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Variable Electricity from Base-load Nuclear Power Plants Using Stored Heat

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Variable Electricity from Base-load Nuclear Power Plants Using Stored Heat

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Abstract – *Restrictions on greenhouse gas emissions and growth of renewables change the price structure of electricity markets with more hours per year of low electricity prices and high electricity prices. This creates large economic incentives to (1) store energy at times of low electricity prices to produce electricity when prices are high and (2) couple base-load nuclear plants to heat storage to avoid selling electricity at times of low prices and increase electricity sales at times of high prices. Nuclear energy coupled with thermal energy storage has potentially superior economics to alternative energy storage technologies for peak electricity production because (1) heat storage is cheaper than electricity storage, (2) economics of scale for energy storage, (3) more storage cycles per year and (4) dispatchable electricity generation that avoids full depletion of energy storage systems. Nuclear with heat storage is potentially the enabling technology for a zero-carbon nuclear renewable electricity grid. The changing electricity market, nuclear thermal energy storage options, and market analysis using the Texas electricity grid as an example are described*

I. INTRODUCTION

The electricity grid is changing: deregulation of electricity markets, incentives to develop a zero-carbon electricity grid, and introduction of large-scale renewables. This changes the hourly price structure for electricity and creates incentives to couple thermal storage systems to nuclear power plants to produce peak electricity. The changes in the electricity markets, available thermal energy storage technologies that couple to nuclear power plants, and economic analysis of storage using the Texas electricity grid are described.

II. ELECTRICITY PRICE IMPLICATIONS OF RENEWABLES AND LOW-CARBON

In a free market the price of electricity varies with time. Figure 1 shows the market price of electricity versus the number of hours per year electricity can be bought at different prices in California (blue bars). Power plants with the lowest operating costs are dispatched first. As the price of electricity rises, power plants with higher operating costs come on line. There are near-zero and negative prices for a significant number of hours per year when electricity production exceeds demand and electricity generators pay the grid to take electricity. This is a consequence of two effects.

- *Renewables subsidies*. Production tax credits provide revenue for wind and solar plants to produce output independent of electricity demand. An owner of a wind or solar facility will sell electricity into the grid as long as the price paid to the grid to take electricity when there is excess production is less than the subsidy [1].
- *Operational constraints*. Nuclear and fossil plants can't instantly shut down and restart. They pay the grid at times of negative prices to remain on-line and thus be able to sell electricity a few hours later at high prices.

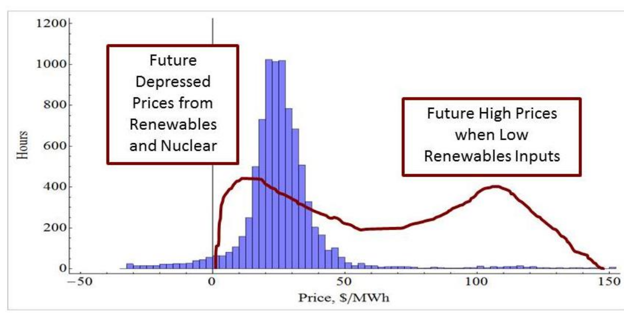

Fig. 1. Distribution of Electrical Prices (bar chart), by Duration, Averaged Over CAISO (California) Hubs (July 2011-June 2012) and Notational Price Curve (Red Line) for Future Low-Carbon Grid.

The addition of significant non-dispatchable wind or solar changes the shape of the price curve. The addition of a small amount of solar is beneficial because the electricity is added at times of peak demand. However, as additional solar is added, it drives down the price of electricity in the middle of sunny days. Each solar owner will sell electricity at whatever price exists above zero. This implies that when 10 to 15% of the total electricity demand is met by solar in California, the output from solar systems during midday for parts of the year will exceed electricity demand, the price of electricity will collapse to near or below zero, and the revenue to power plants at these times will collapse to near zero. Each incremental addition of solar at this point lowers the revenue for existing solar electricity producers. The percentage solar is the percentage of all electricity produced over a year by solar—zero in the middle of the night and exceeding electricity demand initially in June in the middle of sunny days. Relatively small fractions of solar have large impacts on prices in the midday but no impact at night when there is no solar.

The same effect occurs as one adds wind capacity but wind input is more random. As wind penetrates the market it drives the price of electricity down on days with high wind conditions and low electricity demand. Recent studies have estimated this effect in the European market [2-3]. If wind grows from providing 0% to 30% of all electricity, the average yearly price for wind electricity in the market would drop from 73 €/MWe (first wind farm) to 18€/MWe (30% of all electricity generated). There would be 1000 hours per year when wind could provide the total electricity demand, the price of electricity would be near zero, and 28% of all wind energy would be sold in the market for prices near zero.

