Proceedings of WindPower 2009
May 4-7, 2009, Chicago IL USA

Poster/paper 175

Securing Our Energy Future by Efficiently Recycling CO_2 into Transportation Fuels – and Driving the Off-peak Wind Market

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ABSTRACT

The recent sharp drop in the price of off-peak wind-energy in prime wind zones presents a major challenge for continued growth of wind-energy. The average price has decreased year-on-year and instances of negative prices have been increasing rapidly. These trends have accelerated as the rate of installed wind energy has increased. Converting the excess off-peak wind energy into storable synthetic liquid fuels – dubbed WindFuels™ – could (a) generate the off-peak market needed to re-ignite the growth of wind energy, (b) permit complete grid stabilization, and (c) provide a truly sustainable carbon-neutral solution for transportation fuels.

Off-peak low-carbon electricity is used to produce H_2. Some of the H_2 is used in a reverse water gas shift (RWGS) reactor to reduce low-cost CO_2 to CO. The CO and the balance of the H_2 are fed into a Fischer Tropsch reactor where the desired fuels are synthesized. Simulations have shown that major advances can be made in many of the key processes and components. With such, the carbon-neutral fuels produced are predicted to be much less carbon intensive and more competitive than advanced biofuels. This should allow the WindFuels process to scale up in tandem with wind energy production, and ensure off-peak demand and grid stability for decades of accelerating growth in wind energy.

INTRODUCTION

New wind energy in good sites is the lowest cost energy to produce, cheaper than new coal or new nuclear. This has caused wind energy to see unprecedented growth rates over the last decade, as more interest in carbon neutral energy has encouraged a flood of investment into what had seemed to be a perfect green technology. In 2008 there were a total of over 8300 MW of new wind turbines installed in the USA – an increase of 50% over the prior year.

However, low production costs don't always mean high profit, and the rapid growth and continued interest in wind energy may become a liability for today's investors. Profitability and growth in the wind industry are constrained by transmission capacity, the utilization of off-peak excess energy, and size of the market. The winds are not always at their strongest when the demand is highest. In fact the opposite is often true. When the wind produces more energy than there is concurrent demand, the excess electricity must be quickly dumped (sometimes at large expense) to maintain grid stability. Lastly, wind energy cannot be exported to foreign markets – without a storable and portable energy carrier such as WindFuels.

In most prime wind zones, the price for off-peak wind energy is less than half that generally seen less than two years earlier [*1*]. For example, in the Minnesota hub the average monthly price for off-peak grid energy in March of 2008 was $50/MWhr. In March of 2009, it was $14.40/MWhr. This off-peak energy is extremely clean (essentially all nuclear and wind), and the amount available at negative pricing has been rapidly increasing. Growth and profitability of wind (and nuclear) energy would be stunted without a means of utilizing the off-peak energy and idle capacity – and a means of storing wind energy in a form that is easily stored, distributed, and sold on a massive scale.

Electrolyzers could provide a completely flexible demand for such off-peak energy. A revolutionary Renewable Fisher Tropsch Synthesis (RFTS) system could use their hydrogen to recycle waste CO_2 into standard liquid fuels like gasoline and ethanol [*2, 3, 4*].

These carbon-neutral, fully sustainable synthetic fuels – *WindFuels* – present an elegant, ***market-driven*** solution to three major challenges – oil depletion, CO_2 emissions, and grid stability.

The cost of Windfuels will depend mostly on the price of the off-peak energy, the credits available for climate benefit, and the market for the co-products (especially liquid oxygen and heat). Even before considering the incentives of a future cap-and-trade system for carbon emissions, if the mean input energy price is $30/MWhr, Windfuels would usually compete when oil is above $80/bbl. With off-peak energy at $12/MWhr, Windfuels would often compete when oil is as low as $50/bbl. The profitability of WindFuels is extremely important for the potential impact on the wind industry. Any proposed off-peak demand solution that is not profitable on its own merit will never be able to scale up at the rate of wind power, resulting in at best a perpetual cycle of market saturation and threat to the wind industry. The fact that WindFuels will seamlessly compete in the global oil market ensures decades of growth with little threat of market restrictions to their own growth, other than the limit of off-peak wind energy supply. The synergistic fit between the variable production rate of wind power and the variable demand capability of WindFuels would enable each to continue to scale up without restrictions for decades.

The climate benefit of Windfuels is greater than might initially be appreciated. Since the carbon in the Windfuels is captured from point sources, there is very little *new* carbon that is added to the atmosphere for each gallon burned. The fuels most quickly displaced by market competition from Windfuels will be the expensive tar-sands fuels, which have about twice the total carbon intensity of conventional fuels because of their upstream processing. This means that for every ton of carbon that is separated from exhaust and sold to a WindFuels production plant, two tons of carbon will remain sequestered in fossil resources. As Windfuels will be market driven, it could scale up more quickly than sequestration. Replacing all of our petroleum usage with Windfuels will reduce total carbon emissions by 40%, while replacing all oil with biofuels would reduce total carbon emissions by less than 10% [*5, 6, 7*]. Studies [*6*] show that the wind resource is more than sufficient to supply all the global energy needs – including transportation, grid, industrial, and heating.

AN INTRODUCTION TO THE RFTS PROCESS

It has long been understood that it should be possible to convert CO_2 and water into standard liquid hydrocarbon fuels – such as gasoline, diesel, ethanol, methanol, and propanol, and other hydrocarbon chemicals. The problem has been that prior approaches to doing this conversion have had efficiencies less than 35% [*8*].

With the process advances and innovations we have simulated, a mid-term system efficiency target of 60% appears reasonable. Some of these innovations will also have a large impact on other segments of the power, energy, and chemical industries.

The WindFuels system works by using renewable energy to drive a series of chemical reactions which effectively recycle CO_2 back into O_2 and standard liquid fuels. For example, the net result of the sequence of reactions for octane would be:

$$18H_2O + 16CO_2 + \text{energy} \rightarrow 2C_8H_{18} + 25O_2 \qquad (1)$$

For the uninitiated, this may sound like science fiction, but almost all of the needed sub-processes have been commercialized over the past half century.

Fischer Tropsch Synthesis (FTS) is a chemical process of converting CO and H_2 into hydrocarbons and alcohols ranging from gasoline, diesel, and jet fuel to methane, ethanol, propanol, and propylene. Named after the German pioneers who discovered it in the 1920's, FTS was the means by which the Germans produced most of their fuel (from coal) near the end of WWII, and the means by which the South African government produced its fuel during the blockade of the apartheid regime [*9*]. The chemistry has had seven decades of development, and notwithstanding past associations, the process is extremely robust, and FTS products are competitive in today's transportation fuels market.

