Hydrogen and a New Paradigm for Electricity Storage

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EXECUTIVE SUMMARY

A new paradigm is needed for electricity storage in the renewables energy market. Today, what passes for "grid storage" are technologies that provide, at most, eight to 12 hours of discharge. If we are to successfully go to 100% renewables and to wean electricity generation from fossil fuels, we need storage to have up to 592 hours (88,800MWh/150MW from Tables 2 and 3 column 3) of discharge time to back up the modeled wind farm that is intermittent. Sometimes the wind does not blow and the sun does not shine for long periods of time. Long discharge time gives us reliability.

Strong need for storage

It's clear that renewable energy from wind farms, as well as solar energy installations, remains intermittent and frustratingly dependent on fossil fuels. Because of the variable nature of the energy output, a fossil fuel generation plant must be available to be turned up or down.

The renewable energy industry faces a dirty dilemma: Behind every wind farm sits a fossil fuel plant to provide backup power when the skies are still.

We need to change to storing some of the energy harvested by wind turbines and solar panels so we can use it when the output is low. That way a renewable farm/storage combination can become a dispatchable plant controlled just like a fossil fuel plant.

State of storage technology

Lead acid is a tried and true technology. *Lithium-ion*, a newer technology, provides higher power density and longer cycle life. These technologies would need a cost reduction of 98% to economically store 592 hours of output.

Flow batteries have a different construction. An electrolyte liquid flows from tanks through a casing containing the electrodes. Because the electrolyte is separate from the electrode case, flow batteries can be significantly cheaper in cost. The cost still must be reduced by 95% to economically store 592 hours.

Flywheels are very quick to respond and are good for frequency and voltage control. Although high in power, they are low in energy and not suitable for long duration discharge.
Pumped storage is the only significant storage technology in use today. The idea is to pump water uphill when electricity is inexpensive and to harness gravitational energy by releasing the water back down when power is needed.
Compressed Air Energy Storage, or CAES, consists of a compressor that pumps air into a pressure chamber. When electricity is needed, the air is released. The lowest-cost CAES utilizes underground caverns. Good caverns are in short supply. CAES using pressurized containers on the sea floor are higher cost.

Hydrogen on the horizon

In addition to the aforementioned storage solutions, a patented hydrogen storage technology is emerging as a contender to firm wind farms. The projected costs make this technology economic. The hydrogen is stored in a magnesium slurry that can be safely stored on site. The slurry is heated to release the hydrogen to fuel gas turbines, which drive generators. Discharged slurry is recharged. This technology provides the duration to remove intermittency, a low capital expense to keep the cost of generation below $0.10 per kWh, and a clear path to 100% renewables.

Table 1
Storage Summary

		Build Time	Efficiency	Capex, $/kWh	Discharge Time	Gen Cost $/kWh
Slurry		2-3 yr.	50	10	1-1000 hr.	$<0.10
Pumped Storage		9-15 yr.	80	100	1-12 hr.	$0.80
CAES		3+ yr.	55	80	1 hr.-days	$0.60
Flow Batteries		6 mo.	80	200	1-8 hr.	$2.00
Li-Ion		6 mo.	85	400	1-8 hr.	$4.00
Capacitors		2 mo.	99	8000	sec.-minutes	xxxxxxxx
Fly Wheels		1 yr.	95	1000	min-1 hr.	Xxxxxxxx

Generation costs in the far right column are the results of plugging in the capital costs and efficiencies of various storage technologies available today into our models. Capacitors and Flywheels have too low an energy density to remove intermittency.

Storage System using Magnesium/Magnesium Hydride Slurry Technology

The future electric system will incorporate solar, wind, and storage technologies to provide efficient and on-demand supply of electric power. The National Renewable Energy Laboratory (NREL) has publicly stated that Hydrogen (H_2) is key to deeply de-carbonize US Energy use [1].

Safe Hydrogen is developing a Hybrid H_2/Battery storage system that has a 592 hour full power output duration. From electrolysis, H_2 is stored in a slurry of magnesium that is charged with H_2 to a slurry of MgH_2. Light mineral oil is the liquid part of the slurry. A turbine electric generator will use the H_2 from storage to reproduce electricity. The focus of the R&D is to increase the size of the hydriding and dehydriding reactors to 150 MW in a series of steps. The Flow Battery will be cycled in the first 4 hours of the cycles. NREL in [3] show lower costs for a hybrid system over a battery only or hydrogen only system.
The capital cost of this system is about $10/kWh stored. Our modelling, [2], indicates that a system consisting of a wind farm, electrolyzers, our H_2 storage system, and gas turbine generators could provide baseload power at an energy cost of less than $0.10/kWh with the then available subsidies. There will be no geographic limits on siting. The size of the system is 150 MW_e output.