The 'value factor' is defined as the average price at which a generation technology sells its electricity divided by the load-weighted market electricity price. At low penetration, wind and solar generally exhibit value factors of greater than unity as they tend to produce at hours of high demand. But the value factor drops sharply as renewables penetration increases. A review [3] of estimates of the value factor of solar across a wide range of electricity markets found that it is significantly greater than unity and can be as high as 1.3 for the first unit of solar installed on a grid. However, multiple reviewed studies found that the value factor drops sharply – ranging between 0.9 and 0.4 – as solar reaches 10% to 30% market share. This effect is exacerbated by the need to maintain larger quantities of costly peaking capacity at high renewables penetration. The same will occur with nuclear but only when nuclear provides ~70% of the total electricity demand. This is because nuclear plants run at base-load and base-load is about 70% of electricity demand.

In an all fossil-fuel system one does not see near-zero prices because fossil plants have low capital costs and high fuel costs. Fossil plants will shut down when electricity prices go below the costs of the fossil fuels. With renewables and nuclear, prices can approach zero for a significant number of hours per year. Without massive subsidies that increase with renewables penetration, this revenue collapse limits solar to ~10% of electricity production and wind to ~20% of electricity production. This also implies that in the long term the price of electricity at times of low renewable input will rise. If other types of power plants operate half the time because they do not generate electricity at times of high renewable inputs, replacement plants will not be built unless there is a rise in the prices of electricity when renewable energy sources are not producing electricity. The red line in Fig. 1 is a notational price curve one is expected to get if there is large-scale used of renewables with more hours of low-priced electricity (high wind or high solar) and more hours of high-priced electricity with fewer hours of mid-priced electricity. Recent studies on the German grid have reached similar conclusions [4].

The changing shape of the price curve encourages technologies with low capital costs and high operating costs to provide electricity at times of low renewables inputs. The net result is that large-scale wind and solar with existing technologies results in increased use of fossil fuels to provide electricity at times of low solar or wind conditions. Studies by the State of California [5] and Google [6] have come to similar conclusions.

III. THERMAL STORAGE TECHOLOGIES

There are two strategies to enable a low-carbon grid and improve the economics of nuclear power by operating nuclear plants at base-load while producing variable electricity to the gird.

- *Energy storage*. Energy is stored at times of low prices to produce electricity at times of high prices. Energy can be stored as heat or electricity (batteries, pumped storage, etc.). There has been a large effort to develop grid-scale storage by U.S. Department of Energy (DOE) [7] and the Electric Power Research Institute [8]. However, these studies have generally ignored options for using nuclear reactors to charge thermal energy storage systems and the potentially unique economic advantages of these systems relative to other grid-scale energy storage technologies.
- *Hybrid systems.* In a hybrid system a nuclear reactor produce two products: variable electricity and a second product such as steam for industry or hydrogen when the demand for electricity is low. Many of these systems require heat storage.

III.A. Heat Input

Variable electricity pricing creates incentives for thermal power systems with low operating costs (solar thermal and nuclear) to operate at full power, store heat at times of low electricity prices, and produce electricity for sale at times of high prices from operation of the power plant and the heat storage system. Nuclear reactors with heat storage have economic advantages relative to other technologies.

- *Capital Costs of Heat Storage Technologies.* Storing energy as heat (hot water, nitrate salt, firebrick) is cheaper than storing energy in batteries and other devices that take electricity from the grid, store it, and return electricity to the grid. Furthermore, heat storage for peak electricity production has better economics of scale. Larger equipment (tanks containing heat storage media, steam turbines, generators, etc.) have generally lower costs than small equipment per unit output. Solar thermal and nuclear systems would use the same heat storage technologies (below) but the economics of scale [9] will reduce the capital cost per kWh of storage by a factor of 2 to 10 for nuclear systems relative to solar thermal systems.
- *Storage Cycles per Year.* Nuclear plants with 90% capacity factors imply the storage system can be used most of the year. Because of cloud cover and winter, storage systems with solar thermal systems have fewer cycles per year. If there are twice as many storage cycles per year, the capital cost per storage cycle is reduced in half. Capital costs dominate the life cycle cost for all storage technologies [10].
- *Backup Generating Capacity.* All pure storage technologies (batteries, etc.) require backup electricity generating capacity. If there are long periods of low wind or solar, the storage media will be depleted. This generally implies gas turbines with a capital cost of ~$1000/kW. This does not occur with a fleet of nuclear reactors [11]—there is the energy to charge their thermal systems at daily times of low electricity demand. A fleet of nuclear reactors assures electricity production independent of wind or solar conditions and, if coupled with energy storage, can alleviate the need for costly, little-used peaking capacity.

