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Renewable Minnesota

A technical and economic analysis of a 100% renewable energy-based electricity system for Minnesota

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- Arjun Makhijani, Christina Mills, and M.V. Ramana

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This report is available online at http://www.ieer.org/reports/renewableminnesota.pdf.

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Executive Summary

The electric energy sector in Minnesota, and more generally the United States, is in a state of transition, with considerable uncertainty regarding the future costs of carbon-dioxide (CO_2) and other greenhouse gas emissions. Utilities must also comply with more stringent clean air requirements, which particularly affect coal-fired power plants, many of which utilities may opt to shut down. Additionally, there is a growing momentum for utilities to protect themselves and their ratepayers against volatile fossil fuel markets. For some, nuclear power seemed to be the answer to these questions, despite its costs and risks.

At the same time, the pace and scale of renewable energy development has been rapid. The United States has an installed capacity of wind energy approaching 47,000 megawatts (MW) and installed grid-connected solar electric capacity of 3,100 MW. [1] Solar installations have increasingly become large-scale, with growing numbers of photovoltaic (PV) and concentrating solar power (CSP) projects having capacities in the tens or hundreds of megawatts per installation. At the same time, the number of residential solar projects has also continued to increase.

This momentum has also led to improving the cost-effectiveness of renewable energy generation. For instance, in the Dakotas and Wyoming, where wind energy capacity factors are on the order of 40 percent, the costs of wind-generated electricity are comparable to new coal or natural gas combined cycle power plants without including subsidies or a price on carbon. Wind-generated electricity is also less expensive than nuclear and remains lower than nuclear even when storage costs are added.[2]

Renewable energy resources are plentiful across the country. Studies of the Midwest and the footprint of the regional transmission organization, the Midwest Independent Transmission System Operator (MISO), have routinely shown the high wind energy potential in the central corridor of the United States, including Minnesota. The state is endowed with ample wind and solar energy resources, and over the years has developed a strong public policy foundation to support development of these resources. This study examines how Minnesota might take advantage of these resources to design a renewable energy-based electricity system.

[1] AWEA 2012 and SEIA and GTM Research 2011 p. 3

[2] All cost estimates in this study are market-based estimates to the extent possible. Specifically, subsidies such as investment tax credits, production tax credits, federal loan guarantees, and interest-free financing by ratepayers are not included in any of the cost estimates.

Our overall goal is to examine whether a fully renewable energy-based electricity system is technically and economically feasible for the state of Minnesota. In 2007 the state articulated a goal of significantly reducing the greenhouse gas emissions from all sectors. Since 1970 the electricity sector has been a leading source of emissions, and has been the only sector to continually increase its emissions over the past 40 years. Clearly a dramatic reduction in electricity sector emissions will be critical in achieving any significant reduction in greenhouse gas emissions overall.

Pioneering a renewable grid: dealing with the "relational system peak"

A principal insight that emerges from this study is that the conventional notion of a "peak load" needs to be replaced in designing an electricity system with a high proportion of solar and wind energy. At present the system peak is determined entirely by consumers – it is the time of highest simultaneous load on the system. In a renewable energy system with storage, depending on how it is configured, it is entirely possible that there may be plentiful electricity generated at such times. The crunch time may be during periods when the wind and solar supply are low *relative* to demand. So it is possible for a system "peak" – i.e., maximum use of generation from stored energy – to occur when demand is not at its highest. Indeed, this will often be the case. We have called this phenomenon the "relational system peak." The electricity system of the future, if it is to have a large fraction of solar and wind energy, will need to optimize these renewable energy investments with investments in specific technologies such as combined heat and power (which increases both generation and efficiency), making use more efficient at critical times of the year, and demand dispatch to reduce the relational system peak. Instead of the peak load that drives marginal investments in generation as at present, dealing with the relational system peak will require comprehensive consideration of investments throughout the system – generation, demand, and storage (though not necessarily by utilities in all cases).

We used historical data on electricity supply and demand from Xcel Energy, which is the state's largest electricity provider and is a good representative of these parameters for the state as a whole, and the best available industry data on the various energy technologies. This approach allowed for a methodology that limited the potential for error that can be expected from a more complex and resource intensive forecast model, while also providing a reasonable analysis of the feasibility of a fully renewable electricity system. Using the same criteria for reliability that apply today, we found that it is technically and economically feasible to meet the entire 2007 electricity demand of Xcel Energy using only renewable energy generation combined with storage technology and energy efficiency improvements. We assume that the composition of renewable energy generation is a mix of commercial-scale wind energy and rooftop solar PV, due to economies of scale and the most likely application of each technology in Minnesota. Further, Minnesota's renewable energy resources are large enough to accommodate any foreseeable growth in electricity demand in the next four decades and beyond. Hence, we were able to start with the analysis of the 2007 Xcel data and extend it to the whole state when assessing cost and jobs implications.

This study is a first step. We did not attempt to model an intelligent electricity grid in which large numbers of distributed generation sources and storage types, and smart appliances are managed as an integral part of a larger grid operation, due to the difficulties in estimating the costs and shape of such a system. Neither the data nor the system integration modeling capabilities are publicly available today at a level of detail needed for a reliable technical analysis, much less a cost analysis. Yet the need for such a design tool emerges very clearly from our analysis.

The storage technology that we assume for our analysis is compressed air energy storage (CAES), which has been used commercially for decades with coal-fired power plants in two locations: Germany and Alabama. Compressed natural gas storage in caverns and aquifers is also a standard technology. CAES is only one option for commercial scale storage technology, and because it has a proven track record, we have used it as the placeholder technology for the storage capacity needed. Minnesota does have geology that may be suitable for CAES at many locations; however, in-depth investigations are needed to identify potential sites. A single storage technology allows a straightforward determination of technical feasibility as well as cost. In practice a mix of storage technologies as well as demand dispatch, which shapes the part of load curve in relation to the available supply and storage, would be used.

The notion that solar and wind energy cannot be the mainstay of an electricity generation system because they are intermittent is incorrect. This study shows that they can be dispatched reliably – when there is storage. In our analysis we maintain the usual reliability criterion – 12 percent reserve margin over demand – for every hour of the year. And such a system does not have to be prohibitively costly. As it turns out, a 100 percent renewable energy-based electricity system for Minnesota increases rates by a mere 1-2 cents per kilowatt hour when sufficient reasonable and economical investments are made in energy efficiency.

While one reason to pursue renewable energy in the electricity sector is to provide a hedge against volatile fossil fuel prices and to provide a lower financial risk for investors, another reason is that renewable energy-based electricity provides a better product to society. The electrons speeding through the wires of the grid are the same, but the social, health, and safety consequences are far different. People will literally breathe easier, water use will be lower, and the risks related to CO_2 emissions will be nearly eliminated from the electricity sector. We do not examine the net jobs impact, but do discuss the broader overall jobs potential from renewable energy development in Minnesota.

Main Findings

- **A renewable energy-based electricity sector is technically feasible**, using available and proven technologies. If this is supplemented with an intelligent grid with two-way communication and more efficient use and integration of distributed generation and storage resources, this can help reduce the costs of implementing a renewable energy-based electricity sector.
- **There are ample renewable resources in Minnesota**. There is more than enough wind and solar energy potential to meet the entire 2007 demand of Xcel Energy's customers every hour and to accommodate growth in the foreseeable future. These technologies are already commercially available. While we have not examined the subject in detail here, there is evidence that the requisite amount of utility-scale storage technology can also be installed within the state.
- **An efficient, renewable electricity system can be achieved at an overall cost comparable to the present total cost.** The added costs of renewable energy generation, as compared to the current generation from mature and fully-depreciated fossil fuel and nuclear generation facilities, can be offset by increasing the energy efficiency of household and building appliances. The net costs of electricity services – lighting, cooling, running appliances, etc., would be the same as today, but partitioned between generation, storage, efficiency, transmission and distribution.
- **Energy efficiency lowers the effective cost of electricity services and electricity bills.** There are ample opportunities for reducing electricity use while maintaining the same level of services such as lighting and cooling and running computers. For instance, a more efficient refrigerator or air conditioner would provide the same level of cooling, but would use less electricity to do so. But the investment in the refrigerator would be a little more compared to an average model. Appliance and building energy standards, supplemented by utility programs, are an effective way to have high penetration of energy efficiency measures and achieve cost savings.

Recommendations

In order for Minnesota to achieve any significant reduction in greenhouse gas emissions, dramatic changes to the electricity sector are necessary. We have identified a number of steps that can help position Minnesota to utilize its available renewable energy resources, as well as create a more informed technical and cost framework for transitioning to a renewable energy-based electricity sector:

- Initiate a detailed, state-wide energy efficiency study, including the technical and economic aspects and the effect of efficiency and demand dispatch investments on the electricity demand pattern and on relational system peaks.
- Require utilities to include increased renewable energy and storage in their Integrated Resource Plans by modeling what it would take to meet their projected demand with only renewable energy resources and the steps, time, and investment it would take to accomplish that goal..
- Initiate a study that would address how demand dispatch, storage, specific efficiency measures, and combined heat and power could be combined to reduce the costs of a fully renewable electricity system.
- Initiate a detailed exploration of the feasibility of CAES and other utility-scale storage options in Minnesota.
- Further refine the findings in this report by developing an optimized framework for reducing the relational system peak.
- Conduct similar studies at the regional level in cooperation with other states in the Midwest.
- Adopt a state-wide goal for achieving a 100 percent renewable energy standard, with achievable benchmarks and milestones and a periodic review of progress every few years.

I. Purpose of the Study

A. Introduction

Like many other states, Minnesota is grappling with the complex issues that surround energy, economics, and the environment. An important element in the discussion of these interrelated issues is the expanding role of renewable energy in meeting our future electricity needs. Minnesota has been a leader in the integration and use of renewable energy – from the wind farms in the southwest portion of the state to an increasing number of solar panels found on urban rooftops.

Minnesota has an opportunity to build on this momentum and set a path towards a fully renewable and efficient electricity system. This report is the first step towards that goal by answering questions about what we do when the sun is not shining and the wind is not blowing. Specifically, this report aims to provide a technical and economic framework showing that the same level of reliability that prevails with nuclear and fossil fuels can be achieved with a fully renewable electricity system in Minnesota.

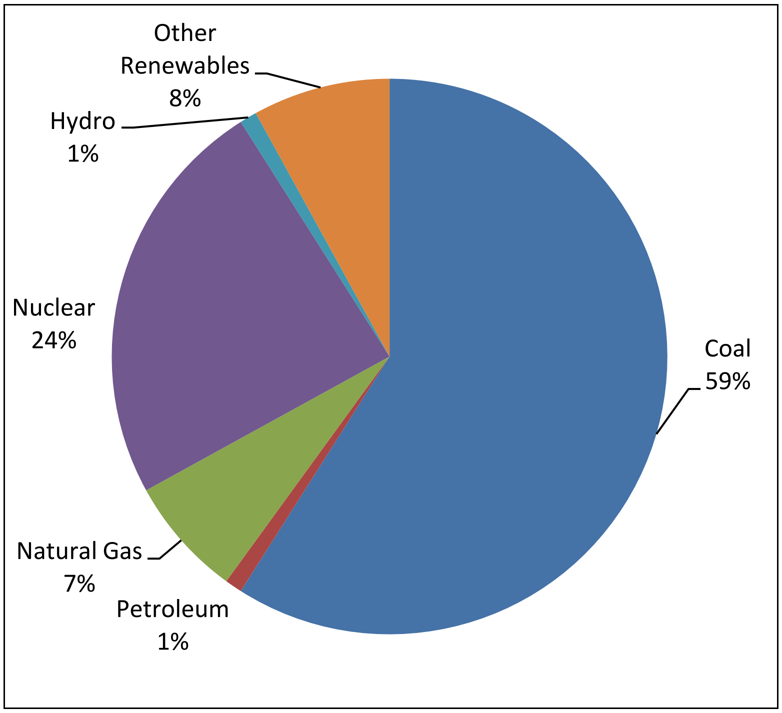

Figure I-1: Minnesota electricity generation by source, 2007. *Source: IEER. Data source: EIA 2010 Minnesota Profile Table 5*.

For this report, we chose to look at 2007 data, the last year before the recession, as an indication of more normal, pre-recession electricity patterns. In 2007 Minnesota generated 59 percent of its electricity from coal, 7 percent from natural gas, 24 percent from nuclear, 8 percent from wind, solar, biomass, 1 percent from hydroelectric, and 1 percent from petroleum.[3] (See Figure I-1) By utilizing 2007 electricity demand data for Xcel Energy's

[3] EIA 2010 Minnesota Profile Table 5

planning area as reported to the Federal Energy Regulatory Commission (FERC)[4] and renewable energy supply information from the U.S. Department of Energy's Energy Information Administration (EIA) and National Renewable Energy Laboratory (NREL), and available energy efficiency data, we were able to develop a cost-effective electricity generation scenario using 100 percent renewable energy to sufficiently meet the electricity demand of the state's largest electric utility, without requiring significant changes in lifestyle.

Minnesota has a long history of state leadership on complex environmental and energy issues. In 1994 the state enacted a ban against the construction of new nuclear power facilities as a result of concerns with how to manage the state's nuclear waste. Because building a nuclear power plant is so costly and time-intensive, it tends to consume most available financial and political resources. By removing the nuclear option from consideration for future electricity supply, regulators and utilities in Minnesota have had the ability and resources to instead invest, successfully, in renewable energy and energy efficiency technology in order to meet demand.

Further, in setting forth a vision of the state's energy future in the 2007 Next Generation Energy Act,[5] the Minnesota legislature enacted what was at the time, the country's strongest Renewable Energy Standard (RES),[6] requiring 25 percent of the electricity produced by the state's utilities to come from renewable sources, primarily wind, by 2025 (30 percent by 2020 for Xcel Energy).[7] Since then, an increasing number of other states have strengthened and expanded their commitments to renewable energy. For instance, California increased its state renewable energy standard target for electricity producers to 33 percent by 2020[8] and included the option for utilities to integrate storage technology.[9] Other states include Hawaii (40 percent by 2030)[10] and New York (30 percent by 2015).[11]

[4] Hourly demand data are in the control planning area for Xcel-NSP (utility number 216) as report to the Federal Energy regulatory Commission on Form 714. This data corresponds mostly but not completely with the NSP's electricity supply to Minnesota customers alone.
[5] Next Generation Energy Act of 2007
[6] Sometimes called a Renewable Portfolio Standard (RPS), these policies place an obligation on electricity supply companies to provide a certain percentage of their electricity from renewable energy sources.
[7] See Minn. Stat. § 216B.1691, 2011 Subd. 2(a) and Subd. 2(b). The law requires that electric utilities who owned a nuclear reactor as of January 1, 2007, are required to meet higher percentages of renewable energy generation. Xcel Energy is the only such utility in Minnesota that meets those criteria.
[8] Pursuant to California's Executive Orders S-14-08 (California 2008) and S-21-09 (California 2009).
[9] Pursuant to AB 2514, signed into law in September 2010, which directs the California Public Utilities Commission to begin proceedings on requirements for such systems. (California 2010)
[10] Pursuant to Hawaii HB 1464, signed into law in June 2009 (Hawaii 2009)

Also in the 2007 Next Generation Energy Act, the Minnesota legislature mandated that a plan be developed to reduce state-wide greenhouse gas emissions by 80 percent from 2005 levels by mid-century.[12] As the largest source of the state's greenhouse gas emissions, Minnesota's electricity sector has a major role to play in achieving this goal. Doing so will require efforts beyond meeting Minnesota's existing RES. According to the Minnesota Pollution Control Agency, "[b]aseline 2005 emissions were estimated at 154.1 million CO2-equivalent tons, which implies that a 2015 target level under the Next Generation Energy Act goals of 131.0 million CO2-equivalent tons and a 2025 target of 107.9 million CO2-equivalent tons. Assuming a linear approach or trajectory to these target levels, Minnesota state-level GHG emissions would need to decline about two million CO2-equivalent tons per year to meet these goals."[13]

Given the likely difficulties in greatly reducing greenhouse gases from the agriculture and transportation sectors and the fact that electricity generation and transportation have accounted for the majority of the increased greenhouse gas emissions since 1970 (Figure I-2), an almost complete elimination of greenhouse gas emissions from the electricity sector will be a critical element in achieving an 80 percent reduction in overall emissions. From 1970 to 2006 almost all sectors reduced their greenhouse gas emissions, except for transportation, which stayed fairly level, and electricity generation, which increased by 55 percent during the same time period (Figure I-3).

[11] Pursuant to New York Public Service Commission Order, Case 03-E-0188, Effective January 8, 2010 (New York 2010)

[12] See Minn. Stat. § 216H.02 subd. 1.

[13] Ciborowski and Claflin 2009 p. 111

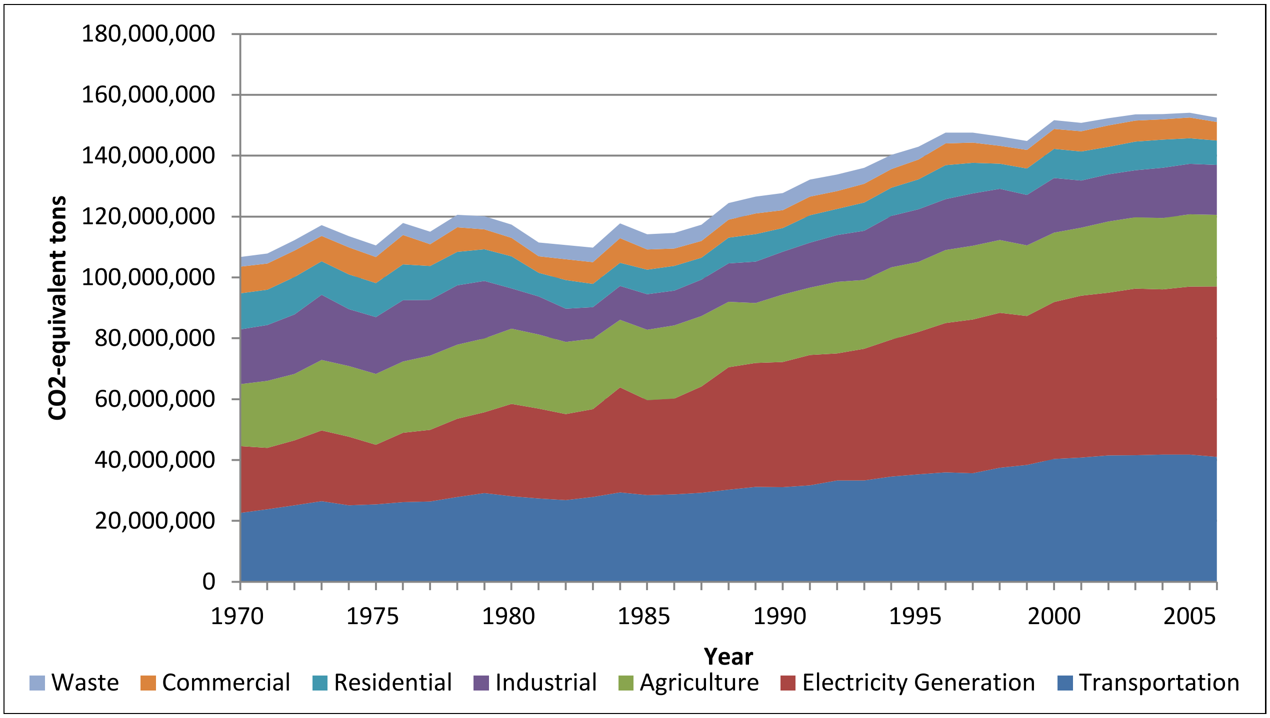

Figure I-2: Total greenhouse gas emissions in MN by sector, 1970-2006. *Source: IEER. Data source: Ciborowski and Claflin 2009 pp. 138-142*

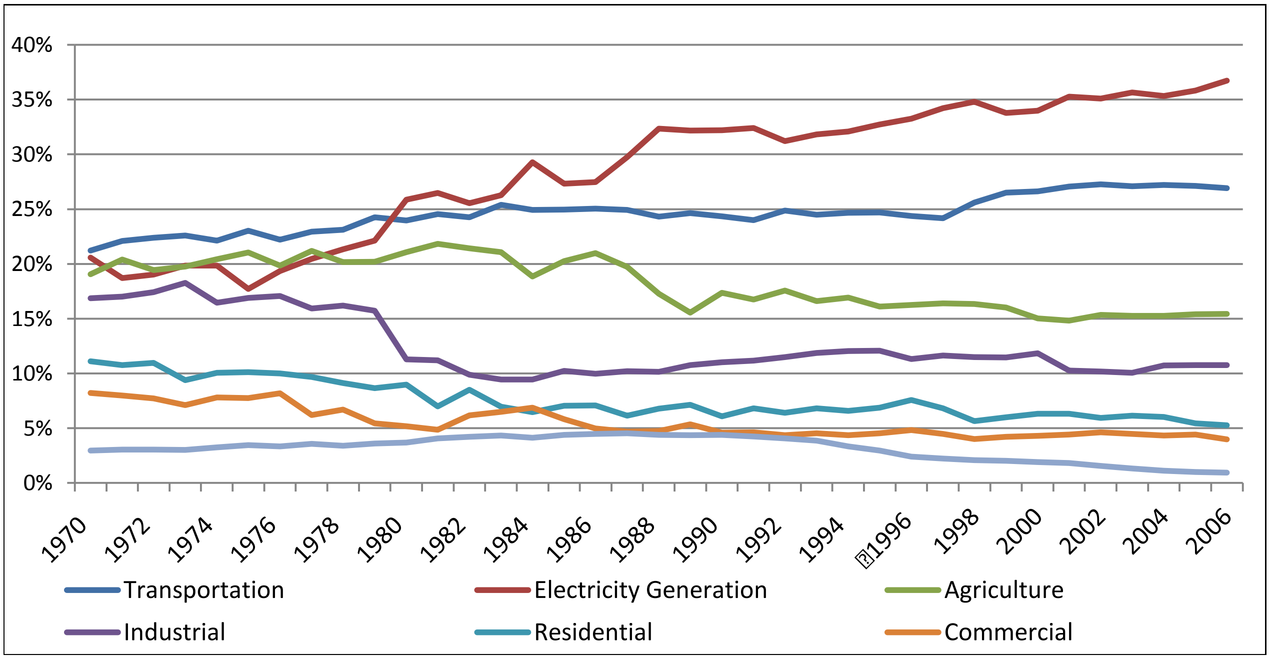

Figure I-3: Percent of total greenhouse gas emissions in MN by sector, 1970-2006. *Source: IEER. Data source: Ciborowski and Claflin 2009 pp 138-142*

B. Goals of the Study

Our goals in studying these issues are to first see whether the electricity demand for a typical year of Minnesota's largest electric utility can be reliably met through a combination of solar, wind, and storage technology, and second, to estimate the rough cost at which this might be done. There is good reason to attempt this type of analysis. As the panel on America's Energy Future, convened by the National Academy of Sciences, stated "renewable resources available in the United States, taken collectively, can supply significantly greater amounts of electricity than the total current or projected domestic demand. These renewable resources are largely untapped today".[14] Much of this is in the form of wind, concentrated primarily in the Midwest. There are also ample solar resources in the Southwest, sufficient to power all of the United States.[15]

As we will discuss, energy efficiency measures will play a significant role in the amount of electricity supply and storage needed, as well as in how much a fully renewable system will cost. A more thorough discussion of energy efficiency technology can be found later, in the discussion on Minnesota's electricity demand. The renewable energy data used in this report is Minnesota specific; our study focuses on only in-state renewable energy resources. Efficiency cost considerations are based on a national analysis. While there are a variety of important issues to consider in planning an electricity system, this report focuses only on the technical and economic framework of a 100 percent renewable electricity system and does not attempt to quantitatively identify the best path to take in order to achieve this goal. Rather, we discuss qualitatively elements that are needed in addition to the quantitative considerations in this report.

