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Electrical Storage Using Hydrogen and Metal Hydride Slurry for Baseload or Dispatchable Power

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Abstract

A method of storing intermittent renewable energy by converting electrical energy into hydrogen and storing the hydrogen in metal hydride slurry is discussed. Economic analyses show how a wind farm can provide baseload or dispatchable electric power to the grid with a 10% return on investment for an electricity price of $88/MWh for baseload and $110/MWh for dispatchable.

Summary

Renewable energy farms, such as wind and solar farms, have the potential to supply all the energy that is needed by the United States [1]. The issue is to use it when it is available or to store it until it is needed. Researchers are exploring both of these options. Smart grids promise to send signals to electricity customers to turn loads on when energy is available and to turn them off when it is not. Energy storage is being explored in the development of grid scale batteries, flywheel storage, pumped hydroelectric, compressed air storage, and hydrogen systems.

We are all quite familiar with stored energy. Our economy is reliant on the energy stored in fossil fuels. The use of stored energy allows us to use energy when we need it to produce light, heat, and motion.

Hydrogen provides an alternative to fossil fuels. Electricity can be stored by electrolyzing water to produce hydrogen and oxygen. A kilogram of hydrogen has a higher heating value of about 39 kWh when burned with oxygen to produce water. It takes more energy to produce the hydrogen because some of the electricity is used in heating the electrolyte (resistance heating of electrolyte) and purifying the water. The best large-scale electrolysis machines can produce a kilogram of hydrogen using 45.6 kWh of electric energy (www.NEL-Hydrogen.com). This hydrogen can be stored until it is needed and then burned with air in a gas turbine to turn a generator and produce electricity again. The byproducts of these reactions, besides electricity, are water and some nitrogen oxides. Or it can be used in a fuel cell to produce electricity directly with byproducts of only water.

Using rechargeable magnesium hydride slurry, we conclude that a renewable energy wind farm using electrolysis machines, hydrogen storage, and hydrogen fueled gas turbine/generators can operate as a baseload power plant at an electricity cost of $88/MWh for an annual internal rate of return of 10% based on the total capital cost (including the wind farm). The system can also be operated to provide dispatchable electricity at a slightly reduced return on investment or a slightly higher price.

Metal Hydride Slurry

History

Rechargeable magnesium hydride slurry has been under development by Safe Hydrogen, LLC for the past eight years. Prior to that, Safe Hydrogen developed magnesium hydride slurry for hydrolysis reactions where the slurry was reacted with water to produce hydrogen. This work was performed with the support of the Department of Energy in a five-year project to investigate metal hydride slurry for hydrogen storage for automobiles. The conclusion of the hydrolysis project was that the hydrolysis system can produce hydrogen for automotive use at a cost of about $4.50/gallon of gasoline equivalent assuming a mature large scale system. The system mass and volume almost met the goals of the automobile industry for energy density.

Work was begun on the rechargeable magnesium hydride slurry project at the completion of the DOE project because we realized that the same technology that we planned to use for the hydrolysis slurry can be used for rechargeable slurry, but the cost per unit of hydrogen carried can be reduced significantly when the slurry can be reused several hundred times.

Characteristics

Rechargeable magnesium hydride slurry is a mixture of magnesium hydride powder and light mineral oil. The slurry can be charged with hydrogen in a reactor designed for the rates of hydrogen available from the hydrogen production system. The slurry can be discharged in the same or separate reactor at rates of hydrogen production required by the generator that uses the hydrogen.

Rechargeable magnesium hydride slurry looks like a thick paint and can easily be pumped from tank to tank. The energy required to move it from tank to tank is quite small as compared with the energy required to compress and store gaseous hydrogen in pressure vessels. The slurry can be stored at ambient temperatures and pressures in conventional liquid fuel tanks. It can be transported using conventional liquid fuel transportation systems (tank trucks, train tank cars, barges, and pipelines). Thus it can be transported at costs similar to the cost of transporting fuel oil.

Magnesium hydride slurry has several features that make it safe to handle and use. Although magnesium hydride and magnesium powder are reactive in air and water, surrounding them in oil prevents contact with air and water and makes them safe to handle. The oil surrounding the particles, in the slurry, prevents water and oxygen from reaching the magnesium hydride particles and significantly reduces the reaction rates. The byproducts of the reactions of magnesium hydride and water, or magnesium and water, are hydrogen and the relatively benign solid product magnesium hydroxide (Milk of Magnesia). Magnesium hydride itself is relatively benign since it reacts very slowly at normal temperatures and pressures. The mineral oil used in the slurry has a low vapor pressure and thus behaves with lower flammability characteristics than fuel oil which itself has a considerably lower flammability than gasoline. Thus transporting slurry will be considerably safer than transporting gasoline.

Magnesium hydride slurry is classed as a non-hazardous material for transportation. The Department of Transportation defines a hydrogen producing material as “hazardous” if a kilogram of the material can produce more than 1 liter of hydrogen in an hour when mixed with water. Our tests have shown that both the charged and discharged states of magnesium hydride slurry, if mixed with water, will produce less than 10 mL of hydrogen in a week at ambient conditions. So magnesium hydride slurry can be transported as a non-hazardous material.

In rechargeable slurry systems, there is very little free hydrogen gas because the hydrogen is chemically bound with the magnesium metal to form the solid magnesium hydride compound in the slurry. This limits the hazard associated with the storage of large volumes of gaseous hydrogen.

The materials needed to make magnesium hydride slurry are in large supply and readily available all over the world. Magnesium is the eighth most common element in the earth’s crust and it makes up 0.13% of seawater. We used a price of magnesium of $2.90/kg. During the past 8 years, the spot price of magnesium has varied from a low of $1.80/kg in 2005 to a high of $6.00/kg in 2008. It is now about $3.10/kg. New technologies under development by Metal Oxygen Separation Technologies Inc. promise to reduce this price considerably by reducing the amount of energy required to produce the metal from its oxide. The costs used in the modeling discussed in this paper are the costs of the raw materials. There is reason to believe, however as noted by the work by MOST that, as the demand for magnesium increases, the price will decrease as we introduce new technology and new magnesium production plants.

State of Development

The development program for rechargeable magnesium hydride slurry first targeted identification and testing of potential “show stoppers”.

- We have demonstrated that the slurry will remain stable for several weeks.
- We have demonstrated that the slurry can be cycled 50 times without degradation. (This is an operational life sufficient to support the economic application of the technology. Since the magnesium hydride was not impaired with this number of cycles, many more cycles are anticipated. Dry magnesium hydride has been reported to have been cycled 1000 times).
- We have demonstrated that the slurry will be classified as a non-hazardous material when transported in either the charged or discharged state.
- We have demonstrated that the rates of hydriding and dehydriding the slurry are significantly higher than with dry powder.

We are currently working on a small demonstration model to show off the technology. Our most recent development activities have been with reactor designs to be used for the hydriding and dehydriding of the magnesium hydride slurry.

Electrical Energy Storage Using Hydrogen and Metal Hydride Slurry

Electrical Storage Concept

Magnesium hydride slurry can be used as part of a system to store renewable energy produced in wind and/or solar farms. With the use of large storage systems, an intermittent energy source such as a wind farm can be part of a baseload or dispatchable electrical energy production system that follows the load. Storing electricity can be performed by using intermittent sources of electrical energy to produce hydrogen from water in an electrolysis machine. The hydrogen can then be stored in magnesium hydride slurry and the slurry stored in large liquid fuel storage tanks. When the intermittent electrical energy is insufficient to meet the demand, hydrogen can be removed from storage and used to produce the electrical power needed by burning it with air in a gas turbine. All the components of this electrical production system are well tested at the scales that we have modeled except for the hydrogen storage system. The slurry costs are based on market prices for magnesium and oil with a 25% additional cost of preparation. The hydride and dehydride reactors are based on the costs of our laboratory scale reactors scaled with a 2/3 power law scale factor to the sizes required for the system.