Nuclear and solar use the same thermal storage systems. All of these systems can be coupled with a light-water reactor (LWR). Each would likely be a stand-alone facility next to the nuclear power plant and coupled by steam lines.

Steam Accumulators

Steam accumulators were developed in the 19th century when piston steam engines were used rather than electric motors in industry. The boiler would produce steam, the steam would be stored, and variable steam would be available to drive the steam engines to match demand. More modern versions coupled to steam turbines are used today [12].

In the 1970s studies [13] were conducted on coupling large PWRs to steam accumulators to produce peak electricity. Those indicated the technology was potentially competitive. In the 1970s peak electricity was produced from oil. There was an oil embargo that drove up oil prices and hence the need to develop alternative methods of peak electricity production. Oil prices dropped and thus work on nuclear-powered accumulators stopped. With renewables, the economic challenge is similar except it is a drop in the price of electricity at certain times.

At times of low electricity demand, steam from the nuclear reactor would be injected into insulated pressurized accumulator tanks partly filled with water. Steam injection would continue until the hot water was at steam temperatures and pressures. At times of high electricity prices, valves from banks of accumulators are sequentially opened resulting in flashing of hot water to steam that is sent to a steam turbine. Today Abengoa® is building steam accumulators in South Africa for solar power towers to maximize electricity production at times of higher prices and avoid revenue collapse. The operating conditions are similar to those required for a nuclear plant.

The primary capital cost is for the pressurized hot-water storage. In some designs it is a series of large pressure vessels. In other designs large natural gas pipe are proposed to provide the storage volume. Natural gas pipeline pressures match typical LWR steam pressures. The advantage of using pipes is that hundreds of kilometers large diameter pipe (>1 meter) are produced each year with cost reductions because of the scale of manufacturing. The pipe accumulators would be in an insulated building so the expense of insulating individual pipe is avoided. The steam accumulator building would be about the size of the turbine building.

Hot Water Storage

The primary cost of a steam accumulator is hot water storage. Several concepts have been proposed [14-15] to store hot water at pressure in mined underground rock caverns. The lithostatic pressure of the earth keeps the hot water at pressure rather than tanks. Large storage systems can be used by mining more space. If the underground caverns are lined, steam with low impurities can be produced and heat loses to the surrounding rock can be minimized. The viability depends upon the local geology.

Hot Rock Storage

Recent studies [11] have examined the option of nuclear geothermal heat storage systems capable of storing a gigawatt-year of heat. This enables seasonal thermal-heat storage. At times of low electricity demand, hot pressurized water is injected underground to heat a zone of rock that has been fractured to increase its permeability to water flow. At times of high electricity demand, this hot rock zone becomes a manmade geothermal power system.

Because the rock zone can't be insulated, there are conduction heat loses. However, the heat loses are proportional to the surface area of the heat storage zone while stored heat is proportional to the volume of the heat storage zone. As the system size increases, the percentage heat loses decrease. The minimum system scale is about 0.1 gigawatt-years to keep heat loses down to a few percent of the total heat being stored. Initial assessments indicate favorable economics in much of the U.S.

Nitrate Salt Heat Storage

The second class of heat storage devices store heat in a liquid or solid media at atmospheric pressure. This implies that heat from high-pressure steam is transferred through a heat exchanger to a secondary storage fluid. That secondary fluid heat capacity can be used to store the heat or used to heat a solid. To produce electricity, the process is reversed. The hot secondary fluid heats water to produce high-pressure steam that is sent to a peaking steam turbine. Depending upon design, this can be a separate set of heat exchangers or the same heat exchangers.

There has been a massive amount of work done on these types of systems for solar thermal power systems. The technology is used at several solar power plants. The universal heat storage media today is a mixture of liquid nitrate salts that operate over the same temperature range as LWRs. While there are many possible storage fluids, the near-term option is the use of nitrate storage salts—exactly the same salts used in solar thermal power systems for the same technical and economic reasons.

III.B. Electricity Input

Significant renewables or restrictions on greenhouse gas emissions implies times of very low electricity prices (Fig. 1)—times when the price of electricity is less than fossil fuels. This occurs today in Germany and California. This favors using electricity to charge-up heat storage systems. Two systems are being developed.

