SUMMARY REPORT

Lenfest Center for Sustainable Energy: 2012 Energy Storage Symposium

May 2nd & 3rd Columbia University

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Transforming the global energy system and the technologies that support it into a non-fossil form will require massive research and advancement in energy storage. Since 2010, the Lenfest Center for Sustainable Energy and the Technical University of Denmark (DTU) have held annual workshops on how to convert low-cost, renewable energy into liquid hydrocarbon fuels. On May 2-3 2012, we expanded the technological scope to cover the full range of energy storage technologies - at grid level, micro-grid, and in buildings - that could underpin a large non-fossil energy infrastructure.

By its very nature, such a symposium required an interdisciplinary discussion to bring out system issues in addition to the usual focus on technological details, bringing together experts from different fields to achieve a better understanding of the systems constraints.

Speakers on Day 1 included:
Klaus Lackner**,** Director, Lenfest Center for Sustainable Energy;
Mogens Mogensen, Research Professor, DTU Department of Energy Conversion and Storage;
Jay Apt, Director, Carnegie Mellon Electricity Industry Center;
Bob van der Zwaan, Senior Scientist, Energy Research Centre of the Netherlands;
Tim Fox, Head of Energy, Environment, and Climate Change, Institution of Mechanical Engineers;
Jay Whitacre, Assistant Professor, Engineering and Public Policy, Carnegie Mellon University.

Speakers on Day 2 included:
Sanjoy Banerjee, Distinguished Professor of Chemical Engineering, Director of the CUNY Energy Institute
A panel discussion with Aubrey Braz, ConEdison; John Bøgild Hansen, Haldor Topsøe A/S; Guy Sliker, New York Power Authority; and Mark Torpey, New York State Energy Research and Development Authority, moderated by Robert Curry, Public Service Commissioner of the State of New York.

The goal was to elucidate the varying challenges and benefits of different storage options, accentuate the complementary combination of the various technologies, define their different economic and market niches, and determine how technologies' cost and performance attributes shape their use. The following report summarizes the presentations and discussions over the course of the Lenfest Center's 2012 Energy Storage Symposium.

INTRODUCTION AND STORAGE OVERVIEW

The availability of energy storage is a linchpin to a future with increased adoption of intermittent renewable energy sources. The many different circumstances in which energy is used give rise to a plethora of various technologies, all with different merits. Researchers at the Lenfest Center place a special interest on technologies that facilitate carbon management, while at DTU and Risø the focus is on electrolysis/fuel cells in an environment with substantial penetration of wind power. Regardless of the focus area, the role of storage is of key importance to both institutions and our hope for the conference was to present many different aspects of energy storage from a variety of perspectives.

From an energy budget perspective, there are enough renewable energy sources to wean the global community off fossil fuels. Introducing a wide variety of storage modes shows how different uses call for different technologies, e.g. portable vs. stationary sources and short vs. long term storage. Special attention is put on synthetic hydrocarbons, as they are superior both in terms of energy density and power density. Mogens Mogensen highlighted the carbon-neutral option of storing energy in the form of hydrocarbons by reducing CO_2, either circulated through the biosphere and retrieved as biomass or captured immediately from the air, in solid oxide electrolytic cells. In collaboration with Haldor-Topsø, DTU/Risø has made significant advances in bringing solid oxide cells to market. These cells are of paramount importance in meeting the goal of a fossil fuel-free Denmark in 2050. A more detailed discussion of Denmark's energy goals is presented later in this review.

GRID-LEVEL ELECTRICITY STORAGE

Restructured electricity markets, also referred to as "liberalized electricity markets," are complex and function on a high degree of price volatility. Thus, the profitability of many forms of electricity storage technologies depends on arbitrage. It is still unclear if the introduction of wind energy (which is the renewable technology closest to reaching cost parity with carbon-based energy sources) will increase this volatility and hence also the arbitrage opportunity of storage. What is clear is that cheaper natural gas will lower the marginal price in the dispatch order and therefore also the arbitrage opportunity. Regarding future profitability of many different storage technologies, most R&D is aimed at improving efficiencies. Increased efficiency is, however, typically less important than reducing capital costs. Furthermore, it has been found that the large scale introduction of electric vehicles, and thereby also battery storage, in the transportation fleet will not serve as a profitable mode of energy storage for the individual car owner.

