 Expander Exhaust Temperature vs. Thermal Storage Efficiency



3.6 Summary

The above studies provide insight into the efficiency and cost of the various types of the CAES and plant configurations. They also provide insight into the effects of the storage environment on the CAES process. For example, CAES with storage in porous rock could have a different efficiency compared to the same plant using a cavern storage or above-the-ground storage and piping (EPRI-DOE, 2003). This study will shed more light on the technical and economic aspects of various modes and configurations of CAES. A final recommendation could be provided based on these findings and a few selected processes could be suggested based on cost and chosen efficiency measures. These results will identify a preferred plant configuration and how to operate a plant for an optimum overall performance.

The CAES stakeholders and builders will be accessed and interviewed not only to obtain real-world data and to verify the results but also to gain more insight into what would be desired by the customer and what solution could be developed for it.

The simulations presented in the previous sections were performed using Aspen Plus in the steady-state mode as mentioned. Although these simulations could create more insight into the nature and behavior of these processes, a more realistic approach using a transient analysis is highly recommended. The real processes do not operate in steady state; air is compressed and stored during the off-peak periods and used when needed. The air reservoir pressure changes during the charge and discharge. Studying the plant in the transient mode will further illustrate the importance of other critical process parameters such the reservoir volume. The problems that could arise from freezing in the expander/turbine are discussed in this report. A transient analysis can be performed to define the times and conditions under which specific reservoirs can operate to avoid the freezing, even without using natural gas.

The heat recovery process simulated in this report is simplistic; it is adiabatic and operates at constant temperatures. The hot and cold thermal reservoirs operate at different times and heat loss could happen. The extent of this heat loss will depend on the storage time (among other factors). A transient analysis defines this heat loss as a function of loss and would represent the plant performance more realistically. Various possible methods to recover heat and to increase the efficiency of the process can be investigated.

4 Summary and Recommendations

In this study, we analyzed siting decisions, charge-discharge strategies, and efficiency factors to better understand the potential for CAES systems to provide practical energy storage for intermittent sources in the U.S.

To identify geographic regions that might be good candidates for CAES siting, we made use of a methodology used by New York State Electric and Gas (NYSERDA, 2009). GIS methods were used to identify regions that simultaneously met desirable infrastructure, geological, and wind-resource criteria. The infrastructure criteria used were proximity (*i.e.*, within 20 statute miles) to natural gas lines, high-voltage transmission lines, and markets for wholesale electric power. Appropriate geologies considered were domal salt formations, bedded salt formations, and aquifers. Wind resources were considered sufficient at a level of Class 4+ or greater, which corresponds to a wind power density of greater than 400 W/m^2 at 50 m, or average annual wind speeds greater than ~7.0 m/s.

Locations within the continental U.S. that met all the desired siting requirements included sites in the upper Midwest, Great Plains states, Texas coast, Great Lakes coast, and upper Appalachian states. As a specific example, several regions in the eastern part of West Virginia were shown to be good candidates for CAES siting.

To get practical insight into how a CAES/wind system might be best operated, we developed a dynamic programming model that takes hourly electricity-price and wind-resource forecasts for a week as inputs, and provides a profit-optimizing operational charge-discharge strategy over the week as an output. During charging, if the available wind power was less than the maximum charging rate, grid power was used to make up the difference. If the available wind power was more than the maximum charging rate, the excess power was sold to the grid at market prices. During discharging, both stored energy and any real-time wind power were sold to the grid. The model takes into account technical parameters such as storage power capacity, energy capacity, ramp-up and ramp-down rates, and start-up and shut-down times.

We developed optimal charge-discharge strategies using technical data for the two existing CAES plants in Huntorf, Germany and McIntosh, Alabama; historical price data from the PJM Interconnection for a week in August, 2009; and historical wind data from the Velocity Suite: PJM Zonal Wind generation, for the same period. For comparison, we also showed optimal strategies for the CAES operations alone, with CAES charging from the grid during low-price periods, and sales back to the grid at high-priced periods. To see the effect of wind forecasts on optimal strategy, we developed a synthetic alternative wind profile and found the optimal dispatch.

In the analysis without wind, the optimal strategies for the Huntorf plant had CAES fully discharged more than once during days when prices were highly volatile. As expected, charging occurred primarily during times with low electricity prices, and discharging during high electricity prices. With the option to sell wind power directly, the Huntorf optimal schedule was similar.

We performed a similar modeling analysis for a hybrid CAES/coal and CAES/natural gas plant, assuming a nominal 100MW coal plant under high-cost and low-cost fuel scenarios and 100 MW natural gas plan. The profitability gains for the hybrid plant over CAES alone were even greater than for CAES/wind cases, and were nearly 25 percent of those for the coal plant alone.

We then developed models to investigate the effects of different operating parameters on efficiency through the compression and expansion cycles. As part of this analysis, we reviewed the literature and identified three ways to measure plant efficiency: equivalent fuel basis, equivalent electricity basis, and adjusted equivalent electricity basis. While retaining the ability to use any of these measures, we based our analyses on a more general definition involving total energy output, total energy input, and energy remaining in storage.

We modeled an adiabatic design that uses Thermalane-800 as the heat storage medium, with some heat loss during underground storage of the compressed air. The overall system efficiency was limited to approximately 75 percent by the physicochemical properties of the heat storage fluid, which degrades at the higher temperatures needed for higher theoretical efficiencies. We used the model to quantify the positive relationship between thermal reservoir temperature and expander exhaust temperature, and between expander exhaust temperature and plant and storage efficiency.

The model demonstrated how an increase in storage pressure increased the efficiency of the expander, but led to more heat loss in the storage phase. We extended the model to a diabatic design, and showed quantitatively how plant efficiency decreases as the expander exhaust temperature increases. As expected, there was a lower expander exhaust temperature and overall process efficiency for the same operating range of the storage pressure and the same thermal reservoir temperature. The model also showed the thermal reservoir temperatures for which icing may occur at the expander under realistic conditions for a diabatic design in the absence of additional heat input, such as from a burner.

These investigations provide insight into some of the more practical aspects of CAES design and operation. We recommend that agencies and firms use similar modeling and analysis approaches, using geographic, economic, and technical parameters appropriate to their applications, to make better decisions on siting, designing, and operating CAES systems. Specifically we recommend that

- Siting studies make use of all available GIS-based geological, infrastructure, and wind-resource data to identify more candidate locations for CAES systems
- Operators use dynamic-programming approaches to develop more profitable operating strategies, and to better estimate the financial performance of proposed CAES systems. In addition to the deterministic programming we demonstrated here using forecast data, stochastic dynamic programming techniques could be used for optimizing operations under uncertain price and wind environments.
- Planners make use of detailed modeling of process configurations and parameters to better understand the benefits, costs, and tradeoffs for different choices in design, configuration, and operations of CAES systems.

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Appendix A – Huntorf Power Plant Optimal Schedule

Exhibit 33 CAES Optimal Schedule (Power)

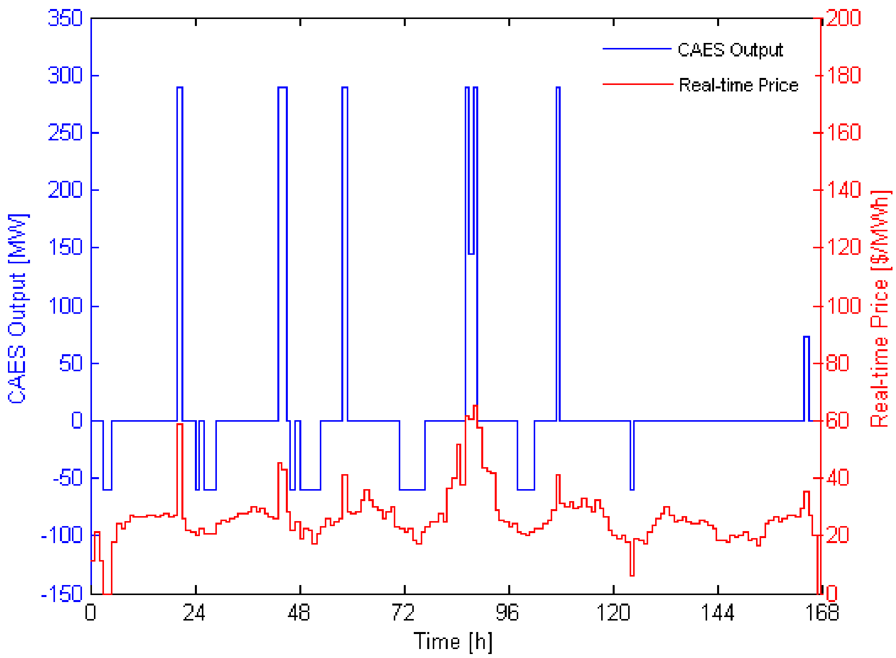


Exhibit 34 CAES Optimal Schedule (Energy)

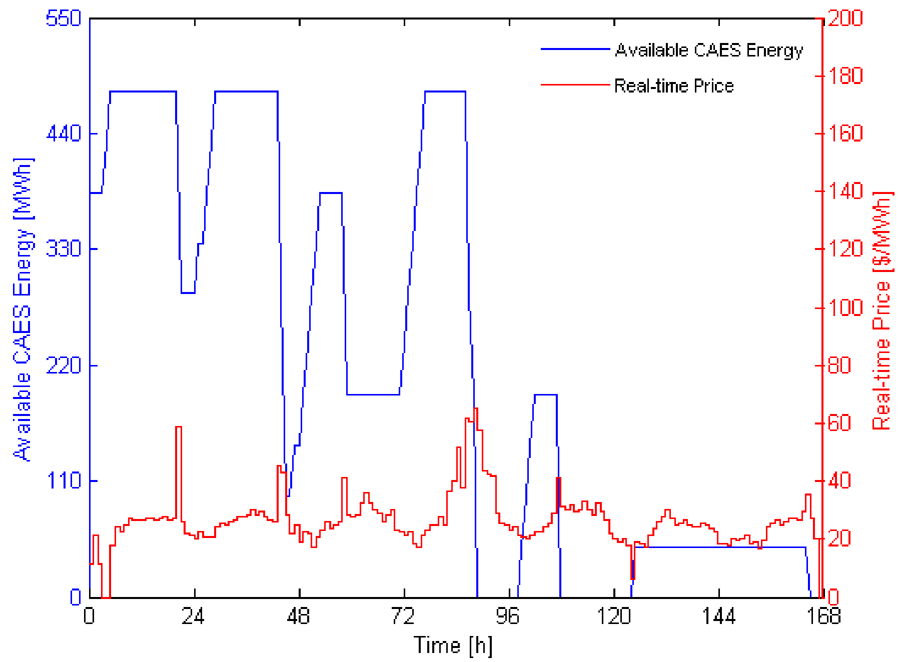


Exhibit 35 Wind Power Plant Optimal Schedule (Power)

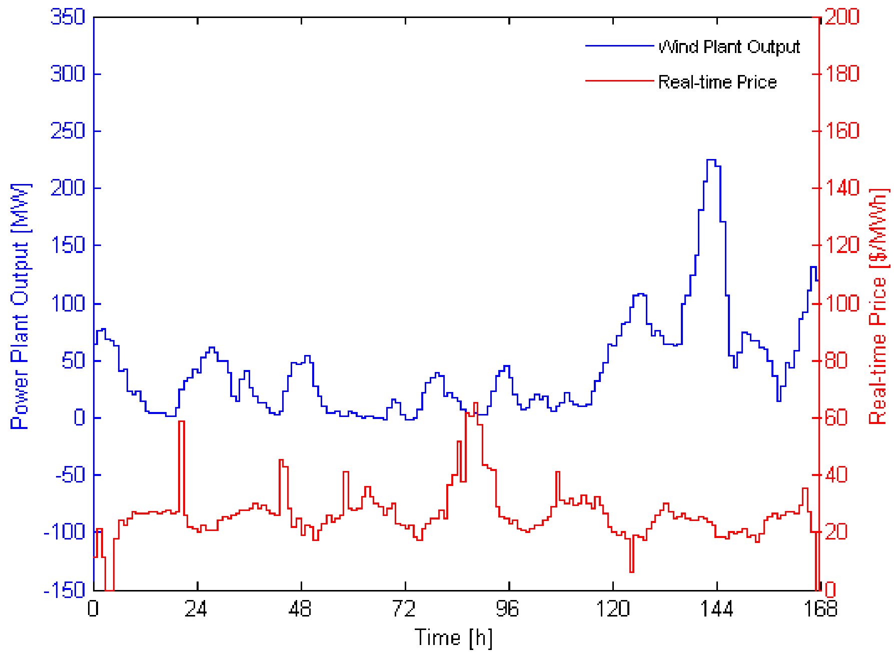


Exhibit 36 Natural Gas Power Plant Optimal Schedule (Power)

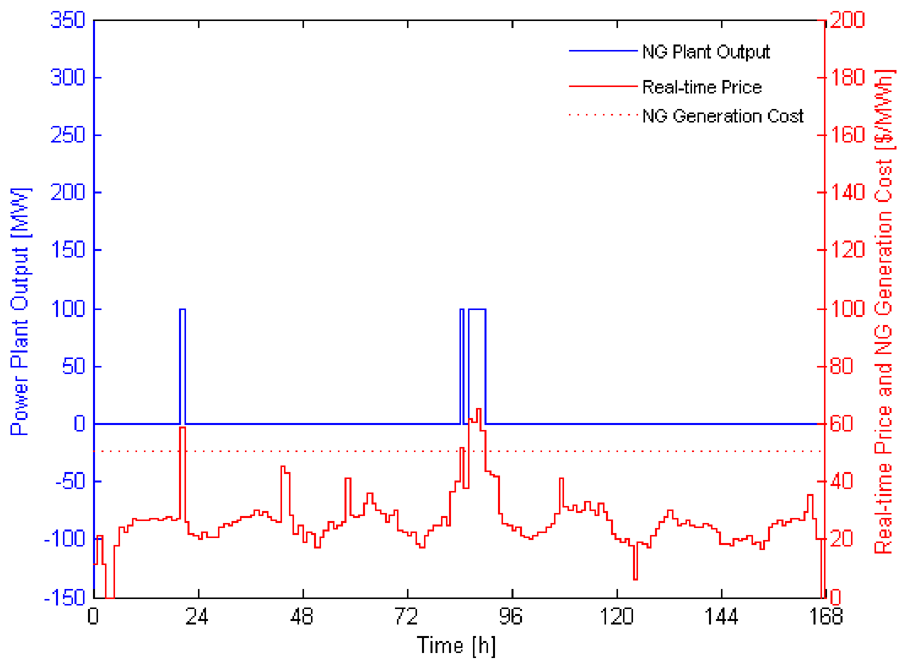


Exhibit 37 Coal Power Plant Optimal Schedule (Coal Cost = $10/MWh)