FHR with Firebrick Resistance-Heated Energy Storage

With electric resistance heating, heat storage can operate at very high temperatures. One advanced reactor system has been proposed to integrate power production with high-temperature heat storage: the Fluoride-salt-cooled High-temperature Reactor (FHR) with Nuclear air-Brayton Combined Cycle (NACC) and Firebrick Resistance-Heated Energy Storage (FIRES)

The FHR is a new reactor concept [16] that combines (1) a liquid salt coolant, (2) graphite-matrix coated-particle fuel originally developed for High Temperature Gas-cooled Reactors (HTGRs), (3) a NACC power cycle adapted from natural gas combined cycle plants and (4) FIRES. The FHR concept is a little over a decade old and has been enabled by advances in gas turbine technology and HTGR fuel. The Chinese plan to build an FHR test reactor by 2020. The liquid salt coolant was originally developed for use in molten salt reactors (MSRs) where the fuel is dissolved in the salt. The original MSR program was part of the Aircraft Nuclear Propulsion Program of the 1950s to develop a jet-powered nuclear bomber. Consequently, the fluoride salt coolant was developed to transfer high-temperature heat from a nuclear reactor to a gas turbine. Advances in utility gas turbines over 50 years have now reached the point where it is practical to couple a salt-cooled reactor to a commercial stationary combined-cycle gas turbine with heat delivered from the FHR between 600 and 700°C. It is that combination that enables the FHR to potentially have the transformational capabilities.

A commercial FHR point design has been developed with a base-load output of 100 MWe [17] to match the capabilities of the GE 7FB gas turbine—the largest rail transportable gas turbine made by General Electric. FHRs with higher output could be built by coupling multiple gas turbines to a single reactor or using larger gas turbines. The development of an FHR will require construction of a test reactor—this size commercial machine would be a logical next step after a test reactor. This point design describes the smallest practical FHR for stationary utility power generation. The market would ultimately determine the preferred reactor size or sizes.

The FHR is coupled to a NACC with FIRES (Fig. 2). In the power cycle external air is filtered, compressed, heated by hot salt from the FHR while going through a coiled-tube air heat exchanger (CTAH), sent through a turbine producing electricity, reheated in a second CTAH to the same gas temperature, and sent through a second turbine producing added electricity. Warm low-pressure air flow from the gas turbine system exhaust drives a Heat Recovery Steam Generator (HRSG), which provides steam to either an industrial steam distribution system for process heat sales or a Rankine cycle for additional electricity production. The air from the HRSG is exhausted up the stack to the atmosphere. Added electricity can be produced by injecting fuel (natural gas, hydrogen, etc.) or adding stored heat after nuclear heating by the second CTAH. This boosts temperatures in the compressed gas stream going to the second turbine and to the HRSG.

The incremental natural gas, hydrogen, or stored heat-to-electricity efficiency is 66.4%--far above the best stand-alone natural gas plants because the added heat is a topping cycle. For comparison, the same GE 7FB combined cycle plant running on natural gas has a rated efficiency of 56.9%. The reason for these high incremental natural gas or stored heat-to-electricity efficiencies is that this high temperature heat is added on top of "low-temperature"

670°C nuclear heat (Fig. 3). For a modular 100 MWe FHR coupled to a GE 7FB modified gas turbine that added natural gas or stored heat produces an additional 142 MWe of peak electricity.