MARKET IMPLICATIONS FROM STORAGE

In responding to a question about the market implications of a widespread adoption of storage capabilities with a subsequent flattening of the demand curve, Jay Apt hinted that the timeline to such widespread adoption is very long. Diurnal arbitrage opportunities will therefore remain for the foreseeable future. The future incarnations of restructured markets are also not certain since today's markets are far from considered successful. Even with increased penetration of renewable energy sources on the grid, variability in supply will certainly not disappear. Furthermore, fluctuations in wind power output are less of an issue at very high frequencies, i.e. over short periods of time. With a high volume of wind energy generation, the storage cycle times are likely to be on the order of days rather than minutes. On these scales, it makes sense to gasify and generate synthesis gas as a form of storage which can then be combusted to generate electricity. However, Mogens Mogensen emphasized that different storage technologies have very different applicability due to variations in energy densities, power densities, and optimal cycle times.

THE FUTURE FOR RESTRUCTURED ENERGY MARKETS

The future, to be blunt, is unclear. According to Jay Apt, further restructuring in the U.S. has come to a halt due to the questionable success of current market structure. For industrial customers, restructured markets have not achieved the desired result. However, there are specific storage technologies which are better suited for restructured markets. Batteries, for example, have the potential to eclipse pumped storage, which is currently one of the main grid level storages. Lackner added that storage in liquid fuels has the ability to match the diurnal demand curve. Also, if electric vehicles are adopted in greater quantities, they could potentially smooth the demand curve as their owners charge them at night. However, it is more likely that these vehicles will only be charged when needed, and thus, their ability to smooth demand on the grid is questionable.

On the topic of synthetic hydrocarbons (HCs), Klaus Lackner pointed to the value-added feature of these liquid fuels which allows them to be used in connection with the grid as well as in the transportation sector. Electricity is the main cost of synthesizing HCs. If the electricity is bought from off-peak wind, it is likely that HCs can be produced at a price of $1.60 per gallon. Ramping up production of the required infrastructure might seem like a daunting task at first glance, but the optimal strategy is likely to be a transition to a regime of mass-produced capital rather than custom-made installations. For instance, every year the output of car engines in terms of capacity to transform chemical energy into mechanical energy exceeds the total current U.S. electricity generation capacity. As Mogens Mogensen mentioned, we must address the likelihood of achieving a round-trip efficiency of 40% for transforming electricity to HCs and back to electricity. The exact price levels are hard to predict, but he estimates that HCs can be synthesized at a cost of €1-2/liter. From the perspective of Haldor-Topsø, John Bøgild Hansen surmised that it would take roughly ten years to increase the production of electrolyzers to the level needed to generate the syngas for further synthesis. Furthermore, he surmised that synthetically produced fuels are competitive with petroleum-derived fuels at an oil price of $110-120 /barrel.

ENERGY STORAGE RELATED FUNDING

There seem to be severe limitations on energy storage funding. This might be due to different reasons: first, the subject is very new and quite vast. We need to identify the different applications and uses for storage. With a wide spectrum of possible storage technologies, it is not easy to find common ground aspects suitable for funding, and effort might become directed purely towards applied research rather than basic science. One of the critical funding needs for energy storage is the creation of a common methodology to assess storage values in different energy mixes and in different geographic/economic conditions. Right now, there are several competitive technologies, but there is no "one size fits all" solution, and there may never be.

A second reason for funding limitations might be the general misconception by funding agencies on how fast one can get results and how dramatic these results can be. In reality, and especially for new technologies, we need different levels of funding, differentiated according to project risk and time length. An interesting, potentially game-changing source of funding is the federal ARPA-E program. This government funding is best suited for two levels: as initial seed-funding for university-level research on specialized aspects of energy storage, such as material and niche technology, and as funding for large-scale demonstration plants. Anywhere in between those two levels, private sector investment communities are better suited than the government to drive innovation and development.