[14] NAS 2010 p. 3
[15] Fthenakis, Mason, and Zweibel 2009 p. 391

II. Renewable Resources in Minnesota

In order to have a 100 percent renewable energy-based electricity system, there have to be sufficient renewable energy resources to draw from. Minnesota possesses abundant wind and solar resources, produces ample biomass, and has access to hydropower purchases from Canada. This report considers only in-state wind and solar energy resources, which creates an artificial limitation because in reality Minnesota operates within a broader regional electricity grid and is part of the Midwest Independent Transmission System Operator (MISO).[16] However, this restriction does make sense from a state development perspective because it allows one to explore what a 100 percent renewable electricity system may mean for jobs and economic development in the state. Due to limited availability of utility data, we have focused our analysis on the demand of the state's largest electric utility, Xcel Energy (formerly Northern States Power), as the state's largest investor-owned utility, and whose 47.6 TWh[17] of 2007 electricity demand as reported to FERC. This total represents approximately 70 percent of the state's total retail electricity sales in 2007 of about 68 TWh .[18]

For Xcel Energy to provide enough electricity solely from renewable energy sources equal to match its hourly 2007 sales, the utility would need to have roughly 12,300 megawatts (MW) of wind energy and 4,600 MW of solar energy connected to its system. When combined with storage capabilities, existing hydropower purchases, and increasing in-state small hydropower and sustainable biomass, Xcel Energy would be more than able to generate enough electricity to meet its 2007 annual electricity demand. If combined with a high level of energy efficiency efforts, it is possible to provide this 100 percent renewable electricity at an economical cost. While there are ample renewable energy resources to meet any foreseeable electricity growth in Minnesota, as we will see, it is economically preferable to meet a large fraction of the growth of electricity demand though efficiency improvements. The costs of new generation requirements can be reduced through judicious development of a smart grid, which is a communication network that complements the electricity generation, transmission, and distribution system.

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[16] MISO is the regional transmission operator for the upper Midwest and parts of Canada. It is responsible for maintaining the high-voltage transmission system within its footprint.

[17] Calculated using the hourly demand data for its service territory in 2007 provided by Xcel Energy to FERC (FERC Form 714)

[18] Calculated by IEER using 47,595,270 total MWh of hourly electricity demand reported by Xcel Energy for its NSP service territory in FERC Form 714 and a total of 68,231 thousand megawatt hours retail electricity sales in Minnesota in 2007 (EIA 2010 Minnesota Profile Table 8). Most but not all of the FERC reported Xcel-NSP data relate to Minnesota demand.

A. Wind Energy

The potential for wind energy in Minnesota has long been recognized. As early as 1991, a Pacific Northwestern Laboratory study found that Minnesota's wind energy potential at 50 meters above the ground, in areas that have winds of Class 3 and higher[19], after factoring in environmental and land use exclusions, was 657 billion kilowatt-hours (kWh)[20] – almost ten times Minnesota's total 2007 electricity demand. More recent estimates have looked at the state's wind resource potential at higher elevations, reflecting advances in wind energy technology, and found that at 80 meters above the ground Minnesota has 1,679 billion kWh of annual wind energy potential[21] – more than 25 times Minnesota's 2007 electricity demand, and translating to a total potential wind energy capacity of 489,000MW. Figure II-1 shows the average wind speeds in Minnesota at 80- and 100-meters above the ground.

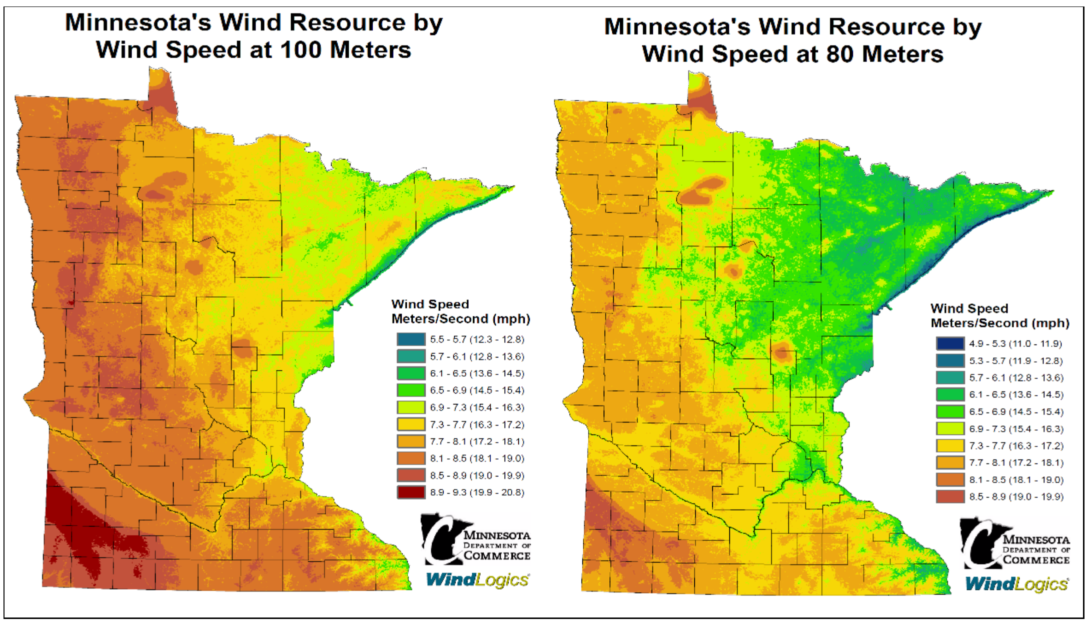

Figure II-1: Minnesota's wind resource at 100 meters and 80 meters above the ground. *Source: MN DOC 2006*

[19] Wind class 3 and higher refers to an area with 6.4-7.0 meters/second wind speeds at a height of 50 meters above the ground (NWCC 1997).
[20] Elliott, Wendell, and Gower 1991 Table B.1 (p. B-2). A kilowatt-hour is the amount of energy equal to the power of one kilowatt running for one hour. This unit of energy is commonly used by utilities in electricity bills. One kilowatt-hour is equal to 1000 watt-hours.
[21] NREL and AWS Truepower 2011. The available power in the wind is a cubic function of the wind speed, so if the wind speed (x) is doubled it means there is 8 times the power (2x*2x*2x=8x^3). Because the wind speed is greater at higher elevations, the height of the wind turbine has a significant impact on the available power potential at that location. See Figure II-1 for an illustration of the differences in wind resource potential at 80 meters and 100 meters above the ground.

Minnesota has historically been one of the leaders in the country in wind energy installations; at the end of 2011, Minnesota ranked 5th in the country with a total of 2,733MW of installed wind capacity.[22] Minnesota has seen a drop in wind energy installations recently, likely due to a combination of factors, including the economic recession, increased public opposition to proposed wind projects, concerns about transmission constraints and cost allocation, and uncertainty regarding the future of federal policies supporting the wind industry. Detailed consideration of these issues is beyond the scope of this analysis; however the realization of a 100 percent Renewable Minnesota, or anything close to it, will need to include consideration of these important issues and practical approaches to deal with them.

1. Cost and Reliability Studies

Utility-scale wind turbines can, and do, "affect utility system planning and operations for both generation and transmission."[23] This has prompted studies, both U.S. and state focused, in recent years to examine the issues involved in incorporating much greater amounts of renewable energy into the electricity mix. Of particular interest to utility and transmission regulators has been the cost of maintaining the reliability of an electricity grid with an increasing amount of wind energy capacity.[24]

In July 2008, the U.S. Department of Energy (DOE) published an assessment of the costs, challenges, impacts, and benefits of wind generation providing 20 percent of the electrical energy consumed in the United States by 2030.[25] This study found that the major barriers to such a goal were largely in the realm of policies and regulatory hurdles, rather than technical challenges, and that integrating 20 percent wind energy onto the electric grid could be done for less than $0.50 per household per month.[26]

Subsequently in 2010, the DOE published the *Eastern Wind Integration and Transmission Study* (EWITS), which was designed to examine a range of technical issues related to a 20 percent wind scenario within the Eastern Interconnection.[27] The study estimates that across the entire

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[22] AWEA 2011 slides 4-5
[23] Smith et al. 2007
[24] From 2000 through 2009, electricity generation in the United States from renewable energy sources (other than hydroelectric) has increased from 2 percent to over 3 percent. Renewable resources in this definition include wood and wood-derived fuels, geothermal, other biomass, solar thermal and photovoltaics (PV), and wind. (EIA Electric Power Annual 2009 Table ES1 (pp. 9-11))
[25] DOE 2008 20% Wind
[26] DOE 2008 20% Wind p. 19
[27] EWITS 2011. "The Eastern Interconnection is one of the three synchronous grids covering the" contiguous 48 states of the United States. "It extends roughly from the western borders of the Plains states through to the

interconnect, there are 1,326 sites with a total potential for 580 GW of wind energy capacity.[28] A similar study has been done for the western United States, which looked at integrating 30 percent wind energy and 5 percent solar power.[29] The EWIT study, identified 121 sites in Minnesota that could support a 100 MW wind project, and estimates that a total of 61,480 MW of wind energy could be installed at these sites across the state where the average capacity factor[30] will be above 25 percent.[31]

At the state level, in June 2003, the Minnesota Legislature called for an independent study of the impacts of integrating more wind power on the Xcel Energy system, above the 825 MW that the utility already had under contract at the time.[32] The study team involved representatives of Xcel Energy other utilities, the Minnesota Chamber of Commerce, the American Wind Energy Association, environmental organizations, the U.S. Department of Energy and its National Renewable Energy Laboratory. Published in 2004, the study concluded, among other things, that "the cost of integrating 1500 MW of wind generation into the Xcel control area in 2010 are no higher than $4.60 per megawatt-hour (MWh) of wind generation, and are dominated by costs incurred by Xcel to accommodate the significant variability of wind generation and the wind generation forecast errors for the day-ahead time frame."[33] This is about four percent of the cost of residential retail electricity in Minnesota.[34] This cost can be compared to $18.38 per megawatt-hour (MWh), which is the assumed cost of producing wind power in the study.[35]

This was followed by another state study that began in 2005. A "broad stakeholder group," including representatives of the Minnesota electric utilities, renewable energy advocates, the Minnesota Legislature, the Minnesota Department of Commerce, Midwest Independent Transmission System Operator (MISO), Mid-Continent Area Power Pool (MAPP), "and national

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Atlantic coast, excluding most of the state of Texas." Minnesota is entirely within the Eastern Interconnection. (EWITS 2011 pp. 22-23)

[28] Brower 2009 Table 3.2 (p. 15)

[29] WWSIS 2010

[30] Capacity factor refers to the ratio of actual output over time compared to the potential maximum output if the plant had operated full time at its maximum rated capacity. For instance, consider a 1 MW wind turbine. Its nameplate capacity is 1 MW, and the maximum potential output for this wind turbine is 1 MW x 8,760 hours per year = 8,760 MW-hours per year. However, the wind doesn't blow all the time so the actual output for this turbine will be some percentage of the maximum potential. Wind turbines capacity factors are typically between 20-40%.

[31] Brower 2009 Table 3.2 (p. 15) and Figure 3.1 (p. 16)

[32] Minnesota Session Laws 2003, 1st Special Session, Chapter 11, Article 2, Section 21 (Minnesota 2003)

[33] EnerNex 2004 p. 38

[34] Calculated using average Minnesota residential electricity costs in 2010 of 10.59 cents per kilowatt-hour or $105.90 per megawatt-hour. (From Table 8 at EIA 2010 Minnesota Profile)

[35] EnerNex 2004 Table 20 (p.113)

technical experts," convened to characterize "the Minnesota wind resource and" quantify the "reliability and operating impacts resulting from" increasing wind generation to 25 percent of Minnesota's electricity supply by 2020.[36] This study was published in 2006 and concluded that the additional costs of integrating greater wind energy capacity, over and above normal costs, could range from $2.11 (for 15 percent wind generation) to a high of $4.41 (for 25 percent wind generation) per MWh.[37]

The 2006 Wind Integration Study also looked at the effect of including four levels of geographic dispersion for potential wind energy sites.- The four levels are 1) Minnesota Southwest (Buffalo Ridge), 2) Minnesota Southwest + Minnesota Southeast (Mower County), 3) Minnesota Southwest +Minnesota Southeast + Minnesota Northeast (Iron Range), 4) Minnesota Southwest +Minnesota Southeast + Minnesota Northeast + North Dakota Central. [38] The study found that each additional level of dispersion reduces the variability in wind energy output.[39] For instance, if all wind capacity is just in southwest Minnesota, then for about 18 percent of the year, wind farms run at capacity factors of less than 5 percent. When just the first increment of geographic dispersion is incorporated, the frequency of generation at less than 5 percent drops to 11 percent. When all four regions are included, this drops even further to just 4 percent. This means that dispersing wind turbines across the state minimizes the amount of the time there is no wind energy being generated. "The dramatic effect of geographic dispersion is even larger in the summer season."[40] This season has the weakest wind resource but the frequency of capacity factors below 5 percent drops from nearly 26 percent for just the Minnesota Southwest site to just under 4 percent for the broadest geographic dispersion scenario. Of course, there is a corresponding decrease in hours with very high capacity factors when the resources are dispersed. [41] But this also has a benefit: it reduces the amount of excess electricity generated, minimizing the need for more storage capacity.

Similarly "large hourly power changes are rare for the intra-Minnesota tri-region generation scenario and very rare for the fully dispersed generation scenario including central North Dakota generation."[42] Again the effect was most dramatic in the summer. For wind dispersed over all the four regions as described earlier, the 2006 Wind Integration Study estimates net

[36] Wind Integration 2006 v.I p. x
[37] Wind Integration 2006 v.I p. 72
[38] Wind Integration 2006 v.II p. 38
[39] Wind Integration 2006 v.II p. 40
[40] Wind Integration 2006 v.II p. 40
[41] Wind Integration 2006 v.II Figure 23 (p. 42)
[42] Wind Integration 2006 v.II p. 44

capacity factors span the range from 32 percent in the summer to 44.5 percent in the fall, with an annual average of 39.6 percent.[43]

Minnesota's Office of Energy Security also commissioned a report on transmission requirements for dispersed renewable energy generation, finding opportunities for many hundreds of megawatts of dispersed wind energy to add to the existing transmission network.[44] The availability of adequate transmission lines for increased renewable energy generation will play a significant role in the advancement of these resources. For instance, the MISO region experienced a doubling of wind energy curtailment, from just 2.2 percent of installed wind capacity in 2009 to 4.4 percent of installed wind capacity in 2010.[45] Wind energy curtailment is the reduction of output from the wind energy generator and occurs, most often, for two reasons: "1) lack of available transmission during a particular time to incorporate some or all of the wind generation; or 2) high wind generation at times of minimum or low load, and excess generation cannot be exported to other balancing areas due to transmission constraints."[46]

The integration of wind power into the electric system over the entire MISO region would further reduce the frequency of generation at less than 5 percent and at the same time provide opportunities for each state to sell its excess generation outside the region, further reducing the frequency of curtailment. The MISO region has the benefit of being spread out sufficiently from its eastern edge to its western edge, such that the effect of different sunrise and sunset times and staggered peak times would also enhance the performance and economics of wind power.

2. Calculating Minnesota's Wind Energy Potential

For estimating the hourly production of electricity from wind turbines in Minnesota, we used the outputs generated by the Eastern Wind Integration and Transmission Study (EWITS), which identified potential land-based wind energy sites across the eastern half of the United States.[47] The EWIT study evaluated 121 sites in Minnesota, identifying a total of almost 61.5 gigawatts (GW) of wind capacity across these sites. The estimated capacity factors at these varied from 24.9 percent to 43.7 percent, with the vast majority being in the range of 30 to 40

[43] Wind Integration 2006 v.II Table 2 (p. 48)
[44] Minnesota Transmission Owners 2008
[45] Wiser and Bolinger 2011 p. 54. This figure does not include curtailment within the Northern States Power territory, which is provided separately. NSP's curtailment stayed the same, at 1.2%, from 2009-2010.
[46] Fink et al. 2009 p. 1
[47] EWITS 2011

percent.[48] In other words, these are all sites with relatively high wind energy potential. The EWIT study also computed the outputs for these sites for three years: 2004, 2005, and 2006. We chose the data just for 2006 as representative for a typical year for our study. A more elaborate analysis could involve using data for all three years and using the variations therein as indicative of variations between years. However, our study is intended only as a first step to demonstrating that despite the general issue of being a variable resource, solar and wind energy can reliably be used to meet the demand for electricity.

In reality, it is unlikely that the potential at each site identified in the EWIT study will be fully developed due to various economic and social reasons, and so we assume that the installed capacity at each of these 121 sites is some fraction of that site's maximum potential. For this report we assumed that 5 percent of the maximum potential will be developed at each of the 121 sites, reflecting this reality. We were able to vary this percentage in order to optimize overall costs of the system. At higher elevations, this percentage could be reduced even further, because of the increased power that would be generated at each site. Thus, we were able to estimate that roughly 13,000 MW of wind energy would need to be installed for a 100 percent renewable Minnesota.

B. Solar Energy

There are three different forms of solar energy technology: photovoltaic or PV, concentrated solar power or CSP, and solar thermal which is used primarily for generating heat rather than electricity. Our report focuses on the use of solar PV technology because it is the most likely application of solar electricity technology for Minnesota. CSP requires a significant amount of land, and therefore would most likely be installed in rural Minnesota thereby competing for agricultural land. In contrast, solar PV is ideal for rooftop installations making the entire state a potential location for solar energy generation. In fact, it has been estimated that 24 percent of the state's electricity demand could be met with rooftop solar alone.[49] This does not include the potential for solar installations over surface parking lots, or ground mounted solar installations.[50] There are also efforts aimed at identifying the potential for increased solar energy use across the country. For instance, the Department of Energy's SunShot Initiative Study, examines the potential for the United States to provide 14 percent of our electricity from solar by 2030 and 27 percent of our electricity from solar by 2050.[51]

[48] Brower 2009 Table 3.2 (p. 15) and Figure 3.1 (p. 16)
[49] Farrell and Morris 2010 p. 12
[50] Farrell and Morris 2010 p. 13
[51] DOE 2012 SunShot p. xix

Though situated outside the portions of the U.S. that typically receive large quantities of solar insolation, "[a] portion of southwestern Minnesota receives an annual average daily solar insolation between 4 and 5 $kWh/m^2/day$ for a North-South axis tracking concentrating collector tilted at latitude, or a South-facing flat plate collector tilted at latitude."[52] Additionally, Minneapolis has the same annual average solar resource as Jacksonville, Florida, and during the summer Minneapolis actually has a better resource "due to longer days and clearer skies, but a" lower resource in the winter.[53] See Figure 5 for an illustration of Minnesota's average solar radiation from 1998-2002.