The most important difference between prior (fossil-based) FTS and *renewable* FTS, or **RFTS**, is the source of the H_2, CO, and the energy required. In all prior FTS, these come from coal or natural gas (methane). In RFTS, they come from wind, exhaust CO_2, and water.

For a natural gas source, for example, the process is known as Gas-to-Liquids (GTL), and the first step is usually partial oxidation, in which methane is partially reacted to get the needed H_2 and CO from the following reaction:

$$2CH_4 + O_2 \rightarrow 2CO + 4H_2 + \text{heat} \qquad (2)$$

Related partial oxidation reactions can be used to get H_2 and CO from coal (coal to liquids, CTL), but in this case there is too much CO produced and not enough H_2, so the so-called water gas shift (**WGS**) reaction is used to get additional hydrogen from steam and CO:

$$CO + H_2O \rightarrow CO_2 + H_2 + \text{energy} \quad (3)$$

Unfortunately, fossil-based FTS, especially from coal, is extremely bad for the climate, as it produces an enormous amount of additional CO_2 in the process. Sasol, the largest player in FTS, is also the world's largest point source of CO_2. The designs often favor capital cost reductions over greater efficiency – and result in very low efficiencies (as was alluded to earlier).

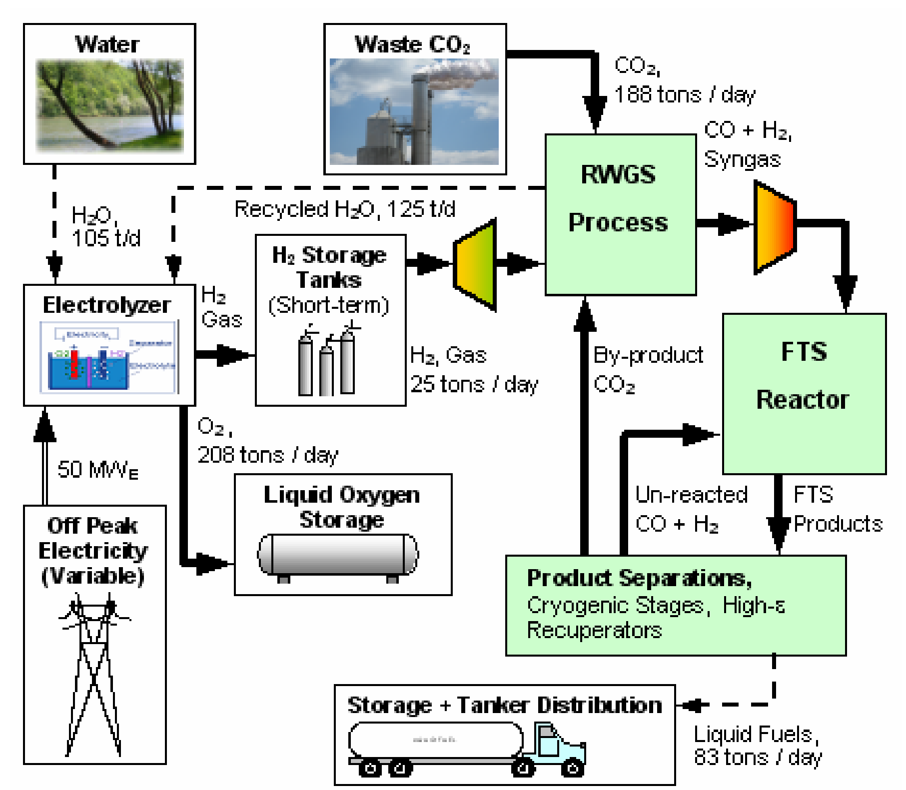

Figure 1: WindFuels System concept schematic.

On the other hand, the WindFuels RFTS process – shown conceptually in **Figure 1** – gets the H_2 by using off-peak clean electrical energy to electrolyze water into hydrogen:

$$H_2O + \text{energy} \rightarrow H_2 + O_2 \quad (4)$$

The needed CO is obtained by reducing CO_2 via the reverse water gas shift (**RWGS**) reaction:

$$CO_2 + H_2 + \text{energy} \rightarrow CO + H_2O \quad (5)$$

As is seen, whether one uses eqs. 2 and 3, or eqs. 4 and 5, one ends up producing CO and H_2. The chemistry that follows for producing liquid fuels is the same either way.

It is helpful to go through the basics of the WindFuels process with reference to Figure 1**.** First, water and off-peak electrical power are fed into a water electrolyzer, which produces the required hydrogen during times that excess electricity is available. The hydrogen and oxygen are stored in sufficient quantities to allow the rest of the plant operations to continue unabated through the periods that electricity prices are higher (when the electrolyzers are shut down). Then low-cost CO_2 and the renewable hydrogen are piped into an improved RWGS process, which permits the reduction of CO_2 to the needed CO at efficiencies near theoretical limits – ultimately, over 94%. (This is a simple endothermic reaction, so there are no Carnot limits to worry about.)

Next the renewable CO and H_2 are fed into an FTS process that includes full recycle. The FTS reactor converts some of the CO and H_2 into the desired products while the balance is efficiently recycled back through the FT reactor. The desired liquid fuels and chemicals may be readily stored and distributed by conventional means – pipelines and tanker trucks. The electrolyzer also produces an enormous amount of oxygen, which may be sold if market conditions warrant, or it may be utilized in novel processes to improve the plant efficiency.

Obviously, the above concept discussion is greatly simplified, and has not been covered in sufficient detail to fully explain the system, as the emphasis of this paper is not the chemistry. Readers interested in more details on the science and engineering are referred to several other recent publications [*2, 3, 4*].

The needed CO_2 could ultimately come from biofuels refineries, ammonia plants, cement factories, ore refining, and power plants.

THE MARKET FOR WIND ENERGY

To better illustrate the problems facing the electrical power industry with the continued growth in wind energy; it is useful to focus on the real-world market in the states that have the highest percentage of their energy derived from wind: Iowa, Minnesota, and North Dakota.

The markets in all the Midwestern states have been deregulated, allowing the power companies and co-ops to buy and sell electricity to one another on an open market. In the region of interest, this is done through a regional transmission operator (RTO) known as MISO (the Midwest Independent transmission System Operator). The Minnesota hub on MISO covers all three states of interest – as well as Wisconsin, South Dakota, and parts of Montana and Nebraska. Therefore, focusing on pricing data from this hub offers a means of understanding the effect that a high penetration of wind energy (~7%) may have on the electricity market at large.