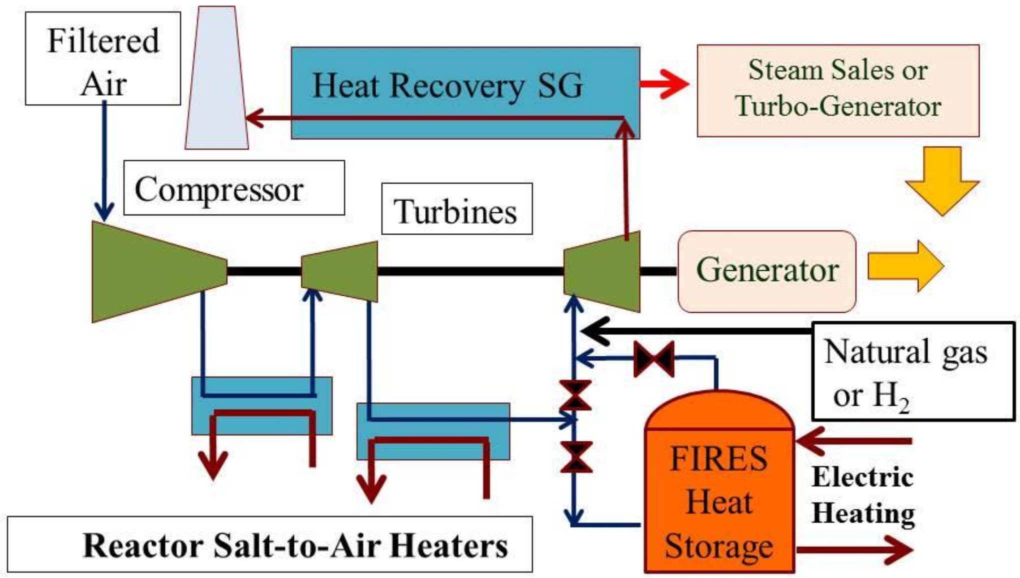

Fig. 2. Nuclear Air-Brayton Combined Cycle (NACC) with FIRES

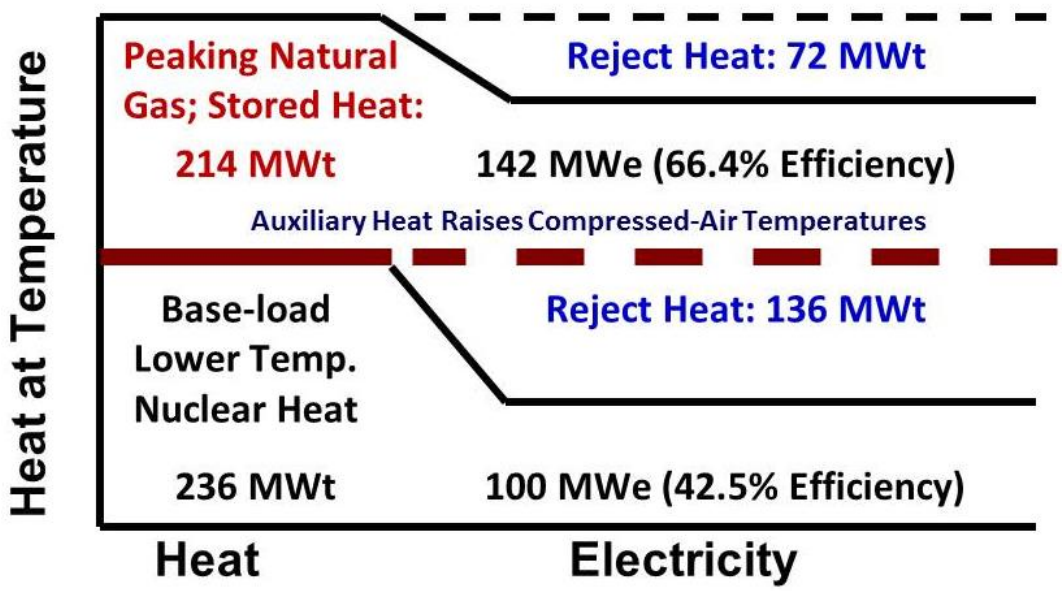

Fig. 3. Heat and Electricity Balance for NACC and FIRES

The heat storage system consists of high-temperature firebrick heated to high temperatures with electricity at times of low or negative electric prices. The hot firebrick is an alternative to heating with natural gas. The firebrick, insulation systems, and most other storage system components are similar to high-temperature industrial recuperators. The round-trip storage efficiency from electricity to heat to electricity is ~66%--based on ~100% efficiency in resistance electric conversion of electricity to heat and 66% efficiency in conversion of heat to electricity. That efficiency will be near 70% by 2030 with improving gas turbines.

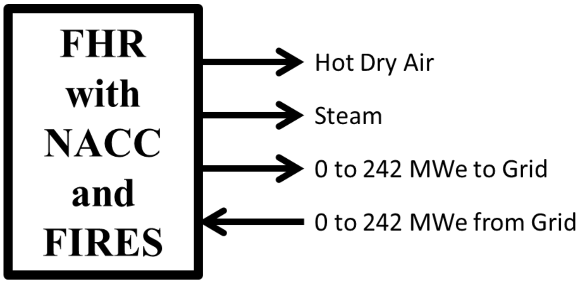

Fig. 4. Capability of Modular FHR with NACC and FIRES

The plant output is shown in Fig. 4. When electricity prices are low (less than the price of natural gas), electricity from the FHR is sent to FIRES. In addition, up to 242 MWe of electricity is bought from the grid. The buy capability of the FHR matches the sell capability and thus does not require upgrades to the grid. Because electricity is used to heat the firebrick, firebrick can be heated to 1800°C to minimize the quantity of firebrick required. The hot compressed gas from FIRES is lowered to the turbine limits by either steam injection or mixing with lower-temperature compressed air.

In the existing Texas and California grids, the revenue for an FHR with NACC is 50% higher than a base-load nuclear plant because of the capability to produce more electricity at times of peak demand and prices. For each market, the starting point is the hourly price of electricity. This was used to determine net revenue for that hour for: (1) the FHR operating under baseload conditions and (2) the FHR producing peak electricity. Net revenue for peak electricity production is the revenue from electricity sales for that hour minus the price of natural gas that was burned. The plant was assumed to operate each hour in the mode that produced the most net revenue. Total yearly revenue was obtained by summarizing revenue for each hour over the year. The difference in revenue between a baseload plant and an FHR with NACC increases with natural gas prices.

