BASELOAD POWER FROM WIND FARMS USING MAGNESIUM HYDRIDE SLURRY FOR HYDROGEN STORAGE

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A method of storing intermittent renewable energy by converting electrical energy into hydrogen and storing the hydrogen in magnesium hydride slurry is explored. Safe Hydrogen is developing magnesium hydride slurry as a medium for storing hydrogen. The slurry is very economical, can be handled in air, stores at ambient temperatures and pressures, and can be moved and transported using the conventional liquid fuel infrastructure. This study shows how magnesium hydride slurry can be used for bulk energy storage of electricity. The economic analyses show how a wind farm can provide baseload or dispatchable electric power to the grid providing a 10% internal rate of return for an electricity price of $88/MWh for a baseload power system and $110/MWh for a dispatchable power system.

Keywords: energy storage, hydrogen storage, magnesium hydride, wind power, economic analysis

INTRODUCTION

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 farm using electrolysis machines, hydrogen storage, and hydrogen fueled gas turbine/generators can operate as a baseload power plant for an electricity cost of $88/MWh with a return of 10% to its investors. A similar system can be operated to provide dispatchable electricity at a slightly reduced return on investment or a slightly higher price.

MAGNESIUM HYDRIDE SLURRY

History

Rechargeable magnesium hydride slurry has been under development by Safe Hydrogen, LLC for the past four 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 much 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 in this analysis. 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. (MOST) promise to reduce this price considerably by reducing the amount of energy required to reform 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 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 are high and that the equipment to perform these operations should be inexpensive.

We are currently working on a small demonstration model to show 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 MAGNESIUM 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 system or a 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 concept in graphical form. This diagram follows the discussion presented by Dr. Samir Succar [2].

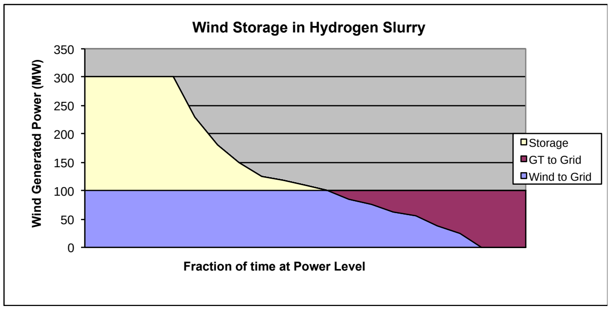

Figure 1 - Typical Annual Wind Energy and Its Use

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. During the rest of the year, 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. With this capability, the electrolyzer capacity can be used to provide 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.

Computer Model

Safe Hydrogen has modeled base-load and dispatchable wind farm systems using load and price data collected hourly (from ISO New England [3]) and wind turbine data for 10-minute intervals (from NREL/DOE [4]) 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 1 - Cost and Performance Characteristics

			Dispatchable	Baseload
Wind turbines	number	#	202	336
	unit cost	$/unit	1,726,000	1,726,000
	capacity	MW	323	538
Electrolyzer	number	#	115	182
	unit cost	$/unit	1,567,658	1,567,658
	capacity	MW	240	379
	capacity	kg/hr	5,014	7,935
Hydrider	number	#	2	3
	unit cost	$/unit	21,870,469	21,870,469
	capacity	kg/hr	5,014	7,521
Slurry	mass H2	MT	5,300	7,700
	mass slurry	MT	138,435	201,122
	unit cost	$/kg H2	60	60
Dehydrider	number	#	3	3
	unit cost	$/unit	26,777,646	26,777,646
	capacity	kg/hr	10,539	10,539
Compressor	number	#	3	3
	unit cost	$/unit	1,500,000	1,500,000
	capacity	kg/hr	10,785	10,785
H2 Gas Turbine	number	#	3	3
	unit cost	$/unit	26,000,000	26,000,000
	capacity	MW	150	150
Contract price for electricity		$/MWh	110	88
Renewable Energy Credit		$/MWh	3	3
ITC on Wind Farm			0.30	0.30
ITC on Storage			0.30	0.30
ITC on Generation from Storage			0.30	0.30
Contract period		Days	2	2
Max grid connection		MW	250	250