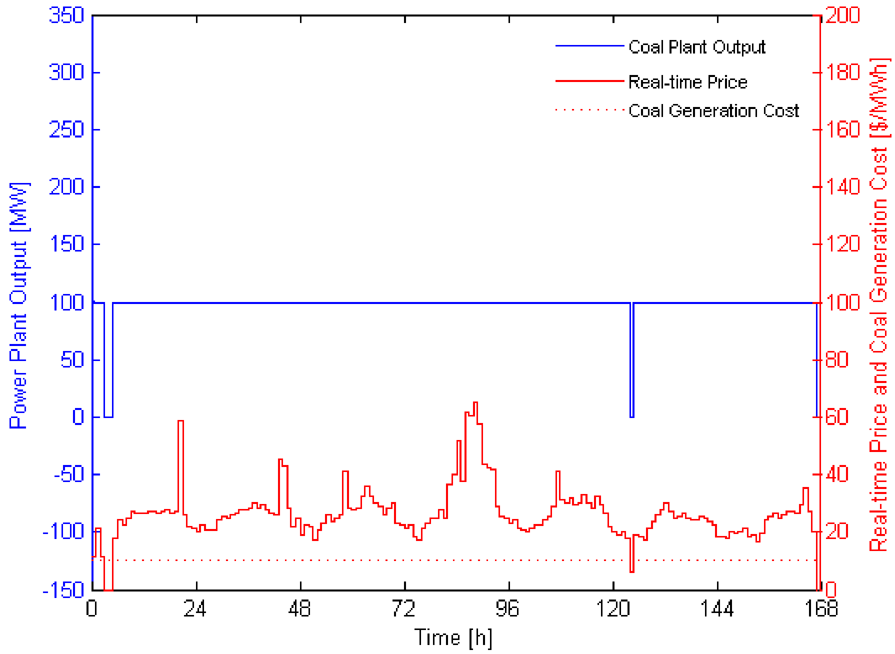


Exhibit 38 Coal Power Plant Optimal Schedule (Coal Cost = $25/MWh)

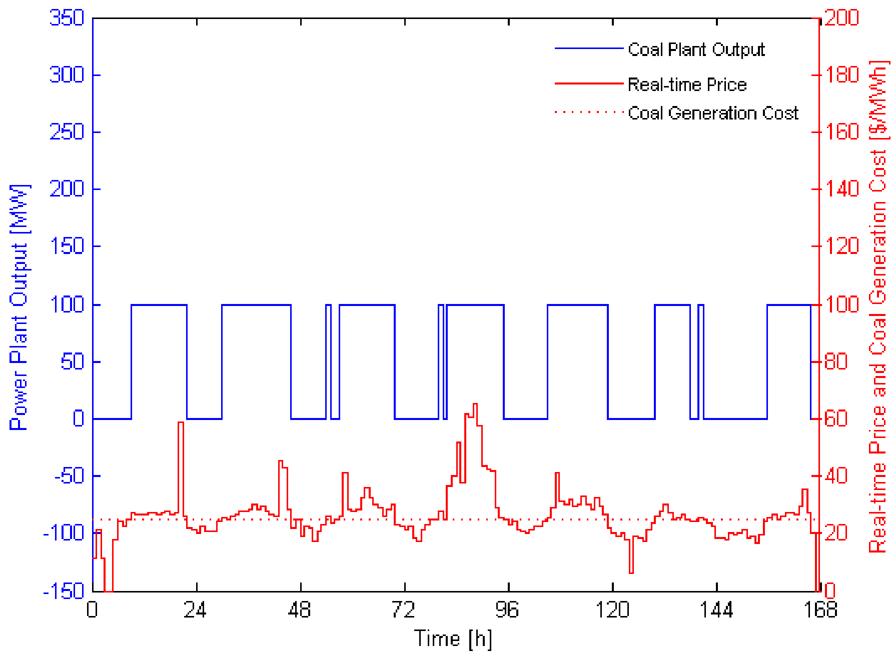


Exhibit 39 CAES Optimal Schedule with Wind (Power)

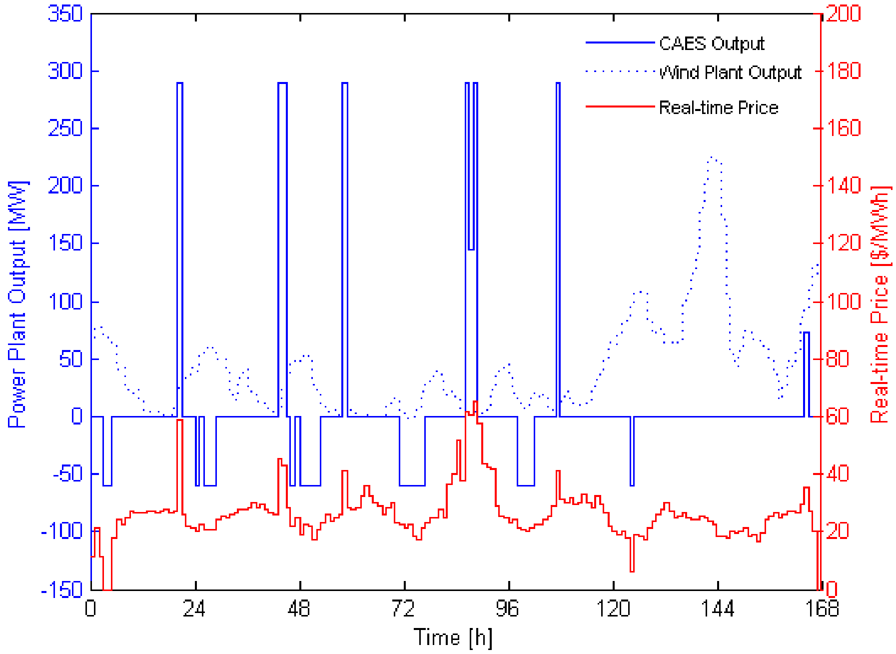


Exhibit 40 CAES Optimal Schedule with Wind (Energy)

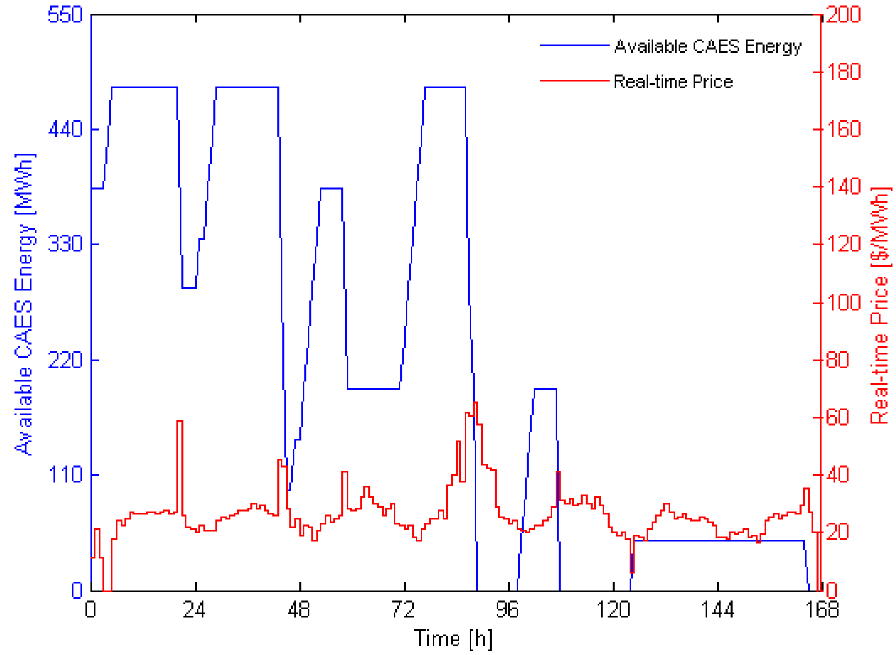


Exhibit 41 CAES Optimal Schedule with Coal (Power) – Coal Cost = $10/MWh

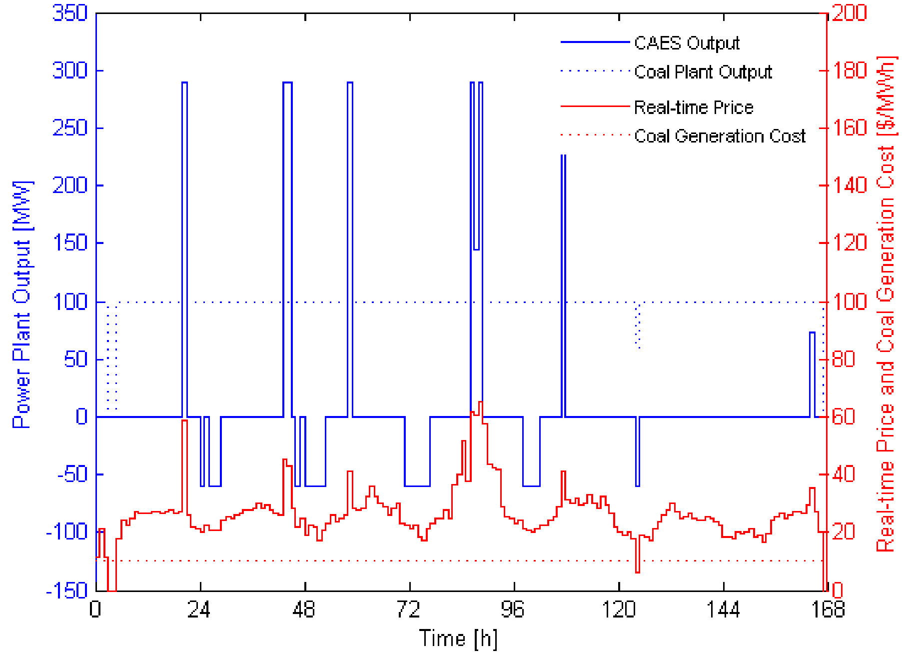


Exhibit 42 CAES Optimal Schedule with Coal (Energy) – Coal Cost = $10/MWh

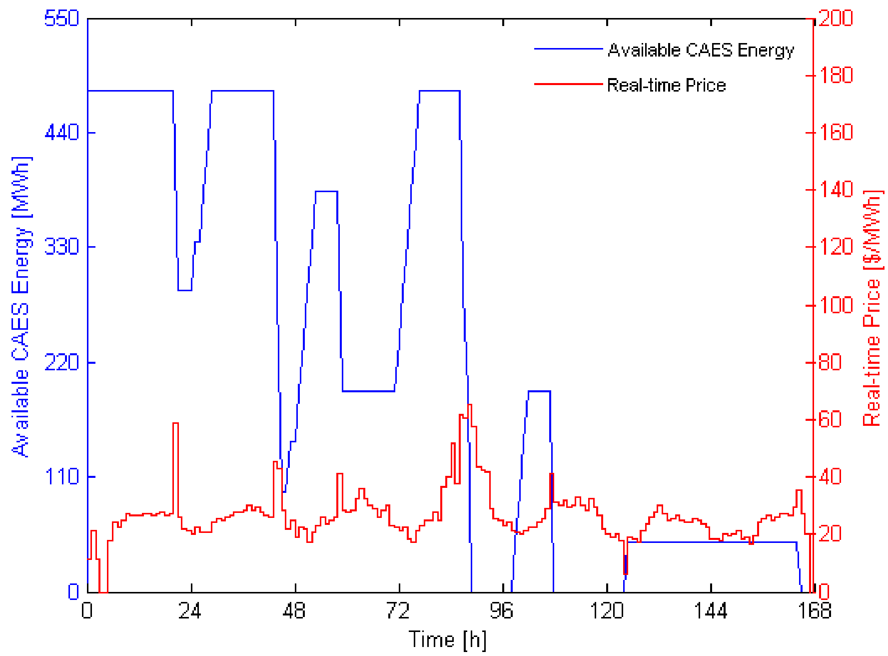


Exhibit 43 CAES Optimal Schedule with Coal (Power) – Coal Cost = $25/MWh

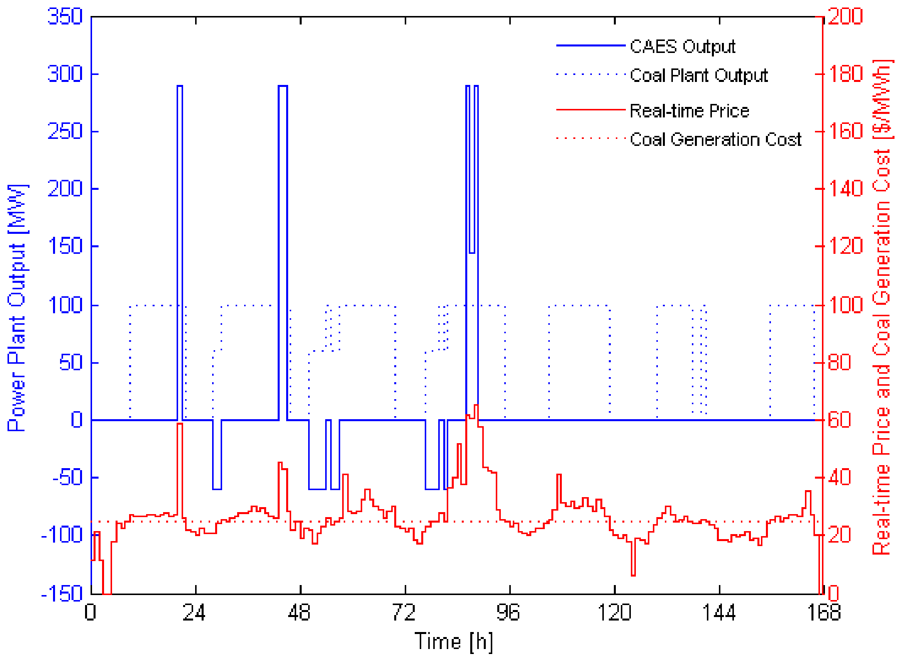


Exhibit 44 CAES Optimal Schedule with Coal (Energy) – Coal Cost = $25/MWh

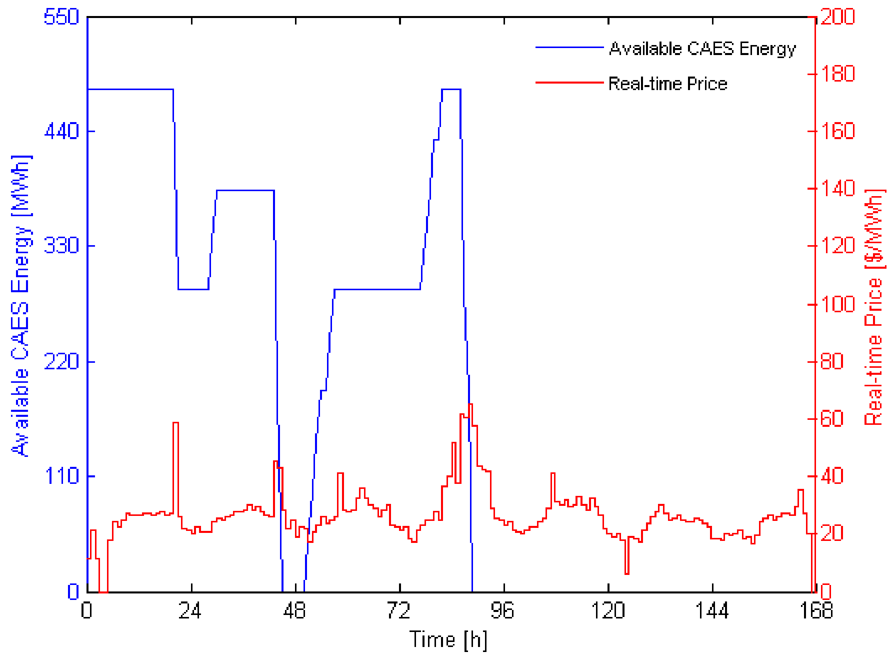


Exhibit 45 CAES Optimal Schedule with Natural Gas (Power)