Figure 1 displays the electrical storage concept in graphical form. This diagram follows the discussion presented by Dr. Samir Succar in Reference 2.

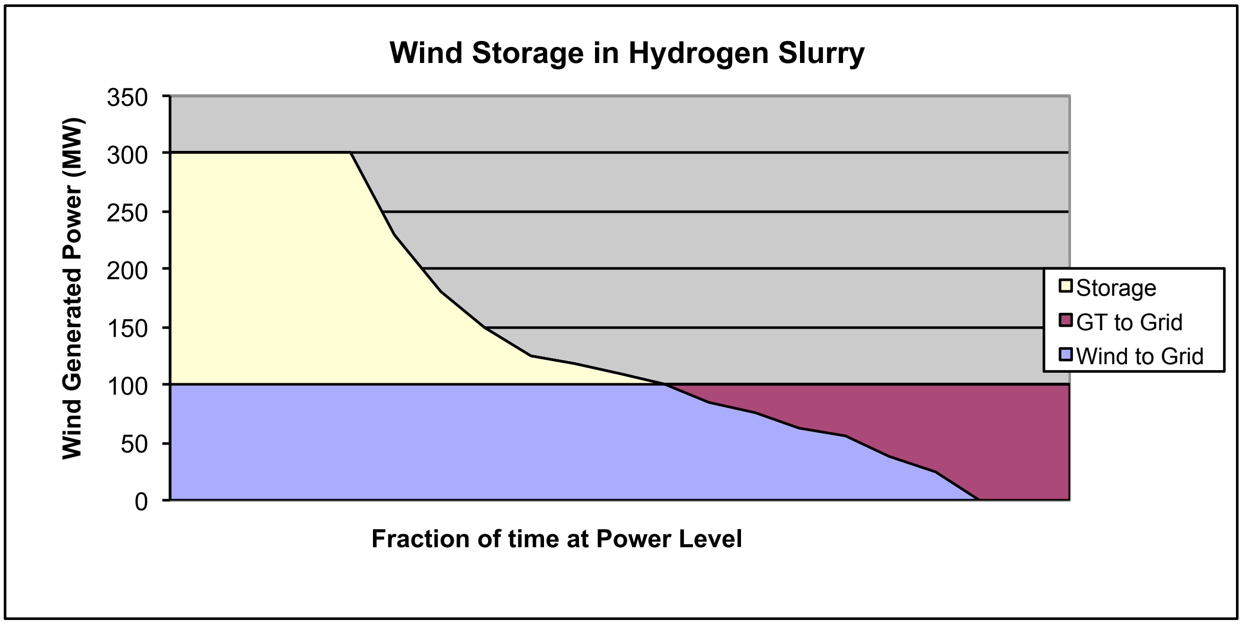

Figure 1 - Diagram Showing Typical Wind Energy and Its Use

The curve that starts at 300MW and declines gradually to zero is a typical wind profile. In this example, for about 20% of the year, the wind farm will produce at its rated power level. For 10% of the year, there will be insufficient wind to produce any output power from the wind farm. Depending on the location of the wind farm, the wind farm will produce energy between its rated power level and zero power. The area above the baseload line is the energy that is to be stored. When the wind farm is producing more than the baseload requirement, the baseload energy goes directly to the grid from the wind turbines and the remainder of the wind generated electricity goes to electrolysis machines to produce hydrogen which is stored. When the wind farm is producing less energy than the baseload requirement, energy is returned from storage to keep the output at the required power level, in this case 100 MW.

If it is desired to produce at a constant power output, or if it is desired to follow the load curve of a particular region, then wind energy must be stored and returned from storage. When more wind is blowing than is needed, the excess can be stored as hydrogen. When less wind is blowing than is needed, the difference must be taken from storage.

For the example shown in Figure 1, when the wind is blowing at 300 MW, 100 MW will go to the grid and 200 MW will go to storage. When the wind blows between maximum and 100 MW, 100 MW goes to the grid and the balance goes to the storage system. When the wind blows between 100 MW and 50 MW, all the wind goes to the grid and the balance comes from the storage system operating one 50 MW gas turbine. When the wind blows between 50 MW and zero MW, all the wind goes to the grid and the balance comes from the storage system operating two 50 MW gas turbines.

There are many additional advantages that result from using a hydrogen storage system with an intermittent energy source such as a wind farm or a solar farm.

- The electrolyzers, required to produce hydrogen from excess wind power, can be used to smooth the fluctuations of the wind farm. Loads on NEL Hydrogen electrolyzers can vary from 10% to 100% in a second. The electrolyzer capacity can be used to provide such regulation services to the grid.
- The use of electrolyzers to follow the load can allow hydrogen fueled gas turbines to operate at more constant loads thus minimizing wear on the equipment. Rapid and frequent changes in load, experienced by some gas turbine operators, have resulted in wear that has significantly reduced the lifetime of the turbine generators.
- The electrolyzers also produce oxygen that can be sold as an additional source of income. The oxygen can also be used to aid in the combustion of hydrogen in the gas turbines to reduce the production of nitrogen oxides.
- The use of fast start gas turbine generators can provide black start capability that can add to the revenue of the wind farm with storage.
- The utility buying the power from the wind farm with storage will be purchasing 100% wind produced electrical energy. The current practice is to back up wind farms with natural gas fired gas turbines.
- The use of storage can provide power during long periods without sufficient power from renewable intermittent sources.

Model Results

Safe Hydrogen has modeled base-load and dispatchable wind farm systems using load and price data collected hourly (from ISO New England - Reference 4) and wind turbine data for 10-minute intervals (from NREL/DOE Reference 5) both for a year of operation. The load and price data is from ISO New England for 2001. The wind data is representative of a location north east of Lubbock, TX. The wind turbine data has been scaled to represent the amount of power that a farm of 1.6MW wind turbines might produce. For the dispatchable model, the load and price data provide the model with a power output curve to follow. The model assumes that the wind farm and storage system will be delivering power to the grid throughout the year whenever the load is above the annual minimum load. The power output is assumed to be at its maximum when the overall demand load is at its peak. In between, the power output is proportional to the load between the maximum and minimum load. An additional revenue source is achieved by providing power above this normal load following output, up to the grid connection limit, whenever the ISO price is greater than the contract price. For the base-load model, the wind farm is assumed to provide a constant output throughout the year. Tables 1 through 4 display some of the characteristics of the two cases studied.

Table 1 displays cost and performance characteristics of the two cases studied. The dispatchable system uses fewer wind turbines and less hydrogen storage than the baseload system because less electrical energy is sold in the dispatchable case than in the baseload case.

Table 2 displays the amount of electrical energy sold directly from the wind, the amount sold from the gas turbines, and the amount of hydrogen produced by the electrolyzers. Both systems spill some wind but the amount spilled is small relative to the total amount produced. The baseload system spills less than 0.2%. The dispatchable system spills less than 3%.

Table 3 summarizes the earnings, costs, and the IRR (Internal Rate of Return) calculated for the two projects. The IRR for the dispatchable system, assuming a contract price of $110/MWh, a 30% investment tax credit, and a renewable energy credit of $3/MWh, is 10%. The electric price for the baseload system, making the same assumption for sales and credits, is $88/MWh for an IRR of 10%. In both cases, the model assumes that the amount of energy that can be contracted is dependent on the amount of energy stored in the hydrogen storage system and the assumption that the wind might not blow. The storage for both cases is sized to ensure that there will always be enough hydrogen to fuel the gas turbines at full capacity for a 2 day period even when the storage system is largely depleted.