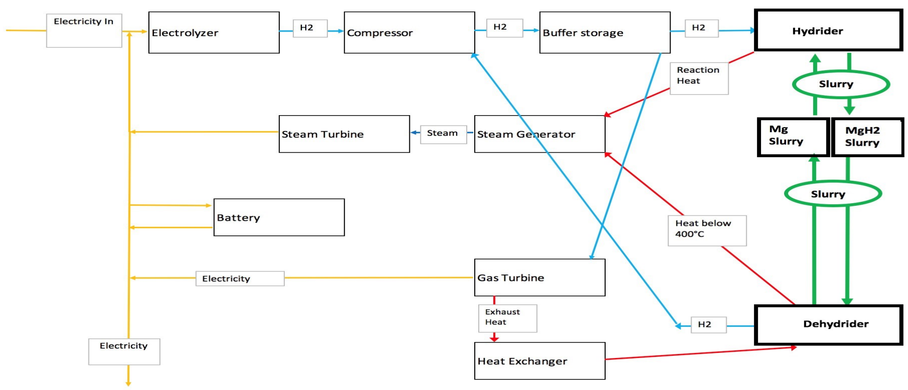

Figure1—Complete system diagram

Proposed System: In Figure 1, the system uses electricity to create hydrogen via electrolysis. The hydrider contains magnesium slurry (magnesium particles suspended in mineral oil). Hydrogen at 17 bar (250 psia) is bubbled through the slurry. The hydriding reactor is run at 300°C to ensure that the reaction rate is high. Heat is generated at the rate of 76 kJ per mole of MgH_2 created. The heat is sent to the steam generator of a combined cycle gas turbine generator set to produce more electricity that is fed to the electrolysis machines. The heat recovery results in a higher round trip efficiency. Fully charged magnesium slurry becomes a slurry of magnesium hydride. The slurry is stored at room temperature and pressure in carbon steel tanks. To supply energy from storage, slurry is pumped to a dehydriding reactor. This reactor is run at 350°C and 5 bar (75psia). The reactor operates as a large heat exchanger. Gaseous hydrogen goes to a compressor and then is injected into a gas turbine. We chose the 75 psia dehydriding pressure to keep the compression energy low for the gas turbine. The exhaust gas from the gas turbine generator provides most of the process heat of 76kJ per mole of hydrogen. The rest of the heat comes from burning hydrogen. 350°C is the decomposition temperature of magnesium hydride at the reactor conditions. Prior development showed that we can dehydride magnesium hydride rapidly into 75 psia. The literature suggests that for powdered magnesium hydride one needs to be under 1 bar or even under vacuum to have rapid reaction rates. This behavior of the slurry clearly was different from powdered hydride. We suspect that the partial pressure of hydrogen around the slurry particle is the key to this behavior. Particles in oil have a partial pressure that consists almost entirely of oil and, therefore have an extremely low partial pressure for hydrogen. After the exhaust gas exits the gas turbine, it goes to the steam turbine. Combined cycle gas turbine generators currently achieve efficiencies of over 60%, [4], now and future systems can be at 70%. We have adding a Vanadium Redox Flow battery to the system that is sized to run for up the first 4 hours of every cycle. The battery reduces the number of electrolysis machines and reduces the amount of hydrogen storage. It also increases the discharge efficiency. NREL has concluded that a combination of battery/hydrogen storage is superior to battery or hydrogen alone, [3]. Our modelling of the hybrid H_2 /Battery storage system supports NREL's conclusion.

In the commercial world, it would not make economic sense to run all of the electricity through the storage system unless the storage system was, for example, collecting heat with concentrated solar. More realistically, one would put together a wind/solar farm where the majority of the electricity went directly to the grid and only a fraction, about 30%, needed to come from storage [2].

Characteristics of Magnesium Hydride Slurry

Physical Characteristics. Magnesium hydride slurry is a suspension of magnesium hydride particles in light mineral oil. We have been working with slurries ranging from 40wt% solids to 75wt% solids. Slurries with 40–50wt. % solids cycle well in the reactors that were tested. In these slurries, the particles stay in suspension for months. When settling eventually occurs, the slurry forms a soft pack, which can be easily stirred back into suspension. The slurry looks like thick paint. The viscosity at a temperature of 30 ^{o}C is about 500 cP. The viscosity at operating temperatures is considerably lower. The slurry is described as a non-Newtonian shear thinning material.