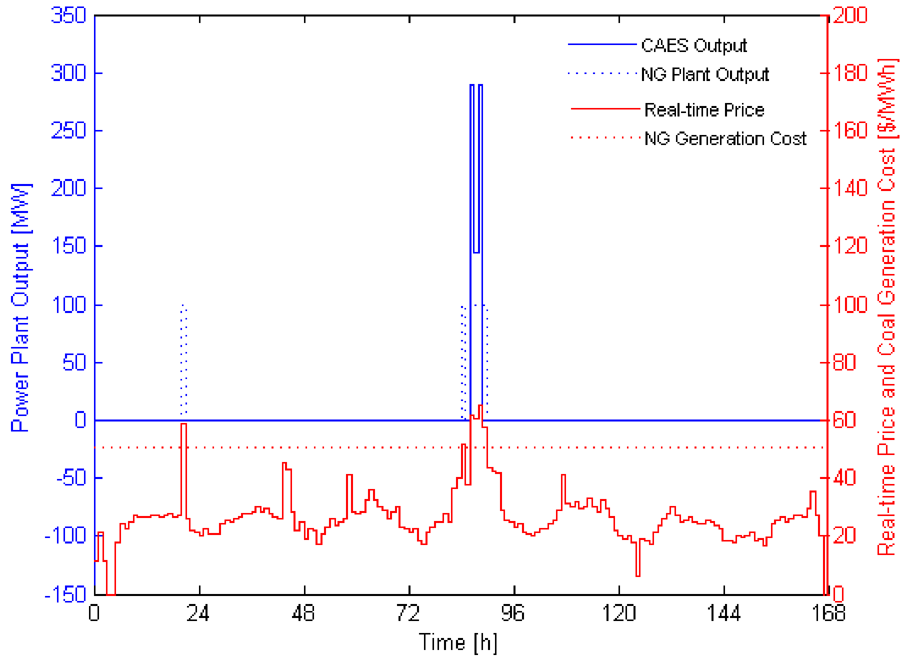


Exhibit 46 CAES Optimal Schedule with Natural Gas (Energy)

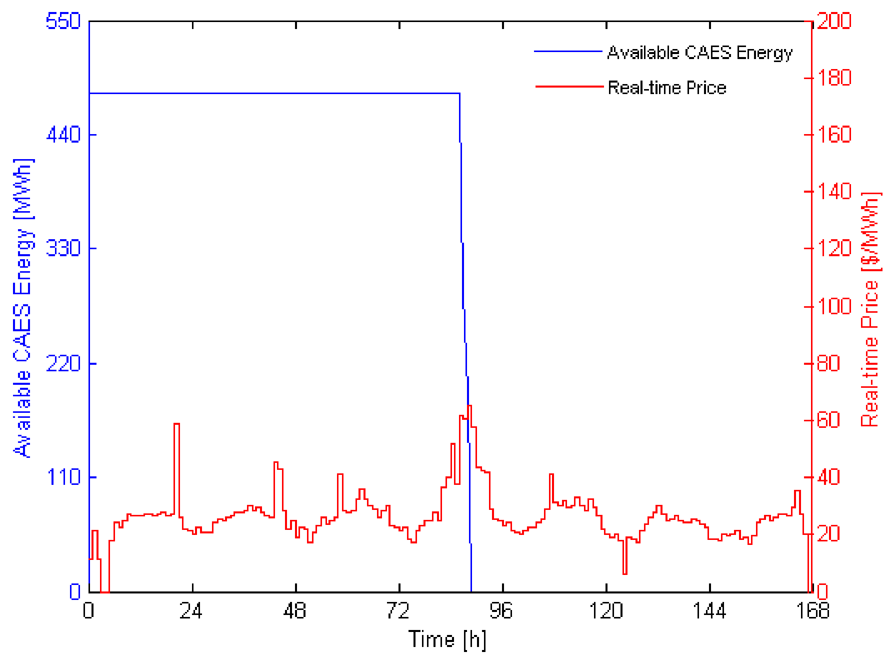


Exhibit 47 CAES Optimal Schedule with Coal and Wind (Power) – Coal Cost = $10/MWh

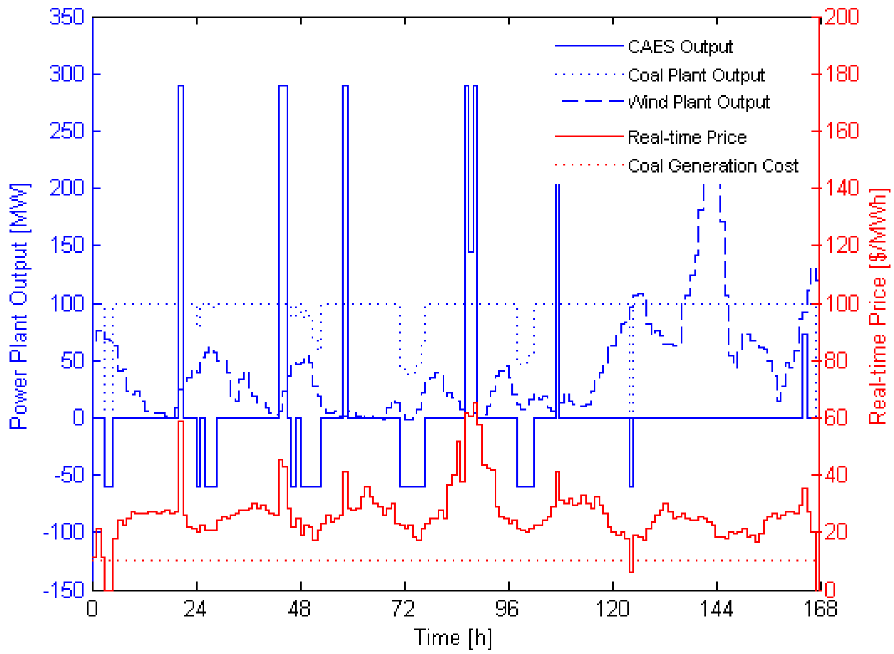


Exhibit 48 CAES Optimal Schedule with Coal and Wind (Energy) – Coal Cost = $10/MWh

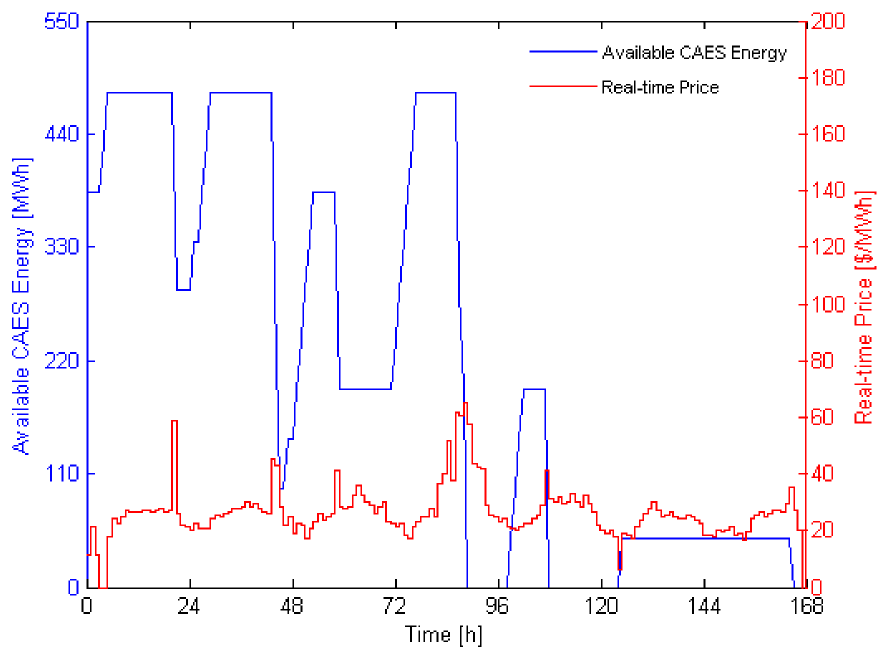


Exhibit 49 CAES Optimal Schedule with Coal and Wind (Power) – Coal Cost = $25/MWh

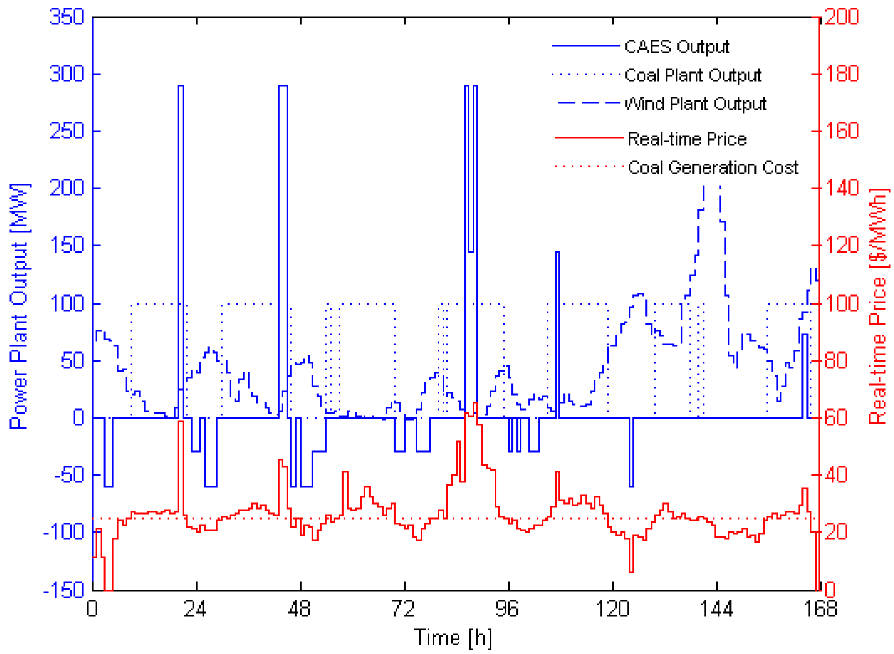


Exhibit 50 CAES Optimal Schedule with Coal and Wind (Energy) – Coal Cost = $25/MWh

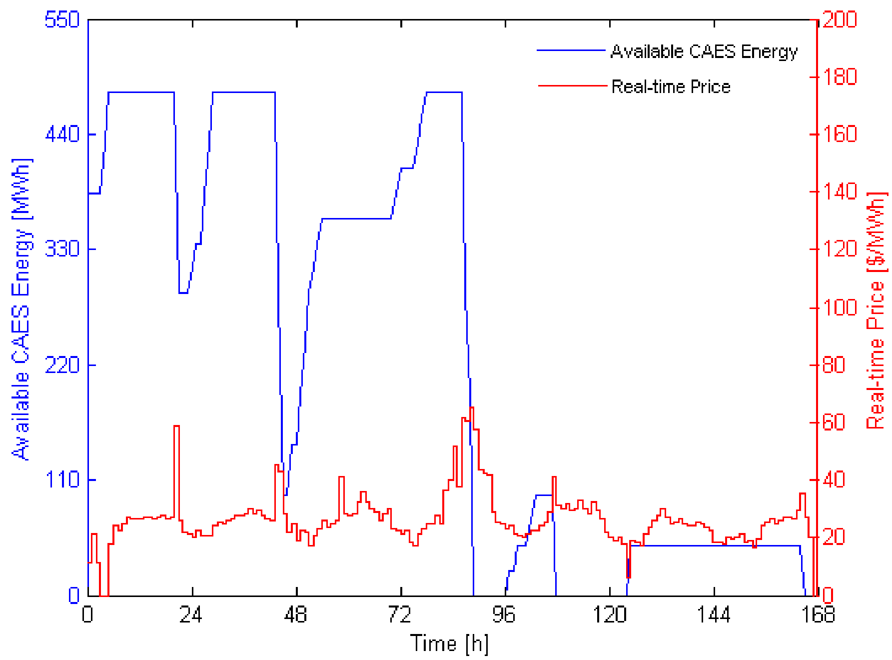


Exhibit 51 CAES Optimal Schedule with Natural Gas and Wind (Power)

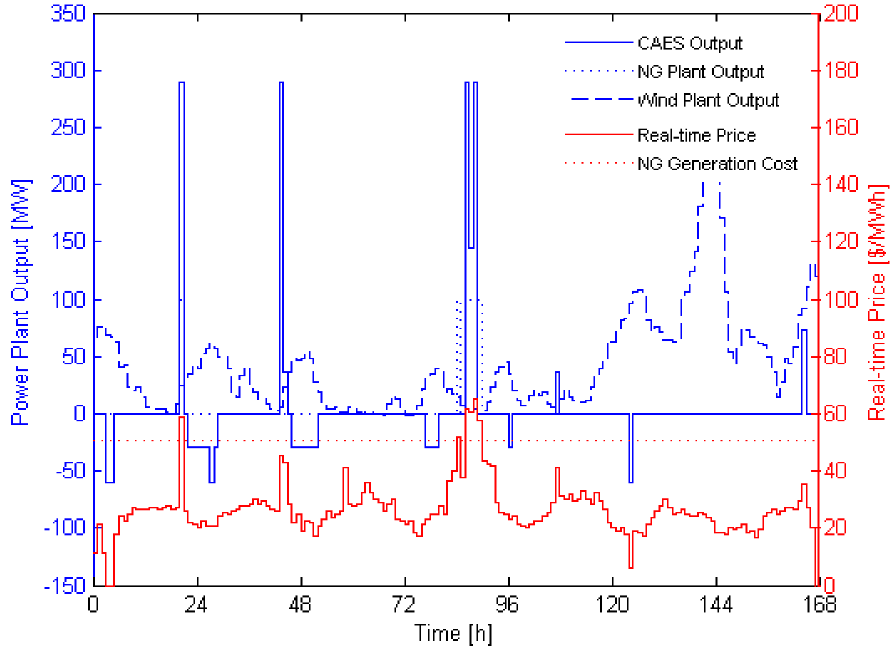
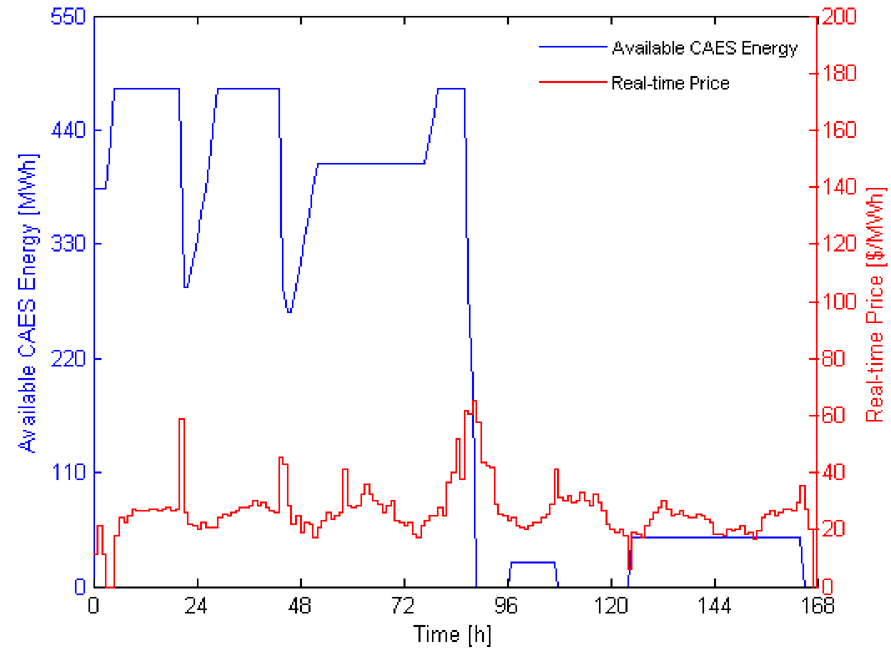