Further, Minnesota has a similar, if not slightly better average solar resource than Germany, the world leader in solar PV. In Germany the average solar PV generation is 700-1000 kWh/kW, from northern to southern Germany, while in Minnesota the statewide average is roughly 1,000 to more than 1,200 kWh/kW.[54] Despite not having the solar resource of the southwestern United States, Minnesota's solar potential is typically strongest when it is needed the most – during late summer afternoons. The generation capacity and the sites we have chosen for indicate that approximately 4,600 MW of solar PV panels, producing on average, 6 TWh per year would be part of the 100 percent renewable electricity system for the data corresponding to the year 2007

1. Calculating Minnesota's Solar Energy Potential

Our analysis uses the estimates of solar electricity generation from the NREL's National Solar Radiation (NSR) Database. For each hour of the year, the NSR database gives diffuse, direct, and total (global) irradiance at various locations around the country.[55] These are modeled from observed cloud cover, light spectrum, and site elevation. From this data, one can infer how much electricity can be generated at any of these sites, taking into account the assumptions about the PV panel's orientation and its efficiency.

For Minnesota, NREL has data from 54 sites across the state. At each of these 54 sites, in addition to data for specific years, NREL has generated 24-hour irradiance data for 365 days per year for what it calls a "Typical Meteorological Year", and we chose this data for our

[52] Reichling and Kulacki 2008 p. 627. Solar insolation is the measure of solar radiation that hits a given area for a given amount of time.

[53] MN Solar Guide p. 3

[54] See Šúri et al. 2007 p. 1300, for the German figure, and MN DOC 2009 p.7, for the Minnesota figure.

[55] Direct solar irradiance is the measure of the rate of solar energy arriving at the Earth's surface from the sun's direct beam, on a plane perpendicular to the beam. Diffuse solar irradiance is a measure of the rate of solar energy arriving on a horizontal plane at the Earth's surface from scattering of the sun's beam. Global solar irradiance is the total measure of incoming solar energy, both direct and diffuse, on a horizontal plane on the earth's surface. For more information, see DOE 2011.

calculations. Unlike the EWIT study, these 54 locations are not chosen for their generation potential. But this is well suited to our purposes. We do not try to optimize the locations of solar PV installations because it is expected that a relatively large fraction of PV generation in Minnesota would be at locations such as rooftops of houses and commercial buildings, parking lots, and so on. Thus, it is more representative of actual installations in the state to consider data from a wide variety of locations.

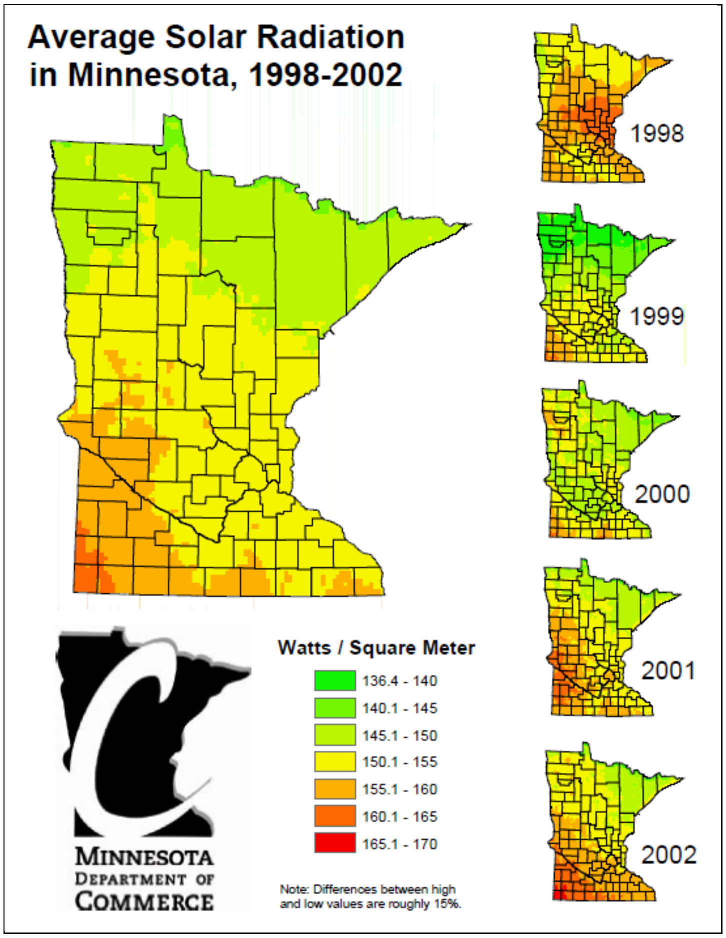

Figure II-2: Average solar radiation in Minnesota 1998-2002. *Source: MN DOC 2004*

We assume that all solar PV panels used in our analysis are horizontal. This configuration generates the least amount of power, however even under such circumstances solar PV can contribute significant amounts of energy at a relatively economical cost. Further, if PV panels are "tilted towards the south at some elevation," then they would produce roughly 10 percent more electricity.[56]

[56] Stodola and Modi 2009 p. 4733

We do not make any explicit assumptions about the efficiency of the panels themselves, but these are implicit in the figure for their rated capacity. For instance, to produce the same amount of power a panel that is only 10 percent efficient would be larger than a panel that is 15 percent efficient . Which panel is chosen for a particular site or application will likely depend on their relative costs, including installation cost, and other extraneous factors such as roof size.

Combining both wind and solar power is one of the keys to efficiently meeting demand in a renewable electricity system. Using the NREL solar database and the EWITS wind data, we find a correlation to the demand of Xcel Energy customers to be nearly 37.5 percent for solar alone, whereas the correlation with wind energy alone is minus 13.6 percent.[57] In other words, the sun tends to shine at the same time that there is greater demand for electricity, such as afternoons, while the wind tends to blow more at night when demand for electricity dips. Thus it makes the most sense to use both wind and solar power, combined with storage, to maximize the potential of each.

C. Hydropower and Biomass

In our analysis we assume the availability of a constant supply of 1,350 MW of generation capacity throughout the year operating at full output. For our purposes we use a combination of hydropower and biomass as placeholder technologies. This supply could be met with a variety of options, including hydropower, biomass, and natural gas. Keeping in line with our efforts to model a 100 percent renewable electricity system that does not result in any CO2 emissions, we have not chosen to utilize natural gas in our scenario, except a very small amount to support compressed air energy storage, which can eventually be replaced by biogas. While the supply of natural gas has a favorable outlook in the near-term, one of the methods used for extracting it, known as hydrofracturing (or fracking" for short), has resulted in growing public opposition,[58] which may impact the future supply and price of natural gas. Therefore, we use a combination of hydropower and biomass as a placeholder technology for the entirety of the 1,350 MW constant supply. Such hydropower capacity could be provided by continuing the existing hydropower purchases from Manitoba Hydro[59] as well as development of additional in-state small-hydro resources.[60] With regard to biomass, while there are a

[57] These are simply the correlation functions as calculated using the Microsoft Office Excel program.
[58] NYT 2012
[59] While the Manitoba Hydro resources do not qualify as an "eligible energy technology" for Minnesota RES compliance purposes (See Minn. Stat. § 216B.1691, 2011 subd. 1, which includes in the definition of an eligible energy technology "hydroelectric with a capacity of less than 100 MW"), Xcel Energy considers this energy as part of their overall effort to reduce their greenhouse gas emissions in accordance with state policy. (Xcel 2010b p. 51)
[60] It is worth noting that hydropower, especially small hydro, will have large seasonal variations. It may be possible to balance those variations through complementary variations in the use of biomass. However, this approach

number of environmental and social concerns with the use of biomass, there are strides being made to commercialize non-food biomass crops that can be economically grown.

1. Hydropower

Currently Xcel Energy and Manitoba Hydro are parties to a power supply agreement as well as seasonal exchange agreements. The existing power supply agreement provides Xcel with 500 MW of capacity from Manitoba Hydro, 5 days per week, 16 hours per day. In addition to this, the exchange agreements require that 350 MW is exchanged between Xcel and Manitoba Hydro seasonally.[61] These contracts have recently been extended.[62] The new contracts between Xcel Energy and Manitoba Hydro would ensure a total of 725 MW of summer capacity (possibly increasing to 850 MW) and 325 MW winter capacity (possibly increasing to 450 MW) through May 2025.[63] These agreements are essentially extensions and updates to the current agreements; however, the new agreements have modified the amounts provided in the summer versus the winter months, reflecting Xcel's greater need for capacity in the summer months.[64]

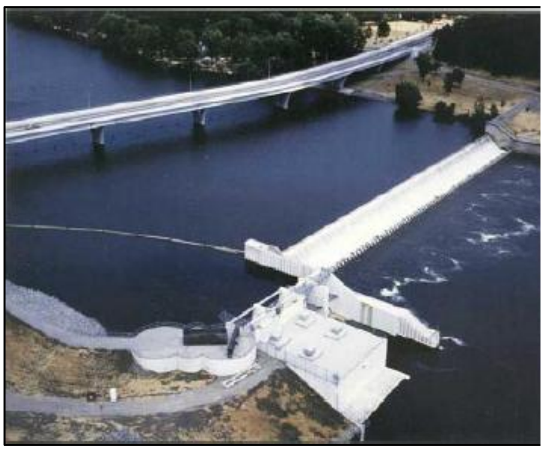

Figure II-3: Aerial view of the City of St. Cloud 8MW Hydroelectric Generation Facility. *Source: City of St. Cloud Public Utilities (St. Cloud 2008)*

Minnesota also has some untapped in-state smaller hydropower potential. In 2006, the U.S. Department of Energy, in collaboration with its Idaho National Laboratory, published a report analyzing the potential for new low power and small hydro projects across the U.S.[65] This study

would mean that where would be times during the year when some fraction of the existing biomass capacity would not be utilized.

[61] Xcel 2010b pp. 1, 6-7, 12. The diversity exchange agreements require Manitoba Hydro to supply 350 MW of capacity during the summer months when Xcel's demand is greater, and for Xcel to provide 350 MW of capacity during the winter months.

[62] Minnesota PUC 2011

[63] Minnesota PUC 2011

[64] Xcel 2010b

[65] Hall et al. 2006

refined a previous 2004 study identifying the gross power potential for undeveloped hydropower sites by applying a set of feasibility criteria[66] and parameters on a development model[67] to determine a more realistic small hydropower potential.

The 2006 study found that of the over 500,000 sites initially identified across the United States in the 2004 study, 127,758 sites satisfied the feasibility criteria. These criteria considered site accessibility, proximity to load centers or transmission lines, and land use or environmental sensitivities that would make development unlikely. [68] The sites that met these criteria were considered feasible sites for potential projects and represent 98,700 MWa[69] in gross power potential. The study then applied a set of development model criteria to the identified feasible sites in order to get a sense of a more realistic potential for developing "small" and "low power" hydro projects. [70] After applying the development model criteria, the study found a total hydropower potential of 30,000 MWa across the U.S., which would be enough to almost double the existing U.S. hydropower capacity – though the authors point out that a more realistic development potential of small hydro projects is about 20,000MWa.[71] The report also included a state by state analysis which found Minnesota to have a total of 1,433 MWa small hydro potential. Of this total, 153 MWa[72] was already developed with hydropower generation and another 484 MWa are excluded.[73] The remaining 797 MWa is the total available hydropower potential for Minnesota, before applying the set of feasibility and development

[66] Feasibility criteria include power potential at least 10kWa (annual mean power value), state and federal laws/policies, land use restrictions, existing facilities, site accessibility, proximity to power infrastructure, and other environmental sensitivities. (Hall et al. 2006 pp. 14-16)

[67] The development model assumed the sites would be either low power (less than 1 MWa) or small hydro (between 1 and 30 MWa) projects and would not require a dam, reservoir, or other obstruction. The model also assumed a penstock (pipe that delivers water to the turbine) parallel to the stream, the return of water to the stream, and restricted the working flow to the lesser of half the stream flow rate at the site, or enough to produce 30 MWa. (Hall et al. 2006 pp. 9,13)

[68] Hall et al. 2006 p. 19-20

[69] Hall et al. 2006 pp. 19-20. The results are given in predicted annual mean power values (MWa) rather than in plant capacity values (MW). This makes it easier to estimate the annual generation of the facility without knowing what the capacity factor of each individual facility is.

[70] Hall et al. 2006 p. 22-23. It is highly unlikely that the entire potential identified in the Hall report would be developed for energy generation. We use this merely as an illustration that some portion of small hydro potential remains untapped in the United States.

[71] Hall et al. 2006 p. 23

[72] The already developed potential for sites specifically in Minnesota is given as 153 MWa in Appendix B, however the main report states on page 26 that 128 MWa is already developed potential for Minnesota. We will cite the numbers found in Hall et al. 2006 Appendix B (pp. B-95 to B-96)

[73] Sites were excluded "based on federal law or policy or because of known environmental sensitivities." (Hall et al. 2006 p. xviii) For this report the federal exclusion zones included areas designated by the federal government as national battlefields, historic parks, parks, parkways, monuments, preserves, wildlife refuges, wildlife management areas, wilderness areas, and all land within one kilometer of designated wild and scenic rivers. (Hall et al. 2006 pp. A-3 to A-6)

model criteria. Once those limitations are applied, Minnesota remains with 140 MWa of potential small and low power hydroelectric generation possible in the state.[74] Developing this entire potential would increase Minnesota's current small hydro production by 109 percent.[75]

2. Biomass

The role of biomass in this study is that of a placeholder, and is not necessarily a recommendation for a particular course of action. Minnesota already has experience with using biomass for electricity and thermal energy production used in heating and cooling systems. St. Paul Cogeneration's facility uses waste wood from the Twin Cities area to generate 25 MW of electricity and 65 MW of thermal energy, which also has a benefit of reducing the need for storage and management of the city's cut wood. The electricity is sold to Xcel Energy and the thermal energy is used to heat buildings in downtown St. Paul – including the state capitol complex, which is the first in the country to be heated and cooled by such a facility.[76]

Figure II-4: St. Paul Cogeneration's combined heat and power (CHP) facility which uses wood waste from the Twin Cities area. *Source: St. Paul District Energy (Courtesy of Ever-Green Energy)*

The use of biomass also has the potential for broader implications beyond the electricity industry. Particularly the use of food crops for fuel creates potential for significant social, economic, and environmental conflicts. Although analysis of these concerns is outside the scope of this report, decision-makers will need to consider these impacts when determining the future of Minnesota's biomass resources. A prior analysis by IEER indicates that the use of food crops for fuel is neither desirable nor necessary for renewable energy development.[77]

Additional research in the biomass area could focus on identification of the biomass resource potential in Minnesota that can be used specifically for electricity generation. And specifically research and innovation can focus on the use of non-food biofuels that have much higher

[74] Hall et al. 2006 Appendix B pp. B-95 to B-96
[75] Hall et al. 2006 p. 26
[76] Ever-Green 2008
[77] Makhijani 2010 CFNF pp. 45-59. Citations to other literature on biomass can be found there.

efficiency potential. For instance, microalgae that are grown in wastewater can form an energy supply for both electricity and liquid transportation fuels.[78] Other plants that thrive in wastewater that also have a high efficiency of solar capture, such as water hyacinths in tropical and semi-tropical climates and cattails in temperate climates, are also very efficient converters of solar energy into biomass.[79] Such biomass sources can also be used as fuel in integrated gasification combined cycle (IGCC) power plants.

D. Environmental Impacts

While a full discussion of environmental impacts from electricity generation is outside of the scope of this study, there are environmental concerns that will need further investigation and discussion, particularly with the use of hydropower and biomass for electricity generation. The use of biomass as a source of electricity can have impacts on whether land is used to grow food crops versus fuel crops, as well as ecological preservation concerns that accompany deforestation practices.

Large-scale hydropower can be disruptive to the environment as well as to local residents. Additionally, there are environmental justice concerns with the large-scale hydro projects owned and operated by Manitoba Hydro.[80] These concerns will need to be part of the discussion and further study. For the purpose of this analysis, the use of hydropower and biomass as a constant electricity supply can be viewed as placeholders and not as specific recommendations.

E. Policy Considerations

Minnesota has had a long history of developing state level policies that support and encourage the development of renewable energy, and in particular, development of wind energy due to the state's wind resource potential. The state policy support not only provides financial incentives to the owners and developers of renewable energy projects, but also encourages the distribution of development across the state and among state residents. Because of early leadership in wind energy, many state policies already in place were designed with wind energy in mind. However, as solar power gains momentum, as it is anticipated to do, many of the same policy mechanisms can be applied to these technologies.

Community involvement and participation in wind energy development has been a cornerstone of the wind industry in Minnesota since its inception. The state has long

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[78] Makhijani 2010 CFNF pp. 48-52
[79] Makhijani 2010 CFNF p. 49
[80] Braun 2012

incentivized local ownership of wind energy, and encourages the use of small distributed wind energy development for individual or business use. The state has also been a leader in the Community Wind movement across the U.S., which aims to increase local community support and involvement in wind development.[81] There has also been interest in setting the groundwork for community solar development.[82]

With regard to policies needed to transition to a 100 percent renewable electricity sector, we do not advocate a particular approach or for long-term subsidies of any form of energy generation. All of the cost calculations are the un-subsidized costs of generation, so that we can evaluate all options on a level playing field.

[81] Minn. Stat. § 216B.1612, 2011 p. 1
[82] See Farrell 2010

III. Joining Supply and Demand

A. Introduction to Renewable Supply Scenario

This report aims to provide an analysis of the various elements contained within a fully renewable electricity system. Due to modeling, data, time, and financial constraints, we do not try to develop a fully optimized renewable energy scenario, though we do maintain system reliability, as is the current practice.

In our analysis, a peak margin of 12 percent above demand is maintained throughout the year, reflecting industry standard reliability requirements. We have also assumed that all generation resources required will be built in Minnesota, with the exception of continued purchases of hydropower from Manitoba Hydro. These assumptions mean that this report is not intended to provide an Integrated Resource Plan scenario, as is the practice of Minnesota utilities. Rather, we have adopted a set of constraints to show that, even in such restrictive circumstances, a fully renewable electricity sector is technically and economically feasible in Minnesota. Relaxation of the in-state resource constraint would likely mean lower costs and a decreased requirement for storage. It may or may not mean less total generation in Minnesota because planning on the level of the entire Midwest Independent Transmission System Operator (MISO) region typically means that electricity would both be exported to and imported from other states in the MISO region.

In setting up the renewable supply scenario, we based our analysis on the following set of limitations and assumptions:

- Renewable resources: only wind, solar PV, and a combination of hydro/biomass are considered.
- Storage technology: we assume a single storage technology: compressed air energy storage, which is described in more detail later.
- Location of storage: we make no assumptions on whether storage will be co-located with generation sources.
- Single solar technology: only a single solar technology is used: distributed solar PV since this is the most likely application of solar in Minnesota. We also do not include application of solar thermal hot water heating technology.
- There will be "spilled energy": this is renewable energy that could have been generated but could not be utilized at a particular time, due to the combination of a lack of a corresponding demand and because no additional storage capacity was available.

One of the most important distinctions between the current electricity system and one that is mainly supplied by wind and solar power complemented by storage is the definition of peak demand. In the current system the peak demand occurs when consumers of electricity simultaneously have the largest combined demand for electricity. Peak load in the current system, is determined entirely by the highest simultaneous demand that consumers put on the system. This typically occurs on summer weekday evenings when a large demand for air conditioners combines with other residential and commercial loads such as lighting. The amount of generation capacity in the system is based on the size of this system load plus a reserve margin, typically 12 percent above demand. Some types of generation take a day or longer to be brought online (e.g. large baseload facilities like nuclear reactors), while others might respond in minutes (for instance, hydropower units and natural gas turbines).