Reaction Rates. Reaction rates are similar to those reported for powder systems. Full hydrides take 1–2hr. Full dehydrides take 3–4hr.

Grid Scale Electricity Storage Grid scale electricity is a potential application for magnesium hydride slurry. We selected this application for a detailed study because it is an opportunity where economies of scale can aid in the cost competitiveness of hydrogen stored in MgH_2 slurry. The slurry can be stored in large storage vessels that are cheaper per unit storage as they get larger. In addition, the reactors will benefit from economies of scale because they will be cheaper, per unit of hydrogen reacted, as they get larger. Another important factor is that utilities are signing agreements with some new wind farms limiting the amount of electricity that they will buy under contract. All the rest of the electricity will be bought by the utility at spot market prices. Since more wind energy occurs during the night when spot prices are low than during the day when spot prices are high, wind farms are not able to get as high a price as they might if they could supply dispatchable power or baseload power.

Electricity Storage Systems. Hydrogen storage can enable electricity storage from intermittent sources. For this process, hydrogen will be produced by electrolysis of water when energy is available and electricity will be produced from the hydrogen when electrical energy is needed and not available from the intermittent systems. Electrical storage can also be achieved by pumped hydroelectric systems, compressed air systems, and a wide array of batteries. Many of the alternative electrical energy storage systems offer higher round trip efficiencies than hydrogen storage systems with magnesium hydride slurry but most cost more than the magnesium hydride slurry approach or are limited by where they can be applied. Batteries cost considerably more than the magnesium hydride slurry approach. Pumped hydro and compressed air storage using caverns are limited in where they can be applied.

Figure 2 displays the concept in graphical form. This diagram follows the discussion presented by Succar [5]. The curve that starts at 500MW and declines gradually to zero is typical of the annual energy provided by a wind farm. 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, at 150MW, 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, energy is supplied from storage.