Through the hubs of MISO, electricity is sold on both a Day Ahead (DA) market for planned electricity production and demand, and a Real Time (RT) market which addresses minute-by-minute excess production or unexpected shortfalls. Due to the variable nature of wind energy, most of the electricity produced from wind would be sold on the RT markets, so these are the prices that will be analyzed.

In the following, all the prices listed for electricity will be the price recorded on the Minnesota hub of MISO. The units are in dollars/MWhr.

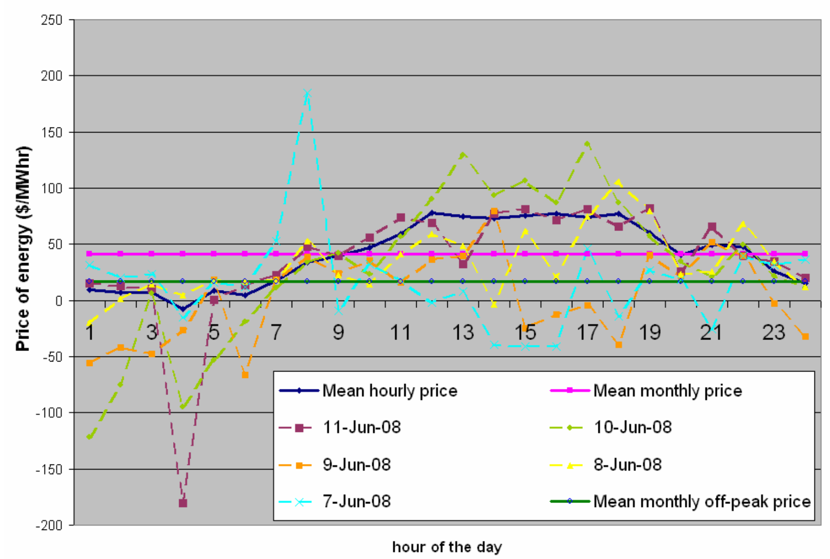

Figure 2: The hour-by-hour deviation in the sales price throughout the Minnesota hub region, both monthly mean prices and selected individual daily real-time (RT) market prices.

THE GRID STABILITY CHALLENGE

The first and most familiar challenge facing the power industry in areas with good wind resources (widely known as the wind corridor) is the grid stability challenge. Wind blows when the weather patterns dictate, not when the power companies wish. The increased penetration of wind has therefore resulted in times when more energy is produced than there is demand, and the price has to drop on the real-time market until that excess energy is fully sold [*10*]. Excess energy must be offloaded or the local grid would be damaged. There are times when so much excess energy is produced; the producers must actually pay other companies to take the energy. This is known as "negative pricing", and it accounted for nearly 3% of the hourly trading prices during 2008. This is a much greater challenge in the profitability of wind energy than most appreciate.

Figure 2 traces the average real-time prices during June 2008, as well as specifically tracing a few extremely volatile days within June to highlight the extent of the problem [*1, 11, 12*]. The worst of the negative pricing occurs during the first 5 hours of the day, when most of us are asleep.

When the wind blows across the plains, it is usually across a very broad expanse. So if the energy is overproduced, it isn't a matter of just selling it to a neighboring county – they will be overproducing power from their installed wind turbines as well. What sometimes occurs when very large fronts drive wind across the expanse of the plains during off-peak hours is a desperate cascade action where each player is "buying" negative priced energy from their neighbors and "selling" negative priced energy to neighboring areas as well, in an attempt to channel the energy overload to large cities or away from the wind corridor at large [*1, 10, 12, 13*]. In these instances, energy prices become steeply negative. We denote these instances as periods of "extreme negative pricing", or pricing below negative $50/MWhr. These are important periods because even after very generous green tags and the federal Production Tax Credit (PTC) subsidies, the wind farms are still seeing a gross loss before depreciation, amortized loans, and O&M costs are considered (negative EBITDA). The worst of these to date occurred on July 5, 2008 when every hub and every node across the entire Midwest saw negative pricing – some approaching as low as negative $300/MWhr.

One under-appreciated aspect of the grid stability challenge is that wind energy will not be the only contributor to the off-peak supply problem. Current nuclear power designs are "always on", allowing no turn-down options. Moreover, the future technology of "clean coal" has extremely slow turn down and ramp-up cycles (several hours). An argument often heard for nuclear is that it can furnish the base-load supply needed to complement solar. Clearly, as more wind is added, the need becomes not for base-load *supply*, but for base-load *demand*.

Some attempts are being made to address this problem by looking for competitive energy storage mechanisms, but as of now the only truly competitive energy storage possibility is pumped hydrostorage in mountainous terrain – which doesn't easily help the flatlands of the wind corridor. There has been considerable buzz surrounding compressed air energy storage (CAES), but reality may be setting in on the proposed Iowa Stored Energy Park (ISEP) [*14*]. It was originally proposed to be completed in 2003. Drilling of test wells finally started in 2008**.** Their current target for completion is 2013. The facility – as it is currently proposed – will only be able to accommodate the additional load of 270 MW peak, which means (if it ever gets built) it may be able to handle 3% of the additional wind capacity (for several hours) that came onstream in 2008 – and with rather poor efficiency.

Energy storage by CAES, batteries, and new pumped hydro (except in some mountainous locals) costs $150 to $1000/kWhr [*15*]. Batteries and pumped hydro offer excellent efficiency and responsiveness. However, the efficiency of CAES cannot easily exceed 54%, except at very high cost, and the responsiveness of higher-efficiency concepts is inferior [*16*]. The tank-component cost of storing energy in stable liquid fuels, on the other hand, is only $0.02/kWhr [*17*].

ELECTROLYSIS and DAILY ENERGY STORAGE

Many readers are aware that small electrolyzers usually achieve under 50% efficiency. However, commercial electrolyzers above 200 kW have achieved 73% HHV (higher heating value) efficiency for at least the past four years [*18*], and small laboratory experiments have exceeded 85% efficiency [*19*]. Moreover, there are additional opportunities for improvements at larger scale [*20, 21*], and recent advances allow the electrolyzer's waste heat to be converted to electricity much more efficiently than previously been thought practical [*3*].