Exhibit 52 CAES Optimal Schedule with Natural Gas and Wind (Energy)



Appendix B – McIntosh Power Plant Optimal Schedule

Exhibit 53 CAES Optimal Schedule (Power)

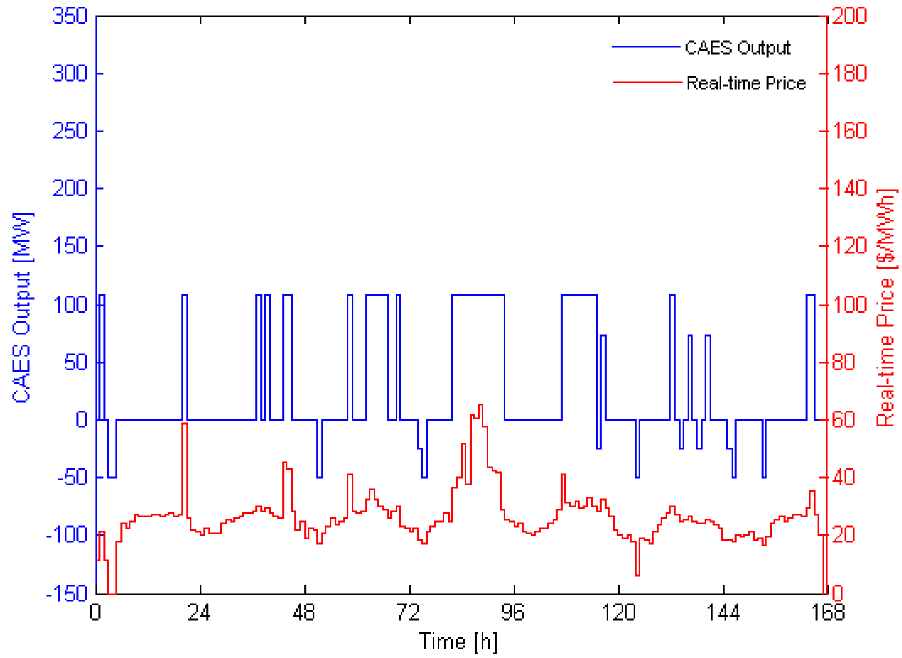


Exhibit 54 CAES Optimal Schedule (Energy)

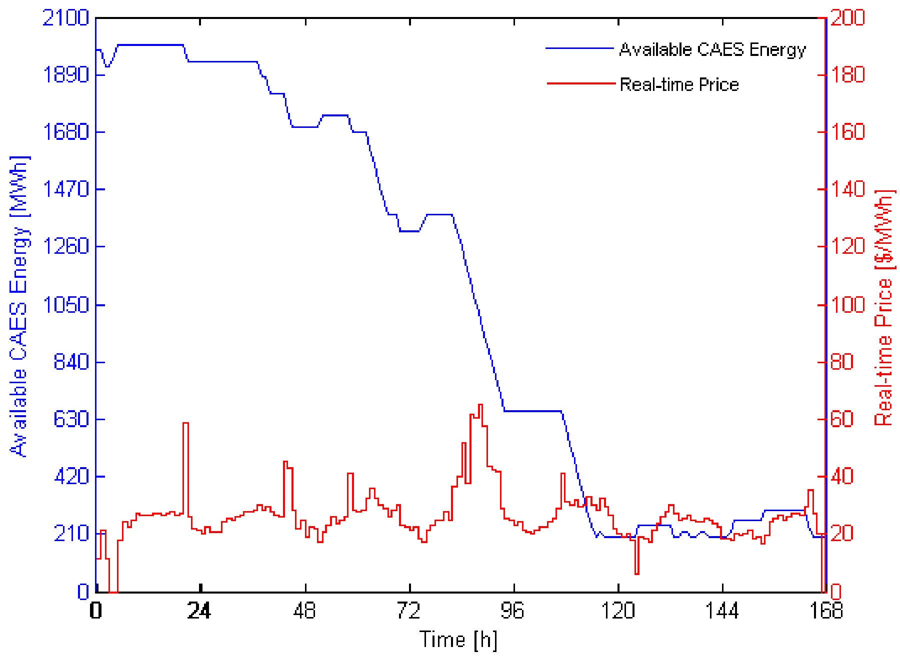


Exhibit 55 Wind Power Plant Optimal Schedule (Power)

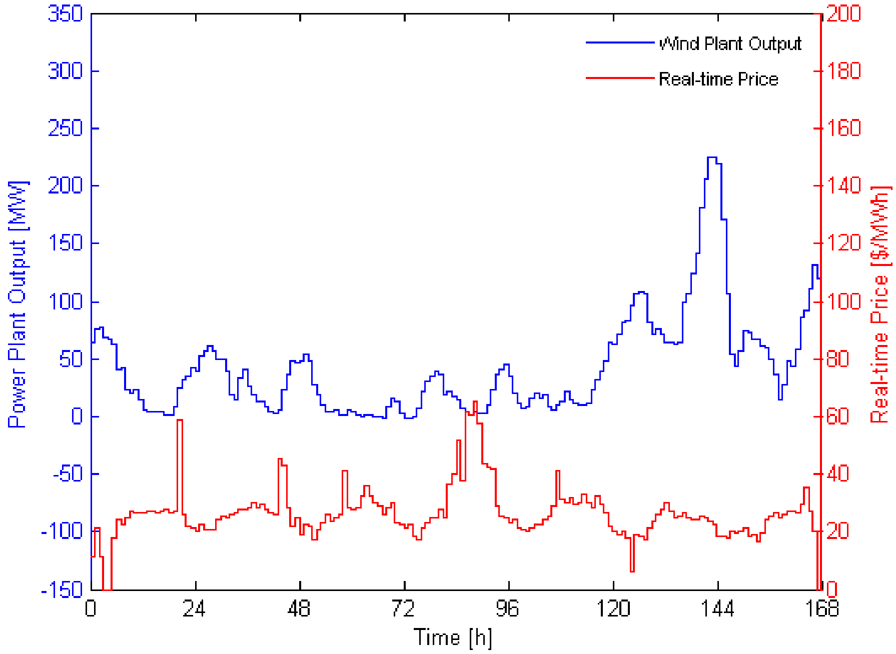


Exhibit 56 Natural Gas Power Plant Optimal Schedule (Power)

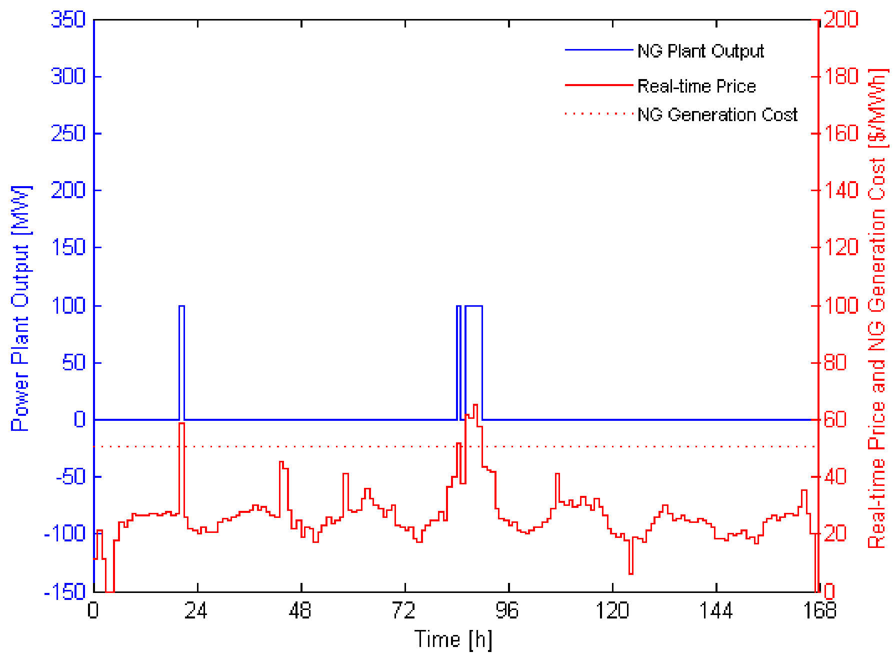


Exhibit 57 Coal Power Plant Optimal Schedule (Coal Cost = $10/MWh)

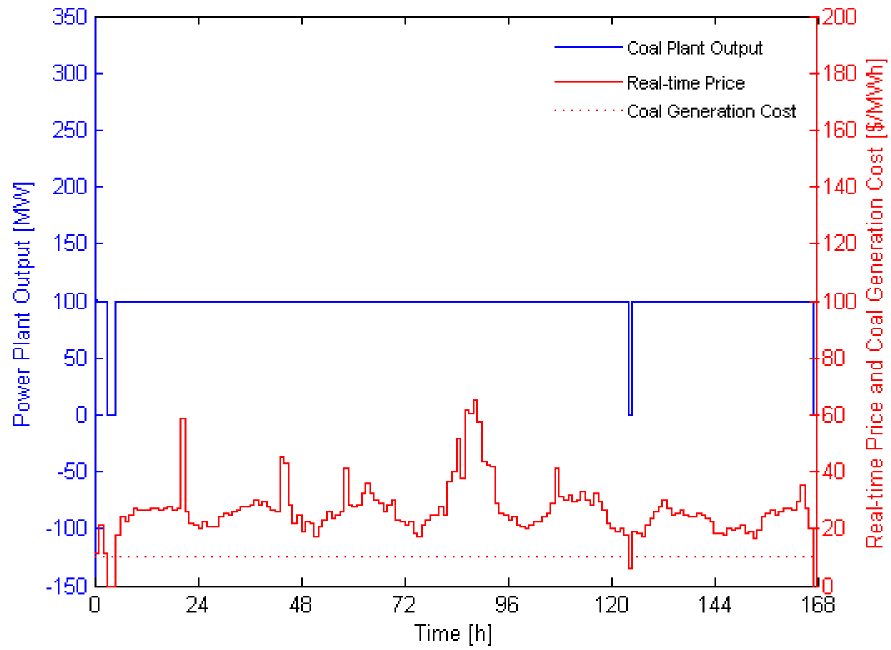


Exhibit 58 Coal Power Plant Optimal Schedule (Coal Cost = $25/MWh)

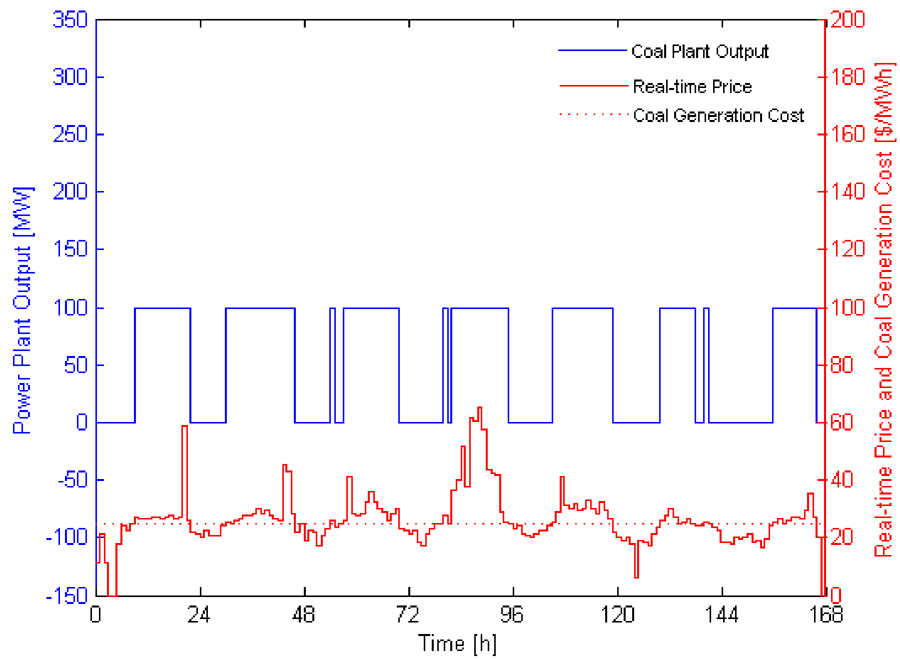


Exhibit 59 CAES Optimal Schedule with Wind (Power)

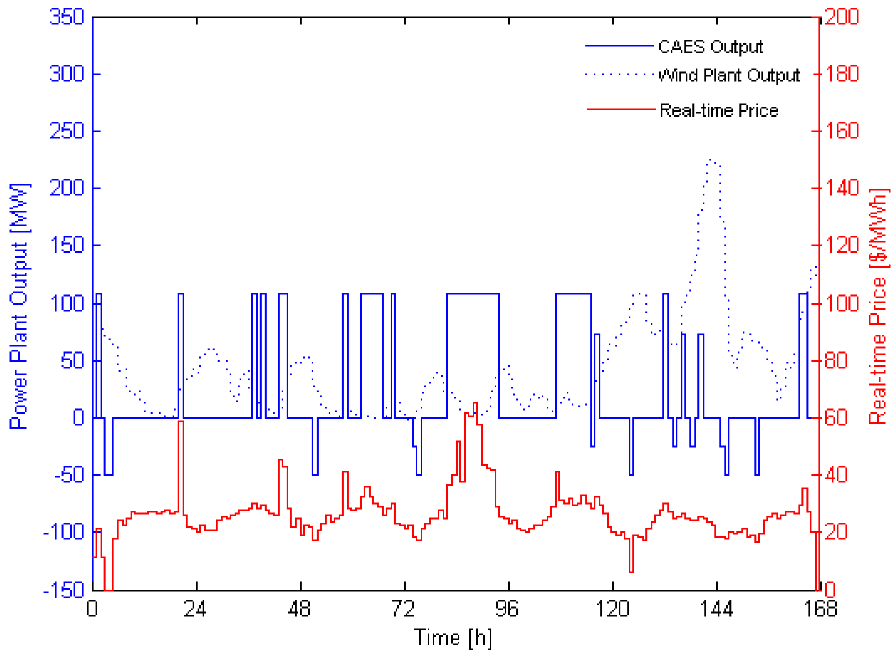


Exhibit 60 CAES Optimal Schedule with Wind (Energy)