Figure 2

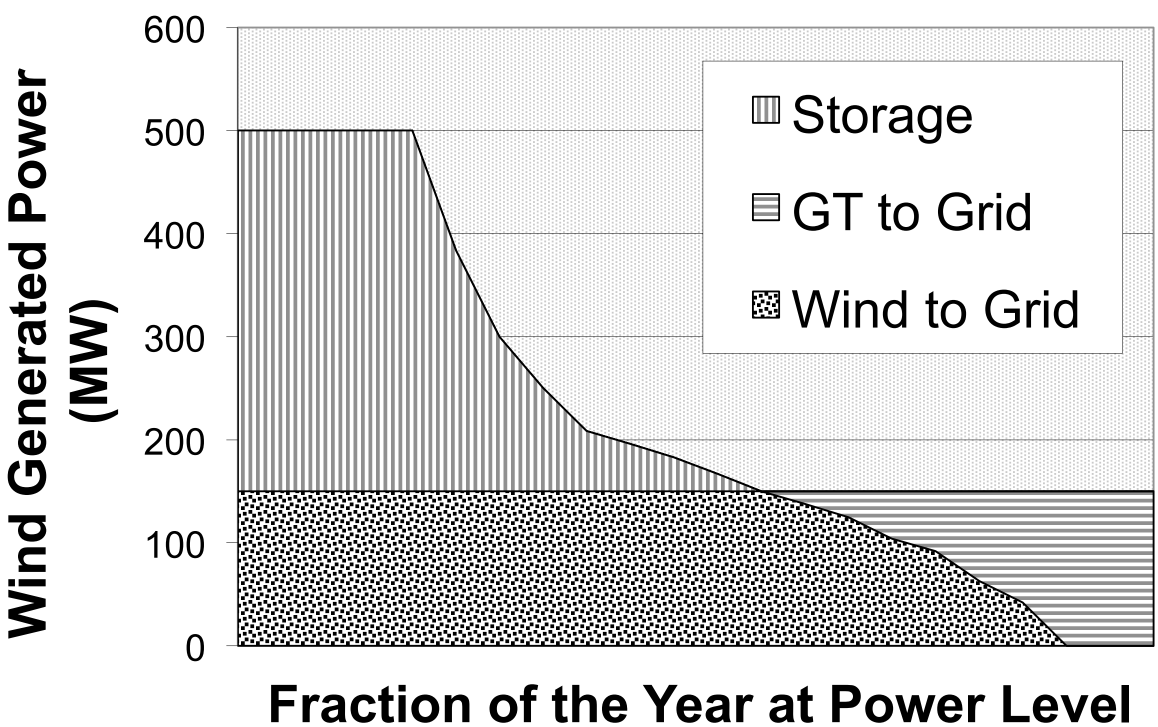

Figure 3

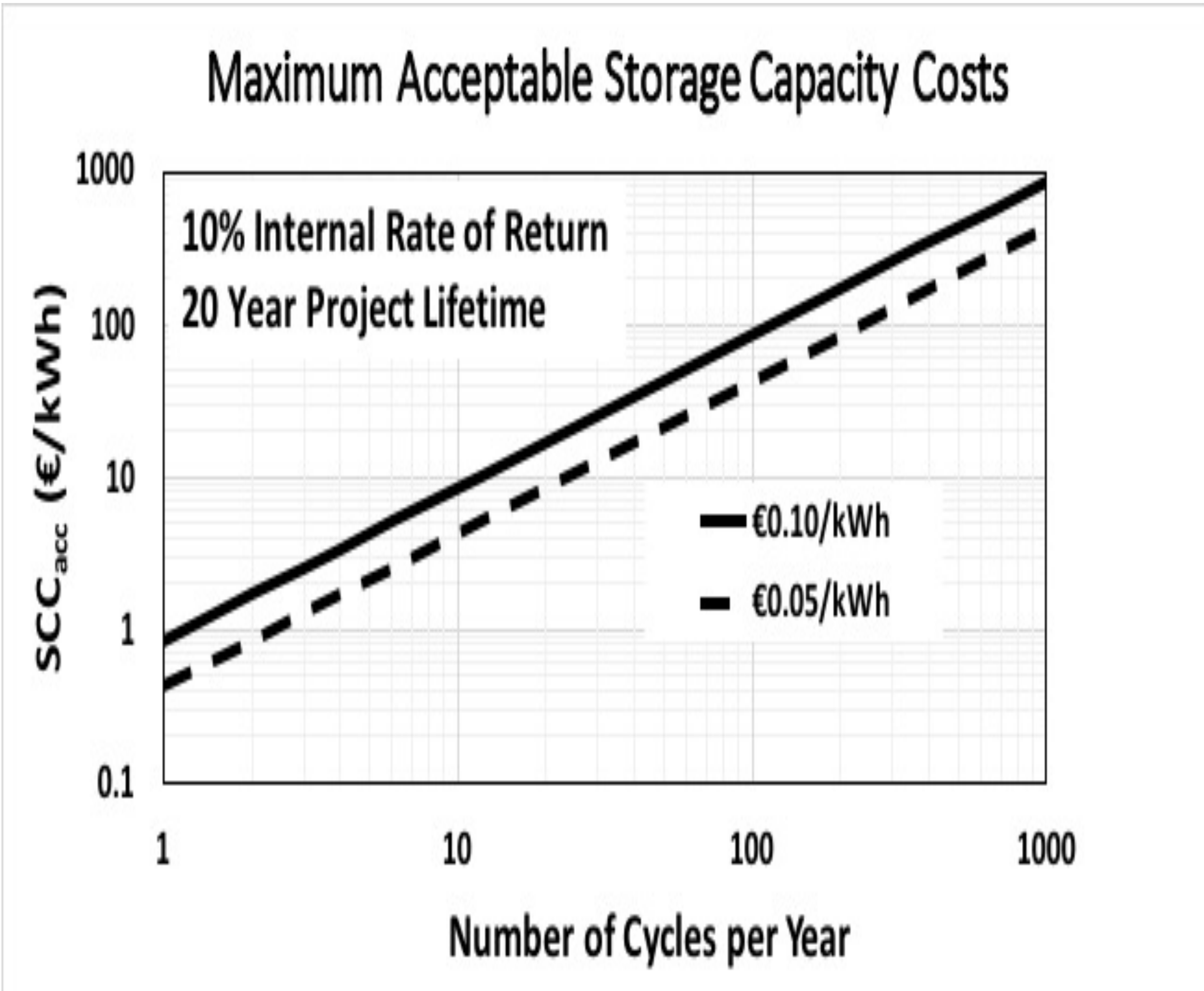

Figure 3 is the relationship between maximum acceptable Storage Capacity Costs and a storage application's number of cycles per year per kWh stored with two different grid generation costs. Modified from [8].

Three common applications for storage today are frequency control, ramping control, and peak load shaving. Batteries used in frequency control and ramping control are cycled multiple times per day. Batteries used in peak load shaving are cycled daily. Applications that have daily cycles or more often can easily cost absorb the capital cost of $400 per kWh stored that batteries have. Batteries work economically for these types of applications.

Removing intermittency from wind and solar farms is a much different type of application. The average number of cycles per year for storage is 3-4.5(calculated from Use of Storage and Storage Capacity at the bottom of Table 3). This number makes sense as the wind is stronger in the winter and demand is higher in the summer from air conditioning. A large part of the storage is cycled only 1 time per year.