Lackner commented that academia tends to have a bias towards improving efficiencies and making system fancier. Instead, more effort should be devoted to making existing functional technologies more affordable.

DIFFERENT STORAGES TECHNOLOGIES: CRYOGENIC LIQUID NITROGEN

Dr. Tim Fox presented a new energy storage technology based on cryogenic liquid nitrogen, which has great potential for the U.K. and beyond. The wind energy industry in the U.K. usually needs 4 to 5 days of storage to make up for weather conditions with low winds. At this time scale, liquid nitrogen can be stored easily in well-insulated thermal tanks. The U.K. renewable strategy helps this implementation, but unfortunately because this technology is very different from Compressed Air Energy Storage (CAES), the facilities used for CAES are neither comparable nor interchangeable with the facilities needed for cryogenic liquid nitrogen storage.

A large-scale system seems viable nevertheless. Canada has already expressed interest in the technology because of abundant wind supply. There are also many aspects of cryogenic energy storage that have unclear economic value today but could potentially become valuable in the future, such as liquid CO_2, which is a waste stream in current storage systems. The economics are further improved if waste heat from other thermal generation can be used in the process. The pilot plant, which has a capacity of 300kW and occupies approximately 30 square meters, corresponds to a scale that could be deployed on a community level to encourage the development of renewables.

It is important to note that a lack of common ground prevents comparison between storage technologies such as CAES and cryogenic liquid nitrogen storage. As mentioned before in the section on funding limitations, there is a huge need for a common methodology to assess and compare storage technologies and their values.

ELECTRO-CHEMICAL STORAGE

Though many different battery technologies currently exist, all technologies have drawbacks. The most significant drawback of existing technologies is high cost, either due to lifetime issues or battery complexity. Flow batteries have the greatest potential for high longevity because there are fewer mechanical processes taking place. Their advantage stems from the removal of diffusion limitations, as opposed to batteries which use ultrasonics/vibrations or surfactants to break up dendrites.

Though cost is the most important factor, it is important to remember that power-driven demand charges address multiple markets, and each market has its own characteristics (e.g. cycles/day, cost of electricity, and required discharge rate). Thus, the required return-on-investment for each deployment varies, and there is no one perfect battery or storage option for all situations. For example, some argue that batteries are good for storing high-quality energy but not for shifting large amounts of energy between the daytime peaks and nighttime troughs like inexpensive thermal storage. On the other hand, thermal storage (e.g. using ice for cooling storage) is not very good in dispersed situations.

DIFFERENT STORAGE TECHNOLOGIES: THE NEW BATTERY

Different storage technologies have different uses, costs, and operating conditions, and new developments are constantly expanding the limits of storage capability. We learned about the features of one exciting new storage technology when Jay Whitacre presented information about his research group's new battery, which is functional down to -10 degrees C. Its current cost is between $200—300/kWh, but hopefully this cost will be cut in half by 2013. His group's goal was a levelized cost of storage energy, amortized over the lifetime of the system. Importantly, unlike many current battery designs, extracting energy quickly from this battery does not correlate with increases in degradation. Although rapid discharging of the battery is less efficient due to heat and diffusion loses, the latter is partly recoverable with recharging the battery. Thus, the proposed battery has a symmetric charge/discharge profile and round-trip efficiency of around 80%. Typically, energy density and cycle life are inversely correlated, but this battery has a unique, high power density that does not correspond to degradation or loss of efficiency with time. Whitacre's research group has found a "sweet spot" between specific cost, energy density, and cycle life. Commercialization of the battery is anticipated in 2014, along with a path to grid-scale distribution and corresponding cost reductions.

Unfortunately, these batteries are too heavy to be used in the transportation sector. On the other hand, it has great potential in other applications, such as situations where extreme temperatures or limitations in current battery technology have constrained storage options.