One potential for reducing the peak demand is to use the air-conditioning load as a spinning reserve.[83] Because the "air conditioning load grows rapidly with temperature", it presents a unique challenge: it "drives the electricity reliability need and provides the reliability solution."[84] As air temperatures increase, the use of air conditioners also increases, which creates a significant source of demand on the electricity grid. Utilities can actually turn off the energy-intensive compressor of the central air conditioners of willing customers for short periods of time; customers who sign up to provide such a service to the utility are typically compensated via a deduction in their electricity bills. This is known as "air-conditioner cycling." And because air conditioning can comprise "as much as 70 percent of net load on hot days," the potential for its use as a de facto spinning reserve is great.[85] Such measures would have minimal impact on daily life since interrupting air conditioning for brief intervals – for portions of an hour up to a full hour – generally has little impact on the customer, causing interior home temperatures to rise only 3-4 degrees Fahrenheit after 30 minutes of interrupted air-conditioning service.[86]

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[83] Spinning reserve usually refers to electricity generators that are connected to the grid and operating at partial power, and are ready to provide additional power in the event of a sudden loss of generation on the transmission line, for instance, if a large generator failed or a sudden drop in wind speeds occurs in areas of high wind energy penetration. (Kueck et al. 2008 p. 1)

[84] Kueck et al. 2008 p. 1

[85] Kueck et al. 2008 p. 1

[86] Kueck et al. 2008 pp. 3, 17. Xcel Energy currently offers its Minnesota customers the option to enroll their central air conditioners into the "Saver's Switch" program. Once enrolled, the utility can then cycle the unit on and off during the hottest days of the year and customers get 15 percent off their electric bill from June-September. (Xcel Saver's Switch 2011)

While all electricity systems need spinning reserves to maintain reliability, the required amount for any particular system will depend on the size of the largest possible contingency, or sudden loss of supply. Often this is the size of the largest generator on a given system. However it may also be possible for grid operators to maintain reliability by decreasing the amount of demand if there is a sudden loss of supply on the system. While individual air conditioners are significantly smaller in size than this, in aggregate they can reach a cumulative capacity that has value for the utility or transmission operator. Additionally, because air-conditioner load is not available all hours of the day, but is generally available during times of high electricity demand, it creates a significant financial incentive as a spinning reserve.[87] The approach of independent companies offering to dispatch reduction of demand in the same manner that independent generators now offer electricity generation for sale on the spot market would provide a suitable instrument for converting a far larger proportion of the air-conditioning load to spinning reserve. More research is needed to create accurate forecasting methodologies to fully utilize this benefit. Further, with smart appliances and two-way communication between consumers and electricity providers around the corner, this kind of arrangement can be generalized to include dishwashing machines, clothes washing machines and other devices whose time of operation may not be critical to some customers. The general arrangement is known as "demand dispatch" and will be possible as appliances, billing arrangements, rates, and other technical and economic infrastructure is able to accommodate more flexibility in the grid. The advent of plug-in hybrid cars and electric vehicles holds the potential to greatly increase demand dispatch capability.

In a system where wind, solar, and storage are the primary sources of supply to the electricity grid, there is now a "relational system peak". This occurs when the combined generation supply from renewables is low relative to demand, putting the maximum strain on generation from stored energy.[88] This may or may not occur at the time of the traditionally defined peak in the current system. It may not even occur in the summer. In the case of the year 2007, the traditional system peak for Xcel Energy occurred on July 25th at about 4 p.m. However, the relational system peak in the renewable energy-based system we have modeled occurred on September 3rd at about 7 p.m. This is the hour that had the largest use of energy generated from compressed air energy storage. Thus in a 100 percent renewable electricity system, the largest gap between available total generation (solar, wind, and hydro/biomass in our case) and the demand at that particular time is the determining factor and gives us the relational

[87] The cost of supplying spinning reserves from a generator is dependent on the wholesale market price for electricity which generally peaks during times of peak demand. (Kueck et al. 2008 pp. 2-3)
[88] In the case of compressed air energy storage, this means the maximum use of expander capacity.

peak. Generally, the relational system peak would tend to occur at times with low wind energy supply and near or after sunset, when there is essentially no solar PV supply (see Figure III-1).

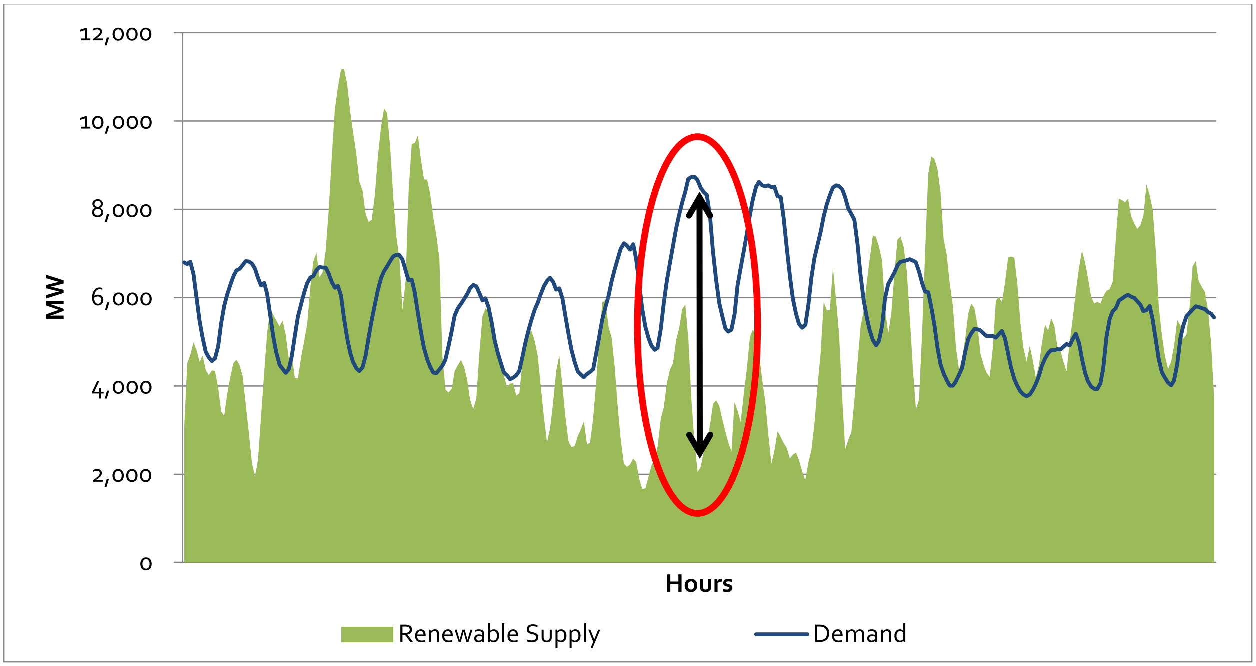

Figure III-1: Illustration of a relational system peak in the fully renewable electricity system modeled in this study. Note that demand and renewable supply are shown for a two-week period from August 27 – September 10. *Source: IEER; Data source: FERC, NREL, DOE.*

B. Renewable Supply

The main constraint that results from the requirement that all electricity generation come from renewable energy sources is the intermittent nature of wind and solar power. (See Figure III-2 and Figure III-3) The fluctuations in wind speeds and solar insolation pose challenges, since energy services are expected to be available whenever demanded. As indicated above and discussed in more detail below, this constraint can be removed if the concept of demand dispatch is integrated into the system. Because we do not assume the existence of a "smart" or "intelligent" grid, demand dispatch (which provides flexibility to shape the load curve to available generation) is not taken into account in our calculations. See the section on energy efficiency for more discussion of this topic. The perception that intermittency is a barrier to increased use of solar and wind is itself important since it is widely held and "[u]tility managers, system operators, energy consultants, and government experts generally believe that the intermittency of renewable resources is a serious obstacle to their wider use in the United States".[89]

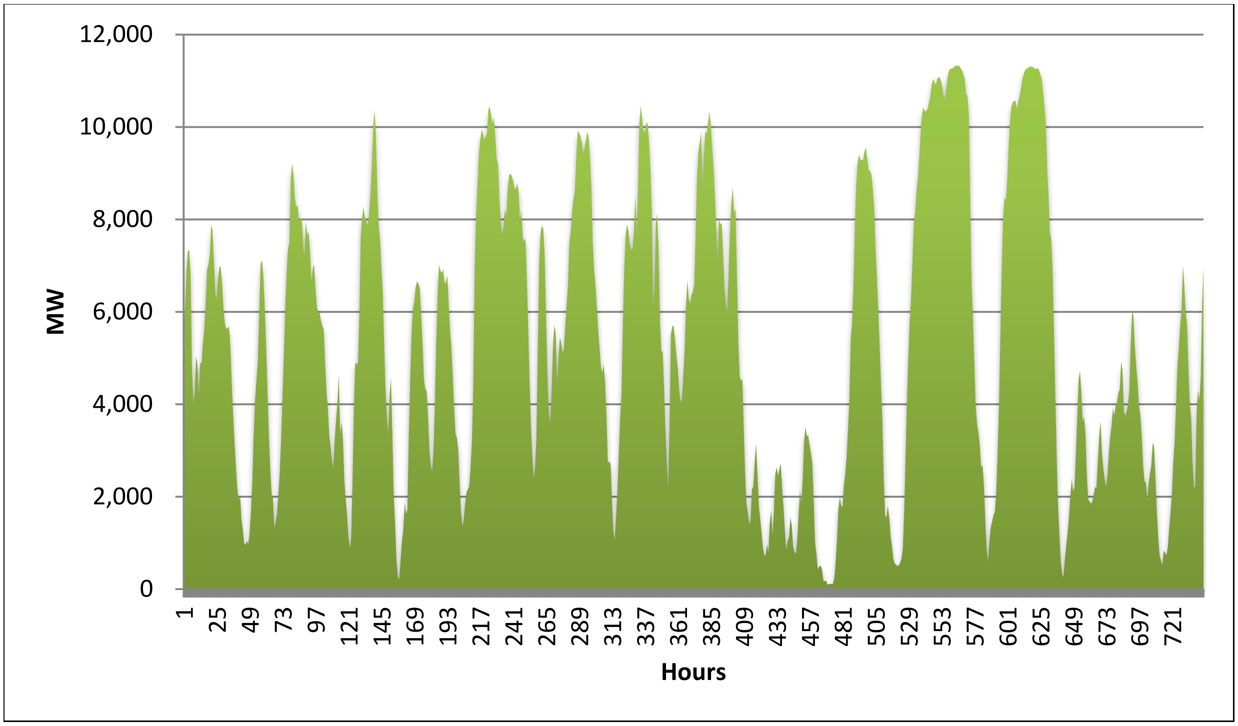

Figure III-2: Wind energy output during January 2007 in a 100 percent renewable electricity system for Minnesota. Note that these values do not represent the actual wind energy generated by Xcel Energy or any other wind energy producer during that time, but reflect some portion of the potential as identified in NREL's EWIT Study. *Source: IEER; Calculation based on EWITS Dataset.*

[89] Sovacool 2009 p. 289

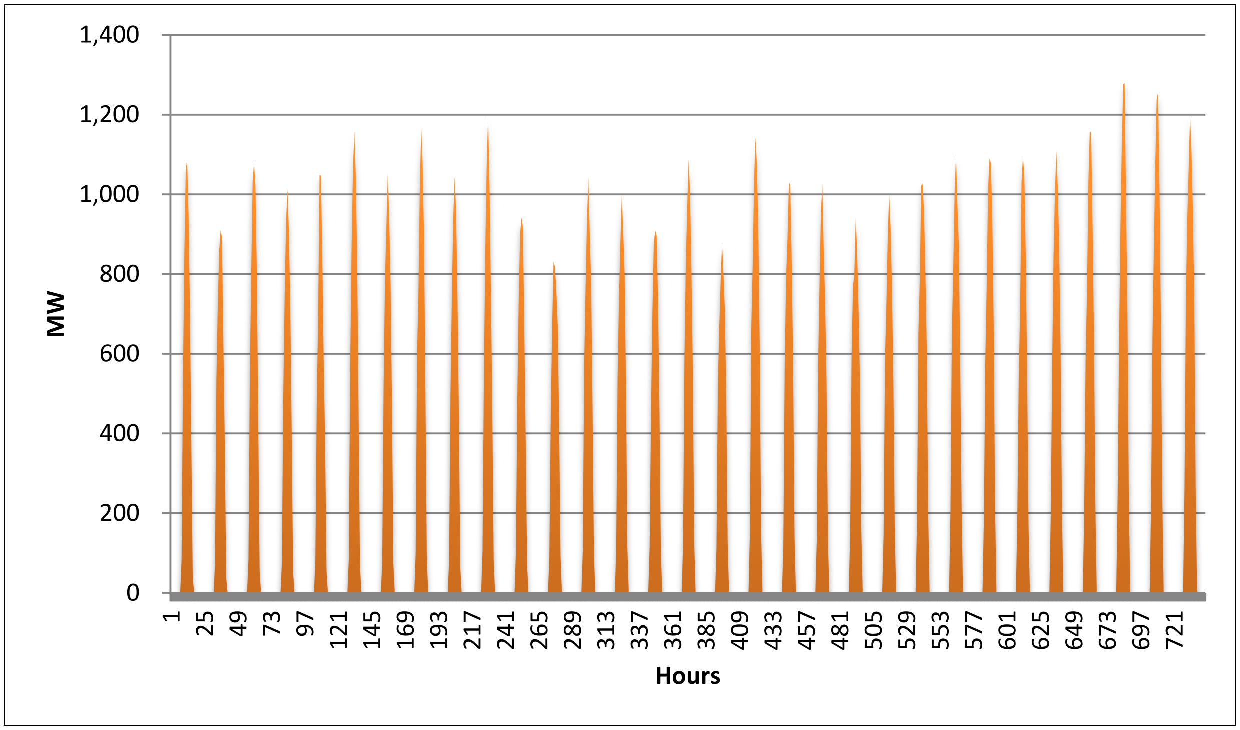

Figure III-3: Solar PV output during January 2007 in the 100 percent renewable electricity system we have modeled for Minnesota. Note that these values do not reflect the actual solar energy generated by Xcel Energy or any other solar energy producer during that time, but reflect a portion of the potential as identified in NREL's insolation database. *Source: IEER. Data source:* Calculation based on NSRDB 1991-2005

Technically, however, intermittency can be dealt with in a number of ways, such as energy storage, specific end use technologies, and the use of combined heat and power to greatly reduce air-conditioning peaks, etc. Utilities have ample experience in managing variability in the form of demand for electricity. Figure III-4 shows the variability in demand on Xcel Energy's system for one month. Because demand and supply have to be balanced at all times, using variable energy sources requires the use of either other sources of generation that can be ramped up relatively fast (to make up for fluctuations in the outputs of wind and solar power) or the use of storage so that excess generation during periods of high wind or solar insolation could be used later, as illustrated in Figure III-5.

Currently utilities balance this variability almost entirely from the supply side, using with hydropower, single stage natural gas turbines, and to a lesser extent, natural gas combined cycle generation. The only demand dispatch technology in widespread use at the present time is air-conditioner cycling. These supply side approaches also incur considerable costs since they mean that equipment used only for peak or intermediate generation is idle for much of the year. The capacity factor – the ratio the actual generation and the theoretical potential if the equipment were generating all the time a full capacity – for generation equipment in Minnesota was only about 42 percent in 2010.[90] This indicates that targeted efficiency improvements in certain sectors and combined heat and power and demand dispatch could make a very substantial contribution to shaping demand to make the system more flexible and reliable and also potentially to reducing costs.

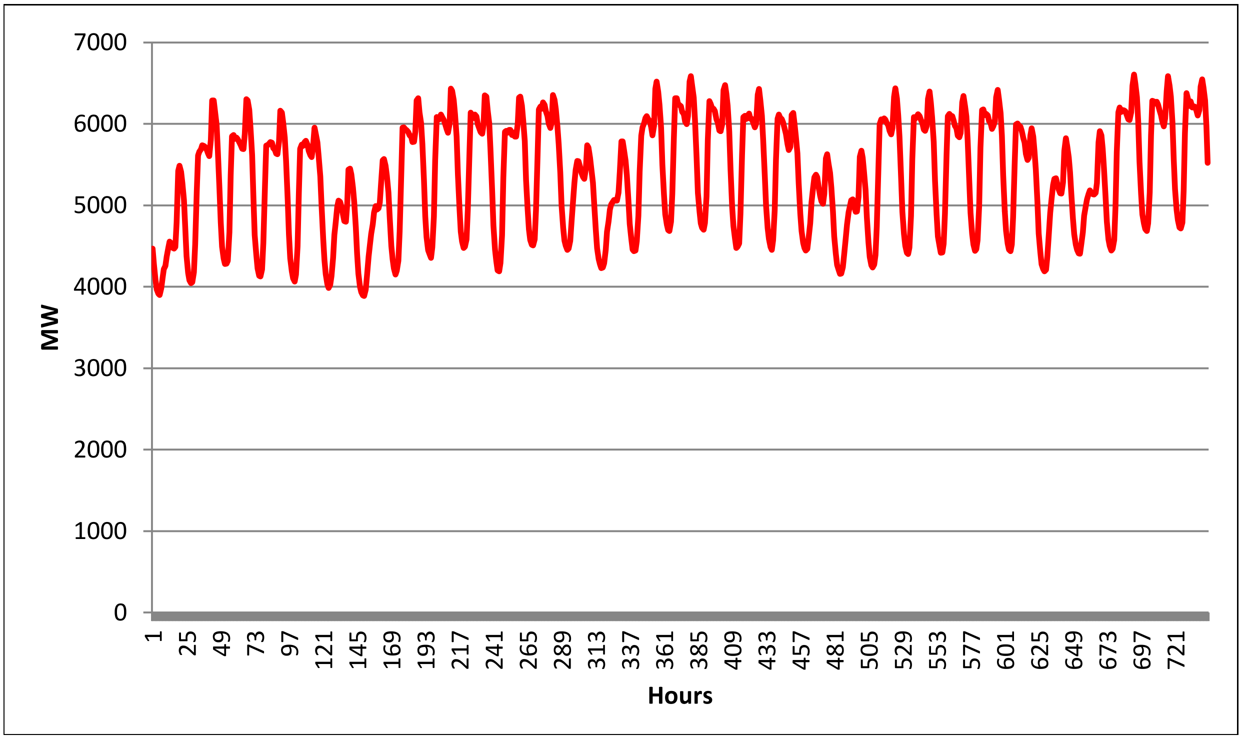

Figure III-4: Hourly electricity demand of Xcel Energy Minnesota customers for January 2007. *Source: IEER. Data source: FERC Form 714*

[90] The total installed generating capacity (net summer) in Minnesota in 2010 was 14,715 megawatts, while the generation was 53,670,227 megawatt hours. This yields an annual average capacity factor of about 42%. The low capacity factor is in large measure due to the fact that the natural gas capacity factor is just under 10% -- meaning that over 4,440 megawatts of capacity is idle over 90 percent of the time - a lower capacity factor than solar in Minnesota. The utilization of the 795 megawatts of petroleum-fueled capacity is even lower at just 0.4%. Calculated from EIA 2010 Minnesota Profile Tables 4 and 5.

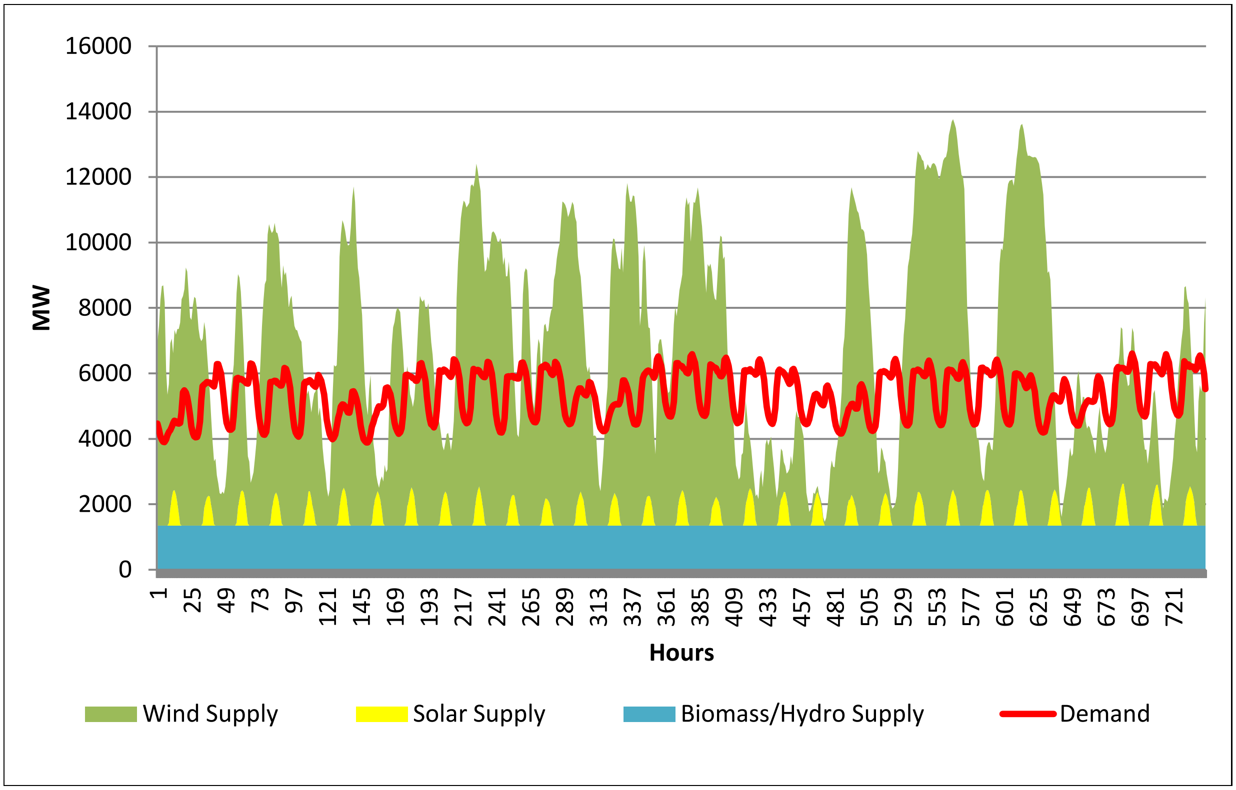

Figure III-5: Total cumulative renewable energy output in a 100 percent renewable energy based electricity system and Xcel Energy electricity demand in Minnesota, January 2007. *Source: IEER. Data sources:* demand, solar, and wind are from Figures III-2, III-3, and III-4 above; biomass/hydro from the constant supply of 1,350 MW of generation capacity used as a placeholder (described in renewable resources section).