Initially, it will not be possible to change flow rates in the FT reactor by large amounts in less than half a day without adverse effects on efficiency and product mix. Hence, to achieve optimum performance in the FT reactor (and in the RWGS reactor), a considerable amount of on-site hydrogen storage will be needed to keep the FT process going when electricity is too expensive to buy. In most cases, the optimum amount of hydrogen storage would be just enough to keep the FT plant running for 18 hours with essentially no electrolyzer operation. In some cases, however, it may be desirable to have several days worth of hydrogen storage – to be better able to utilize more of the cheap grid energy that is often available over windy weekends. (Eventually it will be possible to adjust the flow rates in the FT reactors in ways to better handle weeks or months of high or low winds [*22*].)

Storing 18 hour's worth of energy for a 250 MW plant in pressurized hydrogen (~90 kT) will cost about $35M. Storing all the liquid fuels the 250 MW plant could produce in one month (about 3,500,000 gallons) will cost about $2.5M. Windfuels opens up a new paradigm in renewable energy storage – seasonal storage. ***With Windfuels it will become practical to store some of the excess energy in the spring for use in the summer (when oil is very expensive), and some of the excess energy in the fall could be stored for use in the winter.***

THE WINDFUELS GRID-STABILITY SOLUTION

WindFuels will be able to help the power companies solve their off-peak demand dilemma because of the enormous flexibility of the electrolyzers.

The electrolyzer will be able to go from zero current to full current (or from full-current to zero current, or any percentage of current in between) in little more than half a cycle if necessary (perhaps 0.012 seconds, or 12 ms) [*23*]. This ultra-fast response could virtually eliminate most of the sources of grid damage – rapid loss of major loads due to storm-related accidents. It will also greatly reduce the demand for ultra capacitors and batteries that are currently an essential component of all wind farms, power stations, and solar power plants. The electrolyzers will be able to respond to rapid supply-demand events by simply turning down to its zero limit – in under 15 ms.

The electrolyzers for a 250 MW WindFuels plant would need a peak capacity of 0.5-1 GW. High quality electrolyzers are currently rather expensive (~$0.8/W), but their prices can be expected to drop by at least a factor of three as their market increases by three orders of magnitude.

Windfuels solves a problem for the power industry – the producers would no longer have to frantically ramp up or turn down their fossil plants to keep up with the real-time fluctuations in excess grid energy. This would also improve the efficiency of the fossil-fuel power plants. In exchange for advantageous energy prices, the power companies themselves might be given some control of the WindFuels electrolyzers. They could then simply make plans based on the lower end of the average forecast wind speed and just offload any excess energy produced to the WindFuels facility at the contracted price.

MORE ON THE WIND MARKET

During the first 6 hours of the day – from midnight to 6:00 AM, the average price of energy traded over the Minnesota hub throughout 2008 was only \$19.54/MWhr, and its lowest price was negative \$250/MWhr! On July 5, had a standard 250 MW WindFuels plant been online, power companies in any area within the range of MISO would have saved on average over \$250,000 in a single hour by selling a GWhr to the WindFuels electrolyzers rather than paying to keep the energy from burning out their respective grids.

How important is negative pricing? To put this question into perspective, it is useful to chart the increasing instance of low, negative, and extreme negative pricing traded throughout the breadth of the Minnesota hub since January 2008, as shown in **Figure 3.** Comparing similar months and seasons is more telling than a short chronological trend, since both supply and off-peak demand are greatly influenced by the season (weather influences wind speeds, and the dominant energy demand loads from midnight to 6:00 AM are the heating/air conditioning power requirements of climate control systems left on overnight.) **Figure 4** shows Minnesota Hub average monthly prices from Aug 2007 to Apr 2009. However, extending this chart back further is difficult, as the publicly available data is incomplete.

In the first four months of 2008, there were no hours of extreme negative pricing, and there were only 23 hours each of negative and very low pricing (under \$10/MWhr). In 2009, though the winter and spring were colder than 2008, there were 12 hours of extreme negative pricing, 104 hours of negative pricing, and 158 hours of very low pricing altogether between January 1 and April 30.

Astoundingly, the average price of the 6 lowest-priced hours per day for the first four months of 2009 was under ~\$10.5/MWhr. This

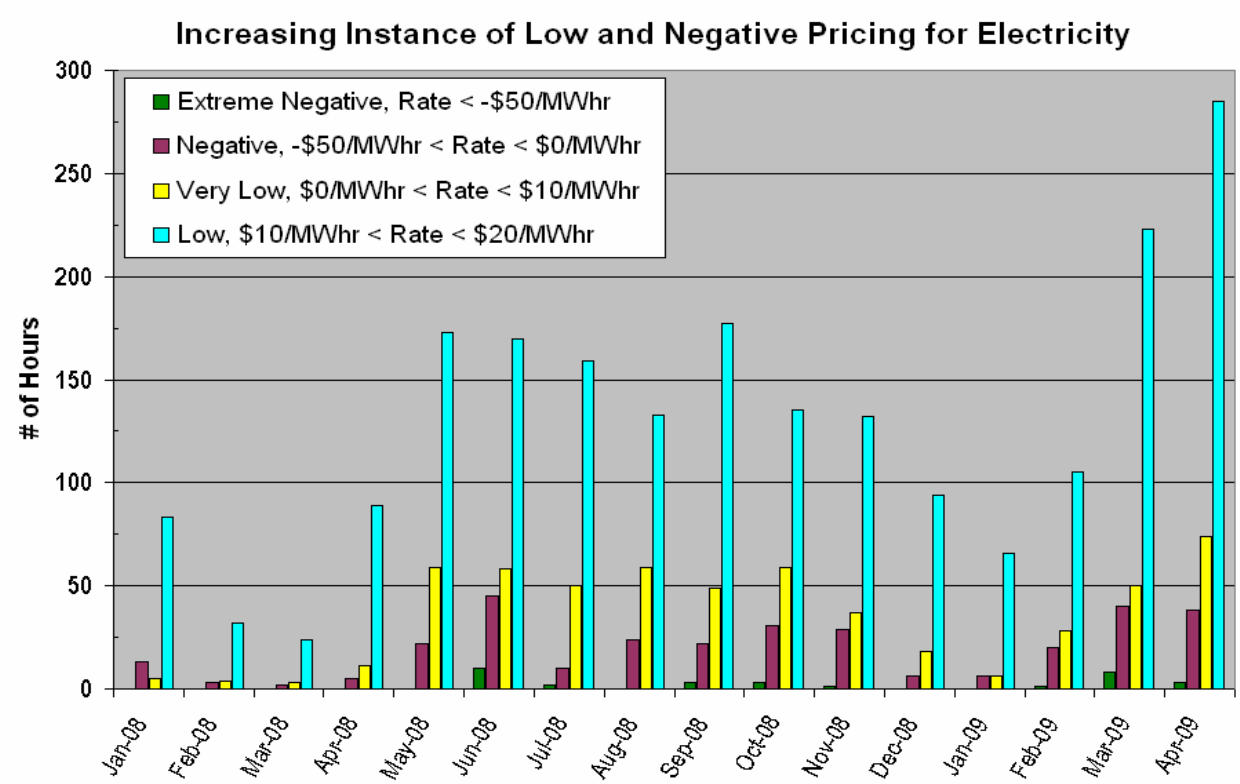

Figure 3. The increasing amount of very cheap grid energy is shown as the number of hours per month that the real-time price was below \$20/MWhr in several ranges.

may be the number that matters the most to Windfuels, as the plan is to operate the electrolyzers for only 5 to 12 hours per day, depending mostly on the real-time energy rates.