Prices have fallen considerably since we first modeled. Using a combined cycle steam plant with the gas turbines will increase the efficiency of the storage system, [4]. Using a Vanadium Redox Flow Battery to smooth short term variations in wind turbine output will further increase efficiency. The combination of combined cycle plus battery will increase the round trip efficiency from approximately 30% to 50%. Electrolyzers are 82% efficient per Nel Hydrogen. The hydriding step is 108% efficient because the heat released generates more hydrogen. The de-hydriding step is 80% efficient. The combined cycle turbines are 64% efficient [4]. The flow battery is 80% efficient. 18% of the energy from storage comes from the battery. 82% of the energy from storage comes from hydrogen. The weighted average of the 80% efficient battery and the 45% efficient hydrogen system is 51%. Higher efficiency requires fewer wind turbines and electrolyzers to reach the goal of 150 MW of base load output. A battery of 150 MW and 600 MWh coupled with a heat recovery system would result in a PPA of 10.0 cents per kWh for a 10% IRR. We chose to use off shore wind data supplied by NREL [7] with pricing by ISO New England [6]. The wind availability in off shore New England is similar to the wind availability in Lubbock, TX [2], [7].

		w/o Subsidies	Lower WT and	4 Hr. Battery
			Electrolyzer	Plus Heat
			Costs	Recovery
Costs are $million				
Wind Turbines	Number	338	150	109
	Unit Cost	1.72	2.52	2.52
	Cap/unit	1.6 MW	3.6 MW	3.6 MW
	Capacity	540 MW	540 MW	392 MW
Electrolyzer	Number	176	176	111
	Unit Cost	1.57	1.26	1.26
	Capacity	379 MW	379 MW	239 MW
	Capacity	7935 kg/hr.	7935 kg/hr.	5004 kg/hr.
Hydrider	Number	3	3	3
	Unit Cost	22	22	22
	Capacity	7521 kg/hr.	7521 kg/hr.	7521 kg/hr.
Slurry	Mass H2	7700 MT	7700 MT	6200MT
	Slurry	201,122MT	201,122MT	163,158MT
	Unit Cost	$60/kgH2	$60/kgH2	$60/kgH2
Dehydrider	Number	3	3	3
	Unit Cost	27	27	27
	Capacity	10,539kg/hr	10,539 kg/hr	10,539kg/hr
Compressor	Number	3	3	3
	Unit Cost	1.5	1.5	1.5
	Capacity	10,785kg/hr.	10,785 kg/hr.	10,785kg/hr.
H2 Gas Turbine	Number	3	3	3
	Unit Cost	26	26	26
	Capacity	150 MW	150 MW	150 MW
Battery	MW			150
	MWh			600
	$/kWh			50
PPA Contract Price		14.1 cents	11.3 cents	10.0 cents
for 10% IRR				
Cost of Generation		3.1 cents	2.1 cents	2.47 cents

Table 2—Selling and Generation Prices

	w/o Subsidies	Lower WT and	4 Hr. Battery
		Electrolyzer	Plus Heat
Costs are in $mllion		Costs	Recovery
Contract Price of Elect. Cents/kWh	14.1	11.3	10.00
Earnings--Contract Sales $	185	148	132
Earnings--spot market $	88	88	0
Earnings--Sale of Oxygen $	41	41	24
Total Annual Earnings $	314	277	156
Annual Operating Costs $	16	13	13
Capital Costs $			
Wind Farm	581	390	274
Electrolyzers	276	220	140
Hydrider	66	66	66
Slurry	463	463	381
Dehydrider	80	80	80
Compressor	4.5	4.5	4.5
Combined Cycle Gas Turbines	78	78	102
Total Capital Costs	1,549	1,301	1048
Other Project Costs	233	195	157
Working Capital	178	156	126
Total Project Costs	1,968	1652	1,331
Storage Cost/Energy Stored $/kWh	11.3	10.6	11.06
Storage Capacity of System MWh	109,593	109,593	88,874
Use of Storage System MWh	364,341	364,341	406,708

Table 3—Costs and Metrics

Charts 2 and 3 show the results of our modeling with the latest equipment prices and more up to date wind data from off shore New England [6]. The first column is modified from [2] to remove any subsidies. We believe that it is better to present results without subsidies since subsidies vary from year to year and by political entity. The middle column shows the effect of lower wind turbine and electrolyzer costs. The third column shows the improvements when a 4 hour battery and combined cycle generation is added. The improvement in round trip efficiency from 30% to 50% is the cause of the improvement.

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