Intermittency needs to be dealt with at multiple time scales. One is at the hourly scale that we focus on here. But one also has to deal with fluctuations at much smaller time scales, since fluctuations on the level of seconds or minutes can cause undesirable fluctuations in the frequency and voltage of the electricity supply. Responding to short time-scale fluctuations is also not a new problem, though it would increase in scale considerably when solar and wind are the main energy supply resources. Responding to short term fluctuations might involve the use of "batteries, fuel cells, supercapacitors, or other fast-ramp-rate energy storage systems".[91] Specialized flywheels that have built-in motor-generator sets, are being increasingly used as well as a more durable alternative to batteries.[92] At the hourly level, coal-fired plants or gas turbines can be "run at less than maximum capacity," which can then be

[91] Apt 2007

[92] See, for instance, KEMA 2007.

increased rapidly, thereby offering a spinning reserve.[93] But we do not adopt that strategy here, since our challenge is to see if the annual electricity demand of the state's largest utility can be supplied entirely with renewable energy sources such as wind and solar, other than a very small amount of natural gas that could be replaced by biogas.

As noted above, expanding the geographical reach of the renewable system will help even out some of the variability inherent in wind and solar energy generation. This has already been studied for wind power in Minnesota and regionally.[94] Additionally, it is also true for solar power – a greater geographical dispersion of solar installations helps to level out the minutely and hourly fluctuations in sunlight from any one given location.[95]

C. Modeling a Renewable Energy System

We began by evaluating the potential to meet a single year of electricity demand of the state's largest electric utility, Xcel Energy, with renewable energy sources. As mentioned earlier, we chose the year 2007, the last year before the recent economic recession, as representative of a more typical average electricity demand. By choosing such a year, we are able to model a system that can meet our current reduced demand, and evaluate the potential to meet a greater demand as the economy improves. Our approach to creating a renewable electricity system includes the following elements:

- Compile hourly demand data from the state's largest utility, Xcel Energy.
- Collect and combine the hourly data from wind and solar energy sites in the state. Note, however, that variations in wind and solar supply from year to year are not taken into account in this analysis.
- Establish a constant energy supply in the scenario. We have used a combination of hydropower and biomass in this study, which is intended to serve as a placeholder and not necessarily a specific technology recommendation.
- Determine appropriate storage technology. We are using compressed air energy storage (CAES), also as a placeholder and not meant as a specific technology recommendation. We are able to adjust the capacity of the storage technology in the model, in combination with the other elements of the system, to satisfy reliability requirements for all hours of the year. In practice a mix of approaches would be used. See Chapter IV below.

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[93] Bélanger and Gagnon 2002 pp. 1279-1280
[94] See Wind Integration 2006 v.I and EWITS 2011
[95] Mills and Wiser 2010 p. 11

- A compressor is chosen for the CAES system, with the size being equal to the largest amount of surplus power generation over demand in the year.
- The size of the CAES expander (which converts part of the energy in hot pressurized gas into mechanical motion) is chosen to meet the largest deficit requirement between generation and demand (including a 12 percent reserve requirement) in combination with storage.
- The available capacity of renewable generation (hydro/biomass, wind energy, solar energy, and storage) must be equal to demand plus 12 percent for each hour of the year.
- We performed a manual adjustment in the model of the solar, wind, expander, and storage capacities so that the minimum reserve capacity does not drop below 12 percent for any hour in the year and so the costs are kept as low as possible. This is not a least-cost approach, which would take efficiency and demand dispatch and a mix of storage technologies into account. Since these aspects would modify the demand curve in a major way, performing a "least cost optimization" with only generation and storage resources is not necessary. We integrate efficiency considerations partially as a separate consideration in the economic analysis and discuss other factors qualitatively.

By looking at the hourly demand for Xcel Energy, and calculating the estimated renewable energy potential available, we could determine the number of hours in which electricity generation fell short of demand and would need to be supplemented with stored energy. Figure III-6 and Figure III-7 show the mix of renewable energy supply and electricity demand in a 100 percent renewable energy system for the weeks of January 1-7 and July 11-17 – two very different weather patterns and electricity needs. The red line indicates the demand for that week, while the blue, yellow, and green shaded areas above the axis indicate electricity generation from hydropower/biomass, solar, and wind power respectively. The purple shaded areas represent the stored electricity that was used to meet demand when generation was insufficient. The orange shaded areas below the axis represent the excess supply that is put into storage when generation exceeded demand, after taking into account the efficiency of the storage system. As we expected and these charts show, there will be variations in the amount of excess energy that is stored at any given time, day, and season.

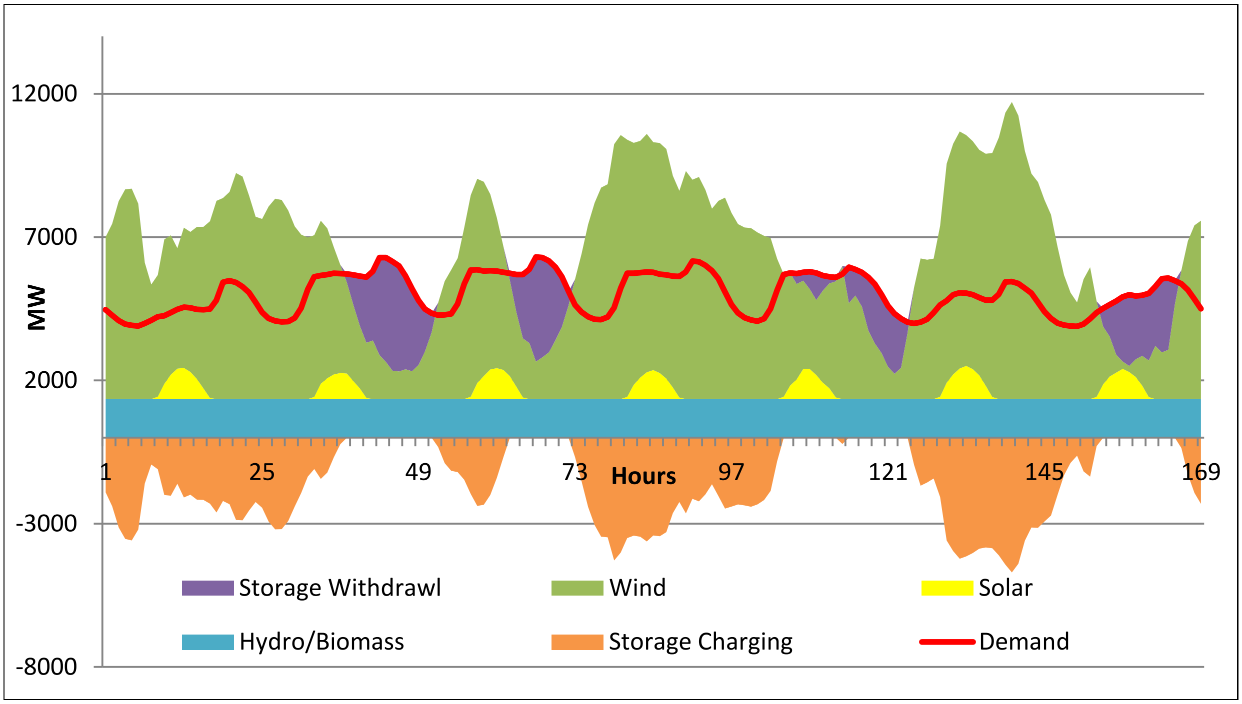

Figure III-6: Hourly supply and demand with storage, January 1-7, 2007. *Source: IEER.*

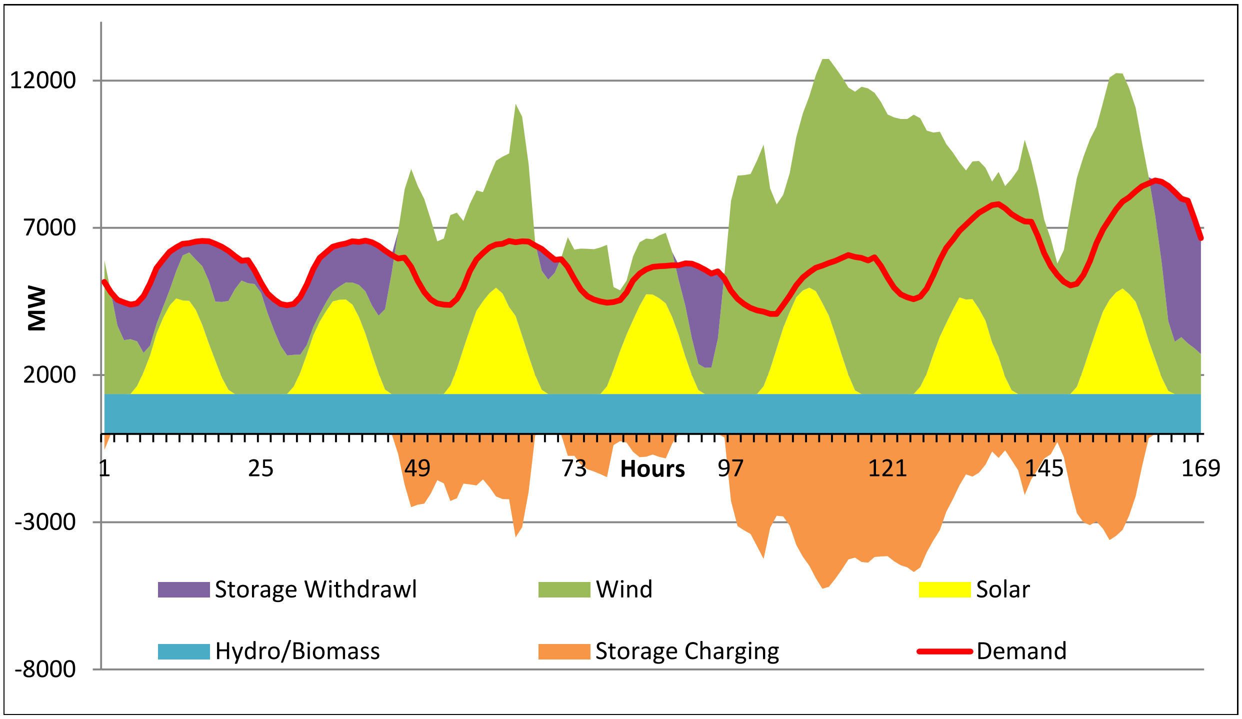

Figure III-7: Hourly supply and demand, with storage. July 11-17, 2007. *Source: IEER.*

IV. Energy Storage

In an electricity system dominated by solar and wind, energy storage plays the part that peaking capacity plays in a traditional electricity system. Ideally, a mix of demand dispatch, combined heat and power, specific load-shaping energy efficiency technologies, and a variety of energy storage devices would be considered together. In case hydroelectricity reservoirs are available, pumped storage could also be added to the mix. Sodium-sulfur batteries could be used in the distribution network for relatively decentralized storage. In this report we rely on a single storage system – compressed air energy storage – to illustrate in the simplest (though not the most cost-efficient) way of how the problem of intermittency might be addressed.[96]

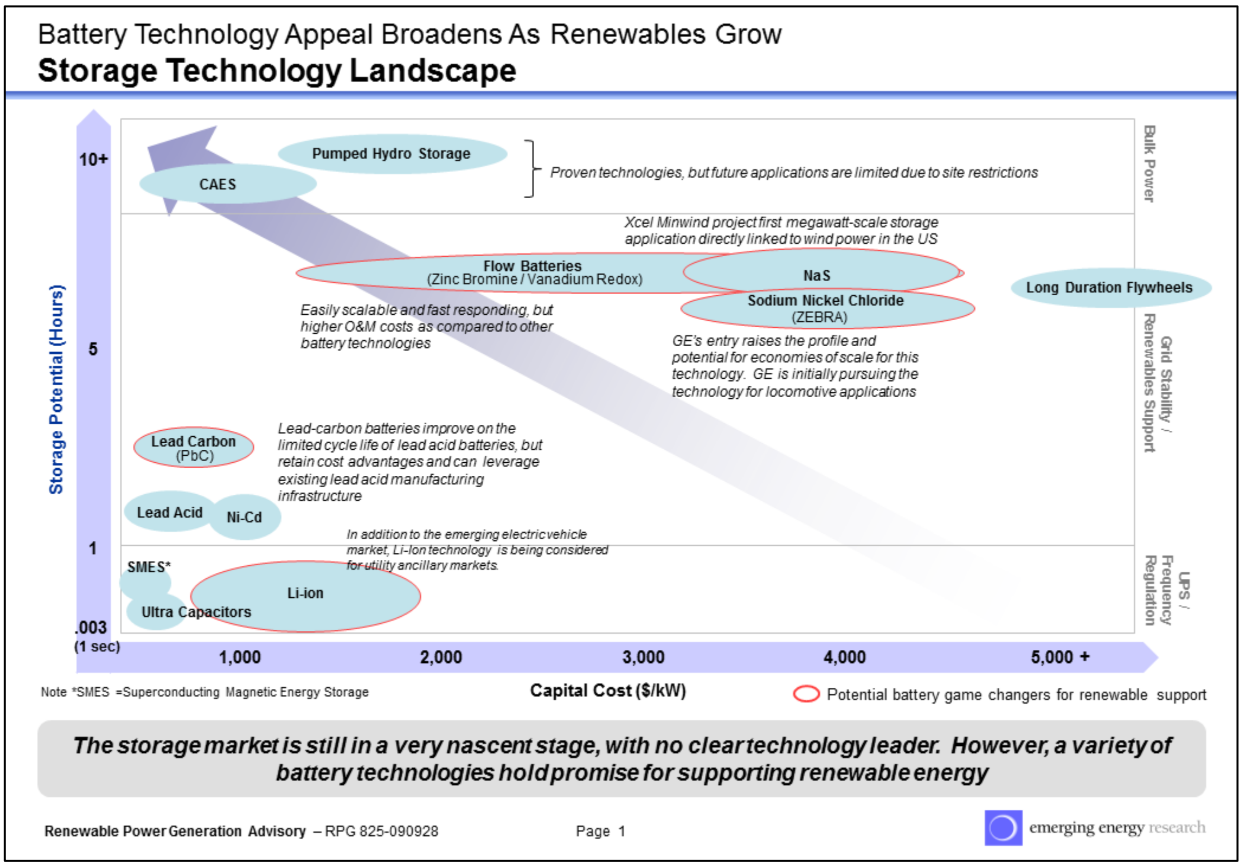

Figure IV-1: Energy storage options as used in Xcel Energy's 2010 Integrated Resource Plan filing. *Source: Courtesy of IHS Emerging Energy Research*

[96] For more information on recent Department of Energy funding of energy storage research and demonstration projects, see DOE 2010a.

Historically, energy storage has on many occasions been conceived of as being related to specific generation facilities. For example, an early analysis from Denmark compared the economic costs of using storage and a wind farm to using a nuclear reactor to meet fluctuating demand.[97] However, as the National Renewable Energy Laboratory says, "It is not cost effective or efficient to couple energy storage resources exclusively to individual wind plants. It is the net system load that needs to be balanced, not an individual load or generation source in isolation. Attempting to balance an individual load or generation source is a suboptimal solution to the power system balancing needs. Hydropower and energy storage capacity are valuable resources that should be used to balance the system, not just the wind capacity".[98] We have used this approach in our study.

Utility scale electrical energy storage has been suggested or used around the world for multiple reasons.[99] This includes capacity reliability,[100] load leveling,[101] and energy arbitrage.[102] There are currently only two large-scale energy storage technologies that are commercial today and could be used with the high penetrations of wind and solar that our study presents: pumped hydro energy storage (PHES) and compressed air energy storage (CAES). Other solutions that are being developed, but are not yet commercial, include storage in large-scale batteries, use of electric vehicles as storage devices, as well as use of natural gas single-stage turbines with the gas eventually replaced by biogas – however the long-term environmental impacts of this approach need further study.

Additionally there are demand-side solutions, such as using excess electricity to generate ice which is then used to for air conditioning and aggregation of air-conditioning and commercial freezer demand that can be later dispatched - similar to present day generation dispatch. Where electric hot water heaters are used, some of the heating could be done at times when excess generation is available. Similarly, commercial freezers and refrigerators could be cooled slightly below normal temperatures at times of surplus renewable supply and turned off at times of deficit. A number of other similar approaches to flexibly use available intermittent resources are being developed and can be combined to reduce centralized storage requirements, reduce cost, and increase flexibility.

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[97] Sørensen 1978
[98] NREL 2011
[99] Parker 2001
[100] Sobieski and Bhavaraju 1985
[101] Giramonti et al. 1978
[102] Walawalkar, Apt, and Mancini 2007. Energy arbitrage occurs when a storage device captures low-cost energy and then sells it later at a higher rate.

Finally, as noted, geographic diversity in locating wind generation also helps. "[G]eographical dispersal improves aggregate reliability" of wind turbines simply because "[i]f the wind is calm at some sites, we can count on it blowing at others."[103] The inclusion of dispersed sites will likely require the construction of more transmission capacity. However, it has been shown that "the economic benefit of expanding the spatial distribution of wind farms to reduce intermittency can exceed the costs of additional transmission infrastructure."[104] Seen in this light, the constraint that all wind energy resources should be located within Minnesota is likely to result in somewhat higher costs than would otherwise be incurred. Thus, expanding the area of study and planning would result in reduced costs, even taking into account the necessary additional transmission infrastructure.

A. Compressed Air Energy Storage

Compressed air energy storage (CAES) is used in this report as a placeholder technology for the storage requirements of the 100 percent renewable electricity system; however it is important to note that any application of this technology will be limited by geography – that is, by the availability of locations for the energy storage reservoirs. The use of compressed air is familiar in a number of everyday contexts, for instance, the use of pressurized air is used to power tools in road repair and automobile garages.

There is also experience with storing compressed air in large underground caverns for the purpose of reducing the use of natural gas fuel in peaking gas turbines in current electricity systems. Two large-scale commercial CAES systems exist, and more are in development. The Huntorf plant in Germany has a capacity of 290MW and has been in operation since 1978. The McIntosh plant in Alabama is 110MW and has been operational since 1991.[105] Pacific Gas and Electric Company (PG&E), in California, received a Department of Energy grant for $25 million in the Smart Grid stimulus funding, under the American Recovery and Reinvestment Act, for a large 300 MW compressed air energy storage (CAES) project.[106] The total cost of this project is estimated at nearly $356 million and expected to complete construction in December 2016.[107]

Even closer to Minnesota, the efforts to develop the Iowa Stored Energy Park, a 270 MW compressed air storage project designed to create dispatchable wind-generated electricity, highlight the complexity with both site selection and integration into the current electric

[103] Kahn 1979 p. 1
[104] DeCarolis and Keith 2006 p. 408
[105] Makhijani 2010 CFNF pp. 69-71. For CAES and wind energy storage see EPRI-DOE 2004. See also NREL 2006 and Cavallo 2001.
[106] PG&E 2009
[107] See DOE 2010b

system. The ISEP partners included a consortium of Midwestern municipal utilities, including the Central Minnesota Municipal Power Agency (CMMPA) of Blue Earth. However, the project was cancelled in mid-2011 due to concerns with the suitability of the rock at the selected site.[108] The project proponents hope the experience of this project will help other CAES projects move forward in the future, noting that the project design and economics were solid.[109]

One such project that may benefit from the experience in Iowa is the proposed CAES development in Nebraska. The Nebraska Public Power District (NPPD) voted to pursue development of an underground storage cavern in the Dakota Sandstone formation, which also covers a portion of Minnesota. The energy used to compress the air will come from a variety of sources including coal, nuclear, and wind, but if successful it is possible to transition this facility to be completely powered by renewable energy. Preliminary estimates indicated NPPD is anticipating a cost of $1,200 - $1,300 per kilowatt.[110] A Canadian study has found that use of CAES with wind energy projects actually improves project revenues in the wholesale electricity market by 15-43 percent.[111] This economic improvement occurs from storing energy when it is cheap and selling it when it is more expensive. In the context of a fully renewable electricity system, the purpose of storage is similar but technical rather than economic – to store energy when it is plentiful (excess supply) and to use it when it is scarce (excess demand).

Figure IV-2 shows the typical configuration of a CAES system. When electricity supply is greater than demand, it is used to compress air (the "Motor & Compressor" element in Figure IV-2). If using a coal-fired power plant to reduce peaking natural gas use, the compressor generally operates at night when demand is low. In the case of a renewable energy system, the compressor would be operated when the total available supply (solar, wind, hydro, and biomass) is greater than the demand in any particular hour. The compressed air is then stored in an underground cavern, which could be a pre-existing cavern or one mined specifically for the purpose. It could also be stored in a tank, but tanks are much more expensive than caverns and can be used for only relatively small amounts of storage.

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108 ISEP Press Release 2011, ISEP Study Summary 2011, and AP 2011
109 AP 2011. Also see Lessons from Iowa 2012.
110 Lincoln Journal Star 2011
111 Alberta Innovates 2011 p. v.