In 2008, wind accounted for ~42% of the new installed power in the USA, and that level of new installation has already proven to be a significant impediment to continued rapid growth of wind energy. The current, widely held assumption is that long-distance electrical grid expansion is the only solution. While there is no doubt that grid expansion (especially high-voltage DC) is needed, the grid cannot be expanded rapidly or easily. With each project, new lines are built through thousands of individuals' private property, dozens of townships, parks, and farms. Objections raised vary from nature enthusiasts worried about aesthetics to city councils worried about zoning. Grid expansion is a nightmare of reconciling property rights, local zoning issues, park and wildlife restrictions, eminent domain issues, multiple state and local laws, and interstate commerce issues.

As a rather typical example, a 220 mile line from Duluth Minn. to Wausau Wis. took less than 2 years for the American transmission company to build, but took more than 8 years for them to get the necessary approvals and permits [*24*]. There are many examples of short grid connections that were approved at the state or local level but then held up by challenges in court for many years. Unless eminent domain is granted at the federal level, the grid simply cannot expand quickly.

The Denmark example of 40% wind penetration has limited applicability to the U.S. Denmark is only about twice the size of New Jersey, and within 500 miles of the border of this tiny country there are over 100 million additional customers to absorb any additional energy. In Germany, the Netherlands, Belgium, and other nearby countries; the average population densities are 10-30 times those seen throughout the wind corridor of the US; so Denmark has an enormous market for its excess wind energy throughout northern Europe. WindFuels can provide the level of flexibility needed for wind to grow essentially without bounds with minimal grid expansion requirements.

The limited effect of negative pricing thus far is due largely to government and private incentives – PTC and green tags – subsidizing wind power to make wind projects more profitable. However, there is also an expectation and requirement for a very high profit margin during peak hours to also help compensate for the losses during off peak hours. The mean energy price during peak hours for the month of June 2008, for instance (displayed in Figure 2), was ~$69/MWhr. So the energy that was produced when the wind blew during the day on weekdays (peak period) was sufficiently profitable to yield an overall profit even with the 55 hours of negative pricing throughout that month. (Of course, the PTC and green tags made a big difference). The peak pricing hours have allowed growth in wind energy to continue despite negative returns in the off-peak market and an extended financial crisis.

For the month of March 2009 the average price of energy on the real time MISO market for all hours was only $21.3/MWhr! Rough comparisons in the peak vs. off-peak pricing show that the price for energy during week days 6AM to 10PM averaged only ~$29/MWhr, and rest of the week averaged about $13/MWhr. The average trading price was less than $***20.5***/MWhr for April 2009.

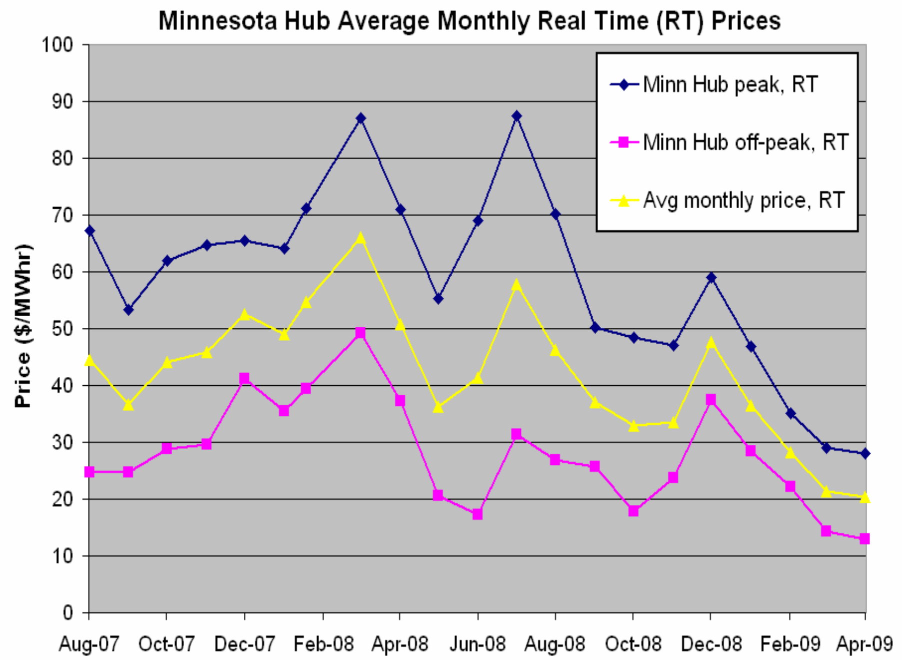

Figure 4: In this graph, "peak" averages the rates for weekdays 6am-10pm, while "off-peak" is comprised of weekends and weekdays from 10pm-6am.

The average RT price for energy in the first four months of 2009 in the Minnesota hub for the cheapest 6 hours each day was $10.5/MWhr. Energy would also be available at higher but still very attractive rates for Windfuels for several more hours each day when the electrolyzers may be operating at 3% to 70% of their peak rating. The trends of the past three years, combined with the stated intent of the DOE and the current administration, suggest growth in wind-energy capacity will continue to exceed the growth in off-peak demand and long-distance grid transmission capacity for at least the next five years. It will likely be at least 15 years before the average for spring and fall off-peak energy prices in the wind corridor will be more than $25/MWhr.

ECONOMICS OVERVIEW

Near-term HHV system efficiencies for RFTS, from electrical input to total chemical-energy output, in large plants are expected to be 54% for mostly ethanol production and 52% if the emphasis is on gasoline production [*25*]. Mid-term efficiencies could be 5% higher. At $15/MWhr and 52% plant efficiency, the energy cost to produce a gallon of gasoline would only be $1.05.