Table 4 displays some figures of merit for this system. The systems store energy at a capital cost of $11 to $12/kWh of storage capacity. The storage capacities of the systems are about 75,000 MWh for the dispatchable case 109,000 MWh for the baseload case. The amount of energy moved through the storage during the year is 232,000 to 364,000 MWh. So the storage is fully cycled slightly more than three times each year.

Table 1 - Performance and Cost Characteristics of System Components

Summary of plant inputs			Dispatchable	Baseload
Wind turbines	number	#	202	336
	unit cost	$/unit	1,726,000	1,726,000
	unit size	MW	1.6	1.6
	capacity	MW	323	538
Electrolyzer	number	#	115	182
	unit cost	$/unit	1,567,658	1,567,658
	unit production rate	kg H2/hr	43.60	43.60
	specific energy consumption	kWh/kg H2	47.78	47.78
	capacity	MW	240	379
	capacity	kg/hr	5,014	7,935
Hydrider	number	#	2	3
	unit cost	$/unit	21,870,469	21,870,469
	unit hydriding rate	kg/hr	2,507	2,507
	capacity	kg/hr	5,014	7,521
Slurry	mass H2	MT	5,200	7,500
	mass Mg	MT	62,711	90,449
	mass MgH2	MT	67,911	97,949
	fraction MgH2		0.50	0.50
	mass oil	MT	67,911	97,949
Slurry	amount	MT	135,823	195,898
	cost Mg	$/MT	2,900	2,900
	cost oil	$/MT	1,000	1,000
	cost manufacture	%	25%	25%
	total cost	$	312,218,027	450,314,462
	unit cost	$/kg	60	60
	capacity	kg H2	5,200,000	7,500,000
Dehydrider	number	#	3	3
	unit cost	$/unit	26,777,646	26,777,646
	unit hydriding rate	kg/hr	3,513	3,513
	capacity	kg/hr	10,539	10,539
Compressor	number	#	3	3
	unit cost	$/unit	1,500,000	1,500,000
	unit compression rate	kg/hr	3,595	3,595
	capacity	kg/hr	10,785	10,785
H2 Gas Turbine	number	#	3	3
	unit cost	$/unit	26,000,000	26,000,000
	unit capacity	MW	50	50
	specific energy consumption	kg H2/hr for 50 MW	3,513	3,513
	capacity	MW	150	150
	capacity	kg H2/hr	10,539	10,539
Contract price for electricity		$/MWh	110	87
Renewable Energy Credit		$/MWh	3	3
ITC on Wind Farm			30%	30%
ITC on Storage			30%	30%
ITC on Generation from Storage			30%	30%
Contract period		Days	2	2
Max grid connection		MW	250	250

Table 2 - Wind Energy and Hydrogen Storage Characteristics

Summary of Power Outputs		**Dispatchable**	**Baseload**
Electrical Energy sold directly from wind	MWh	498,136	960,150
Electrical Energy sold from turbine	MWh	231,107	364,188
Total electrical energy sold	MWh	729,242	1,324,339
Electrical Energy stored	MWh	779,907	1,222,915
H2 produced by electrolyzer	kg H2	16,322,866	25,594,706
Total energy produced from wind	MWh	1,314,957	2,187,255
Total spilled wind	MWh	36,915	4,190
	% of total wind	2.81%	0.19%

Table 3 - Cost Summary

Summary of cost outputs			**Dispatchable**	**Baseload**
Contract price for electricity		$/MWh	110	87
Earnings from contract sale of electricity		$	79,377,120	114,267,975
Earnings from spot market sale of electricity		$	2,082,611	2,302,737
Earnings from credits		$	2,187,727	3,973,016
Earnings from sale of oxygen		$	25,909,882	40,627,412
Total Annual Earnings		$	109,557,340	161,171,139
Annual Operating Expenses		$	10,589,564	15,616,204
Capital costs	Wind farm	$	348,652,000	579,936,000
	Electrolysis machines	$	180,280,670	285,313,756
	Hydrider	$	43,740,938	65,611,407
	MgH2 slurry	$	312,218,027	450,314,462
	Dehydrider	$	80,332,938	80,332,938
	Compressor	$	4,500,000	4,500,000
	Turbine	$	78,000,000	78,000,000
	Total Capital cost	$	1,047,724,573	1,544,008,563
	Other Project costs	$	157,158,686	231,601,285
	Working capital	$	120,488,326	177,560,985
Total Project Cost		$	1,325,371,585	1,953,170,833
Years of operation		yrs	30	30
IRR		%	10%	10.0%

Table 4 - System Figures of Merit

Summary of Figures of Merit		Dispatchable	Baseload
storage cost per unit energy stored	$/kWhr sold	3.83	3.35
total project cost per annual unit energy sold	$/kWh sold	1.82	1.47
cost per unit energy stored by storage capacity	$/kWh stored	11.95	11.42
Storage capacity of storage system	MWhr stored	74,010.82	106,746.37
	days at full load	20.56	29.65
Use of the storage system	MWhr stored/year	232,320.90	364,285.59

Performance Charts from the Modeling

Figures 2 through 9 display results of the modeling of a baseload system and a dispatchable system. Figures 2 through 5 display performance characteristics of the baseload system. Figures 6 through 9 display performance characteristics for the dispatchable system. Figures 2, 3, 6, and 7 display performance characteristics for a year of operation. Figures 4, 5, 8, and 9 display performance characteristics for a 30 day period at the beginning of the simulation to better display the changes in the characteristics and the effects on system performance of load and price changes.

In Figure 2, the top three charts show the wind energy supplying the system, the spot market price of electricity, and the load on the system. The fourth chart shows the wind energy sold throughout the year. There are occasional spikes in the wind energy sold which represent the sale of additional electricity when the spot price goes above the contract price. (The model assumes that additional power, up to the grid connection limit, will be sold if the price is better than the price contracted). The fifth chart shows the power sent to the electrolyzer. This is the power that will be converted to hydrogen. The sixth chart shows the amount of hydrogen stored in the storage system throughout the year. At the start of the year, the hydrogen content of the system is relatively constant as the load is consuming as much energy as the system is storing.

At about day 50, the amount of storage starts to increase indicating that more energy is coming from the wind farm than is leaving for the gas turbines. At day 174, the amount of hydrogen stored starts to decline indicating that less energy is coming from the wind farm than is going to the gas turbines. Charts 7 and 8 display the amount of power sold from the system and the amount of turbine power sold.

Figure 3 displays the extra power sold, the power not available to meet the contract, the contract power, and the wind power spilled. Since the contract power is a constant for the baseload analysis, the contract power chart shows a constant value. The wind power spilled chart shows the results from having less electrolyzer capacity than potential wind capacity. When an additional electrolyzer is added, the return on investment declines indicating that the added cost of the additional electrolyzer does not result in sufficient additional revenue to pay for it.

Figures 4 and 5 display the first 30 days of Figures 2 and 3. From these charts it is possible to see the daily changes in the wind resource and how it is used in the system. As the wind power declines, less and less is sent to the electrolyzers. When the wind power is less than the contract amount, power begins to be delivered from the gas turbines.

Figures 6 and 7 display the same charts for the dispatchable model. It is important to note that the storage again increases through the middle of the year and declines toward the end of the year. For the dispatchable model, the 30 day display shown in figures 8 and 9 are more interesting because the changes in power levels is more easily seen. The dispatchable model is designed to model a system that follows the load. The power from the wind storage system is zero when the load is at its annual trough and it is at its peak when the load is at its annual peak. The wind storage system is capable of following the load and the return on investment is only slightly reduced from the baseload case.