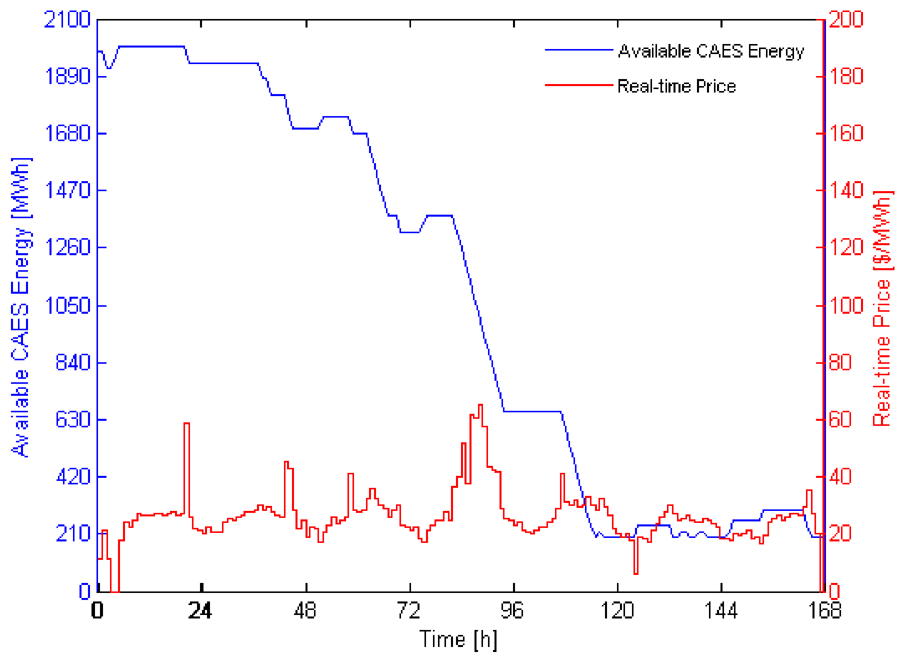


Exhibit 61 CAES Optimal Schedule with Coal (Power) – Coal Cost = $10/MWh

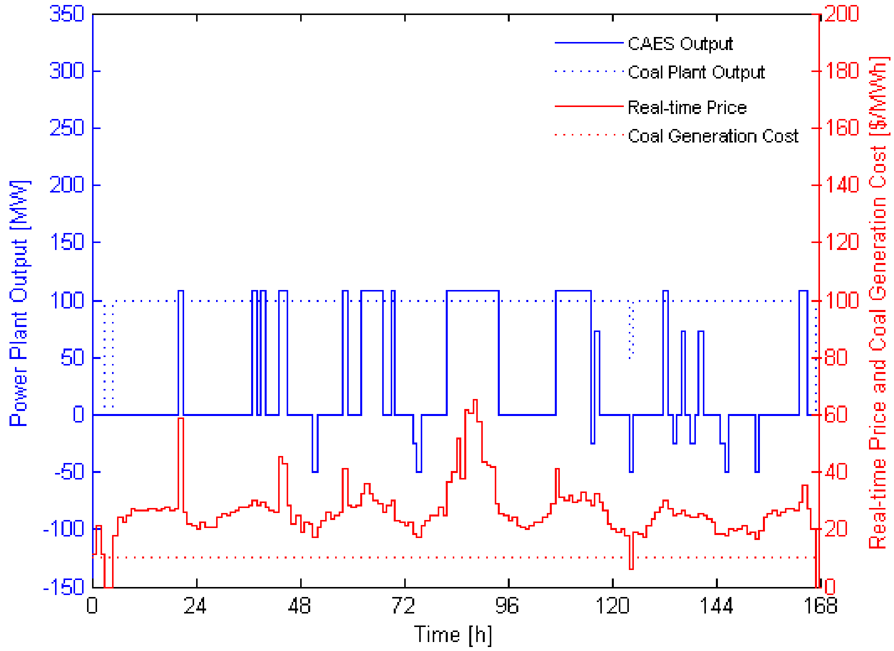


Exhibit 62 CAES Optimal Schedule with Coal (Energy) – Coal Cost = $10/MWh

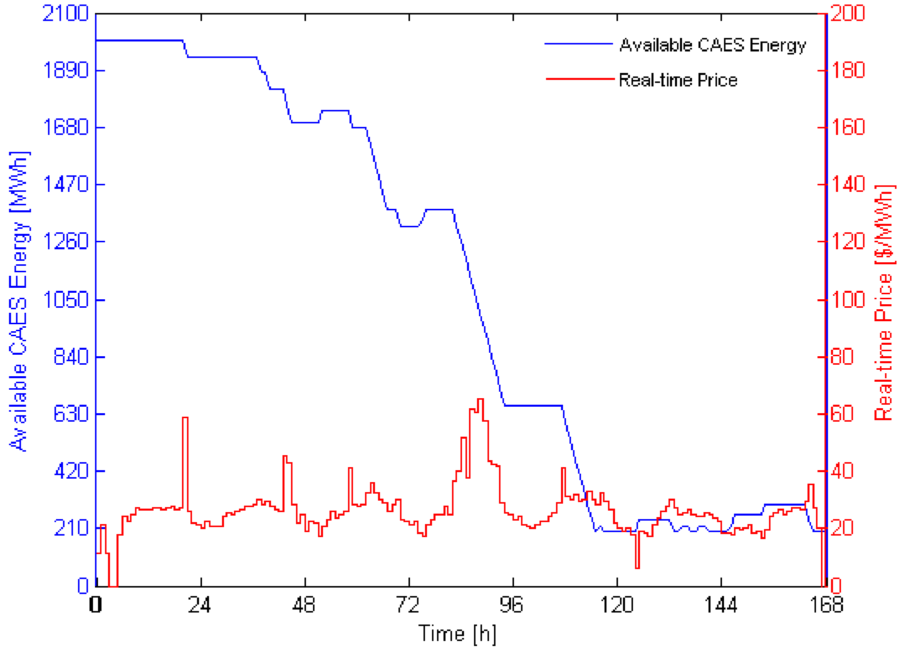


Exhibit 63 CAES Optimal Schedule with Coal (Power) – Coal Cost = $25/MWh

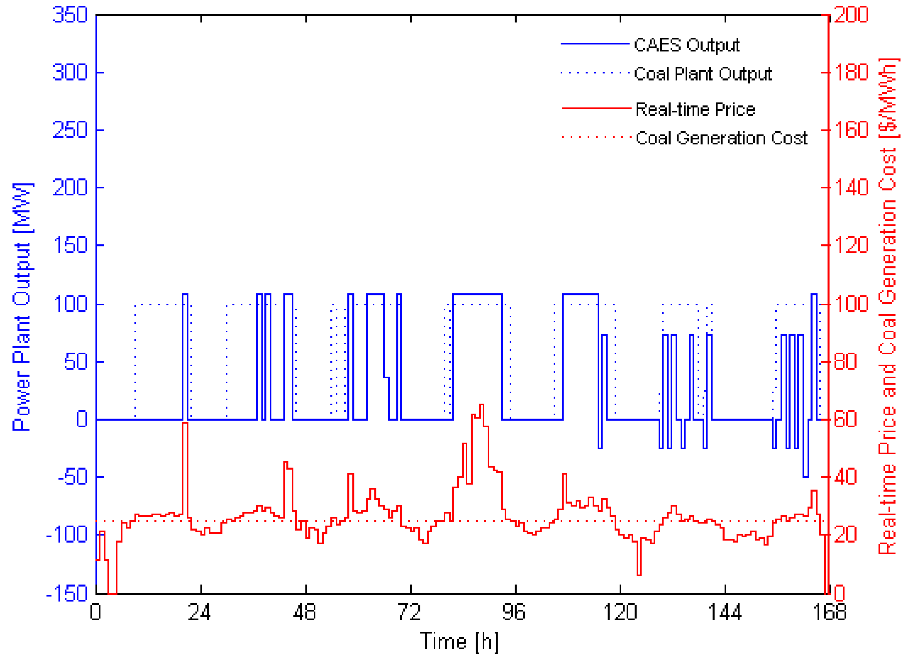


Exhibit 64 CAES Optimal Schedule with Coal (Energy) – Coal Cost = $25/MWh

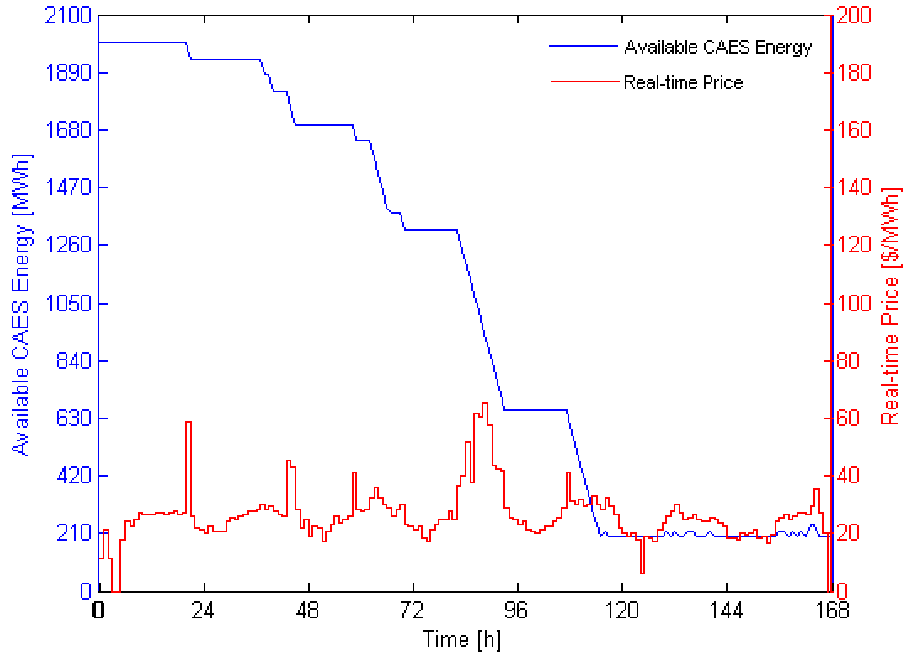


Exhibit 65 CAES Optimal Schedule with Natural Gas (Power)

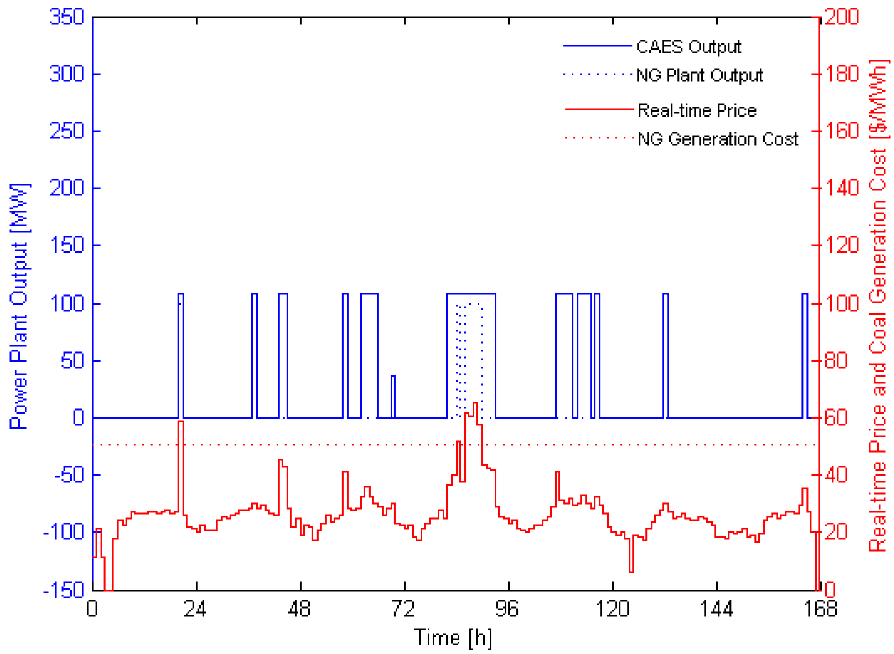


Exhibit 66 CAES Optimal Schedule with Natural Gas (Energy)

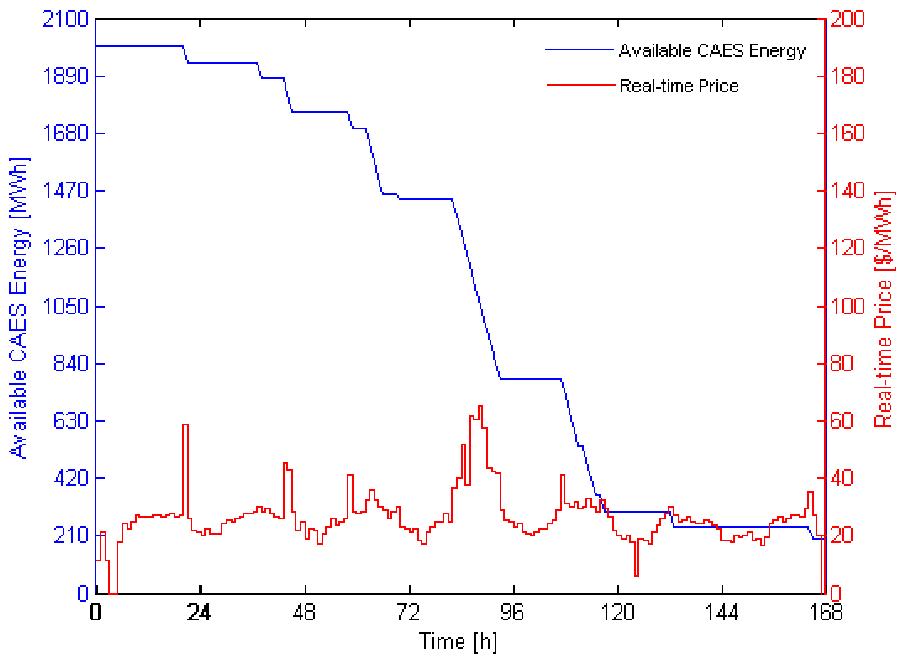


Exhibit 67 CAES Optimal Schedule with Coal and Wind (Power) – Coal Cost = $10/MWh