Of course, there are other costs. There will be costs associated with the clean CO_2 (currently ~$80/ton, or ~$0.70/gallon of Windfuels gasoline), water (under $0.02/gallon of WindFuels gasoline), operating and maintenance (O&M), capital costs (interest rates are likely to remain low for quite some time), and depreciation.

Table 1 summarizes expected annual costs based on preliminary studies [*25*]. It is worth mentioning here that no other source of renewable hydrogen begins to compete with off-peak wind. For example, levelized cost for solar photovoltaic (PV) energy from large PV plants is currently ~$300/MWhr for a discount rate of 6.5% [*26*].

Table 1. Annual Near-term Costs for 250 MW *WindFuels* Plant

Inputs	Rate	Annual Quantity	Unit Price	Annual Cost, $M
CO_2	10 kg/s	320 kT	$75/ton	24
Water	6 kg/s	200 kT	$1/ton	0.2
Off-peak Energy	250 MW	2.2E6 MWhrs	$15/MWhr	33
Other: O&M, depreciation...				30
Total				**87**

Table 2 shows projected revenues from a typical product mix with the assumption that oil prices are back to what was seen in the spring of 2008 – which seems likely within a few years (as we argue in a later section). Clearly, the biggest uncertainty here is in the price of the products – they could be twice what is assumed here, or they could be less than assumed. There will also be government incentives for carbon neutral fuels production – or carbon offsets – and there will be a large income stream from the sale of the co-produced 350 kilotons/year of LOX.

There is also uncertainty in the product mix, as it may be determined that a different FT catalyst than assumed here would deliver a more profitable mix of products.

Table 2. Near-term Revenue from 250 MW *WindFuels* Plant

Product	Rate	Annual Quantity	Unit Price	Annual Revenue $M
methanol	1.1 kg/s	11 M gal	$1.8/gal	20
ethanol	1.1 kg/s	11 M gal	$4.6/gal	50
higher alcohols	0.5 kg/s	5 M gal	$4.8/gal	24
light olefins	0.4 kg/s	12 kT	$2/kg	24
higher olefins	0.3 kg/s	3 M gal	$4.8/gal	14
alkanes, etc.	0.5 kg/s	15 kT	$1.5/kg	22
liquid oxygen	11 kg/s	350 kT	$140/ton	49
Fuel production subsidies			$0.6/gal	24
Carbon offsets		500 kT	$30/ton	15
Total, $M				242

In the fully recycled RFTS process, the FT catalyst has little affect on the system efficiency. Catalysts never change the thermodynamics (heat needed or released) of a specific reaction, they only change reaction rates of different reactions and thus the "selectivity", or the amount of different products produced. The FT reaction always produces a wide range of products – mostly hydrocarbons and alcohols. Most of the FT products are produced with similar efficiencies, and all are valuable, though a few may have very low value in some markets. The catalyst and the operating conditions in the FT reactor (pressure, temperature, flow rates) would be chosen to deliver as much of the most valuable products and as little of the least valuable (methane) as possible.

Considerably higher selectivities are possible for specific ranges of hydrocarbons (gasoline, jet fuel, diesel, lubricants...) than for mid-alcohols (ethanol, propanol, and butanol) [*9, 27, 28, 29*]; but the latter are more valuable per unit energy, which is the primary reason we focused on mid-alcohols in our initial simulations. They also are the lowest toxicity fuels; and highly efficient small engines (more efficient than small diesel) can be designed to operate cleanly on a wide range of mixtures of ethanol, gasoline, and methanol [*30*]. However, the catalysts for making the feedstocks for gasoline or jet fuel are very cheap, while those for mid-alcohols will be somewhat expensive, at least initially. Either way, all of the products have market potential if they are efficiently separated, which is much easier to do in the RFTS plant than in conventional FT plant designs, partly because the inputs are clean.

Catalysts by definition do not participate in the reactions and thus are never "used up". However, their surface conditions change (especially from coking and sintering, or crystal growth) in ways that degrade their activity. Hence, they must frequently be rejuvenated (by a cleaning and chemical process) until they have been degraded to the point that they need to be replaced. The lifetime between rejuvenations in common industrial processes varies from hours to months, and the total lifetime between replacement varies from weeks to years. The same ranges will likely apply to the RFTS catalysts.

One of the advantages of a clean RFTS system is that catalysts and operating conditions can easily be changed to improve profitability by shifting more of the yield to more valuable products as markets change. One can choose to think about it as investing in a diversified energy production portfolio. The product mix shown in Table 2 is what can be expected from one of the best recently reported ethanol catalysts [*28*].

The importance of designing for highly efficient separations, efficient recycling of unreacted reactants (CO, H_2, and CO_2), and flexibility in accommodating different catalysts and reactor conditions would seem obvious from the preceding paragraph, yet it has not been done before. The primary reason is that when the syngas (the feed mixture of H_2, CO and CO_2 going into the FT reactor) is from a fossil source, it is very difficult to control the H_2/CO ratio to the extent needed for much flexibility in catalyst choice and product variability, largely because of the variability of the WGS reaction in the FT reactor. That challenge essentially disappears in the RFTS plant where one has complete and independent control over the H_2, CO, and CO_2 feed rates.

The WindFuels plants would be profitable industrial facilities producing liquid fuels that would be easily stored and distributed to a guaranteed global market. The importance of the solution to the grid stability problem having a market separate from the electrical industry itself can hardly be overstated. On the other hand, with electrical storage options such as pumped hydrostorage, batteries, or CAES, the only market for the excess electricity is still the electrical energy market.

Clearly there is a compelling argument for local power companies to become keenly interested in promoting the development of Windfuels; and the same can be said for several other industries – including electrolyzer manufacturers, wind-turbine manufacturers, wind-farm owners, grid operators, turbomachinery producers, and heat exchanger manufacturers. Even fuel-cells companies should be enthusiastic about WindFuels, as fuel cells may see their best chances for growth as emergency grid backup and peaking power when co-located at a Windfuels plant, where there will also be enormous storage of high-purity hydrogen and oxygen, along with the needed grid connection and controls.

CARBON OFFSETS

Logic dictates that the first products that will be competitively displaced will be the most expensive – which are Coal-to-Liquids (CTL) fuels, oil shale fuels, and tar sands fuels. These fuels not only emit the chemical carbon they contain, but the production of these fuels emits a similar amount in their carbon intensive production [*31*].