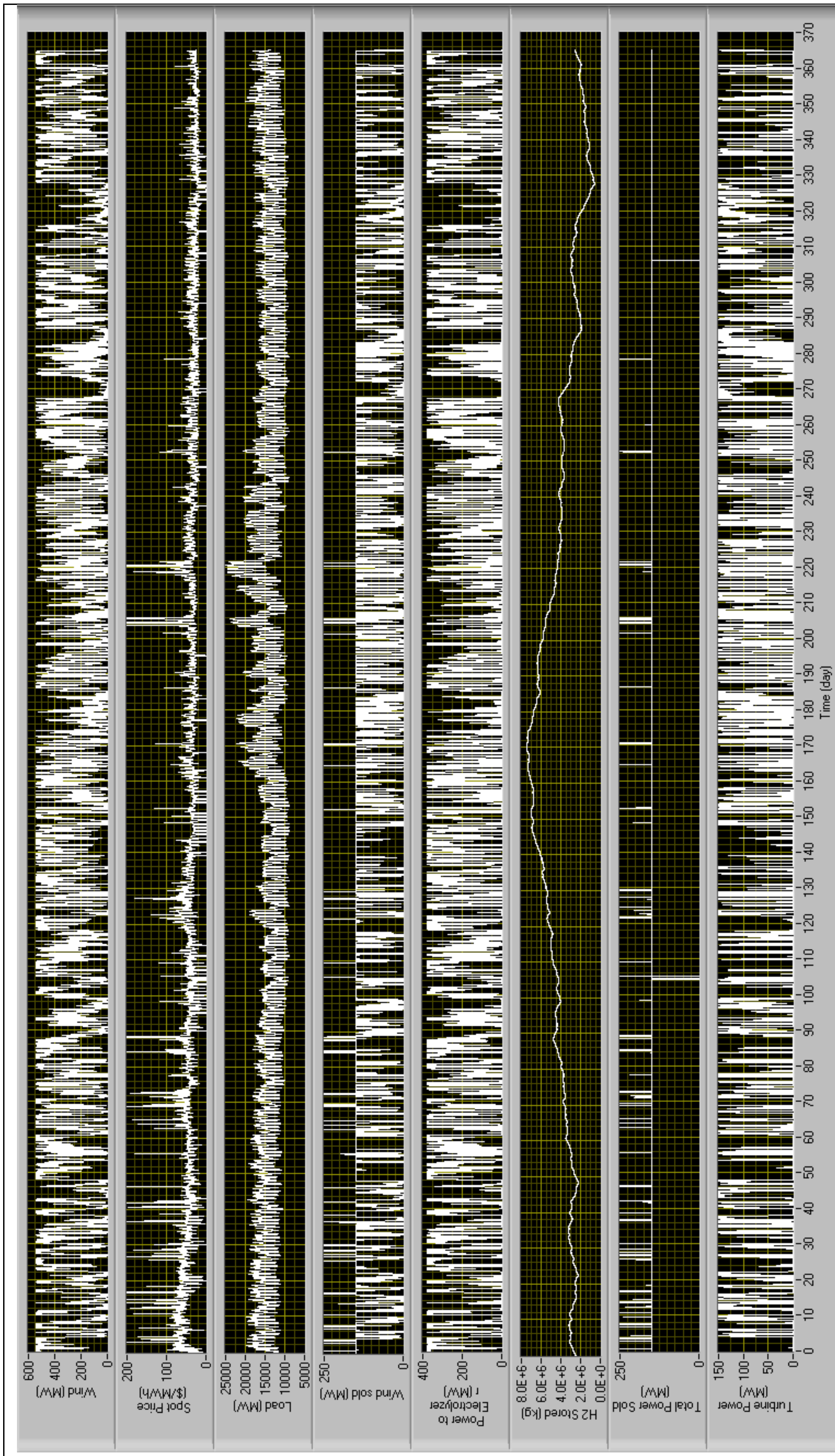

Figure 2 - Baseload System Performance Charts for One Year

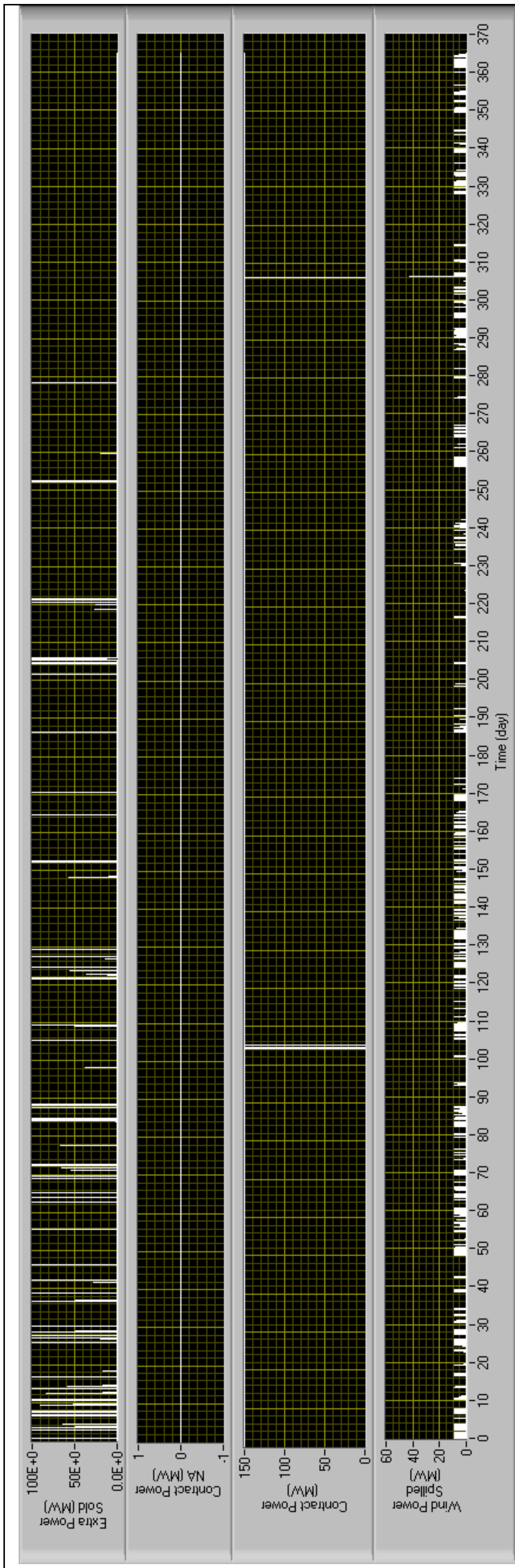

Figure 3 – Baseload System Performance Charts for One Year Continued

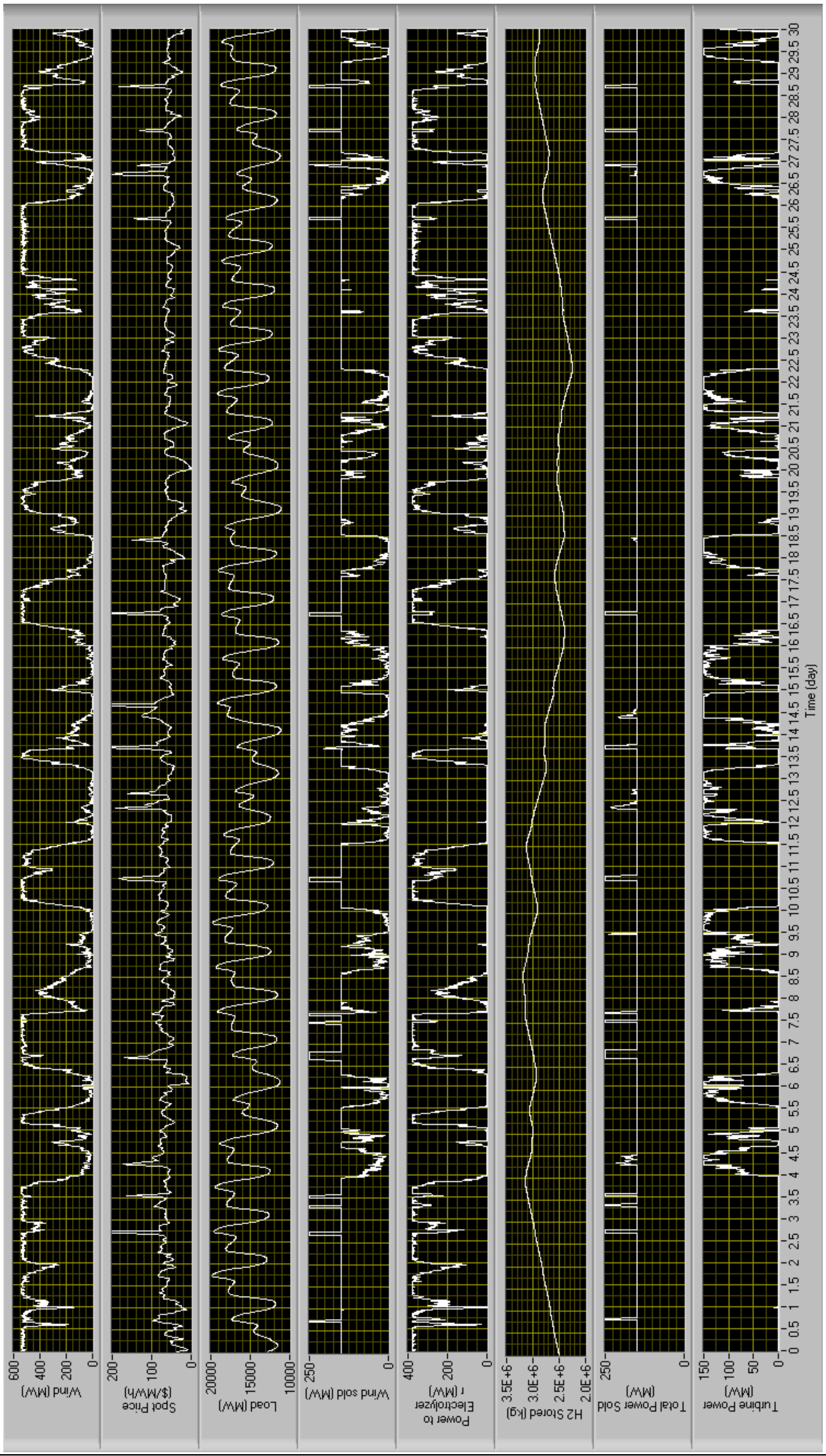

Figure 4 - Baseload System Performance Charts for 30 Days

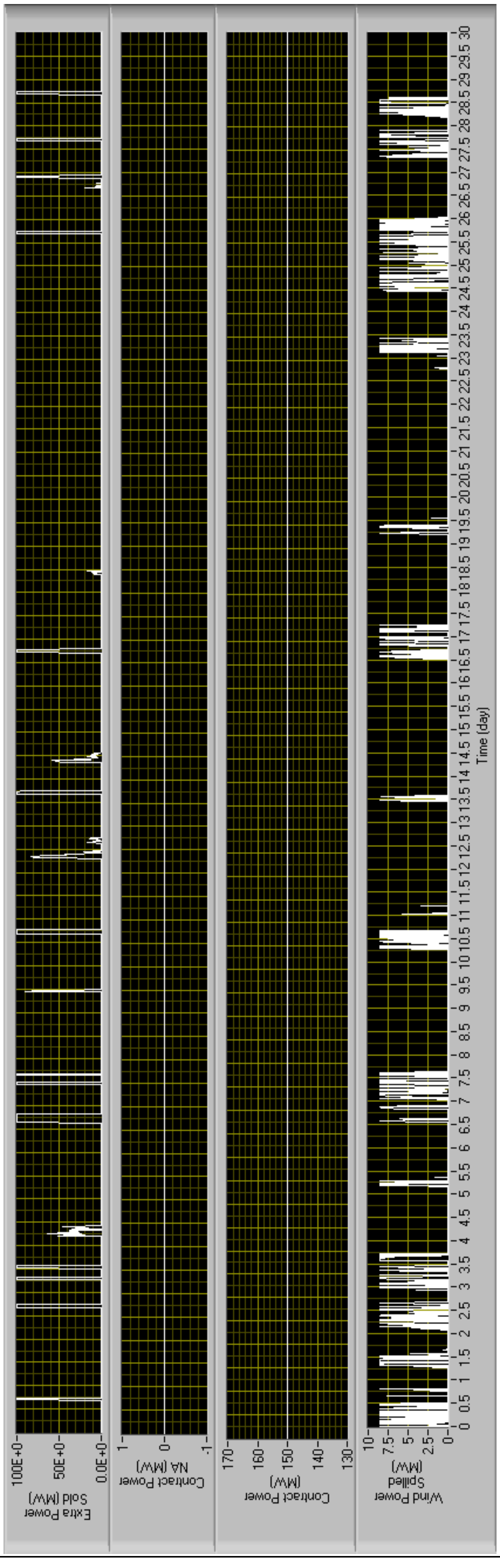

Figure 5 - Baseload System Performance Charts for 30 Days Continued

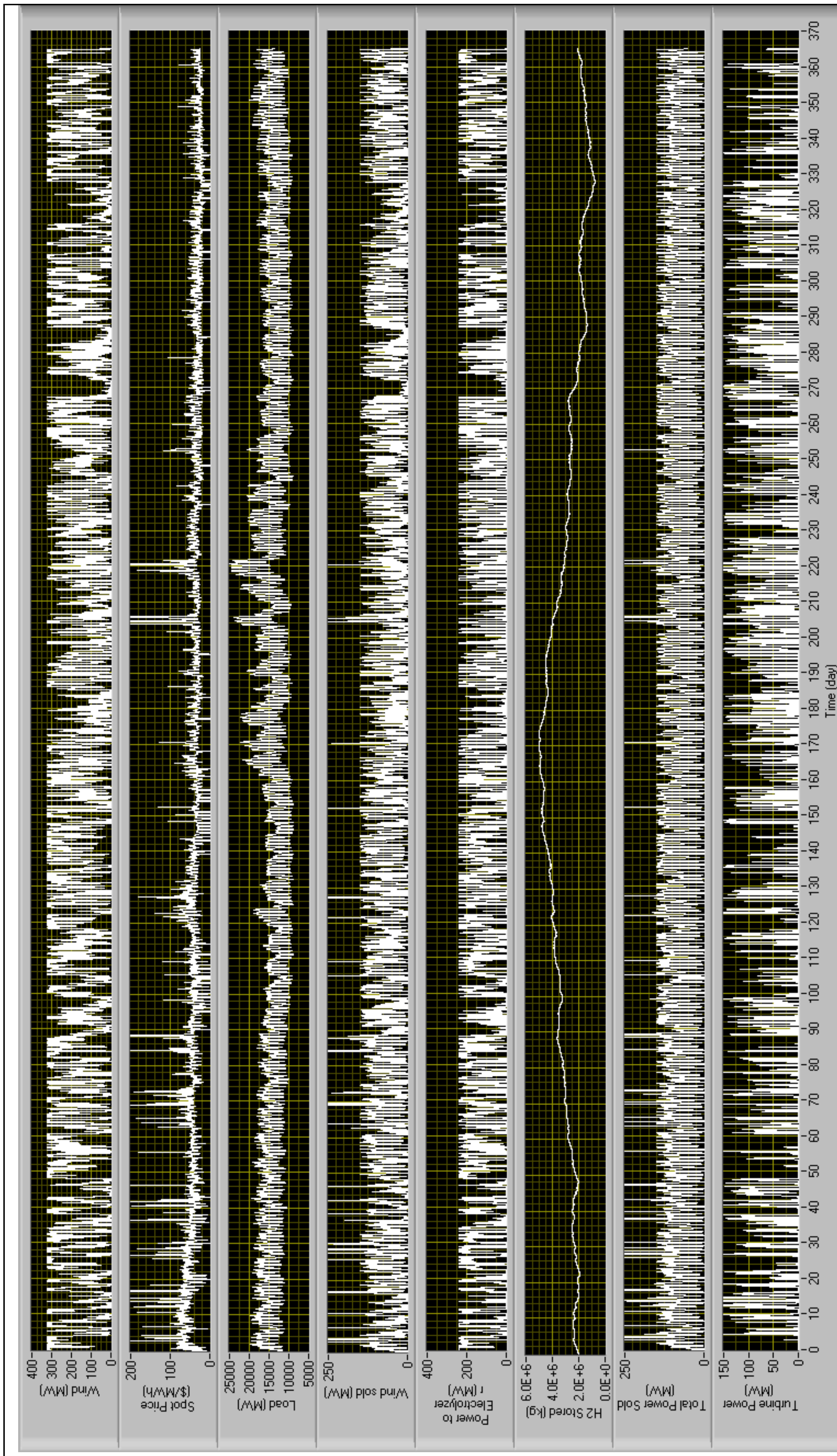

Figure 6 - Dispatchable System Performance Charts for One Year

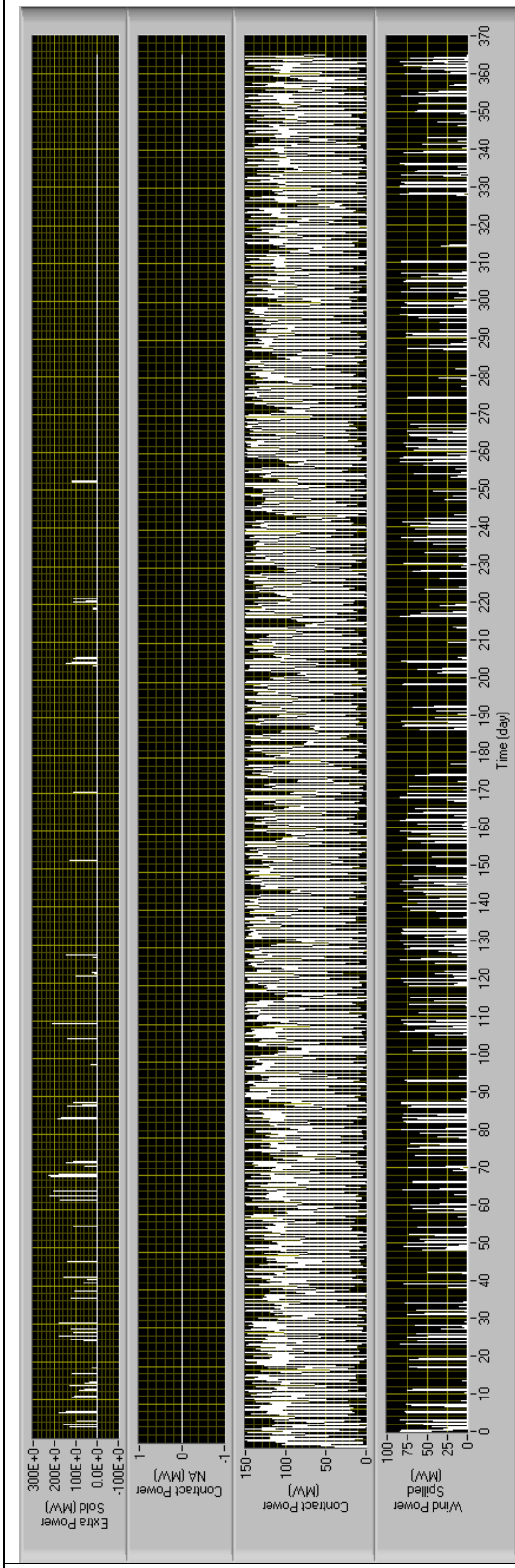

Figure 7 - Dispatchable System Performance Charts for One Year Continued

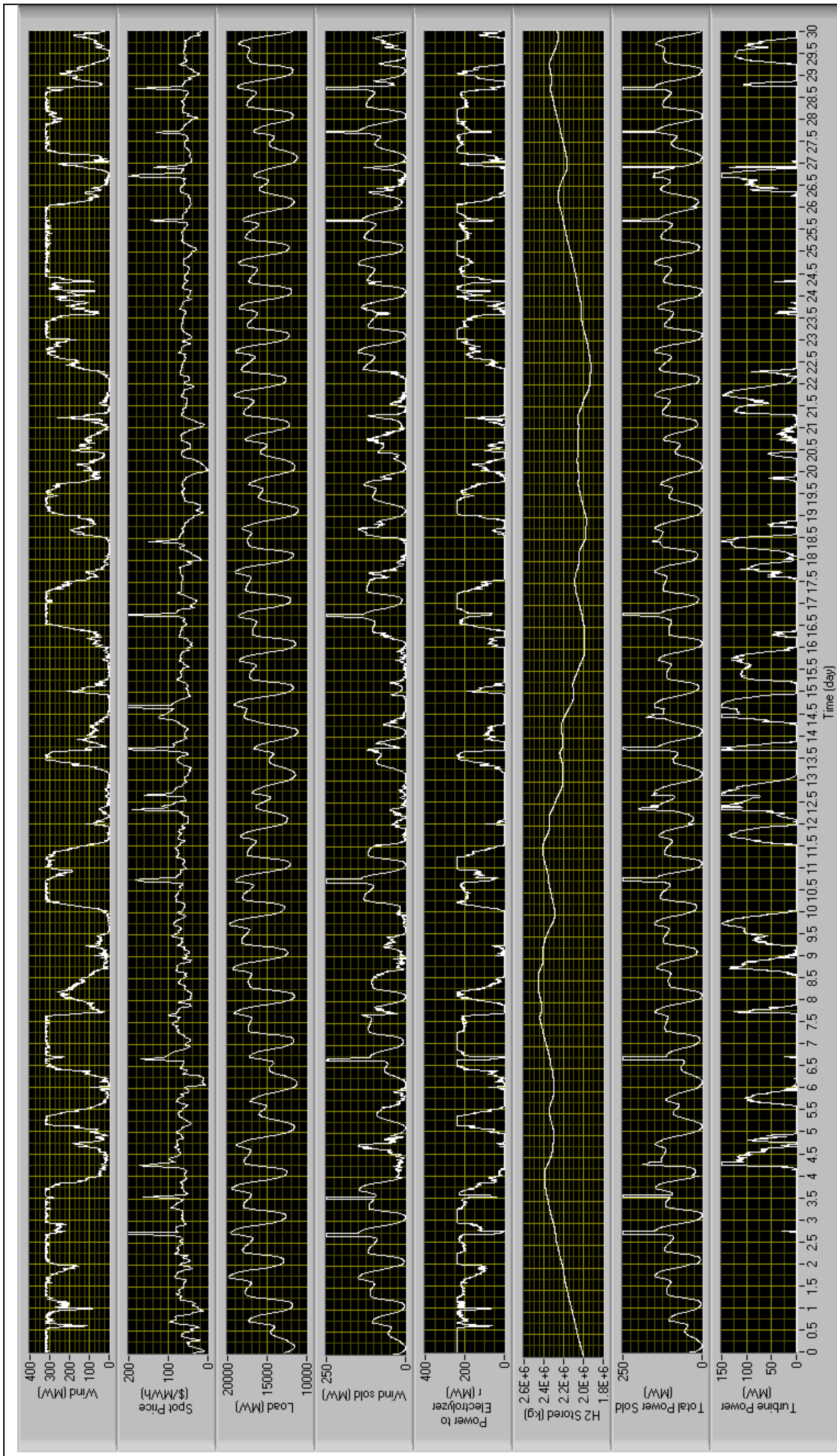

Figure 8 - Dispatchable System Performance Charts for 30 Days

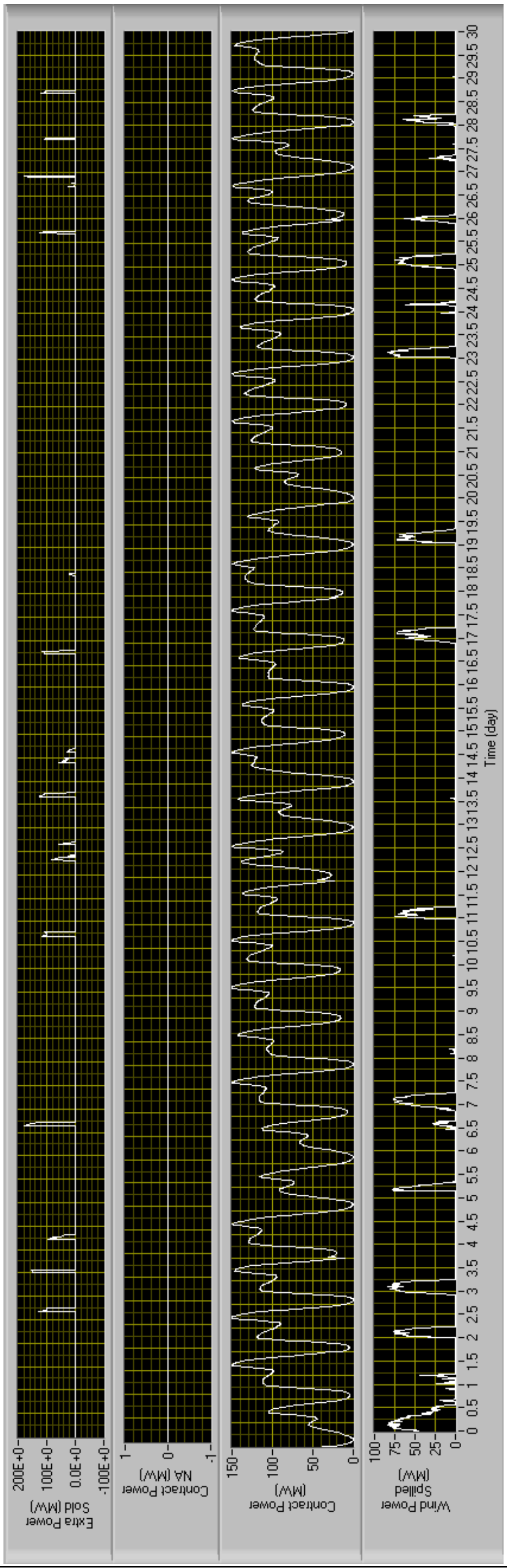

Figure 9 - Dispatchable System Performance Charts for 30 Days Continued

Economic Analysis

The Internal Rate of Return (IRR) has been determined using the calculated capital expense for the various major components. Installation costs and supporting equipment are assumed to be included in the category of Other Project Costs, which is calculated as 15% of the capital cost. Working capital is calculated as 10% of the total capital and Other Project Costs. Operating Costs are assumed to be 1% of the Capital Cost per year for maintenance. In addition, there is a cost of water assumed to come from a water purification plant at a total cost of \$0.77/m^3. Income is from the contract power provided at the contract