TRANSPORTATION MODEL: DEVELOPING COUNTRIES

Professor Van der Zwann presented a model of different transportation system projections. The goal was to identify whether hydrogen or electricity will dominate the transportation sector given stringent climate control. In this case study, stringent climate control is defined as a 20% reduction of CO2 in 2020 and 80% in 2050 with respect to 1990 levels. The results indicate that high oil prices alone do not expediently transition fossil fuels away from the transportation sector, but such decarbonization can be achieved with ambitious climate control. Given the set of assumptions presented in the study, hydrogen is the best choice for the transportation sector from an economic standpoint, but extreme reductions in battery costs or non-economic factors could have a powerful impact on hydrogen's role in transportation.

This model was created and adapted for developed countries, but the assumptions and conclusions might be very different for developing nations. The projection is based on the assumption that the level of technology production is high enough to reach a low energy cost. In developing countries, the demand might not be high enough to verify this assumption. It may be interesting to work with a bottom-up system through small granular energy production. A parallel of this phenomenon can be seen in cell phone use in developing countries. These countries did not follow the same progress from conventional land-line phones to cell phones as seen in the 20th century in developed countries. Instead, they leapfrogged to deploying cell phones and the corresponding infrastructure. Theoretically, the same could be accomplished within the energy sector by combining small (possibly renewable) energy systems and storage technologies. An example could be an off-grid cell phone tower powered by small wind turbines and paired with adapted storage technology. These local energy systems are potentially less expensive than creating country-wide grids, especially if they can be economically mass-produced. Distributed energy systems would also benefit developing nations by making low-carbon energy sources the foundation of their energy infrastructure and giving them the freedom to build in diverse types of energy options to suit specific area needs. This would give storage a new value, rather than limit its role to merely a grid arbitrage tool, as seen in developed countries.

Lackner noted that van der Zwann presented a scenario in his model where the price of oil would reach 150 dollars a barrel. Lackner stated that such a scenario is probably not realistic. Cheaper alternatives would arise before oil reaches such a high price. Those cheaper alternatives would create a diminishing demand for oil, and this, in turn, would cause downward pressure on oil prices. However, Lackner believes that it is still interesting to reflect on the importance of energy security and prices. In a situation of high and/or volatile prices, distributed systems have a potential advantage for developing countries because of their ability to follow market opportunities: for example, if gasoline prices become high enough, non-fossil-based liquid fuels become economically viable; otherwise, those fuels can be used as a storage medium.

CYCLICITY IN ENERGY SECTOR: THE EFFECT OF SHALE GAS RESERVES EMERGENCE

Cheap natural gas has been detrimental to alternative energy technologies. Several examples were presented at the conference of situations where alternative energy companies have gone bankrupt. The situation today resembles that of 30 years ago, when an extended period of turmoil in global oil markets generated interest in renewable technologies, but once the price of oil decreased, alternative energy solutions went out the window. The negative environmental impact of the production of shale gas and other unconventional gas resources could be greatly reduced by the introduction of additional regulations, but that would increase the price of extracting the gas. It should be noted that the occurrence of shale gas has been known for a long time; only recently has technology improved to the point where the gas can be economically extracted.

Hydraulic fracturing and the production of shale gas are not developing in Europe for several reasons. First, there is a strong environmental and political opposition to developing these resources. Second, or perhaps as a consequence of the former, land ownership in Europe does not extend to mineral rights. This means that it is not up to the individual land owner to lease or sell the land for development. Tim Fox suggested that the U.K. has a different attitude about developing mineral resources than the rest of Europe; if shale gas is found in the U.K., it will most likely be developed.

A 30-YEAR CYCLE: HOW TO CHANGE THE GAME BEFORE 2040?

It is likely we'll see a reconfiguration of technologies prior to 2040; previous applications of developed technologies will be adapted to suit new purposes. In 2040, we will likely talk about the same issues but under different conditions; climate change will definitively be on the agenda but will probably be regarded with greater urgency. Lackner explained that he is a short-term pessimist but a long-term optimist when it comes to our impact on the environment. In 2040, the world will most likely still run on fossil carbon, and our resolve to do anything about it will remain weak until the consequences become noticeable and too dire to ignore. It should be noted that this cyclicality does not apply to atmospheric CO_2 levels. Hansen added that studies in Denmark show that the country could be completely CO_2 neutral by 2050 for an annual cost of around 2% of GDP. He believes that 2% is not an insurmountable cost, which led him to agree with Lackner's outlook. Hansen summarized the situation by borrowing a quote from Churchill: "Americans can always be counted on to do the right thing...after they have exhausted all other possibilities."