It takes burning only ~80 gallons of gasoline produced from tar sands to increase net atmospheric CO_2 by 1 ton, and about 50 gallons of CTL diesel, whereas it might take 1800 gallons of WindFuels ethanol to produce the same net increase in atmospheric CO_2. Therefore, every 100 gallons of ethanol that is produced by a WindFuels facility will offset about 1 ton of net CO_2 emissions, at least as long as more tar sands and CTL are being used than WindFuels. It may take two decades before WindFuels starts offsetting some of the less carbon-intensive deep-water projects.

Carbon offsets offer a considerable advantage over simple carbon sequestration, in that the net offset is considerably more than the carbon that is recycled into fuels.

Windfuels are expected to be 5 to 20 times more carbon neutral than most biofuels. Most analyses have concluded most biofuels are about 25% carbon neutral, but those results are without considering the effect of land-use change. More recent studies show that the "carbon-debt" associated with CO_2 and CH_4 release from the tilling of new soil for biofuels will take 30 to 250 years for the biofuels grown on that soil to repay [*5, 6, 7, 31*]. Moreover, cellulosic ethanol studies have not yet properly considered the effect of inefficiently converting biocarbon that is currently sequestered (as on forest floors) into liquid fuels using processes in which most of this biocarbon is released as CO_2 at the bio-refinery [*32*]. The latest studies conclude that most USA biofuels result in more life-cycle release of GHGs than conventional gasoline [*33*].

For Windfuels, on the other hand, the only sources of power on the regional grid when the electrolyzers are operating would normally be wind and nuclear. The other primary net carbon addition from WindFuels is that associated with the CO_2 separation at its source. A recent study has shown that the *practical* limit for the energy required for separation and compression of CO_2 from coal power plants is likely to be about 1.2 MJ per kg of CO_2 [*34*]. The energy in the WindFuels made from this recycled CO_2 would be 10 to 15 times greater. Hence, WindFuels should be over 85% carbon neutral.

THE REALITY OF PEAK OIL

Peak oil as an issue dropped off the radar screen when commodities crashed in the 4th quarter of 2008. The price of oil dropped from $147/bbl to $30/bbl and had to be supported by OPEC production cuts to again hover at $50/bbl. When this happened, most seemed to forget that oil prices were important. But there haven't been any new discoveries since then that would justify the sudden lack of concern. Nor has there been a technological breakthrough that would make it less expensive to drill for deep water or polar oil, or somehow make the extremely carbon-intensive tar sands projects less costly or cleaner.

The oil supply is just as frighteningly limited as it was in July 2008. The biggest change is that the world economy hit its worst recession in more than half a century, which impacted demand. Also, the boom in investment in new oil production during the preceding six years yielded a 4% increase in net global production capacity, but further opportunities here are very limited. The demand will rebound with the economy, and the oil supply will once again not be able to support that demand.

If anything, the recession has made us more vulnerable to the price of oil in the future. The last time the price of oil crashed was in 1997-1998, as a result of the crash in the Asian stock market. The price of oil dropped all the way down to ~$10/bbl. Then a decade of rampant oil inflation followed, peaking at $147/bbl, or nearly 15 times the nadir. This is because a crash in the oil market disencentivizes investment in new production, and when the producing wells go dry (which they are doing constantly), there isn't enough oil supply to keep the price stable. New production takes 4 to 7 years from the period of the first investment. As long as the world economy keeps growing, the oil producers find themselves trying to keep up with a moving target.

The latest estimates from the IEA indicate that currently producing oil wells worldwide are seeing a global production drop totaling over 3 million bbls/day/year (bpd/year) [*35*]. This means that oil companies must invest in exploration and develop new production at a rate of 3+ million bpd/year or the global oil supply can quickly become critical.

In late 2008, the IEA estimated 44 major oil production projects were in development that were expected to add 9M bpd by 2013 at a cost of somewhat over $1T. Because these and other smaller projects would largely replace declining output from existing wells, the margin between supply and the increased demand by 2013 would be back to about what was seen in the spring of 2008.

At the same time that global finance froze, the price of oil dropped considerably below what is needed for virtually all new projects to be profitable – deep water, polar, tar sands, even most conventional oil, and virtually all biofuels projects. Therefore, the exploration and development needed to secure global production rates 2 to 5 years from now is no longer being invested [*36*]. Sufficient investment is not likely to resume until the economy is rebounding and oil prices have sustained a level above $75/bbl for at least half a year. By some accounts, two-thirds of the projects underway in mid 2008 are either now, or soon likely to be, on hold until the oil and financial markets have strongly recovered. As a result, the oil analyst with one of the best track records over the past decade expects that the global margin between the supply and demand by late 2010 (or summer of 2011 at the latest) will be as tight as it was in the spring or summer of 2008 [*36*].

It has been over 15 years since new discoveries exceeded the amount of oil consumed in any year, and the $2.1T invested in oil production from 2000 to 2008 barely budged supply growth. Only when annual investments in oil production reached $400B in 2008 did new production come on stream at a rate sufficient for supply to keep up with demand growth under normal economic conditions. However, the opportunities that remain for adding to the supply this easily will be largely exploited within a few more years.

For decades, many in the coal industry have been projecting that CTL will rise to the occasion and mitigate the challenge of declining oil reserves. However, recent research indicates coal is much more limited than earlier estimates, and the rapidly rising demand for coal will make it too expensive to be utilized as an oil substitute to any significant extent [*37*]. Recent research suggests we could see peak gas by 2025 and peak coal before 2030 [*37*]. In view of all of the severe limitations on economically available fossil resources, it is not hard to believe that oil prices will return to over $150/bbl in the next few years and soar well beyond that level by 2015.

That projected oil market will yield a very high return on WindFuels investments and should allow four decades of extremely rapid scale-up for WindFuels production plants.

CONCLUSIONS

The price of off-peak wind energy (especially from 11:30 PM to 5:30 AM) dropped by a factor of three between the spring of 2008 and spring of 2009 in the MISO hub, and similar drops were seen in other prime wind zones. This trend seems likely to continue for two decades as wind continues to be added faster than the grid can be expanded.

Novel processes have been analyzed and simulated for converting off-peak wind electricity and captured CO_2 into standard liquid fuels, called Windfuels, that can be pumped from existing gas stations into existing cars. These synthesized fuels are expected to be 4 to 20 times more carbon neutral than most biofuels. The very low price of off-peak grid energy in high-wind regions is expected to make it possible for Windfuels to compete in some cases when oil is as low $50/bbl.