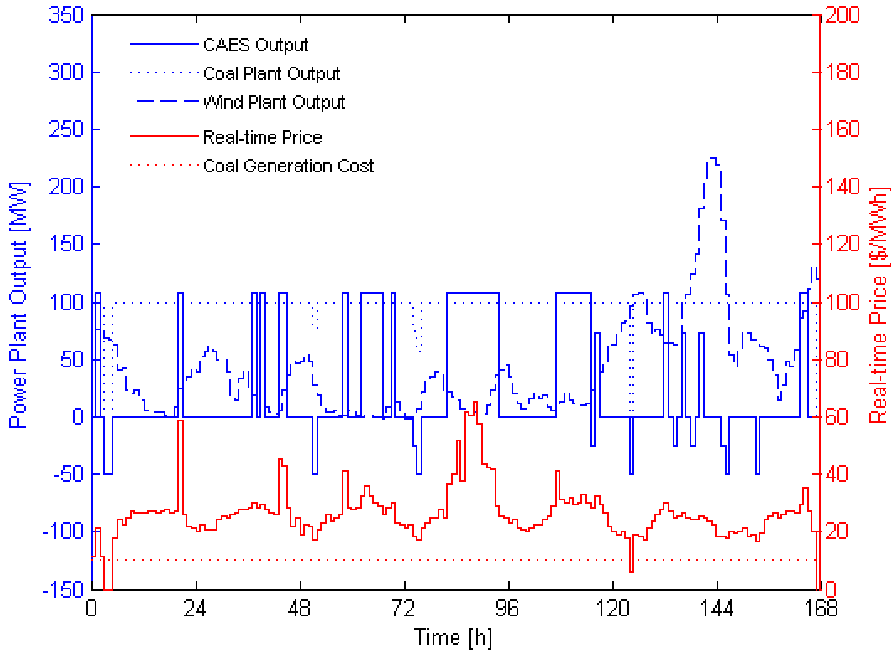


Exhibit 68 CAES Optimal Schedule with Coal and Wind (Energy) – Coal Cost = $10/MWh

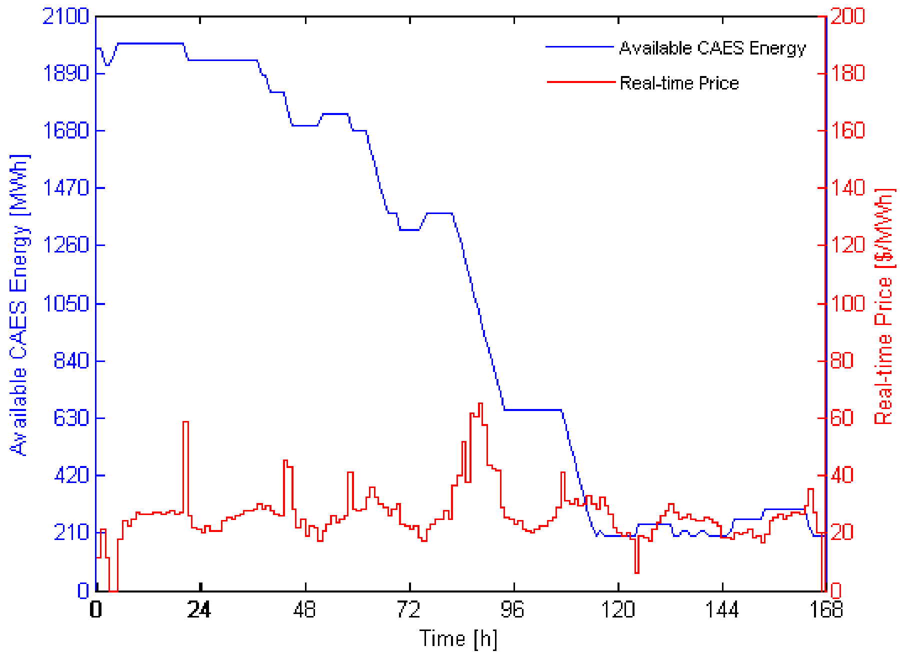


Exhibit 69 CAES Optimal Schedule with Coal and Wind (Power) – Coal Cost = $25/MWh

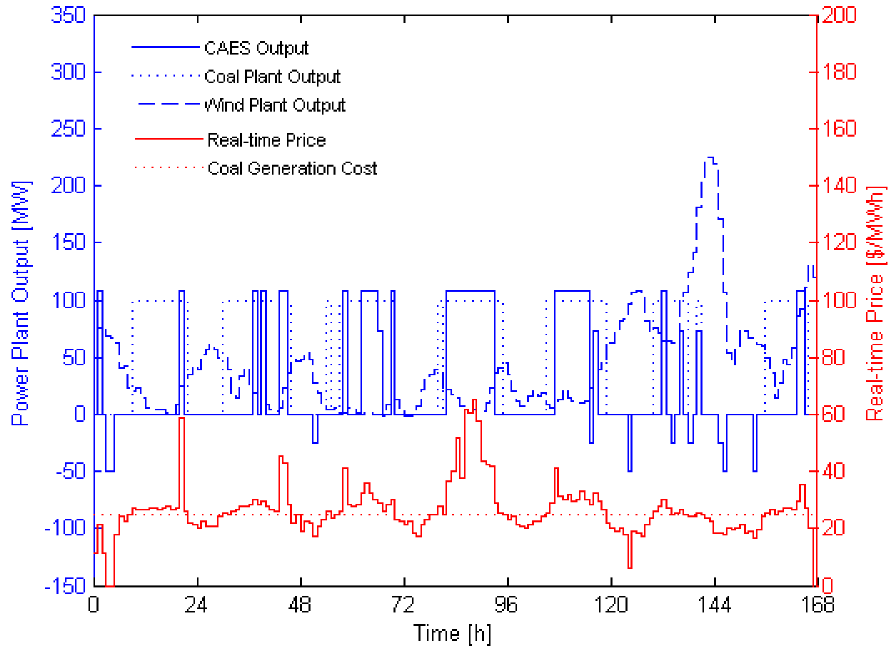


Exhibit 70 CAES Optimal Schedule with Coal and Wind (Energy) – Coal Cost = $25/MWh

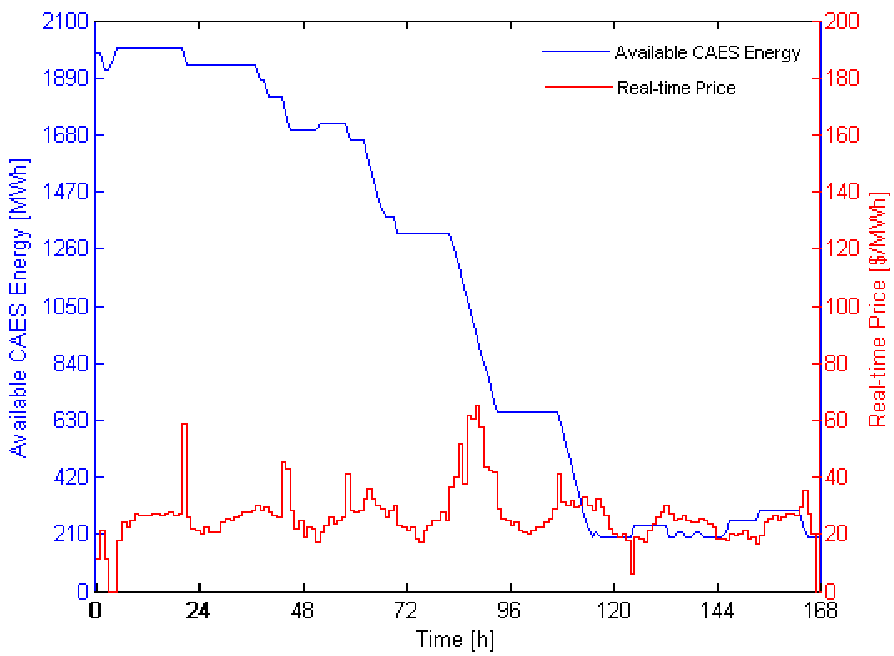


Exhibit 71 CAES Optimal Schedule with Natural Gas and Wind (Power)

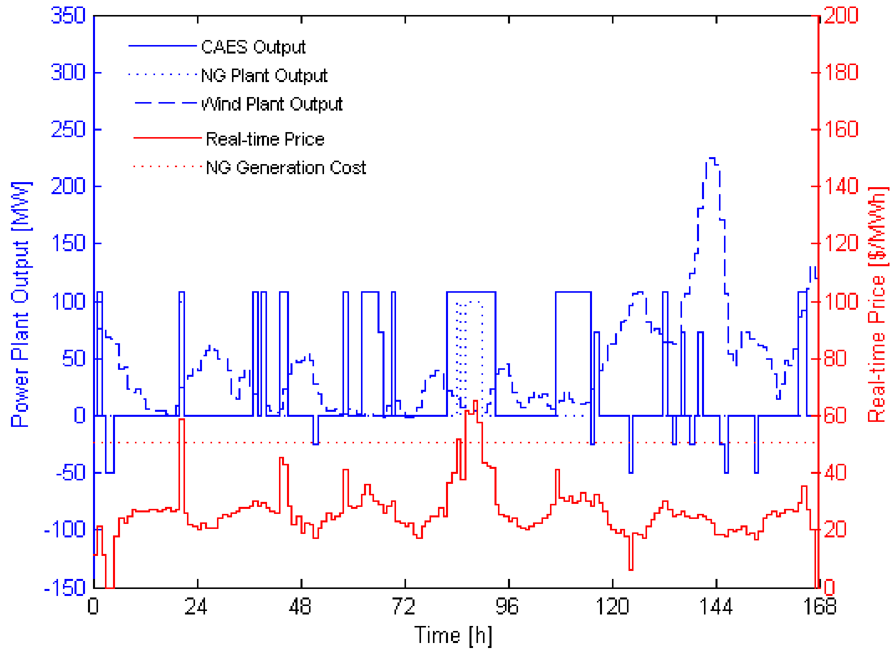
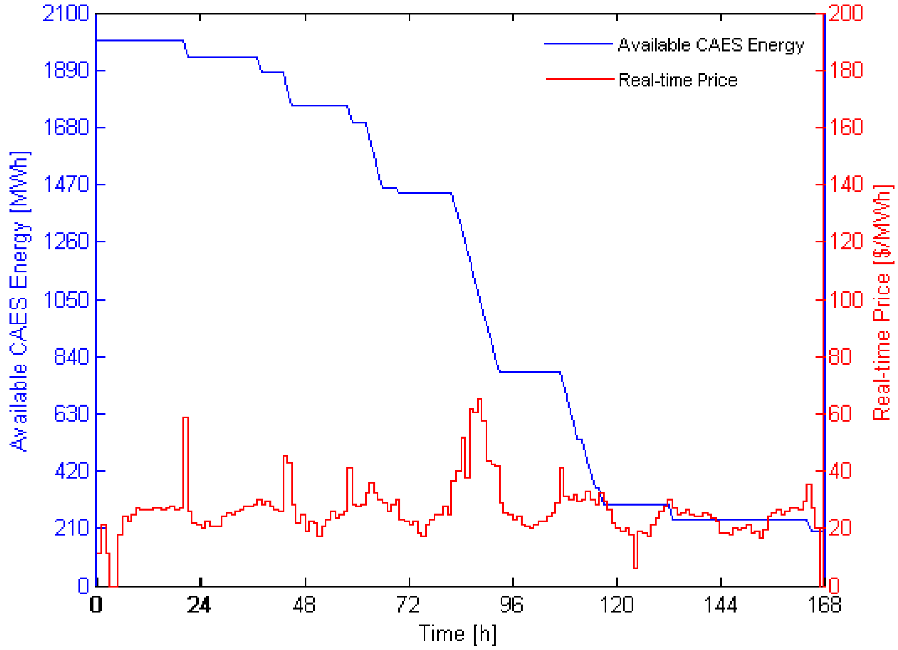


Exhibit 72 CAES Optimal Schedule with Natural Gas and Wind (Energy)