price for the electrical energy, the additional electrical energy sold at spot market prices, the Producer Tax Incentive, the Renewable Energy Credit, and the sale of oxygen. The total initial investment is the Capital Expense, the Other Project Costs, and the Working Capital. An Investment Tax Credit of 30% of the Total Capital Cost has been assumed for the cases displayed. Cases performed using the Producer Tax Credit required a slightly higher price of electricity to achieve 10% IRR. The IRR is calculated from this initial Total Capital Cost minus the Investment Tax Credit and the difference between the Income and Expenses over a 30-year lifetime.

Comparison of storing hydrogen in slurry vs compressed or liquid hydrogen

Magnesium hydride slurry offers a lower cost option for storing hydrogen than as compressed or liquid. We have compared magnesium hydride slurry to compressed hydrogen storage and liquid hydrogen storage using cost estimates presented in Reference 3.

Compressed Hydrogen

Reference 3 presents the capital cost of a compressed hydrogen storage for 3,265,848 kg of hydrogen \$402 million from chart on page D-3. As the data was adjusted for 1995 dollars, we have converted them to 2016 dollars using an average inflation rate of 3% per year for 21 years. This is a 1.86 factor. We have also increased the storage to 7700 MT to agree with the magnesium hydride slurry hydrogen storage. This requires a factor of 2.36. With these factors, we calculate the cost of a comparable compressed hydrogen storage system to be (402 X 1.86 x 2.36 =) \$1,765 million