THE CURRENT STATE OF ELECTRICITY GENERATION AND STORAGE IN DENMARK

As part of a parliamentary agreement, Denmark has committed to generate 50% of its electricity by renewable energy by 2020 and to eliminate the production of electricity by fossil fuels by 2035. The approval by parliament is vital as it provides regulatory stability. The 50% goal will be met by largely by wind energy, while the 100% hydrocarbon free electricity system will be met by a combination of wind and electrolysis. These goals are currently funded by a 1-2¢/kWh surcharge for research. The cost is about $100 per month for the average family, or 1-2% of the country's total GDP.

Denmark's wind potential is based upon its long coastline and prevalent off-shore wind sites. In fact, wind is Denmark's most important resource, particularly since there is limited biomass available in the country. Denmark exports surplus wind energy to Norway, Sweden, and Germany. Currently, the country uses these relationships to balance mismatched supply and demand. However, the efficiency of this approach is somewhat limited since the region has largely the same wind profiles across national boundaries, and nearby countries will likely experience similar supply surges and shortfalls as wind generation increases.

To realize the long-term goal of fossil-free electricity, the country's natural gas grid and high power grid, both owned by Energy Net DK, must be coupled with biomass and wind generation for system stability and energy storage. The long-term idea is to use off-peak low-cost electricity and solid oxide cells to create hydrogen for energy storage since electrolyzers can be turned on and off quickly without complications. The round-trip efficiency of the process is expected to be over 50%. The hydrogen will then be coupled with biomass to produce transportation fuels or methane, which can be stored in the natural gas grid or in storage caverns, where the gas has a 3 month lifespan. In total, this requires a $10 billion investment with a minimum lifetime of 50 years.

There are additional projected ancillary benefits to the above proposal. Because Denmark is planning to utilize the in-state expertise of Haldor Topsøe, there will be job creation due to technology development. Also, in the long term, assuming the price of fossil fuel increases and the price of the catalyst does not, methane use will reduce costs.

THE CURRENT STATE OF ELECTRICITY GENERATION AND STORAGE IN NEW YORK

New York State is a deregulated market with about 50% bilateral contracts. Of the 35 GW peak demand, the regulation market accounts for only 200 MW, the difference between supply and demand. Currently, the price of the regulation market is set by the price of natural gas, which makes it difficult for renewable energy to compete.

New York State, which is four times larger than Denmark, has a commitment to develop new technology. This commitment is funded by a tax on all state ratepayers amounting to 0.5 ¢/kWh of delivered charge. The monies collected are used to fund New York State Energy Research and Development Authority (NYSERDA), a public benefit corporation with 350 employees. NYSERDA's annual budget of $650 MM is broken down into 3 categories: funding for efficiency projects, managing the state's renewable portfolio standards (RPS) program, and the research and development (R&D) program. The RPS program is targeting 30% renewable energy by 2015, which will be anchored by 20% existing hydro. Within the R&D program, there are about 51 active storage R&D projects spanning the gambit of technologies accounting for $5 MM/yr.

New York Power Authority (NYPA) is a sister agency to NYSERDA that regulates rates in the state and is the largest state owned utility company in the country. NYPA has two main focus areas: operating and energy service and energy storage programs. The operating and energy service side operates a 2700 MW large scale hydro system near Niagara and an independent 1000 MW pumped storage facility in the Catskills. This facility was originally designed for arbitrage but currently is being used as a "pinch hitter" for startup or if a unit goes offline. NYPA has invested in a $200 MM/yr energy service program, which sell light bulbs and targets other energy efficiency opportunities. NYPA's energy storage programs are part of the energy services offered by the company, and they focus on thermal storage, batteries, flywheels, and other technologies that can be used on a distributed basis. Overall, they are not seeing value proposition opportunities, but they do have several projects in the works such as the Electric Transportation Program.