Appendix C – Code for Proposed Models

All cases in Chapter 2 are simulated using the Matlab code below.

```
clear all
close all

%% Simulation Settings

McIntosh = 1; % McIntosh = 0 => Simulation of Huntorf Power Plant
              % McIntosh = 1 => Simulation of McIntosh Power Plant

year = 0;     % year = 1 => Simulation on annual bases
week = 1;     % week = 1 => Simulation on weekly bases

if year == 1
    T = 24*365;
elseif week == 1
    T = 24*7;
else
    T = 12*24*30;
end

% coal = 0;      % coal = 0 => Charging CAES from wind
                 % coal = 1 => Charging CAES from coal power plants
                 % coal = 2 => Charging CAES from NG power plant

% CAES = 1;      % CAES = 0 => Simulation without CAES
                 % CAES = 1 => Simulation with CAES

% wind = 1;      % wind = 0 => Simulation without wind
                 % wind = 1 => Simulation with wind

% wc = 1;        % wc = 1 => Simulation with wind and coal power plants
% wng = 0;       % wng = 1 => Simulation with wind and natural gas power plants

%%Scenarios
% Scenario = 1 - CAES only
% Scenario = 2 - Wind only
% Scenario = 3 - Coal only
% Scenario = 4 - Natural gas only
% Scenario = 5 - CAES/Wind
% Scenario = 6 - CAES/Coal
% Scenario = 7 - CAES/Natural Gas
% Scenario = 8 - CAES/Wind/Coal
% Scenario = 9 - CAES/Wind/Natural Gas

Scenario =1;

C_p = 0;
NG_p = 0;
CAES_p = 0;

if Scenario == 1
   CAES = 1;
   coal = 0;
   wind = 0;
   wc = 0;
   wng = 0;
   CAES_p = 1;
elseif Scenario == 2
   CAES = 0;
   coal = 0;
   wind = 1;
   wc = 0;
   wng = 0;
   CAES_p = 0;
elseif Scenario == 3
   CAES = 0;
```

```
   coal = 1;
   wind = 0;
   wc = 0;
   wng = 0;
   CAES_p = 0;
   C_p = 1;
elseif Scenario == 4
   CAES = 0;
   coal = 2;
   wind = 0;
   wc = 0;
   wng = 0;
   NG_p = 1;    % NG_p = 1 => store natural gas power plant output power in gas_power_t
   CAES_p = 0;
elseif Scenario == 5
   CAES = 1;
   coal = 0;
   wind = 1;
   wc = 0;
   wng = 0;
   CAES_p = 1;
elseif Scenario == 6
   CAES = 1;
   coal = 1;
   wind = 0;
   wc = 0;
   wng = 0;
   CAES_p = 1;
   C_p = 1;
elseif Scenario == 7
   CAES = 1;
   coal = 2;
   wind = 0;
   wc = 0;
   wng = 0;
   NG_p = 1;    % NG_p = 1 => store natural gas power plant output power in gas_power_t
   CAES_p = 1;
elseif Scenario == 8
   CAES = 1;
   coal = 0;
   wind = 1;
   wc = 1;
   wng = 0;
   CAES_p = 1;
   C_p = 1;
elseif Scenario == 9
   CAES = 1;
   coal = 0;
   wind = 1;
   wc = 0;
   wng = 1;
   NG_p = 1;    % NG_p = 1 => store natural gas power plant output power in gas_power_t
   CAES_p = 1;
end

%% Input Data for Huntorf and McIntosh Power Plants

if McIntosh == 0
    % Input Huntorf Power Plant
    Pcharge_max = 60;                         % Maximum charging power [MW]
    Pdischarge_max = 290;                     % Maximum discharging power [MW]
    t_ch_max = 8;                             % Maximum charging time [h]
    E_CAES_max = Pcharge_max*t_ch_max;        % MWh
    E_CAES_min = 0;                           % Minimum CAES energy [MWh]
    ramp_up = 30;                             % Ramp-up time [MW/min]
    ramp_down = 30;                           % Ramp-down time [MW/min]
    start_up = 10;                            % Strart min
    shut_down = 10;                           % min

    gas_ratio = 1.56;       % MWh of natural gas for 1 MWh of CAES output
    electric_ratio = 0.83;  % MWh of electric power for 1 MWh of CAES output
```

```
    %1 MWh = 3.413 mmbtu
    gas_for_1MWh = gas_ratio*3.413;  % MMBttu of natural gas for 1MWh of CAES output

    efficiency_compressor = 0.8;     % Efficicency of CAES compressor
    efficiency_CAES = 0.42;          % Efficciency of CAES
else
    % Input McIntosh Power Plant
    Pcharge_max = 50;                     % Maximum charging power [MW]
    Pdischarge_max = 110;                 % Maximum discharging power [MW]
    t_ch_max = 40;                        % Maximum charging time [h]
    E_CAES_max = Pcharge_max*t_ch_max;   % Maximum CAES energy [MWh]
    E_CAES_min = 1*E_CAES_max/10;        % Minimum CAES energy [MWh]
    ramp_up = 30;                         % Ramp-up time [MW/min]
    ramp_down = 30;                       % Ramp-down time [MW/min]
    start_up = 10;                        % Start-up time [min]
    shut_down = 10;                       % Shut-down time [min]

    gas_ratio = 1.17;        % MWh of natural gas for 1 MWh of CAES output
    electric_ratio = 0.69;   % MWh of electical energy for 1 MWh of CAES output

    %1 MWh = 3.413 mmbtu
    gas_for_1MWh = gas_ratio*3.413;  % MMBttu of natural gas for 1 MWh of CAES output

    efficiency_compressor = 0.8;     % Efficicency of CAES compressor
    efficiency_CAES = 0.54;          % Efficciency of CAES
end


%% Electricity, coal and natural gas price
real_time_price =xlsread('LMP PJM DUQ 10_1_2009 - 9_30_2010.xls','Sheet1','G8762:G17521');

% Gas price
gas_price = xlsread('Monthly NG Price for Utilities.xls','NG','B2:B8761');

% Wind production
if coal == 0    % Wind
   if wind == 1 % With wind
     wind_power= xlsread('Wind PJM East 10_1_2009 - 9_30_2010.xls','Sheet1','F7:F8766');
      %wind_power= xlsread('Wind PJM East 10_1_2009 - 9_30_2010.xls','Sheet1','I7:I174');
   else         % Without wind
      wind_power = zeros(1,8760);
   end

   if wc == 1              % Wind and coal power plants
      coal_power = 100;    % Capacity of coal power plants [MW]
      coal_price = 10;     % Coal power plant marginal costs $/MWh
   elseif wng == 1
      gas_power = 100;     % Capacity of natural gas power plants [MW]
      heat_rate = 12.428; % mmBtu/MWh
      gas_price_dollars = gas_price * heat_rate; % Natural gas power plant marginal cost [$/MWh]
   end

elseif coal == 1        % Coal
    coal_power = 100;    % Capacity of coal power plants [MW]
    coal_price = 10;     % Coal power plant marginal costs $/MWh
elseif coal == 2        % Natural Gas
    gas_power = 100;     % Capacity of natural gas power plants [MW]
    heat_rate = 12.428; % mmBtu/MWh
    gas_price_dollars = gas_price * heat_rate; % Natural gas power plant marginal cost [$/MWh]
end

%% Dynamic programming approach
% State is stored energy; % Energy storage discretization
ramp = round((Pcharge_max*efficiency_compressor))/2;
% States are available energy in CAES
NoStates = 0;
for s = E_CAES_min : ramp : E_CAES_max
    NoStates = NoStates + 1;
    states_E (NoStates,1) = s;
end
```

```
if states_E(NoStates) ~= E_CAES_max
    NoStates = NoStates + 1;
    states_E (NoStates,1) = E_CAES_max;
end

TransitionCost = inf * ones(NoStates,NoStates);
OptimalCost = inf * ones(T+1, NoStates);
OptimalPolicy = zeros (T+1, 1);
OptimalPath = zeros (T+1, NoStates);
OptimalCost(1,:)=0;
OptimalPath(1,:)=0;
CAES_power_T = zeros(T+1, NoStates);
coal_power_T = zeros(T+1, NoStates);
gas_power_T = zeros(T+1, NoStates);

for tt = 1:T
    t = tt;
    TransitionCost = inf * ones(NoStates,NoStates);
    coal_power_grid = zeros(NoStates,NoStates);
    coal_power_CAES = zeros(NoStates,NoStates);
    gas_power_grid = zeros(NoStates,NoStates);
    gas_power_CAES = zeros(NoStates,NoStates);
    CAES_power = zeros(NoStates,NoStates);

    for s = 1: NoStates
        %% Action 1 - Charge CAES (wind or network (in ramp MWh steps))
        wNo = 0;

        % Charging CAES from wind, coal, natural gas, wind+coal or
        % wind+natural gas
        for w = ramp : ramp : Pcharge_max*efficiency_compressor

            if CAES == 0
                w=0;
            end

            wNo = wNo + 1;
            state_new = states_E (s) + w;

            if state_new <= E_CAES_max
               [rInd, cInd, No] = find(states_E == state_new);
               if CAES_p == 1
                  CAES_power(s,rInd)=-w/efficiency_compressor;
               end
               if coal == 0
                   % CAES is charged by wind, or wind and coal, or wind
                   % and natural gas and excess power is sold to the grid
                   if wind_power(t)<w/efficiency_compressor && wc == 1
                      % wind power is supplemented by coal power plants to charge CAES
                      from_coal = -(wind_power(t)-w/efficiency_compressor);
                      TransitionCost(s,rInd) = from_coal*coal_price;
                      coal_power_CAES(s,rInd)=from_coal;
                      if real_time_price(t)> coal_price
                         TransitionCost(s,rInd) = TransitionCost(s,rInd) - (coal_power-
from_coal)*(real_time_price(t)-coal_price);
                         coal_power_grid(s,rInd)=coal_power-from_coal;
                      end
                   elseif wind_power(t)<w/efficiency_compressor && wng == 1
                      % wind power is supplemented by natural gas power plants to charge CAES
                      from_gas = -(wind_power(t)-w/efficiency_compressor);
                      TransitionCost(s,rInd) = from_gas*gas_price_dollars(t);
                      gas_power_CAES(s,rInd)=from_gas;
                      if real_time_price(t)> gas_price_dollars(t)
                         TransitionCost(s,rInd) = TransitionCost(s,rInd) - (gas_power-
from_gas)*(real_time_price(t)-gas_price_dollars(t));
                         gas_power_grid(s,rInd)=gas_power-from_gas;
                      end
                   elseif wind_power(t)<w/efficiency_compressor            % wind
                      % wind power is supplemented by grid to charge CAES
```

```
                      TransitionCost(s,rInd) = -(wind_power(t)-
w/efficiency_compressor)*real_time_price(t);
                   else
                      % Excess wind power is sold to the network
                      TransitionCost(s,rInd) = -(wind_power(t)-
w/efficiency_compressor)*real_time_price(t);
                      if wc == 1
                          % Excess coal power plant power is sold to the network
                          if real_time_price(t)> coal_price
                             TransitionCost(s,rInd) = TransitionCost(s,rInd) -
(coal_power)*(real_time_price(t)-coal_price);
                             coal_power_grid(s,rInd)=coal_power;
                          end
                      elseif wng == 1
                         % Excess natural gas power plant power is sold to the network
                         if real_time_price(t)> gas_price_dollars(t)
                            TransitionCost(s,rInd) = TransitionCost(s,rInd) -
(gas_power)*(real_time_price(t)-gas_price_dollars(t));
                            gas_power_grid(s,rInd)=gas_power;
                         end
                      end
                   end
               elseif coal == 1
                   % CAES is charged by coal power plant and excess
                   % power is sold to the grid
                   if real_time_price(t)> coal_price
                       TransitionCost(s,rInd) = -(coal_power-
w/efficiency_compressor)*real_time_price(t)+coal_power*coal_price;
                       if C_p ==1
                         %coal_power_grid(s,rInd)=coal_power-w/efficiency_compressor;
                         coal_power_grid(s,rInd)=coal_power;
                         coal_power_CAES(s,rInd)=w/efficiency_compressor;
                       end
                   else
                       TransitionCost(s,rInd) = w/efficiency_compressor*coal_price;
                       if C_p ==1
                           coal_power_grid(s,rInd)=w/efficiency_compressor;
                           coal_power_CAES(s,rInd)=w/efficiency_compressor;
                       end
                   end
                elseif coal == 2
                   % CAES is charged by natural gas power plant and excess
                   % power is sold to the grid
                   if real_time_price(t)> gas_price_dollars(t)
                       TransitionCost(s,rInd) = -(gas_power-
w/efficiency_compressor)*real_time_price(t)+gas_power*gas_price_dollars(t);
                       if NG_p ==1
                         gas_power_grid(s,rInd)= gas_power-w/efficiency_compressor;
                         gas_power_CAES(s,rInd)= w/efficiency_compressor;
                       end
                   else
                       TransitionCost(s,rInd) = w/efficiency_compressor*gas_price_dollars(t);
                       if NG_p ==1
                           gas_power_CAES(s,rInd)=w/efficiency_compressor;
                       end
                   end
               end
            end
        end

        %% Action 2 - Discharge CAES and sell wind/coal
        reachMin = 0;
        con = electric_ratio*efficiency_compressor;

        for i = 0 : ramp : Pdischarge_max*con

            if CAES == 0
               i=0;
            end

            state_new = states_E (s) - i;
```

```
if state_new < E_CAES_min
   reachMin = reachMin+1;
   state_new = E_CAES_min;
elseif state_new == 0
   reachMin = reachMin+1;
end

if reachMin < 2 && state_new ~= states_E(s)
   [rInd, cInd, No] = find(states_E == state_new);
   NG_Cost = (i/con)*gas_for_1MWh*gas_price(t);
   P_benefit = -(i/con)*real_time_price(t);
   if CAES_p ==1
      CAES_power(s,rInd)=i/con;
   end
   if coal == 0
       W_benefit = - wind_power(t)*real_time_price(t);
       TransitionCost(s,rInd) = NG_Cost + P_benefit + W_benefit;

       if wc == 1
          if real_time_price(t)> coal_price
             C_benefit = -coal_power*(real_time_price(t)-coal_price);
             TransitionCost(s,rInd) = TransitionCost(s,rInd) + C_benefit;
             coal_power_grid(s,rInd)=coal_power;
          else
             coal_power_grid(s,rInd)=0;
          end
       elseif wng == 1
          if real_time_price(t)> gas_price_dollars(t)
             NG_benefit = -gas_power*(real_time_price(t)-gas_price_dollars(t));
             TransitionCost(s,rInd) = TransitionCost(s,rInd) + NG_benefit;
             gas_power_grid(s,rInd)=gas_power;
          else
             gas_power_grid(s,rInd)=0;
          end
       end

   elseif coal == 1
       if real_time_price(t)> coal_price
          C_benefit = - coal_power*(real_time_price(t)-coal_price);
          TransitionCost(s,rInd) = NG_Cost + P_benefit + C_benefit;
          if C_p ==1
             coal_power_grid(s,rInd)=coal_power;
          end
       else
          C_benefit = 0;
          TransitionCost(s,rInd) = NG_Cost + P_benefit + C_benefit;