The economics of adding FIRES depends upon how many hours per year the price of electricity is below the price of natural gas. The economics are expected to be favorable in the California market by 2020. By then there will be sufficient renewables to drive electricity prices below those of natural gas for significant periods of time. It enables replacement of "expensive" natural gas with cheaper electricity. FIRES enables buying massive quantities of electricity when the price is low. Unlike batteries and other electricity storage devices, resistance heaters are inexpensive and thus the system can absorb massive quantities of low-price electricity even if available for short periods of time.

Cryogenic Energy Storage (CES)

In a CES system [18] electricity is used to produce liquid air using current industrial processes. The cryogenically cooled air is stored at atmospheric pressure. At times of high electricity demand, the liquid air is compressed, heated with steam from a light-water reactor (LWR) to produce high-pressure air, sent through a turbine, and exhausted to the atmosphere. The round trip efficiency exceeds 70%. The peak power is about three times the rated electrical power of the LWR.

IV. HYBRID ENERGY SYSTEMS

Hybrid systems are the second option to enable nuclear plants to operate with variable electricity output where energy is used to produce a second product when the price of electricity is low. That second product could be steam for industrial uses, hydrogen, or some other product. Many hybrid systems will require heat storage to enable efficient production of the second product.

V. MARKET ANALYSIS

Energy storage systems can benefit nuclear power generation by avoiding selling to the grid when prices are low and capitalizing on periods of high prices. Using 2013 hourly price and load data from the Texas ERCOT ISO [19], this section illustrates the potential benefits associated with short term (daily / overnight) energy storage, as well as long term (seasonal) storage. For a typical summer week on the ERCOT grid, the peak afternoon-evening electricity demand can be more than double the overnight minimum. Annually, there is a substantial seasonal variation between winter and summer, with demand consistently twice as high during the warmest months.

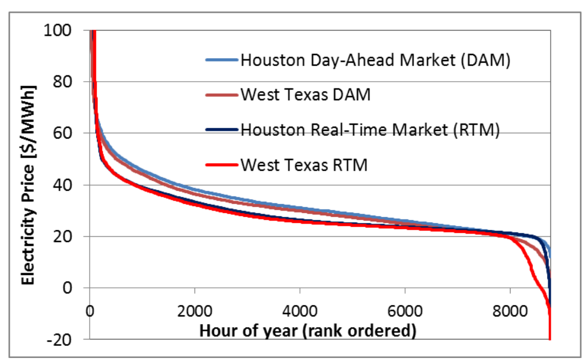

Fig. 5. Price Duration Curves, Houston and West Texas ERCOT Hubs, 2013

The study considers the Houston and West Texas ERCOT hubs. Fig. 5 shows the distribution of hourly day-ahead and real-time market (DAM and RTM) electricity prices for each hub in 2013. The DAM is a forward market in which hourly prices are calculated for the next operating day based on generation offers, demand bids and scheduled bilateral transactions. The RTM is a spot market in which current prices are calculated several times an hour based on actual grid operating conditions. RTM typically represents a small share of transaction volume in ERCOT.

The electricity price on the Houston hub is relatively stable: well over 90% of hours in 2013 fell between \$20 and \$60/MWh. This limits the potential value of energy storage. Conversely, the West Texas grid has high penetration of non-dispatchable wind which introduces the market effects discussed in Section II. The technology mix in West Texas is likely more typical of future electrical grids. The difference between the Houston and West Texas markets was considerably more dramatic prior to 2011 when new 345 kV transmission capacity alleviated congestion issues between West Texas and the rest of the state [20].

This study considers a generic storage technology characterized by its efficiency, which is set at 75% and 90% in two sensitivity cases. Storing and discharge rates are assumed equal, and three operating modes are allowed for the plant and storage system. These are: 1) production of electricity from both the plant and storage system, 2) charging of the storage system with no electricity production, 3) production of electricity by the plant with neither charge or discharge from storage. The storage system can hold up to 12 hours of full-capacity energy production from the plant. A specific storage technology is not selected but is assumed to offer moderate capacity and fast discharge, so that it is best suited for daily load management as opposed to weekly or seasonal storage cycles. The steam accumulator and nitrate salt technologies mentioned in section II, among others, offer such characteristics.

Optimal storage plans are derived from the hourly electricity price data. The plans are specified by the start and duration of the storing period for each day, as well as the start of the selling period. The daily storage plan is optimized by calculating the revenue from every feasible plan. Revenues are calculated per MW of generation capacity. This methodology was applied over 365 unique days of price data; illustrative results for a typical week in the Houston day-ahead market, October 13-19, 2013, are shown in Fig. 6. Table 1 shows that for both the Houston and West Texas hubs there is a considerable revenue enhancement associated with storage.