Con Edison supplies electricity, gas, and steam to the 5 boroughs of New York City and much of Westchester, an area that provides unique challenges within New York State. Their territory covers about 1% of the state's footprint but about one-third of the state's demand with a peak demand of greater than 13,000 MW. For comparison, the average energy density statewide is less than 1 MW/mi^2, but the average energy density in ConEd's territory is 20 MW/mi^2, and, in Manhattan, it is 200 MW/mi^2. Traditionally, summer cooling demands peak the system. Thus, on average, there are only about 36 hours/year during which demand exceeds 12,000 MW. For ConEd, peak load management is a unique opportunity. ConEd tries to use demand-side management; to date, they have no grid storage programs per se, but there is some customer-side storage.

NEW YORK TO DENMARK COMPARISON

In short, Denmark currently has the political will and public support for their renewable energy goals. It was (and is) a long, tortuous process in Denmark that required an awareness of problems such as climate change. Action must be based on public perception. The average New York family is simply not prepared to pay the additional $100 per month that their peers in Denmark are paying to improve the energy system. As an example, compare the required $10 billion investment required for Denmark's system to the $5 MM/yr for storage R&D projects at NYSERDA while remembering the New York is four times as big as Denmark.

In addition, the current electricity generation mix (and future potential) in New York is vastly different than that of Denmark. New York State relies heavily on large-scale hydro, which has huge upfront costs and large difficulties in permitting. New York does not have the same offshore wind potential or flexibility as has Denmark. The situation in New York is further complicated by several factors. First, it is easier to store natural gas than it is to store electricity. Second, state-wide wind generation (only 15 MW) is such a small contributor to the energy mix that there is not yet the same kind of intermittency issues currently present in Denmark to drive the need for a large scale storage system in the state. Lastly, the cost of energy in New York is relatively cheap (compared to California, for example) so the low-hanging fruit in the state is still efficiency measures. It doesn't make sense to consider storage and renewable energy if the energy is wasted at the end, which would be the case at present in New York with current energy prices. Given the current situation in New York, there is a belief that a smart grid in the state will lead to managing demand rather than energy storage.

Right now in New York, projects are simply not economically justified particularly due to the low price of natural gas. Identifying environmental externalities and building in their cost would help justify the economics. In addition, policymakers can increase the value of energy storage in meeting renewable energy targets by giving some renewable energy credits to energy storage projects. The good news is that NYSERDA does have value proposition projects on a distribution level, and it has a 25% success rate overall, which is relatively high. Some large-scale customers are seeing value in local storage. Furthermore, New York and California are the only states where commissioners take public money for societal benefit. There is successful thermal storage in the city at $500/kW. Compared to the rest of the U.S., New York is doing very well.

OVERVIEW

This symposium presented a broad spectrum of views which indicates that, as a community, we are on the right track. Overall, storage is useful for demand moderation. Fossil carbon addresses storage up front, but when utilizing renewable energy, one must solve storage issues. For example, in the transportation sector, fuel can connect automobiles to storage. Additionally, storage in grid arbitrage as well as round-trip times was also discussed. Batteries are still in the $100-200/kW storage range, but progress is being made. Importantly, we are left with questions that must be addressed. We must determine how low prices must go to make storage technologies viable, and we must identify the value of delivering power at a given time (i.e. power capacity.) Ultimately, the bottom line is cost, cost, cost. The ideal electrolyzer has 0% efficiency and $0 cost. As reviewed in this conference, the current state of national gas reliance in New York indicates that, at a price of $2/GJ, the political will to transition to renewables is simply not there. In this case, natural gas prices will dominate electricity prices. Denmark's example shows that political will and policy have a profound impact. As of yet, we don't understand the true impact of storage and how the current system will be effected by distributed or centralized storage. The system at present was designed given a set of constraints and assumptions. With modifications such as those discussed at this conference, the original variables may have changed considerably. We, as a country and as a global community, need research on the policy and systems to understand these questions.

For full presentations and more articles on the 2012 Energy Storage Symposium, please visit the Lenfest Center website at www.energy.columbia.edu.