          if C_p ==1
             coal_power_grid(s,rInd)=0;
          end
       end
   elseif coal == 2
       gas_price_dollars(t) = heat_rate * gas_price(t);
       if real_time_price(t)> gas_price_dollars(t)
          NG_benefit = - gas_power*(real_time_price(t)-gas_price_dollars(t));
          TransitionCost(s,rInd) = NG_Cost + P_benefit + NG_benefit;
          if NG_p == 1
             gas_power_grid(s,rInd)=gas_power;
          end
       else
          NG_benefit = 0;
          TransitionCost(s,rInd) = NG_Cost + P_benefit + NG_benefit;
          if NG_p == 1
             gas_power_grid(s,rInd)=0;
          end
       end
   end
elseif reachMin < 2 && state_new == states_E(s)
   [rInd, cInd, No] = find(states_E == state_new);
   if CAES_p ==1
      CAES_power(s,rInd)=0;
```

```
            end
            if coal == 0
                W_benefit = - wind_power(t)*real_time_price(t);
                TransitionCost(s,rInd) = W_benefit;
                if wc == 1
                   if real_time_price(t)> coal_price
                      C_benefit = -coal_power*(real_time_price(t)-coal_price);
                      TransitionCost(s,rInd) = TransitionCost(s,rInd) + C_benefit;
                      coal_power_grid(s,rInd)=coal_power;
                   else
                      coal_power_grid(s,rInd)=0;
                   end
                elseif wng == 1
                   if real_time_price(t)> gas_price_dollars(t)
                      NG_benefit = -gas_power*(real_time_price(t)-gas_price_dollars(t));
                      TransitionCost(s,rInd) = TransitionCost(s,rInd) + NG_benefit;
                      gas_power_grid(s,rInd)=gas_power;
                   else
                      gas_power_grid(s,rInd)=0;
                   end
                end
            elseif coal == 1
                if real_time_price(t)> coal_price
                   C_benefit = - coal_power*(real_time_price(t)-coal_price);
                   TransitionCost(s,rInd) = C_benefit;
                   if C_p ==1
                      coal_power_grid(s,rInd)=coal_power;
                   end
                else
                   C_benefit = 0;
                   TransitionCost(s,rInd) = C_benefit;
                   if C_p ==1
                      coal_power_grid(s,rInd)=0;
                   end
                end
            elseif coal == 2
                gas_price_dollars(t) = heat_rate * gas_price(t);
                if real_time_price(t)> gas_price_dollars(t)
                   NG_benefit = - gas_power*(real_time_price(t)-gas_price_dollars(t));
                   TransitionCost(s,rInd) = NG_benefit;
                   if NG_p == 1
                      gas_power_grid(s,rInd)=gas_power;
                   end
                else
                   NG_benefit = 0;
                   TransitionCost(s,rInd) = NG_benefit;
                   if NG_p == 1
                      gas_power_grid(s,rInd)=0;
                   end
                end
            end
         end
     end
end

for c2 = 1:NoStates
    for c1 =  1:NoStates
       pom = TransitionCost(c1,c2)+OptimalCost(tt,c1);
       if (pom < OptimalCost(tt+1,c2))
           OptimalCost(tt+1,c2)=pom;
           OptimalPath(tt+1,c2)=c1;
           if CAES_p ==1
              CAES_power_T(tt+1,c2) =CAES_power(c1,c2);
           end
           if C_p == 1 || wc == 1
              coal_power_T(tt+1,c2) = coal_power_grid(c1,c2);
           end
           if NG_p == 1 || wng == 1
              gas_power_T(tt+1,c2) = gas_power_grid(c1,c2);
           end
       end
```

```
        end
    end

    clear TransitionCost coal_power_grid gas_power_grid CAES_power coal_power_CAES gas_power_CAES

end

[MimimumCost Configuration]=min(OptimalCost(T+1,:));

fprintf('%10f',MimimumCost)

OptimalPolicy(T+1) = OptimalPath(T+1,Configuration);

if CAES_p == 1
   CAES_power_opt(T+1)= CAES_power_T(T+1,Configuration);
end
if C_p == 1 || wc == 1
   coal_power_opt(T+1)= coal_power_T(T+1,Configuration);
end
if NG_p == 1 || wng == 1
   gas_power_opt(T+1)= gas_power_T(T+1,Configuration);
end

for y = T+1: -1: 2
    OptimalPolicy(y-1) = OptimalPath(y,OptimalPolicy(y));
    if CAES_p ==1
       CAES_power_opt(y-1)= CAES_power_T(y,OptimalPolicy(y));
    end
    if C_p == 1 || wc == 1
       coal_power_opt(y-1) = coal_power_T(y,OptimalPolicy(y));
    end
    if NG_p == 1 || wng == 1
       gas_power_opt(y-1) = gas_power_T(y,OptimalPolicy(y));
    end
end

% Exhibits
figure('color','w')
x=0:T;
if coal == 0
    if C_p == 1
       [AX,H1,H2] = plotyy(x,[CAES_power_opt(1:T) CAES_power_opt(T)],x,[real_time_price(1:T);
real_time_price(T)]','stairs','stairs');
       hold(AX(1), 'on');
       stairs (x,[coal_power_opt(1:T) coal_power_opt(T)],'b:','Parent', AX(1));
       stairs (x,[wind_power(1:T,1); wind_power(T)]','b--','Parent', AX(1));
       hold(AX(1), 'off');
       hold(AX(2), 'on');
       stairs (x,coal_price*ones(1,T+1),'r:','Parent', AX(2));
       hold(AX(2), 'off');
       set(get(AX(1),'Ylabel'),'String','Power Plant Output [MW]','fontsize',10)
       set(get(AX(2),'Ylabel'),'String','Real-time Price [$/MWh]','fontsize',10)
       set(AX(2),'YColor','r');
       set(H2,'Color','r');
       h1 = legend(AX(1),'CAES Output', 'Coal Plant Output', 'Wind Plant Output');
       h2 = legend(AX(2),'Real-time Price','Coal Generation Cost');
       set(h1,'fontsize',8);
       set(h2,'fontsize',8);
    elseif NG_p == 1
       [AX,H1,H2] = plotyy(x,[CAES_power_opt(1:T) CAES_power_opt(T)],x,[real_time_price(1:T);
real_time_price(T)]','stairs','stairs');
       hold(AX(1), 'on');
       stairs (x,[gas_power_opt(1:T) gas_power_opt(T)],'b:','Parent', AX(1));
       stairs (x,[wind_power(1:T,1); wind_power(T)]','b--','Parent', AX(1));
       hold(AX(1), 'off');
       hold(AX(2), 'on');
       stairs (x,[gas_price_dollars(1:T,1); gas_price_dollars(T)]','r:','Parent', AX(2));
       hold(AX(2), 'off');
       set(get(AX(1),'Ylabel'),'String','Power Plant Output [MW]','fontsize',10)
       set(get(AX(2),'Ylabel'),'String','Real-time Price [$/MWh]','fontsize',10)
       set(AX(2),'YColor','r');
```

```
        set(H2,'Color','r');
        h1 = legend(AX(1),'CAES Output', 'NG Plant Output', 'Wind Plant Output');
        h2 = legend(AX(2),'Real-time Price','NG Generation Cost');
        set(h1,'fontsize',8);
        set(h2,'fontsize',8)
    elseif wind == 1
        if CAES_p == 1
           [AX,H1,H2] = plotyy(x,[CAES_power_opt(1:T) CAES_power_opt(T)],x,[real_time_price(1:T);
real_time_price(T)]','stairs','stairs');
           hold on
           stairs (x,[wind_power(1:T)' wind_power(T)],'b:','Parent', AX(1));
           set(get(AX(1),'Ylabel'),'String','Power Plant Output [MW]','fontsize',10)
           set(get(AX(2),'Ylabel'),'String','Real-time Price [$/MWh]','fontsize',10)
           set(AX(2),'YColor','r');
           set(H2,'Color','r');
           h1 = legend(AX(1),'CAES Output', 'Wind Plant Output');
           h2 = legend(AX(2),'Real-time Price');
           set(h1,'fontsize',8);
           set(h2,'fontsize',8);
        else
           [AX,H1,H2] = plotyy(x,[wind_power(1:T)' wind_power(T)],x,[real_time_price(1:T);
real_time_price(T)]','stairs','stairs');
           hold on
           set(get(AX(1),'Ylabel'),'String','Power Plant Output [MW]','fontsize',10)
           set(get(AX(2),'Ylabel'),'String','Real-time Price [$/MWh]','fontsize',10)
           set(AX(2),'YColor','r');
           set(H2,'Color','r');
           hold on
           h1 = legend(AX(1),'Wind Plant Output');
           h2 = legend(AX(2),'Real-time Price');
           set(h1,'fontsize',8);
           set(h2,'fontsize',8);
        end
    else
        [AX,H1,H2] = plotyy(x,[CAES_power_opt(1:T) CAES_power_opt(T)],x,[real_time_price(1:T);
real_time_price(T)]','stairs','stairs');
        set(get(AX(1),'Ylabel'),'String','CAES Output [MW]','fontsize',10)
        set(get(AX(2),'Ylabel'),'String','Real-time Price [$/MWh]','fontsize',10)
        set(AX(2),'YColor','r');
        set(H2,'Color','r');
        hold on
        h1 = legend(AX(1),'CAES Output');
        h2 = legend(AX(2),'Real-time Price');
        set(h1,'fontsize',8);
        set(h2,'fontsize',8);
    end
elseif coal == 1
    if CAES_p == 1
        [AX,H1,H2] = plotyy(x,[CAES_power_opt(1:T) CAES_power_opt(T)],x,[real_time_price(1:T);
real_time_price(T)]','stairs','stairs');
        hold(AX(1), 'on');
        stairs (x,[coal_power_opt(1:T) coal_power_opt(T)] ,'b:','Parent', AX(1));
        hold(AX(1), 'off');
        hold(AX(2), 'on');
        stairs (x,coal_price*ones(1,T+1),'r:','Parent', AX(2));
        set(get(AX(1),'Ylabel'),'String','Power Plant Output [MW]','fontsize',10)
        set(get(AX(2),'Ylabel'),'String','Real-time Price and Coal Generation Cost
[$/MWh]','fontsize',10)
        set(AX(2),'YColor','r');
        set(H2,'Color','r');
        hold on
        h1 = legend(AX(1),'CAES Output','Coal Plant Output');
        h2 = legend(AX(2),'Real-time Price','Coal Generation Cost');
        set(h1,'fontsize',8);
        set(h2,'fontsize',8);
    else
        [AX,H1,H2] = plotyy(x,[coal_power_opt(1:T) coal_power_opt(T)],x,[real_time_price(1:T);
real_time_price(T)]','stairs','stairs');
        hold(AX(2), 'on');
        stairs (x,coal_price*ones(1,T+1),'r:','Parent', AX(2));
        set(get(AX(1),'Ylabel'),'String','Power Plant Output [MW]','fontsize',10)
```

```
        set(get(AX(2),'Ylabel'),'String','Real-time Price and Coal Generation Cost
[$/MWh]','fontsize',10)
        set(AX(2),'YColor','r');
        set(H2,'Color','r');
        h1 = legend(AX(1),'Coal Plant Output');
        h2 = legend(AX(2),'Real-time Price','Coal Generation Cost');
        set(h1,'fontsize',8);
        set(h2,'fontsize',8);
    end
elseif coal == 2
    gas_price_dollars(1:T) = heat_rate * gas_price(1:T);
    if CAES_p == 1
        [AX,H1,H2] = plotyy(x,[CAES_power_opt(1:T) CAES_power_opt(T)],x,[real_time_price(1:T);
real_time_price(T)]','stairs','stairs');
        hold(AX(1), 'on');
        stairs (x,[gas_power_opt(1:T) gas_power_opt(T)] ,'b:','Parent', AX(1));
        hold(AX(1), 'off');
        hold(AX(2), 'on');
        stairs (x,[gas_price_dollars(1:T)' gas_price_dollars(T)],'r:','Parent', AX(2));
        set(get(AX(1),'Ylabel'),'String','Power Plant Output [MW]','fontsize',10)
        set(get(AX(2),'Ylabel'),'String','Real-time Price and Coal Generation Cost
[$/MWh]','fontsize',10)
        set(AX(2),'YColor','r');
        set(H2,'Color','r');
        hold on
        h1 = legend(AX(1),'CAES Output','NG Plant Output');
        h2 = legend(AX(2),'Real-time Price','NG Generation Cost');
        set(h1,'fontsize',8);
        set(h2,'fontsize',8);
    else
        [AX,H1,H2] = plotyy(x,[gas_power_opt(1:T) gas_power_opt(T)],x,[real_time_price(1:T);
real_time_price(T)]','stairs','stairs');
        hold(AX(2), 'on');
        stairs (x,[gas_price_dollars(1:T)' gas_price_dollars(T)] ,'r:','Parent', AX(2));
        set(get(AX(1),'Ylabel'),'String','Power Plant Output [MW]','fontsize',10)
        set(get(AX(2),'Ylabel'),'String','Real-time Price and NG Generation Cost
[$/MWh]','fontsize',10)
        set(AX(2),'YColor','r');
        set(H2,'Color','r');
        hold(AX(2), 'off');
        h1 = legend(AX(1),'NG Plant Output');
        h2 = legend(AX(2),'Real-time Price','NG Generation Cost');
        set(h1,'fontsize',8);
        set(h2,'fontsize',8);
    end
end

xlabel('Time [h]','fontsize',10)

if McIntosh == 0
    axis (AX(1),[0 168 -150 350])
    axis (AX(2),[0 168 0 200])
    xlimits = [ 0 T];
    ylimits = get(AX(1),'YLim');
    xinc = (xlimits(2)-xlimits(1))/7;
    yinc = (ylimits(2)-ylimits(1))/10;

    set(AX(1),'XTick',[xlimits(1):xinc:xlimits(2)],...
              'YTick',[ylimits(1):yinc:ylimits(2)])

    xlimits = [ 0 T];
    ylimits = get(AX(2),'YLim');
    xinc = (xlimits(2)-xlimits(1))/7;
    yinc = (ylimits(2)-ylimits(1))/10;

    set(AX(2),'XTick',[xlimits(1):xinc:xlimits(2)],...
            'YTick',[ylimits(1):yinc:ylimits(2)])
else
    axis (AX(1),[0 168 -150 350])
    axis (AX(2),[0 168 0 200])
    xlimits = [ 0 T];      ylimits = get(AX(1),'YLim');
```

```
    xinc = (xlimits(2)-xlimits(1))/7;
    yinc = (ylimits(2)-ylimits(1))/10;

    set(AX(1),'XTick',[xlimits(1):xinc:xlimits(2)],...
              'YTick',[ylimits(1):yinc:ylimits(2)])

    xlimits = [ 0 T];
    ylimits = get(AX(2),'YLim');
    xinc = (xlimits(2)-xlimits(1))/7;
    yinc = (ylimits(2)-ylimits(1))/10;

    set(AX(2),'XTick',[xlimits(1):xinc:xlimits(2)],...
            'YTick',[ylimits(1):yinc:ylimits(2)])
end

if CAES_p == 1
   figure('color','w')
   [BX,H1,H2] = plotyy(x,states_E(OptimalPolicy),x,[real_time_price(1:T);
real_time_price(T)]','plot','stairs');
   set(get(BX(1),'Ylabel'),'String','Available CAES Energy [MWh]','fontsize',10)
   set(get(BX(2),'Ylabel'),'String','Real-time Price [$/MWh]','fontsize',10)
   set(BX(2),'YColor','r');
   set(H2,'Color','r');
   h1 = legend(BX(1),'Available CAES Energy');
   h2 = legend(BX(2),'Real-time Price');
   set(h1,'fontsize',8);
   set(h2,'fontsize',8);

   xlabel('Time [h]','fontsize',10)

    if McIntosh == 0
        axis (BX(1),[0 168 0 550])
        axis (BX(2),[0 168 0 200])
        xlimits = [ 0 T];
        ylimits = get(BX(1),'YLim');
        xinc = (xlimits(2)-xlimits(1))/7;
        yinc = (ylimits(2)-ylimits(1))/5;

        set(BX(1),'XTick',[xlimits(1):xinc:xlimits(2)],...
                  'YTick',[ylimits(1):yinc:ylimits(2)])

        xlimits = [ 0 T];
        ylimits = get(BX(2),'YLim');
        xinc = (xlimits(2)-xlimits(1))/7;
        yinc = (ylimits(2)-ylimits(1))/10;

        set(BX(2),'XTick',[xlimits(1):xinc:xlimits(2)],...
                'YTick',[ylimits(1):yinc:ylimits(2)])
    else
        axis (BX(1),[0 168 0 2100])
        axis (BX(2),[0 168 0 200])
        xlimits = [ 0 T];
        ylimits = get(BX(1),'YLim');
        xinc = (xlimits(2)-xlimits(1))/7;
        yinc = (ylimits(2)-ylimits(1))/10;

        set(BX(1),'XTick',[xlimits(1):xinc:xlimits(2)],...
                  'YTick',[ylimits(1):yinc:ylimits(2)])

        xlimits = [ 0 T];
        ylimits = get(BX(2),'YLim');
        xinc = (xlimits(2)-xlimits(1))/7;
        yinc = (ylimits(2)-ylimits(1))/10;

        set(BX(2),'XTick',[xlimits(1):xinc:xlimits(2)],...
                  'YTick',[ylimits(1):yinc:ylimits(2)])
    end
end

TheEnd =1
```