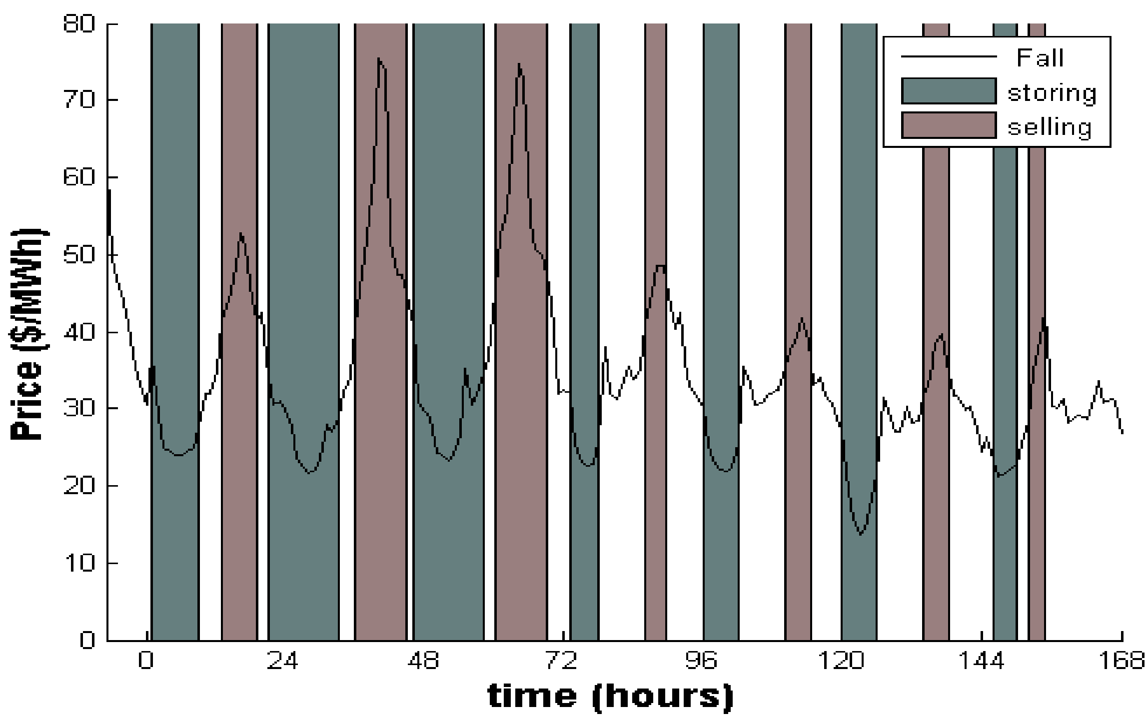

Fig. 6. Optimized energy storage strategy for a representative week

Table 1. Revenue enhancement from generic daily storage technology

	Day-Ahead Market (% Annual Revenue Increase due to Storage)	Real-Time Market (% Annual Revenue Increase due to Storage)
Houston Hub	11.5% (@ 75% eff) 17.0% (@ 90% eff)	15.0% (@ 75% eff) 19.9% (@ 90% eff)
West Texas Hub	12.2% (@ 75% eff) 17.7% (@ 90% eff)	16.9% (@ 75% eff) 21.8% (@ 90% eff)

Next, a generic storage technology that can store much greater quantities of energy for longer time periods is considered. The underground hot rock storage technology described in Section II provides an example. To model such a system, the price duration curve is used to produce an annually optimized electricity storage strategy for a system with large storage capacity. Such an optimization assumes storage is possible on the timescale of months, and as such it provides an upper bound on the economic benefit of storage technology. The results of this analysis, given in Table 2, show that greater revenue enhancement can be achieved if large seasonal differences in demand and price are leveraged.

Table 2. Revenue enhancement from generic seasonal storage technology

	Day-Ahead Market (% Annual Revenue Increase due to Storage)	Real-Time Market (% Annual Revenue Increase due to Storage)
Houston Hub	14.8% (@ 75% eff) 21.2% (@ 90% eff)	19.1% (@ 75% eff) 24.7% (@ 90% eff)
West Texas Hub	16.2% (@ 75% eff) 22.6% (@ 90% eff)	22.2% (@ 75% eff) 27.7% (@ 90% eff)