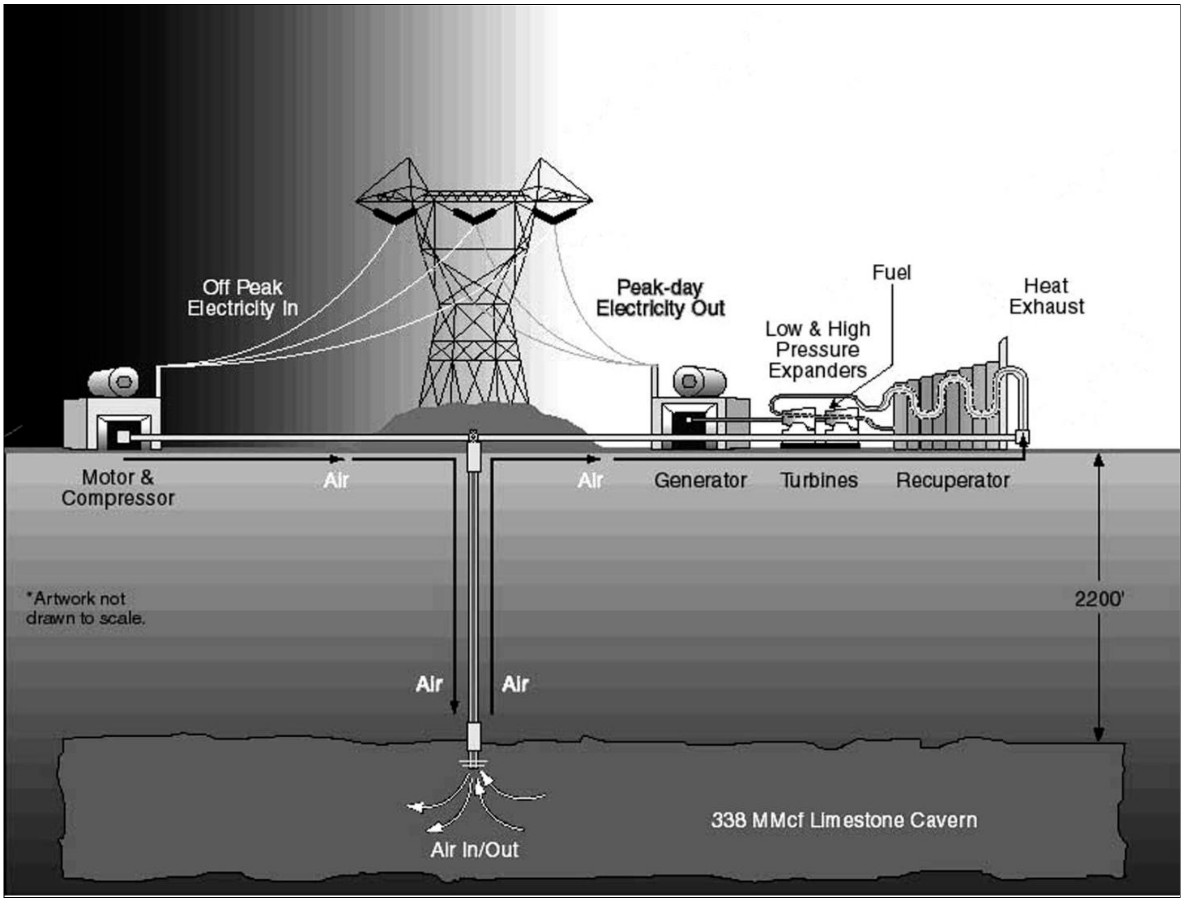

Figure IV-2: Main elements of a Compressed Air Energy Storage (CAES) system. *Source: Sandia National Laboratory (Sandia 2001).*

Underground formations, such as salt domes and depleted gas fields, can be adapted for use with CAES technology. The caverns at the Huntorf and McIntosh sites are in salt formations which were solution-mined for the volume needed specifically for the purpose of providing compressed air storage to these facilities. This is a well-understood technology, since compressed natural gas is often stored in solution-mined caverns. Compressed air can also be stored in aquifers, much as a portion of natural gas is today, notably in the Midwest.[112] Compressed air would be stored as a large bubble of pressurized air. As air is pumped into an aquifer, many bubbles form; these merge eventually into a single bubble as more air is pumped in. A cushion of residual pressurized air is needed to maintain the single bubble. CAES systems appear to be practical in a power range from above 100 MW up to several thousand megawatts. The cost of CAES technology is highly dependent upon the cost of preparing underground caverns or other geophysical domains for compressed air storage. The storage

[112] EIA Natural Gas 2004

period in CAES can be over a year due to very small losses; this is longer than other storage methods, except for pumped hydro storage.[113]

Over a decade ago, Cavallo found that "[w]ith compressed air energy storage (CAES) (and with a negligible economic penalty), capacity factors of 70–95 percent can be achieved."[114] This has been elaborated by Succar and Williams who point out that "areas favorable for air injection into porous rocks" have a large overlap "with areas with wind resources of class 4 and above" which "includes large areas of Colorado, Wyoming, Montana, Kansas, Iowa, and Minnesota". [115] These overlaps can help decide which areas to explore first. However, "detailed geologic site characterization is needed to ascertain whether a site is actually suitable for CAES development."[116]

In its 2007 Resource Plan, Xcel Energy dismissed the CAES possibility stating "Minnesota has neither suitable salt dome geology nor large-scale underground mines sufficient to support a 1,000 MW CAES facility. The Company was also concerned about the complexities entailed in operating such a facility."[117] Likewise it was dismissive of pumped hydro storage systems because of concerns about "how effective" the technology "would be relative to its cost."[118] However, in its most recent 2010 Resource Plan filing, Xcel Energy appears to now be open to considering CAES, saying it is "the only other commercially available technology besides pumped hydro able to provide very large system energy storage deliverability to use for commodity storage or other large-scale setting."[119]

There is one problem with CAES when it comes to creating a 100 percent renewable energy-based system – it requires the use of natural gas, albeit at levels much lower than for conventional electricity generation. Use of CAES technology requires about 4,600 Btu per kWh of natural gas to reheat the compressed air. While using natural gas for this purpose is not ideal for a fully renewable-energy based electricity system, it is only 40 percent of the fuel required for a single natural gas turbine which is what is typically used for meeting peak loads. In principle, sometime in the future, this may be avoided by using methane generated through renewable energy resources, including biogas. There are efforts at finding methods of compressed air energy storage that do not require the use of natural gas. The U.S. Department

[113] Chen et al. 2009 p. 296
[114] Cavallo 1995
[115] Succar and Williams 2008 pp. 42-43
[116] Succar and Williams 2008 pp. 42-43
[117] Xcel 2007 p. F-13 (In Section 3)
[118] Xcel 2007 p. F-12 (In Section 3)
[119] Xcel 2010a p. F-2

of Energy has funded a research project in Massachusetts that is developing a CAES system that requires no fossil fuel use.[120] Further, in principle, renewable energy can be used to make methane, the essential ingredient of natural gas, though considerable research and development remains.[121] Finally, hydrogen generated from excess renewable supply, for instance by electrolysis of water, could also be used.

More research is needed to identify the geological constraints for potential CAES sites in Minnesota. For instance, aquifers with oil will be disqualified because the oil cannot be displaced and pose the threat of reactions and oxidations. An interview with Dr. William Lang, a geological consultant, regarding compressed air storage systems is included as an appendix to this report.

Figure IV-3 shows a National Renewable Energy Laboratory simulation of wind plus CAES as a baseload system. This contains all the elements discussed here for high penetration of wind – surplus renewable generation for compression, withdrawal of compressed air for generation at times of deficit renewable supply, and "spilled energy." This is somewhat of a misnomer to indicate excess electricity supply that is not used – it is available but not generated. Some turbines would be shut down for instance at times when there is insufficient demand and the storage capacity is full. Note that there are remaining gaps in supply. These can be filled with additional storage and/or some other element of electricity supply, such as geothermal energy.[122] Because our analysis looked first at Xcel Energy's hourly demand, we could design a fully renewable electricity system model that did not contain these types of gaps.

[120] See DOE 2010a p. 23-24.
[121] For one interesting research experiment, see UPI 2009.
[122] Geothermal electricity generation uses heat from the earth's core to heat up liquid injected deep into the earth. The hot liquid is then pumped to the surface and, similarly to other thermal generation plants, uses steam created by the hot liquid to turn a turbine and generate electricity. (MIT 2006)

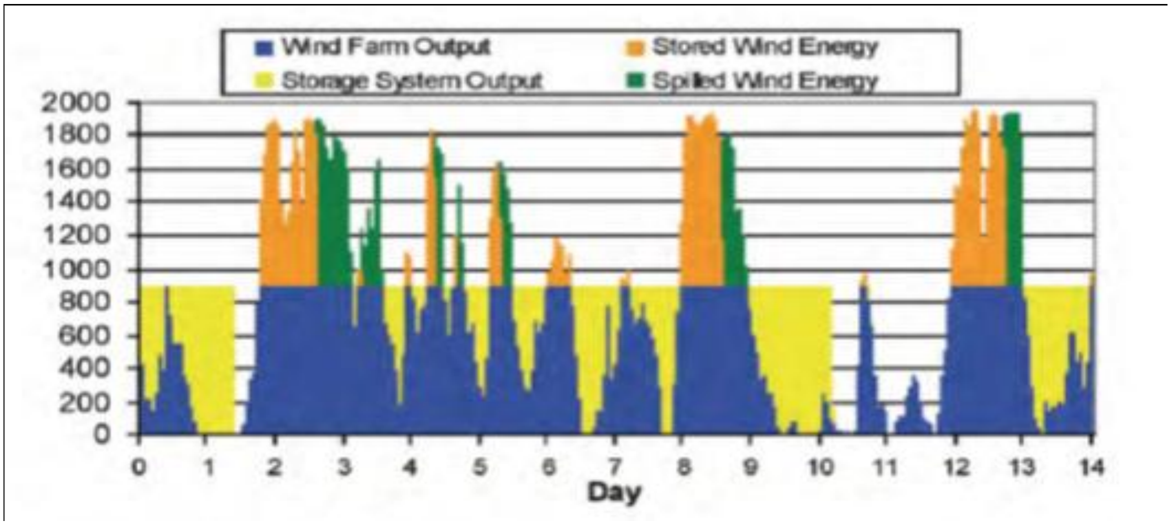

Figure IV-3: National Renewable Energy Laboratory example of dispatchable wind with compressed air energy storage. *Source: NREL 2006. This figure was developed by the National Renewable Energy Laboratory for the U.S. Department of Energy.*

Not all of the energy used to compress air is recovered when electricity is generated from storage. Figure IV-4, from the National Renewable Energy Laboratory, shows the energy flow in their wind energy plus CAES system. Note that in this example, spilled energy is only about 8 percent of total generation (range 5 to 15 percent). This appears to be because some gaps were left in the generation to be filled in from other sources. The heat rate – that amount of natural gas used to reheat the compressed air is about 4,600 Btu per kWh. However, since most of the wind-generated electricity is supplied directly to the grid, the amount of natural gas needed per unit of electricity dispatched into the grid is much smaller. In the baseload example, it is estimated at under 1,000 Btu per kWh. Finally, NREL estimates greenhouse gas emissions at 40 to 80 grams per kWh dispatched – about 4 to 8 percent of the emissions of a conventional coal-fired power plant.[123]

[123] NREL 2006, for CAES emissions; EIA 2011 FAQ, for the coal plant emissions. Calculation done by IEER.

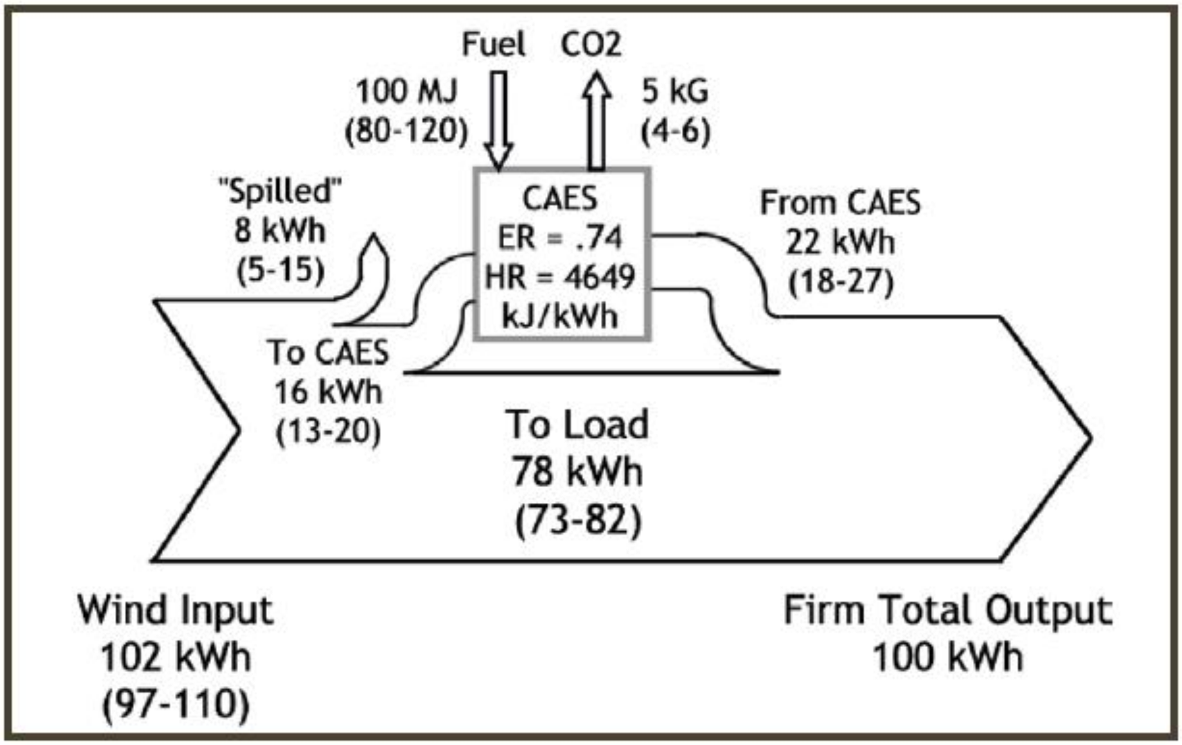

Figure IV-4: Energy flows and overall input of natural gas required from a CAES system coupled to a wind farm. Note "kJ" stands for "kilojoule" which is a unit of energy equal to about 0.95 Btu. *Source: NREL 2006. This figure was developed by the National Renewable Energy Laboratory for the U.S. Department of Energy.*

In our case, only about 14 percent of the total of 47.6 million MWh supplied to meet demand is generated from storage. At a heat rate of about 4,500 Btu per kWh, the use of natural gas for this level of generation from storage in our scenario would be about 31 billion Btu, or just 650 Btu per kWh of final load served – creating just 34 grams of CO_2 per kWh. This can be compared to a heat rate of about 6,500 Btu/kWh for a typical combined cycle power plant and 10,000 Btu for coal-fired power plants.

We assume that the overall round-trip efficiency of the compressed air system is about 75 percent – that is, for every 100 kWh used to compress air, 75 kWh of electricity output will be dispatched into the grid. This is represented in Figure IV-4. In this renewable scenario, losses due to CAES use constitute about five percent of the solar and wind electricity output. These are much less than spilled energy, which is the main loss in the system as modeled here. We might regard spilled energy in this system as the rough equivalent of idle capacity in the present fossil-fuel-nuclear-dominated system, when a large fraction of the capacity is idle much or most of the time, so as to be able to accommodate peak demand. Spilled energy appears in a fully renewable system since a certain generation capacity from storage is needed to meet the relational system peak. As noted, demand dispatch and other technologies can be used to reduce idle capacity/spilled energy.

There are many areas that would be suitable for siting CAES caverns in the United States based on technical considerations alone. Figure IV-5 shows a map of potential CAES caverns in salt or aquifers. Minnesota has many potential locations for compressed air energy storage in aquifers, located largely in the same area as the state's wind resources. That said, we recognize that siting will likely be a challenge in realizing this storage potential, especially if a primarily centralized approach is adopted. The siting challenge would be greatly reduced by including elements of storage in the distribution part of the grid,[124] reducing storage requirements through demand dispatch when relational system peaks occur, and employing efficiency and combined heat and power in a strategic way to reduce relational system peaks.

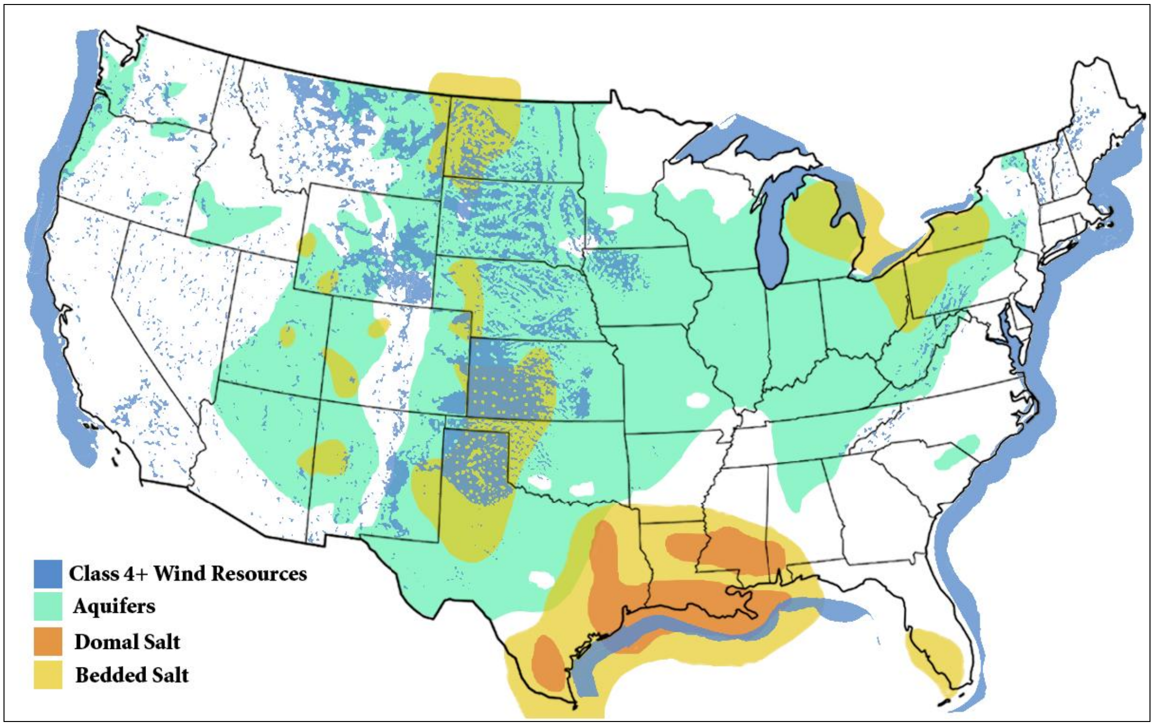

Figure IV-5: Areas in the United States with potential for siting CAES. *Source: Succar and Williams 2008 Figure i (p. 8) and Figure 17 (p. 42) for citations to the data sources*.

[124] The electricity grid consists of a network of wires that carry high-voltage electricity on transmission lines from where it is generated to substations which step down the electricity current to a lower voltage for distribution and use in homes and businesses. For more information about the grid and how it works, visit DOE 2012 Electricity

A CAES facility can be, but does not need to be, co-located with a renewable energy system. There are advantages and disadvantages to co-location. The significant economic advantage is better use of transmission capacity, since intermittency is overcome at the wind or solar site by storage. The disadvantage is that the best sites for solar and wind energy may not have suitable sites for CAES. Minnesota appears to be fortunate in that a large area with potential for CAES siting could allow co-location of wind energy and CAES systems. A cautionary note is in order here. We have not examined CAES siting issues such as overlap with historical or cultural areas, populated areas, and environmental impacts.

The maximum storage pressure in a CAES system is a design feature that would partly depend on factors such as cavern characteristics and maximum anticipated length of storage time over which leakage needs to be minimized. The Huntorf plant storage pressure is 70 atmospheres with a cavern of 300,000 cubic meters. The McIntosh plant in Alabama operates in the 45 to 74 atmospheres range, with a cavern volume of 5.32 million cubic meters. When its full capacity is utilized, it could supply almost 3,000 MWh of power output over the course of 26 hours.[125]

B. Pumped Hydro Energy Storage

Pumped hydro energy storage (PHES) has the potential to play a significant role in the transition to a renewable energy electricity system, including in Minnesota. It is the one of the least expensive options for storing large amounts of electricity, with only compressed air energy storage being less expensive.[126] A PHES facility (see Figure IV-6) would use excess electricity generated by wind and solar power at times of excess supply to pump water from a lower reservoir up to a higher reservoir. When demand exceeds the electricity that wind and solar are generating at that time, water is released from the upper reservoir and passes through turbines which generate electricity. In a closed-loop PHES system, the water is cycled between two self-contained reservoirs. In an open PHES system, the water is moved between two parts of a water body, typically a river, and returns to the water body once it passes through the turbines.