Seasonal energy storage – storing excess clean energy from spring or fall to when it is expensive in the summer or winter – would be several thousand times more expensive using compressed air, batteries, or (except in a few choice locations) pumped hydrostorage than storing a similar amount of energy in Windfuels.

WindFuels could create a huge demand for off-peak wind energy, and address the challenges of grid stability, energy security, oil depletion, climate change, and industrial competitiveness. The combination of peak oil, climate change, and grid instability will drive Windfuels, and Windfuels will drive the wind industry.

ACKNOWLEDGEMENTS, COPYRIGHTS, TRADEMARKS, and PATENTS.

The research and developments presented herein and on the WindFuels website http://windfuels.com/ were supported by Doty Scientific, Inc.

These developments would not have been possible without the generous contributions of numerous other friends and colleagues, especially Judy M Doty, Kranti Pamarthy, Paul D Ellis, Thomas A Davis, and Carl Oppedahl.

REFERENCES

1. MISO, http://www.midwestiso.org/publish/Folder/10b1ff_101f945f78e_-75e70a48324a, 2009.
2. FD Doty and S Shevgoor, "Securing our Transportation Future by Using Off-Peak Wind to Recycle CO_2 into Fuels", ES2009-90182, ASME Joint Conferences, San Francisco, 2009.
3. FD Doty and S Shevgoor, "A Dual-source Organic Rankine Cycle (DORC) ..." ES2009-90220, ASME Joint Conferences, 2009.
4. FD Doty and S Shevgoor, "Compact, High-Effectiveness....Compound Recuperator with Liquid Intermediary (CRLI)", HT2009-88372, ASME Joint Conferences, San Francisco, 2009.
5. T Searchinger et al, "Use of U.S. Croplands for Biofuels...", Sci. 319, 1238-1240, Feb 29, 2008.

6. Mark Z Jacobson, "Review of Solutions to Global Warming, Air Pollution, and Energy Security", EES, 2, 148-173, 2009.
7. JF Kreider and PS Curtiss, "...Future Automotive Fuel Replacements", Proc. Energy Sustainability 2007, ES2007-36234.
8. C Delacourt, PL Ridgway, JB Kerr, and J Newman, "Design of an Electrochemical Cell Making Syngas...", J Electrochem. Soc., Vol 155, Issue 1, pp B42-B49, 2008.
9. AP Steynberg and ME Dry, eds. *Studies in Surface Science and Catalysis 152, Fischer-Tropsch Technology*, Elsevier, 2004.
10. http://en.wikipedia.org/wiki/Electricity_market .
11. Ucilia Wang, "Texas Wind Farms Paying... to Take Power", Greentechmedia, Dec 10, 2008, http://www.greentechmedia.com/articles/texas-wind-farms-bring-free-energy-and-cash-bonuses--5347.html
12. Dan Charles, "Renewables Test the IQ of the Grid", Science, 324, 172-175, 10 Apr., 2009.
13. R Wiser, M Bolinger, "Annual Report on US Wind Power Installation, Cost, and Performance Trends: 2007", DOE-EERE.
14. See http://www.isepa.com/ and http://www.sandia.gov/ess/About/docs/haug.pdf.
15. Dan Rastler, "New Demand for Energy Storage", Electric Perspectives, Sept 2008.
16. See http://dotyenergy.com/Markets/CAES.htm , 2009.
17. A 600,000 gallon tank was quoted by Brown Minneapolis Tank Company as costing about $420K, or under $0.02/kWhr for jet fuel.
18. Daniel Lumanauw, "Hydrogen Bubble Characterization in Alkaline Water Electrolysis", Univ Toronto, 2000.
19. J Ivy, "Summary of Electrolytic Hydrogen Production", NREL/MP-560-36734, 2004.
20. SPS Badwal, S Giddey, and ET Ciacchi, "Hydrogen and oxygen generation with polymer electrolyte membrane (PEM)-based electrolytic technology", Ionics 12:7-14, 2006.
21. MW Kanan and DG Nocera, Science, 321, 1072-1075, 14 Sept., 2008.
22. FD Doty, "Hydrocarbon and Alcohol Fuels from Renewable Energy...", PCT WO 2008/115933, http://windfuels.com/PDFs/WO2008115933.pdf.
23. The electrolyzer responds essentially instantaneously to a change in current. There is a small, time-dependent voltage effect, but the effect is primarily to enhance efficiency at the leading edge of a current pulse. Hence, the rectified current does not need much smoothing, though inductive storage equivalent to several milliseconds is beneficial. Thus, the standard controlled-rectifier circuit will be able to go from zero current to full current (or from full-current to zero current) in little more than half a cycle if necessary.
24. See http://www.nytimes.com/2009/02/07/science/earth/07grid.html?_r=3] , 2009
25. See http://dotyenergy.com/Economics/EconOverview.htm , 2009.
26. Ed Regan, Gainesville (Florida) Regional Utilities Assistant General Manager, concluded a feed-in tariff of $320/MWhr would permit a 5% ROI in large-scale PV investments, Feb. 2009. Other studies, including European PV Industry Assoc., reached similar conclusions.
27. PL Spath and DC Dayton, NREL/TP-510-34929, 2003.
28. M Xiang, D Li, H Qi, W Li, B Zhong, Y Sun, "Mixed alcohols synthesis from CO hydrogenation over K-promoted β-Mo_2C catalysts", Fuel 86, 1298-1303, 2007.
29. V Subramani and SK Gangwal, "A Review of...Catalytic Process for ...Syngas to Ethanol", Energy & Fuels 22, 814-839, 2008.
30. RJ Pearson, JWG Turner, and AJ Peck, "Gasoline-ethanol-methanol tri-fuel vehicle development...", to be published, Low Carbon Vehicles Conference, Inst. Mech. Engr. Conf., London UK, May 20-21, 2009.
31. Alex Farrell, "The Low-carbon Fuel Standard and Land Use Change", 2008.
32. http://dotyenergy.com/Markets/Biofuels.htm
33. D. Charles, "Corn-Based Ethanol Flunks Key Test", Science 324, p 587, 1 May 2009.
34. KZ House, CF Harvey, MJ Aziz, and DP Schrag, "The energy penalty of post-combustion CO_2 capture...", EES, 2, 193-205, 2009.
35. See http://www.eia.doe.gov/oiaf/aeo/ , 2009.
36. M. Simmons, 2009, http://www.simmonsco-intl.com/research.aspx?Type=msspeeches .
37. David Rutledge, "Hubbert's Peak, The Coal Question, and Climate Change", http://www.rutledge.caltech.edu, 2009.

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