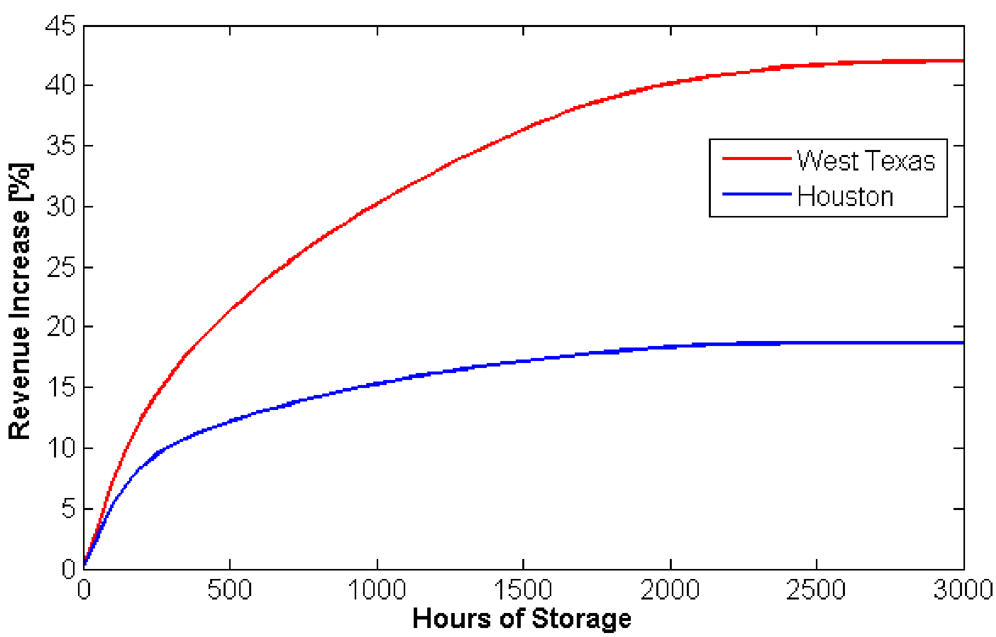

Fig. 7. Revenue enhancement for optimized long-term storage system using 2011 ERCOT price data

The revenue enhancement from high capacity seasonal storage is shown in Fig. 7 as a function of the hours of energy stored annually for a generic system with 75% efficiency. 2011 ERCOT price data was used to prepare this curve; as this was prior to the upgrading of high-voltage transmission capacity between West Texas and the rest of the state, the impact of large wind generation in West Texas is accentuated and the potential benefit of energy storage is much larger, exceeding 40%. Each point on this curve represents the optimal annual storage strategy for a given number of hours of storage capacity, so it can be seen that the marginal benefit of additional storage capacity decreases.

VI. OTHER ANALYSIS METHODOLOGIES

We use a market analysis methodology because it is the basis for most decision making in the United States. This will remain the dominate methodology for energy decisions because historically between 5 and 10% of the gross national product is energy—with peaks as high as 14%. Four out of five recessions since the 1970s can be explained by oil price shocks [21]. Doubling energy costs imply large decreases in the standard of living for the entire world. In contrast, U.S. defense spending is 4% of the gross national product. A political decision for a 50% increase in defense spending has a much smaller impact on societal standards of living than political decisions on energy options. Economic efficiency is important.

There are alternative methodologies. Energy systems [21] can be analyzed based on energy return on investment (EROI). This is the energy out of an energy system (coal, oil, natural gas, nuclear, wind, etc.) divided by the energy inputs. Such analysis provides similar results to a market analysis but with some exceptions. In particular, it does not distinguish between the unique value of liquid fuels for transport versus other energy sources. What EROI emphasizes is the importance of operating capital-intensive energy systems (wind, solar, nuclear) at maximum capacity since the EROI decreases with capacity factor.

There are technical viability analyses, including nuclear renewable systems with heat storage [22]. These determine the technical ability to meet variable electricity demand with different systems and can provide insights to the technical aspects of the challenge.

VII. CONCLUSIONS

Changing from an electricity grid based on fossil fuels to a low-carbon nuclear-renewable electricity grid changes the electricity price curve. There are more hours of near-zero price (or negative-price electricity if subsidies) electricity and more hours of high-priced electricity. Efficient use of capital-intensive electricity generating assets (nuclear and renewables) requires that these generating assets operate at full capacity. The technologies to achieve efficient utilization of capital-intensive assets are energy storage and hybrid energy systems.

The current strategy to address the low-carbon grid has been R&D and subsidies to develop energy storage devices (batteries, pumped storage, etc.) backed up by gas turbines when those storage devices are depleted. Systems studies (Hirsh, California, Google, etc.) indicate such strategies can't eliminate the use of fossil fuels. An alternative strategy is integration of thermal storage systems with nuclear power plants. This makes nuclear the enabling technology for a zero-carbon grid and the enabling technology for much larger use of solar and wind by reducing the revenue collapse challenge.

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