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 2 - Summary of Power Flows

		Dispatchable	Baseload
Electricity directly from wind	MWh	498,094	959,959
Electricity from Turbine	MWh	231,089	364,091
Total electrical energy sold	MWh	729,183	1,324,050
Electrical Energy stored	MWh	779,947	1,223,103
H2 produced by electrolyzer	kg H2	16,323,718	25,598,630
Total energy from wind	MWh	1,314,957	2,187,255
Total spilled wind	MWh	36,916	4,194
	% Wind	2.8%	0.2%

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 3 - Cost Summary

		Dispatchable	Baseload
Contract price for electricity	$/MWh	110	88
Earnings - Contract Sales	$	79,370,543	115,581,400
Earnings - spot market	$	2,082,611	2,277,501
Earnings - credits	$	2,187,548	3,972,150
Earnings - sale of oxygen	$	25,911,234	40,633,641
Total Annual Earnings	$	109,551,935	162,464,691
Annual Operating Expenses	$	10,649,612	15,736,315
Capital Costs			
Wind farm	$	348,652,000	579,936,000
Electrolyzers	$	180,280,670	285,313,756
Hydrider	$	43,740,938	65,611,407
MgH2 slurry	$	318,222,220	462,322,848
Dehydrider	$	80,332,938	80,332,938
Compressor	$	4,500,000	4,500,000
Turbine	$	78,000,000	78,000,000
Total Capital cost	$	1,053,728,766	1,556,016,949
Other Project costs	$	158,059,315	233,402,542
Working capital	$	121,178,808	178,941,949
Total Project Cost	$	1,332,966,889	1,968,361,441
Years of operation	yrs	30	30
IRR	%	10%	10%

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 and 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 4 - Figures of Merit

		Dispatchable	Baseload
Storage Cost/Turbine Energy Sold	$/kWhr sold	3.9	3.4
Project Cost/Energy Sold	$/kWh sold	1.8	1.5
Storage Cost/Energy Stored	$/kWh stored	11.8	11.3
Storage capacity of storage system	MWhr stored	75,434	109,593
	days full load	21	30
Use of the storage system	MWhr/year	232,333	364,341

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 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. The power level chosen for the cost per kW was the 150 MW turbine capacity. If we had chosen the grid connection capacity of 250 MW, the value would be lower. If we had chosen the wind farm capacity and increased the grid connection capacity, the value would have been even lower.

Table 5 - System Comparisons

	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	min. to 4 hr
H2/Slurry Dispatchable	2-3	40	12	5500	474
H2/Slurry Baseload	2-3	42	10	8000	769

Sensitivity Analysis on Contract Price for Baseload Electricity

Figure 2 displays the sensitivity of the internal rate of return on the contract price.

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 fewer opportunities available.

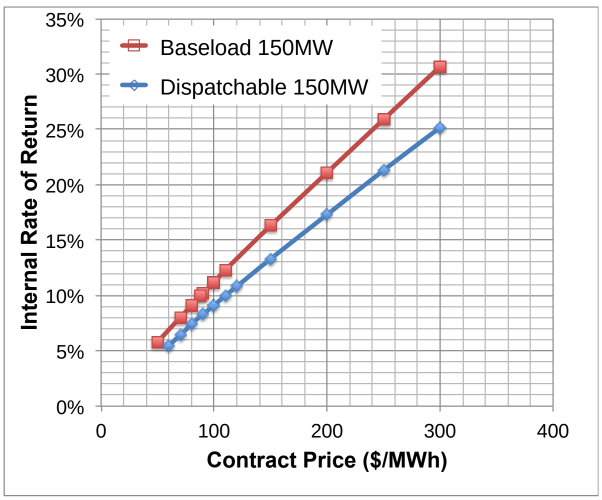

Figure 2 - IRR vs Contract Price

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, an internal rate of return of 10% can be achieved for a baseload wind/storage project. Further, the study concludes that the system can be configured as a dispatchable power project (one that follows 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 is about 30% efficient. 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 and from the gas turbine exhaust 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. The addition of such a system would result in a reduction of the number of wind turbines in the system.

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