Liquid Hydrogen (LH)

Similarly we have calculated the cost of a liquid hydrogen system using the capital cost of \$142 million from the chart on page D-7 of Reference 3. This figure is for a hydrogen storage of 3,362,368 kg of hydrogen. Converting to 2016 dollars with an average inflation rate of 3% for 21 years is a 1.86 factor. Increase storage to 7,700,000 kg of storage requires a factor of 2.29. With these factors, we calculate the cost of a comparable liquid hydrogen system to be (142 x 1.86 x 2.29 =) \$563 million.

It takes about 35% of the heating value of hydrogen to liquefy it to 20^{o} K. This means that the liquid hydrogen option is about 15% less efficient than the compressed or slurry storage options.

Safety issues are also more critical with liquid hydrogen than with the slurry option because of the cryogenic handling needed. Boil off will also be relatively constant and will require a constant input of energy.

Magnesium Hydride Slurry

We have estimated the capital cost of the magnesium hydride slurry storage system to be about $603 million. This includes the cost of the hydriders, dehydriders, slurry, and tanks.

Conclusions

Magnesium hydride slurry offers a superior option to the compressed option because of lower costs. Liquid hydrogen and slurry are very similar in capital costs.

Slurry is superior to the liquid hydrogen option because of its lower operating costs and from the higher efficiency of the slurry system over the liquid hydrogen option. In addition, the liquid hydrogen system will require constant monitoring to deal with the boil off. Safety issues are more of a concern liquid hydrogen than with the slurry option because of the precautions needed with the cryogenic material

Comparison with Competing Storage Systems

The baseload wind farm system, using magnesium hydride slurry for hydrogen storage, compares well with competing electric storage technologies. The advantage of the rechargeable slurry system is that the cost of bulk energy storage is low so that large quantities of energy storage are possible in an economical system. Table 5 displays comparison characteristics of several competing storage technologies. The systems are compared by Build Time, Efficiency, Capital cost (on a $/kWh basis and $/kW basis), and Discharge Time. The typical comparison criteria for generation equipment are the Capital Cost comparisons of cost/kWh stored and cost/kW installed. The Discharge Time helps to differentiate the various technologies. The H2/slurry storage system offers a very large storage capacity that can allow very long discharge times. This places the H2/slurry storage system in a class of its own. In addition, it does not suffer from location restrictions. Despite the high cost per kW, the system produces a high return on investment. The cost per kW is high because this storage system is assumed to include the whole system including the wind farm.