[125] Gandy 2000 pp. 18-20. See E.ON Kraftwerke 2010 for the recent history of the Huntorf plant.
[126] Mandel 2010, Xcel 2010a p.F-2

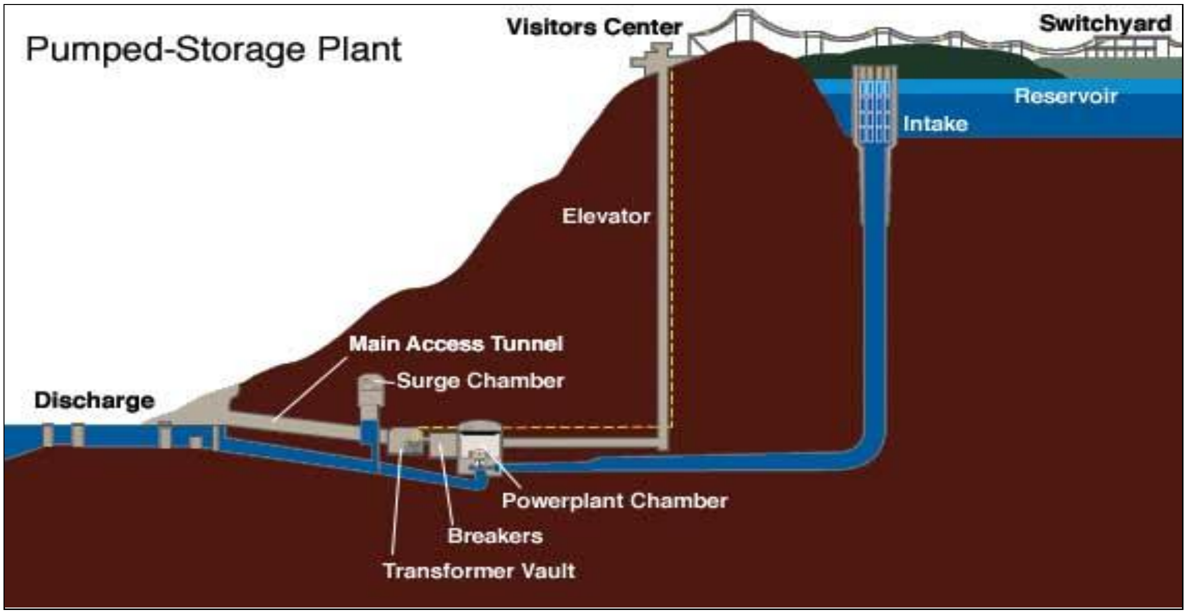

Figure IV-6: Diagram of a pumped hydro storage system. *Source: Tennessee Valley Authority (TVA Hydro)*

Because PHES provides electricity during peak hours, it can substitute for other forms of peaking generation, such as natural gas, in a manner similar to CAES. In a renewable electricity system, it can be used to meet the relational system peak. It is a commercial technology that is deployed on a wide scale today. About 22,000 megawatts of PHES capacity exists in the United States.[127] The U.S. currently has 40 PHES systems, most of which were built between 1960 and 1985 as a result of increased natural gas prices and to complement the growing nuclear power industry. See Figure IV-7. With the slow-down in nuclear power construction, and the decrease in natural gas prices, PHES development also slowed down. In addition to the economic challenges to PHES projects, there has been public opposition to large-scale hydropower and PHES projects around the country due to the large size of the reservoirs. Local opposition based on concerns for watershed health and aquatic wildlife was successful in shutting down many proposed PHES projects between 1985 and 2005.[128]

[127] EIA Electric Power Annual 2010 Table 1.2
[128] Yang and Jackson 2011

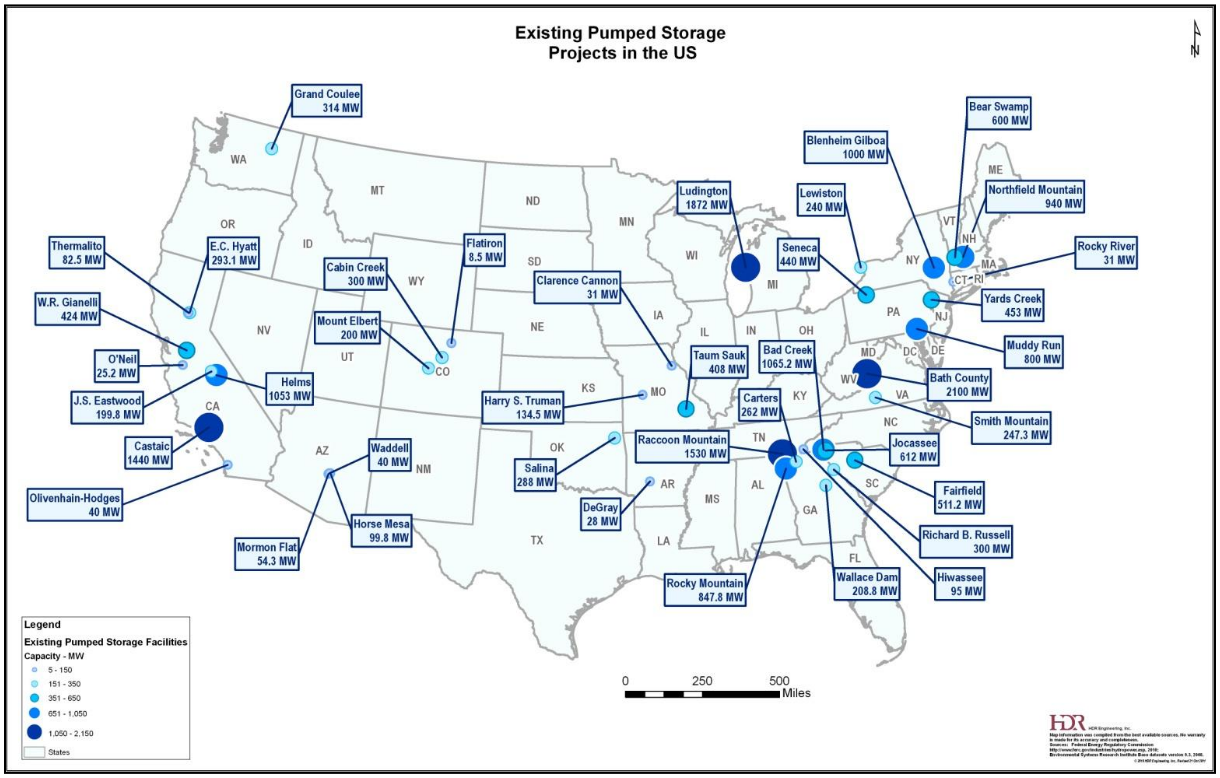

Figure IV-7: Location of existing PHES facilities in the U.S. *Source: Courtesy of HDR Engineering, Inc., 2011*

Current proposals at the Federal Energy Regulatory Commission (FERC) indicate an increased interest in PHES systems as a means of managing the intermittency of the increasing use of renewable energy (wind and solar) as well as a means of potentially managing wastewater. As of January 2012, FERC had issued 44 preliminary permits for pumped hydro storage projects across the U.S.[129] This included two projects in Minnesota: the Chippewa County Pumped Hydro Facility, and the Granite Falls Pumped Hydro Facility, neither of which is moving forward at this writing. Each project was estimated to cost approximately $2 billion dollars and utilize a closed-loop system with a capacity of 1,000 MW. In the permit application, Riverbank LLC estimated that each of the facilities would be able to provide 2,190 GWh annually,[130] or roughly one-third of the total storage generation estimated in our study that would be needed to support 100 percent renewable electricity for Minnesota.

[129] FERC 2012 Permits

[130] FERC 2010 Chippewa and FERC 2010 Granite. On January 18, 2012, FERC issued orders to both projects cancelling their preliminary permits for delays in submitting required status updates, and for not making progress on the projects. See FERC dockets P-13654 and P-13655. (FERC 2012 Chippewa and FERC 2012 Granite)

Additionally, a collaboration between University of Minnesota scientists, policy research, and members of local utilities and businesses recently examined the potential for pumped hydro storage in abandoned mines in northern Minnesota's Iron Range. The electricity infrastructure already exists near these mines, making them attractive for the researchers to pursue their goal of finding a cost-effective way to facilitate greater renewable energy development in the state.[131] The study teams concluded their first phase and released their findings in November 2011.[132] The report lays the groundwork by providing the key parameters and considerations for developing such projects in the future, particularly along the Iron Range. The researchers identified nine potential sites that would be investigated further in a follow-up study.[133]

While not a comprehensive analysis of the actual costs of developing pumped hydro storage in northern Minnesota, the study does provide that the hypothetical PHES systems modeled for the Minnesota Iron Range had a levelized cost range of $237 to $378 per MWh, with the costs of obtaining the "mineral rights" identified as the most uncertain cost for the system.[134] These costs estimates are limited in their application and the study notes that:

> "There are several factors and future developments that could make storage technologies, like PHES, more economically attractive within the overall system:
>
> - Technological advances could improve the efficiency and flexibility of turbines. For example, advances in variable speed technology and control systems allow for power control when the PHES facility is in pumping;
> - Increasing prices for coal and natural gas also improve the economic merits of storage compared to alternatives;
> - MISO ancillary service market rules could be modified to reward the response speed fast-ramping PHES; and
> - Markets could adopt rules that reward PHES's contributions to improving power quality and system reliability."[135]

And there might even be a growing interest by Minnesota utilities to develop and test the potential for the development of pumped hydro storage technology. In its 2010 Resource Plan,

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131 Fosnacht 2010 slides 14, 17, and 29

132 The report is a compilation of findings from each of the four main study teams: Facilities, Geotechnical, Policy, and Environmental. (NRRI 2011)

133 NRRI 2011 p. xx

134 NRRI 2011 p. xxiv

135 NRRI 2011 pp. xxiv-xxv

Xcel Energy stated that pumped hydro is one of two technologies able "to provide very large system energy storage deliverability to use for commodity storage or other large-scale setting".[136] Xcel Energy further went on to state that "[t]he grid would be more efficient and reliable" if there were "cost-effective ways of storing electrical energy."[137]

There are potential benefits from PHES beyond storage capacity as well. In California, a proposed PHES facility plans to use wastewater from the Tracy City wastewater treatment plant. Because the PHES facility will be close to the wastewater treatment plant, which is close to the population center, it will also reduce the need for additional transmission for the facility, greatly reducing the project's costs. Additionally the aeration of the wastewater is anticipated to improve the quality of the recycled wastewater, which in turn will improve overall water quality as the water is returned to the watershed.[138]

Hydropower, and particularly pumped hydro storage, could also be effectively combined with solar PV development. Pontoon-mounted solar panels, so-called "flotovoltaics" or "floatovoltaics", suitable for deployment in hydropower reservoirs, have been developed and have begun to be deployed.[139] Such a PV system offers a number of advantages:

- The solar installation can be large scale but requires no land.
- It could use the same transmission lines as hydropower with hydro generation being backed off when solar generation is high and the transmission lines are near capacity.
- It complements hydro peaking capacity in the summer.
- It may help reduce water loss due to evaporation, especially in the summer and in times of drought (though this is not generally expected to provide a major boost to generation).
- The installations can also be used with pumped hydro storage reservoirs.

In order for pumped hydro energy storage to be deployed on the scale necessary for Minnesota to achieve a fully renewable electricity system, significant progress needs to be made in establishing a market for energy storage so planners can obtain financing for the projects. Currently, there is not a clear method of establishing a value of PHES.[140] Electricity storage occupies the uncertain territory between power generation and transmission, which is often

[136] Xcel 2010a p. F-2. The other technology identified was compressed air energy storage (CAES).
[137] Xcel 2010a p. 8-6
[138] Yang and Jackson 2011 pp. 842-843
[139] NYT 2011
[140] Mandel 2010; NHA 2011

separated in the electric power industry, leaving PHES and other energy storage options with one foot in each market, but no leg to stand on.[141] There have been recent efforts to clarify this uncertainty. FERC issued an order in 2007 requiring that non-generation resources, such as storage and demand management, be evaluated just as generation resources are evaluated "in meeting mandatory reliability standards, providing ancillary services, and planning the expansion of the transmission."[142]

The increase in proposals for closed-loop PHES facilities, and the desire to combine PHES with increasing use of renewable energy has the potential to overcome the previous barriers to widespread PHES deployment in the U.S. As indicated in Figures IV-4 and IV-7, both compressed air energy storage and pumped hydro are ultimately dependent on availability of appropriate sites. This can include concerns with geology, environmental impacts, aquifer impacts, and if pairing these technologies with renewable generation, access to appropriate renewable resources (i.e., wind turbines). Unless a site has existing facilities that have appropriate infrastructure, those costs and construction requirements will also need to be considered.

[141] Yang and Jackson 2011 p. 840
[142] Yang and Jackson 2011 p. 840

V. Energy Efficiency

The role of energy efficiency is central to the cost-effectiveness of a 100 percent renewable electricity system because it has a direct impact on the amount of electricity generation and storage capacity required. We have modeled a single storage technology here – compressed air energy storage (CAES). This generates electricity when the combination of biomass/hydro, wind, and solar generation is insufficient. Because renewable energy generation must be combined with effective storage technologies in order to provide a reliable and adequate electricity supply, reductions in electricity usage at key times and periods will reduce the need for investing in additional storage and generation capacity.

In our analysis, there are 55 hours of the year where 5,000-7,000 MW of electricity generation capacity from storage (expander capacity in a compressed air energy storage system) is needed. See Figure V-1. The use of this top 2,000MW seems to occur at the end of the day during summer, though not every summer day, and when demand is still relatively high and the percentage of solar and wind generation is low. These 55 hours may be regarded as the relational peaks in the system for the year that is modeled here –they determine the expander capacity that is needed. Accommodating these 55 hours of demand comes at great cost. See Table V-1. Reducing demand when renewable supply is low relative to demand, through demand dispatch and use of efficiency measures in the devices causing the peak at times of low renewable energy supply, can be economically very beneficial.[143] While, the exact times of the relational peak will vary from year to year, just as the exact day and time of peak demand varies in the present system (depending on the weather, mainly), it will tend to occur at similar times of the year – in this case in the summer and early fall.

Figure V-1 also shows that the most frequent use of the 3,000 to 5,000 MW tranches of expander capacity occur in the same period (summer and early fall). The repeated high withdrawals from storage at times of relatively high demand compared to solar and wind generation also put a strain on storage capacity. Figure V-2 shows the amount of energy stored in the CAES cavern at the start of each hour in the year 2007. Note that an arbitrary starting amount is included at the start of the year. Since the heavy demand from storage occurs in the summer and early fall, the storage capacity requirement is insensitive to the starting storage assumption. The largest amount of spilled energy occurs in the spring and fall, when the storage is full most frequently.

[143] Demand dispatch gives transmission control operators the capability to increase and decrease demand, in addition to increasing or decreasing generation supply.

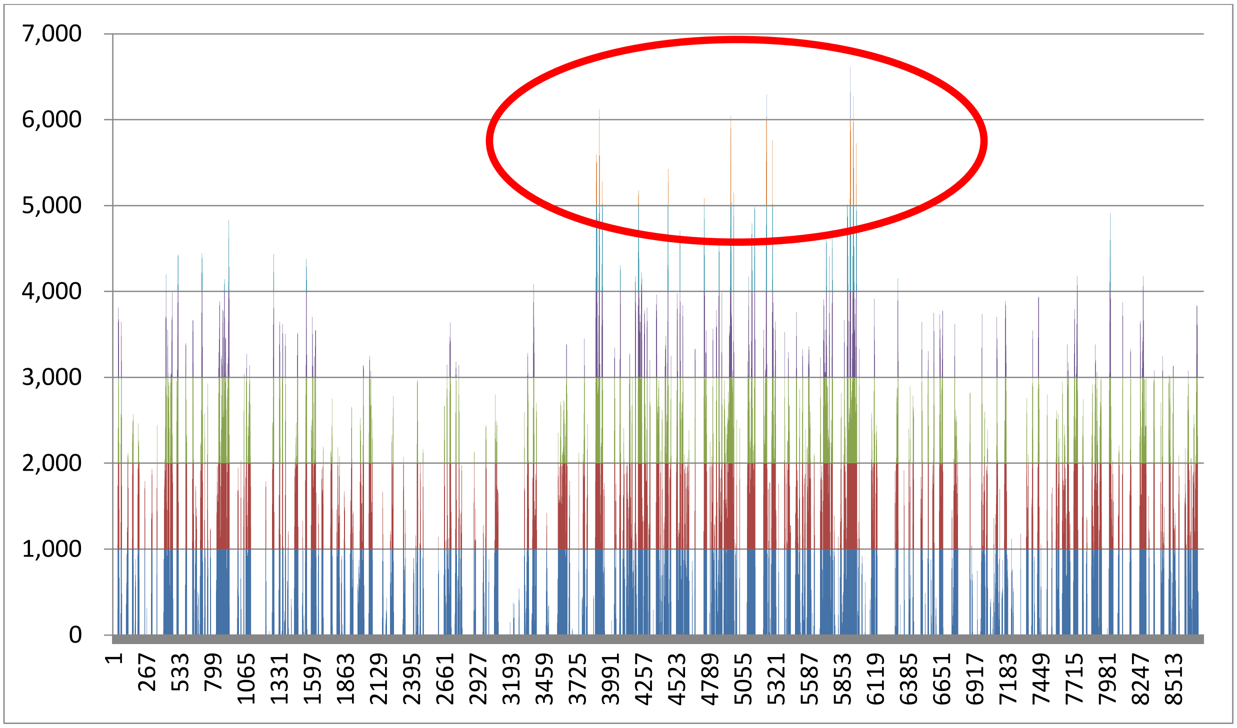

Figure V-1. The generation required from electricity storage, CAES in this case, as calculated for Xcel Energy customers in 2007 by IEER. Note the circle indicates the highest capacity needs which only occur 55 hours of the year.

Generation segment (MW)	Hours segment is used	Average segment generation, MW	Total segment generation, MWh	Expander capital cost, $/MWh
0-1000	3,661	871	3,187,712	8
1000-2000	2,711	797	2,160,519	12
2000-3000	1,581	680	1,074,551	24
3000-4000	631	558	352,378	72
4000-5000	159	578	91,965	277
5000-6000	46	492	22,623	1,126
6000-7000	9	196	1,768	14,401

Table V-1. The capital cost of electricity generation from storage (CAES in this case) for each 1,000 MW segment of storage capacity. The highest costs, highlighted, are associated with the need to have storage capacity from 5,000-7,000 MW, which is only needed 55 hours per year.

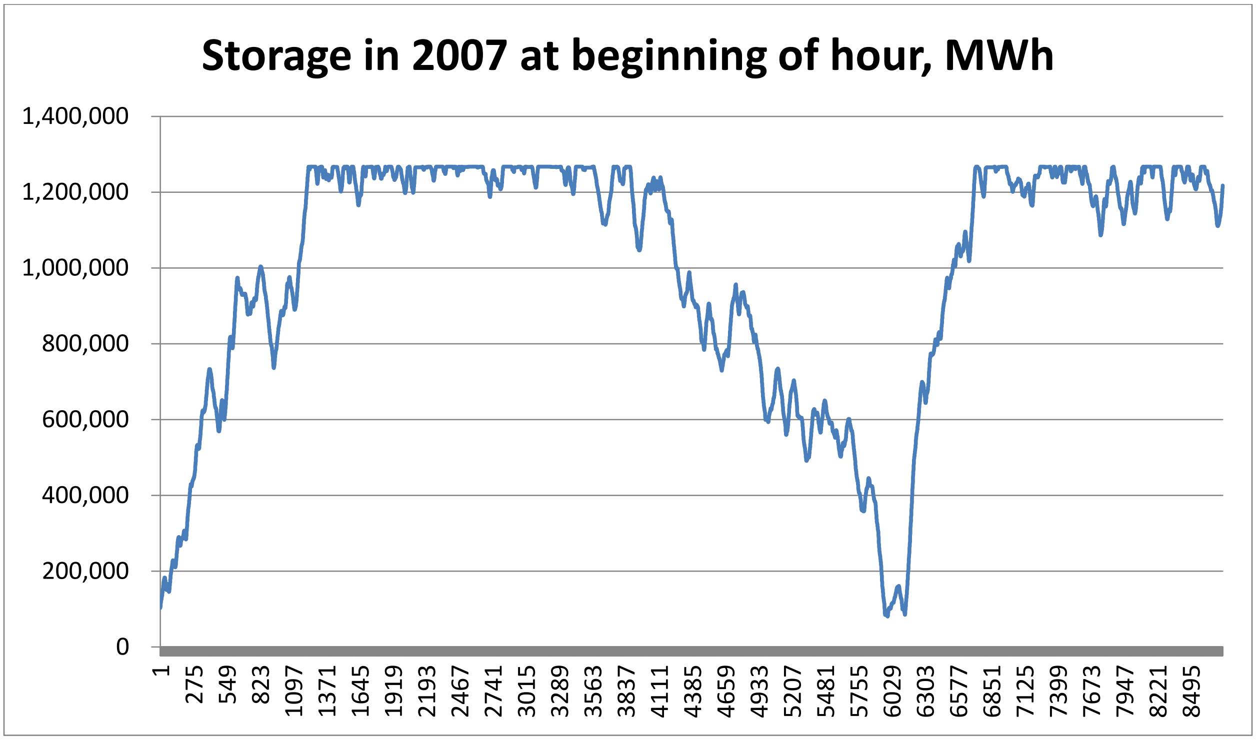

Figure V-2: Amount of energy storage at the start of each hour in 2007, showing the strain on storage in the late summer/early fall, a period of high demand relative to solar and wind generation. The lowest energy stored occurs in early September (at Hour 5998; Hour 1 = midnight to 1 am, January 1.). Maximum storage = 1,267,473 MWh.