Table 5 - Comparison

	Build Time	Efficiency	Cap Cost		Discharge Time
	yrs	%	$/kWh	$/kW	hr
Pumped Storage	9-15	80	100	1000	1-24
CAES	3+	55	80	800	1-8
Batteries	0.5	75-85	500-2000	500	seconds-8
Capacitors	0.17	99	8000	200	seconds
Flywheels	1	95	1000	300	minutes to 4 hr
H2/Slurry Dispatchable	2-3	57	12	5500	474
H2/Slurry Baseload	2-3	61	10	8000	769

Sensitivity Analysis on Contract Price for Baseload Electricity

Figure 10 displays the sensitivity of the contract price on the internal rate of return.

As the price of electricity increases, the income on the contracted electricity increases but the income on extra power sold, when the spot price is above the contract price, declines since there are few opportunities available.

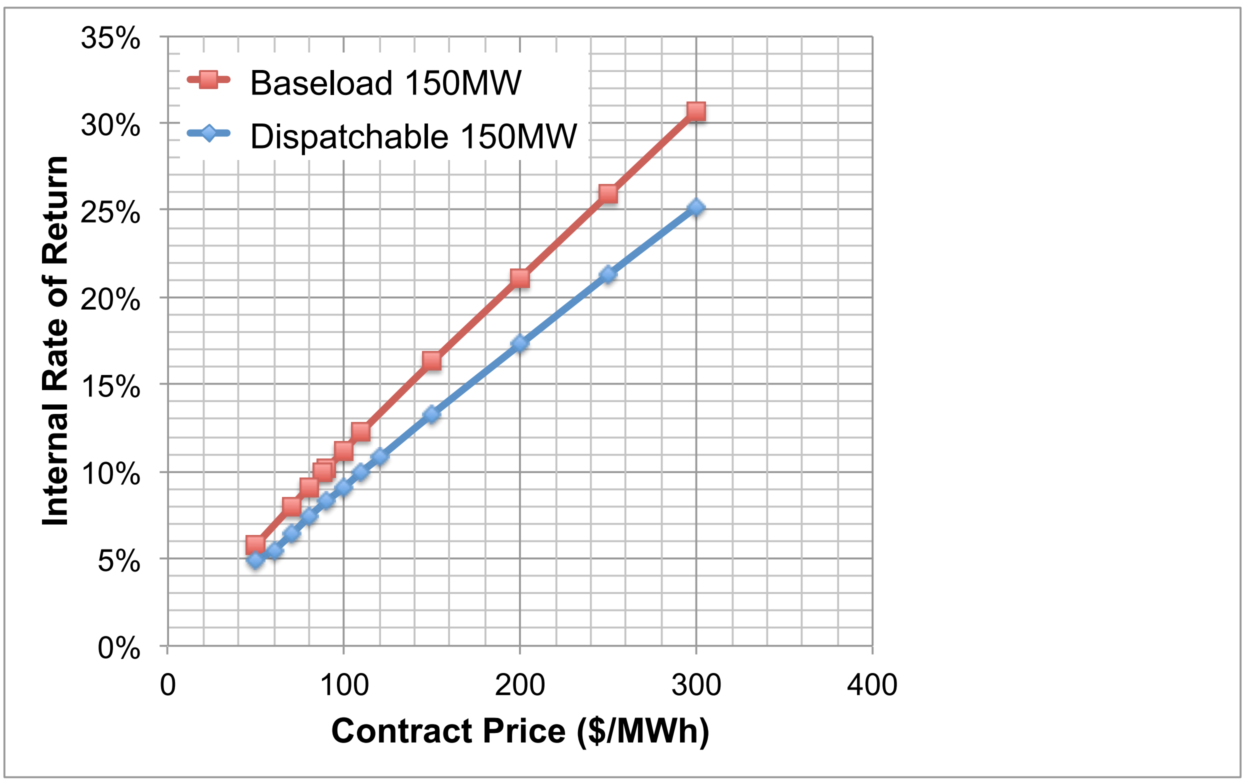

Figure 10 - Sensitivity of IRR on Contract Price

Conclusions

An analysis has been performed to evaluate the potential for using magnesium hydride slurry to store hydrogen produced from a wind farm. The wind data was provided by NREL as part of the Western Wind and Solar Integration Study performed for the US DOE. This was modeled data rather than measured data but it is representative of actual wind data. The data provided power output every 10 minutes. A site located northeast of Lubbock, TX was used. The result of this analysis is that, given a price for the electricity of $88/MWh, a return on investment of 10% can be achieved for a baseload wind/storage project. Further, the study concludes that the system could be configured as a dispatchable power project (one that would follow the load throughout each day) for a price of electricity of $110/MWh.

The project would provide 100% renewable energy. This compares favorably to the current system of supporting wind farms with natural gas fired gas turbines. At best, wind farms produce 45% of the nameplate capacity of the farm. Natural gas fired gas turbines are being called upon to provide the other 55% of the energy required. Thus less than half of the energy delivered from the current system comes from renewable energy. To reach a goal of 80% renewable energy, we will need to have an excessive amount of overcapacity of wind (resulting in a large fraction of wind energy being spilled and wasted) or we will need storage.

As the capacity for renewable energy increases to larger fractions of the total installed electric generation capacity, then more conflicts will arise between the intermittent energy sources and the baseload energy providers. At low load periods during the night, when the wind is blowing most heavily and the electric power system has ramped down such that only baseload providers are operating, there will be too much electrical energy available for the load. Either the wind farms or the baseload power plants will need to reduce production. When this has happened in recent years, the wind farms have been asked to feather their turbine blades because of negative impacts to the baseload power providers. Wind capacity in ERCOT is currently requiring wind curtailment 15% of the time. Bulk energy storage can solve this problem and deliver 100% renewable energy.

The system described uses about 61% of the energy produced by the wind farm to produce a 150MW baseload system. The storage system modeled is about 30% efficient. The storage system efficiency can be improved to about 40% with the use of a heat recovery boiler that would use heat from the hydrider and the waste heat from the gas turbine. The storage system has a capacity to deliver 150MW for 30 days. This is the storage capacity that is required to provide the baseload capacity through the entire year. Since more energy is delivered in the winter months than in the summer months, the storage system must be sized to store some energy in the wind rich part of the year for use during the wind poor part of the year. If a solar generation capacity was added to the system that provides more energy in the summer than in the winter, the storage system could be reduced in size and the system cost could be reduced.

This model does not include any heat recovery from the hydriding system. Heat recovery from the hydriding system could provide additional power that could be used to produce hydrogen or to offset some of the hydrogen consumption. We have estimated that heat recovery could produce an additional 8% of electrical energy into the electrolysis system. This could result in a reduction of the number of wind turbines in the system.

References

1. National Renewable Energy Laboratory. (2012). Renewable Electricity Futures Study. Hand, M.M.; Baldwin, S.; DeMeo, E.; Reilly, J.M.; Mai, T.; Arent, D.; Porro, G.; Meshek, M.; Sandor, D. eds. 4 vols. NREL/TP-6A20-52409. Golden, CO: National Renewable Energy Laboratory. http://www.nrel.gov/analysis/re_futures/.

2. “The Storage-Transmission Nexus Renewables Integration and Wind-CAES Economics”, Samir Succar, Staff Scientist, Center for Market Innovations, Natural Resources Defense Council, Washington D.C. Presented at Renewable Energy Storage, American Conference Institute, February 2-3, 2011, Hilton Washington Embassy Row, Washington, DC

3. National Renewable Energy Laboratory. (1998). Costs of Storing and Transporting Hydrogen, Amos, Wade A., NREL/TP-570-25106, Golden, CO, pages D-3 and D-7.

4. ISO-New England, Hourly Historical Data Post-Market May 1999 - Feb 2003, http://www.iso-ne.com/markets/hstdata/hourly/his_data_post/index.htm

5. NREL: Wind Integration Datasets - Western Wind Dataset, National Renewable Energy Laboratory, Golden, CO, http://www.nrel.gov/electricity/transmission/wind_integration_dataset.ht