We do not assume any changes in lifestyle in our scenario. Any energy efficiency improvements assumed here are technical, resulting in the same provision of the services that are currently provided. For instance, more efficient lamps would provide the same amount of light and more efficient air conditioners would provide the same amount of cooling, but both would use less electricity in doing so. We do not incorporate demand side management or demand dispatch programs that result in load curtailment in our model. We assume such programs (i) are voluntary and (ii) participants are compensated. Both these features are expected to continue as demand side management programs are expanded and converted into demand dispatch within an intelligent grid.

A. Energy Efficiency Standards

Efficiency standards for appliances and buildings are, in our judgment, generally an economic, efficient, and equitable way of reducing electricity demand and improving the overall economics of the electricity system, defined as the cost per unit of electricity service, such as lighting or air conditioning or computer use, without affecting lifestyles. By that last phrase we mean that the level of energy services, such as lighting, heating, cooling, appliance use, is maintained, but an investment is made in the building or appliance to decrease energy use for the same output or service.

Figure V-3 shows a "supply curve" of efficiency services – what it would cost to provide a service by increasing efficiency compared to the cost of electricity (the dashed red line). The impact of efficiency standards has already been proven in many cases, with refrigerators being the most dramatic example as illustrated in Figure V-4. It should be pointed out that standards may not always be a suitable means to achieve efficiency in every sector, as is likely the case with heavy industry, for instance. These industries are used to keeping an eye on their energy bills and responding to price signals. However, even in this case, some equipment, such as small motors used widely in industry, may suitably be improved through a standard setting process.

Standards are most efficient when there is competition in the field, as among appliance makers or builders. Also standards are the best way to overcome the so-called split incentive in buildings, whereby builders and landlords have little incentive to invest in energy efficiency improvements even when it is economical because they do not pay the utility bills. Figure V-3 shows the cost of various efficiency measures for appliances in the form of a supply curve – that is, it shows the amount of efficiency that can be achieved at a particular price in cents per kWh.

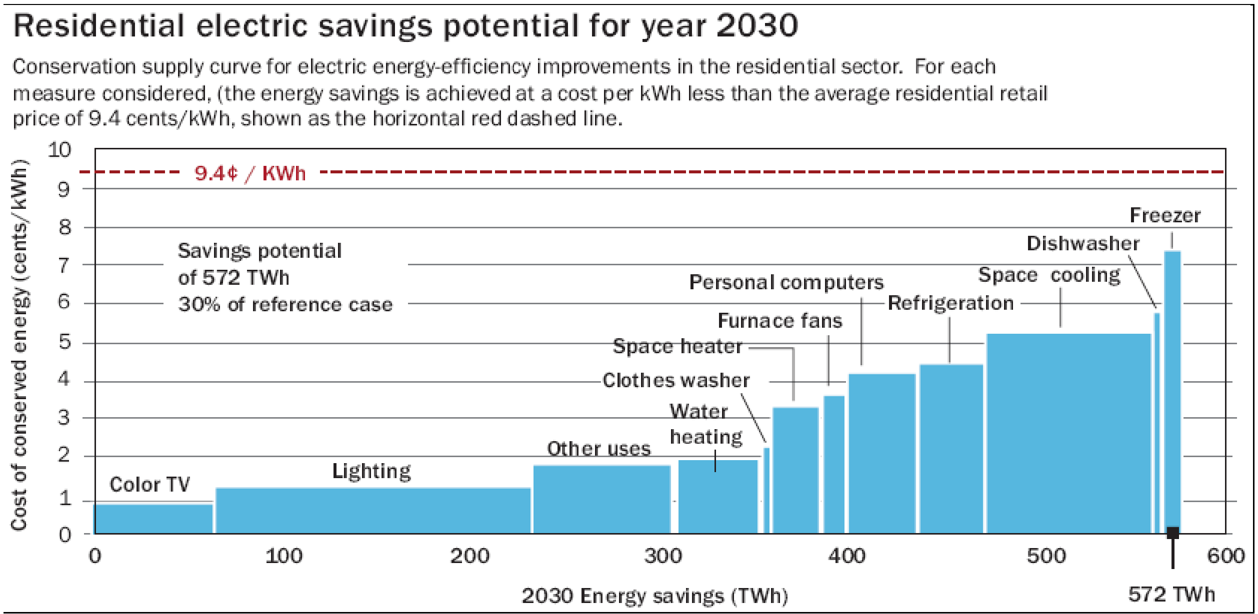

Figure V-3: Supply curve for residential electricity efficiency improvements. *Source: APS 2008 Figure 25 (p. 76).* Used with permission, from the American Physical Society's report: "*Energy Future, Think Efficiency*" (2008)

For instance, standards for more efficient water heaters would save about 50 million MWh (50TWh) nationally at a cost of about 2.0 cents per kWh. Water heaters are an example of a product with a split incentive. In the case of rented houses, the savings from the lower electricity bills go to the tenant whereas the increased capital cost of the more efficient heaters will usually be borne by the landlord. Similarly, the national efficiency potential for residential lighting is huge – 170 million MWh (170 TWh), at a cost of about 1.2 cents per kWh.

Item	Savings (TWh)	Cost (cents/kWh)	Total Cost (million $)
TV	60	0.8	480
Lighting	170	1.2	2,040
Other Uses	70	1.8	1,260
Water Heating	50	2.0	1,000
Clothes Washer	5	2.2	110
Space Heater	35	3.2	1,120
Furnace Fans	15	3.5	525
Personal Computers	25	4.1	1,025
Refrigerators	30	4.3	1,290
Space Cooling	100	5.2	5,200
Dishwasher	5	5.7	285
Freezer	7	7.4	518
Totals (average per kWh)	**572**	**(2.6)**	**$14,853**
Note: Values in the savings and cost per kWh columns were read off from the efficiency supply curve shown in Figure V-2 and are therefore approximate. Note that the "refrigerators" item in this table is under the more general rubric of "refrigeration" in Figure V-2.			

Table V-2: Residential energy efficiency measures with costs and savings for 2030. *Source: Based on APS 2008 Figure 25 (p. 76) – see Figure V-2.*

Table V-2 shows the data from Figure V-2 in detail; this enables a calculation of an average cost over all measures. The amounts of electricity saved for each end user corresponds to national data, and because almost all of the savings other than furnace fans and space cooling are independent of the weather, this supply curve can apply broadly.

Table V-2 shows that the average cost of all measures is 2.6 cents per kWh or $26 per MWh. This is much less than the 2009 average cost of residential electricity in Minnesota of $104 per

MWh, or 10.04 cents per kWh.[144] While building and appliance standards could be a central policy tool to achieve the low average level of costs, more thorough implementation of the measures can be achieved by supplementing them with utility incentive programs that help customers update aging appliances and systems. For instance, refrigerators are rather durable appliances that can last for decades, but refrigerators that are 25 or more years old typically consume three times or more the electricity of new ones. So long as the cost of the efficiency measure is less than the retail cost to the residential (or commercial) customer, the investment in that measure will be worthwhile. Hence all the measures shown in Figure V-2 would be economical in Minnesota.

The 2008 study by the American Physical Society reports that if all of the measures in Figure V-2 are implemented, about 30 percent of residential electricity use can be economically eliminated by 2030.[145] If the changes are brought about mainly by building and appliance standards, the costs are primarily borne directly by consumers via the prices of buildings or appliances (though, as we see below, prices do not always rise in response to regulations requiring higher efficiency). Hence the above cost table is not a cost table reflecting utility efficiency program costs, but the costs of actually purchasing higher efficiency lighting, televisions, refrigerators, air conditioners, etc. However, the effectiveness and reach of appliance standards can be increased, especially in the case of improvements in existing buildings and accelerated replacement of appliances, by utility rebate and education programs. We therefore add 0.4 cents per kWh (or about 15 percent) to the cost of 2.6 cents per kWh to 3 cents per kWh ($26 to $30 per MWh) to reflect supplemental utility incentives and overhead costs.

From a societal/utility point of view, the above efficiency investments are justified since the average cost of all measures would still be well below the average cost of electricity in Minnesota. Further, if these extra measures are focused on reducing the relational system peak load then the economics of efficiency can be further enhanced.

The importance of the issue of standards for appliances is illustrated in Figure V-4, which shows the history of three household appliances – refrigerators, central air conditioners, and gas furnaces. Refrigerator standards reinforced market-based trends that were occurring in the first part of the 1970s; the combination resulted in efficiency improvements by a factor of four in about 30 years. Smaller but significant improvements also occurred in the other two cases.

[144] EIA 2010 Minnesota Profile Table 8. We ignore the slight effect of inflation in the comparison years (2007 to 2009), since inflation was low in those years and the calculations are approximate.
[145] APS 2008 p. 76

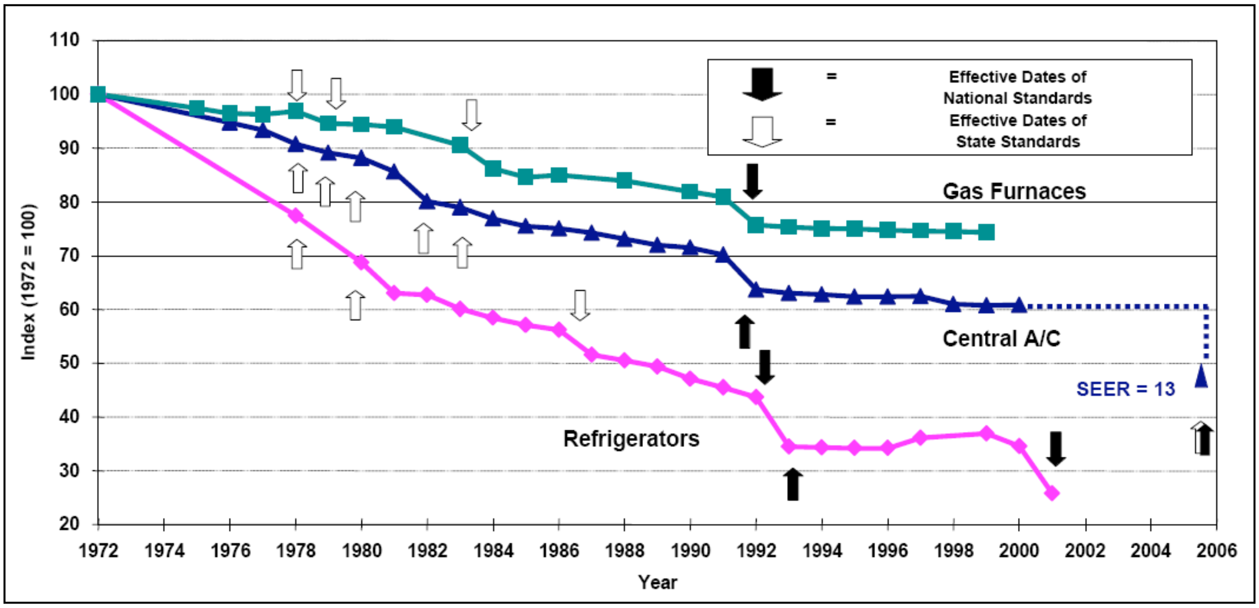

Figure V-4: Impact of standards on efficiency of three household appliances. *Source: Rosenfeld 2008 Slide 7, adapted from S. Nadel, ACEEE, in ECEEE 2003 Summer Study, www.eceee.org*

Figure V-5 shows how effective standards can be in achieving in energy efficiency. Since 1972, residential refrigerators have increased in size and functionality, but are only using a quarter of the electricity their earlier predecessors consumed to provide the same function – to keep perishable goods cold. The average price (in constant dollars) fell by almost a factor of 3 since the early 1970's.

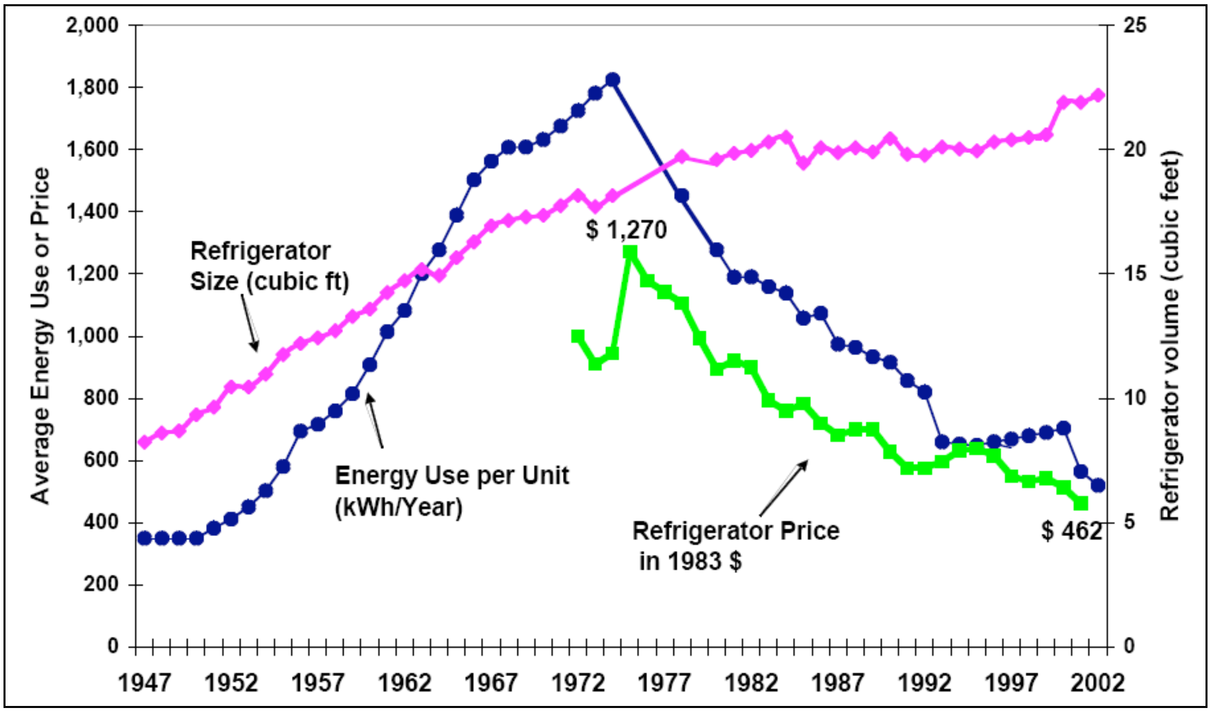

Figure V-5 Efficiency, size, and prices of refrigerators over time in the United States. *Source: Rosenfeld 2008 Slide 8 (crediting David Goldstein)*

The 2008 American Physical Society report on energy efficiency cited the following reasons in support of the need for standards for appliances and buildings:[146]

> "Minimum efficiency standards are needed to overcome market failures that restrict the use of more efficient products. Among these failures are:
>
> - Third-party decision makers (e.g., landlords and builders) who purchase appliances but do not pay the operating costs of the products they purchase;
> - Panic purchases that leave little time for consumers to become educated;
> - Inadequate and misleading information about the relative energy performance of products; and
> - High first costs for efficient equipment due to small production quantities and the fact that manufacturers frequently combine

[146] APS 2008 p. 77-78

efficiency features with extra non-energy features in expensive trade-up models."

Appliance and equipment standards will continue to play a significant role in the success of buildings to reduce their overall energy use. For instance in the design model for the Kopp Student Center at Normandale Community College in Minnesota included an estimate of the energy load that is due to plug-in technology such as computers, phone chargers, appliances, etc., at 26 percent of the entire building's energy use.[147] This type of load is a particular challenge because neither the design team, the construction team, nor even the building owner has control of this type of load. The only predictable energy savings for this "plug load" will come from standards placed on the various equipment and technology before the consumer even purchases the item.

New construction and retrofits of existing buildings also provide a significant source of energy efficiency potential. Currently buildings account for 40 percent of U.S. energy use and 70 percent of its electricity use.[148] In recognition of the potential that buildings have to reduce our need for electricity, the American Institute of Architects (AIA) adopted, in 2006, the Architecture 2030 goal of zero net energy buildings by 2030.[149] This goal calls for an immediate 50 percent reduction in the fossil fuel use in buildings, with additional 10 percent improvement every five years, reaching carbon neutrality by 2030.[150] Net zero buildings generally require some form of on-site renewable electricity generation in addition to high levels of energy efficiency elements.[151] In the net-zero building concept, high efficiency eliminates most of the energy footprint for a given level of energy services. On-site renewable energy supplies the rest.

There are similar efforts to improve building energy use in Minnesota. In the spring of 2008, Sustainable Buildings 2030 (SB2030) was signed into Minnesota law.[152] This law requires a cost-effective, science-based method of reducing the total carbon emissions to zero by 2030 of new and significantly remodeled buildings that receive state money for the build or remodel. Based on the Architecture 2030 program, SB2030 outlines specific performance targets of a 10 percent reduction in building emissions every five years, starting with 60 percent by 2010 and ending at 100 percent reduction (zero emissions) by 2030. The reductions are based on a

147 Carter 2011
148 Zeller 2010
149 Architecture 2030 FAQ
150 AIA 2011
151 Peabody Net-Zero
152 Minn. Stat. §216B.241 Subd. 9, 2011

baseline of the average energy use of a building in Minnesota in 2003. [153] These guidelines are required for buildings that receive state money for their building project, they are encouraged for other public buildings, and ideally incentives will encourage private buildings to meet these limits as well. A key to widespread success of this type of program is getting the utility companies to understand that buildings adhering to the SB2030 program also provide a way to meet their state requirements for energy savings.[154]

In a report to the legislature dated February 18, 2010, the Minnesota Office of Energy Security (OES)[155] found that these requirements are actually cost-effective for the building owners.[156] The OES also referenced a previous report by the Center for Sustainable Research in 2009 which found that 94 percent of the buildings that participated in similar programs in the region had enough energy cost savings over a 20 year timeframe to make the investments cost-effective for the building owner.[157] The SB2030 requirements have been incorporated into the existing Minnesota Sustainable Building Guidelines (B3)[158] and became effective on July 1, 2010.[159]

As of the writing of this report, there was not an opportunity to obtain any preliminary data to determine the effect of this program. We anticipate that in a year's time, there may be such data that can be analyzed for its impact on building energy use, and may also give us guidance on the impact of such a program on the larger electric grid system.

There are, however, a number of buildings that have been analyzed for their *potential* to successfully meet the requirements of the SB2030 program, even though they are not required to. Using these buildings as case studies, a local design and architecture firm was able to calculate the ability of a building to meet the SB2030 guidelines, the CO2 savings, and also calculate a simple payback estimate.[160] The redesign and addition to Quality Bicycle Products, a Bloomington, Minnesota, company provides a good example of the information available from these case studies.[161] The project began in 2004 and was completed in 2005, with a 91,000 square foot warehouse and 38,000 square foot office building. Looking through the lens

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[153] Minn. Stat. § 216B.241 Subd. 9, 2011
[154] Minn. Stat. § 216B.241 Subd. 9, 2011
[155] Now called the Division of Energy Resources, or DER (as of April 8, 2011 (MN Exec. Order 11-14)).
[156] MN DOC 2010a p. 2
[157] CSBR 2009a p. 7
[158] MSBG 2009 p. 4.3
[159] CSBR 2009b
[160] The simple payback calculation does not include the cost of capital, or the rising cost of energy, but does assume a constant 3 percent inflation rate. Carter 2011 (part of our conversation)
[161] LHB 2009 slides 7-9

of the SB2030 program, a similar commercial building, constructed according to the 2003 building code would consume 119.9 kBtu/sq. ft. per year, which means that in order for a building to meet the SB2030 guidelines for 2010 it would need to achieve 60 percent energy savings, or use only 48 kBtu/sq. ft./year. The design model for the Quality Bicycle Products project estimated an annual energy use of 47 kBtu/sq. ft., while the actual energy use of the building has been even *lower* than that at 42.4 kBtu/sq. ft./year. The annual energy savings are around $75,000 per year.[162] There are continuing challenges in meeting these same goals, particularly relating to certain types of buildings such as restaurants, which have rather specific heating and cooling needs.[163]

The payback on energy efficiency investments can be a significant benefit for home and building owners. Measurements of retrofits in low-income housing in Florida, for instance, showed payback times of one year to less than four years for most measures.[164] Measurements, though scarce, indicate a similar result in commercial building retrofits:[165]

> "In determining what efficiency gains are possible with current and emerging technologies, it is useful to start by looking at what is happening under current standard practices. Contractors focused on energy upgrades to existing residential buildings achieve energy efficiency improvements ranging from 15 to 35 percent by installing better and more efficient insulation, windows (in some instances) and lights; by eliminating infiltration and duct leakage, by upgrading furnaces, boilers and air conditioners; by replacing the power supplies that waste electricity when their devices are in standby or low-power mode; and by replacing old appliances with newer, more efficient ones.
>
> Energy service companies (ESCOs) regularly work with larger commercial customers to perform energy audits followed by upgrades in lighting, HVAC equipment and system controls, by which they achieve cost-effective energy savings. We were unable to locate performance data for U.S. ESCOs. In Berlin, Germany, however, ESCOs have improved the energy efficiency of 1,400 buildings by an average of 24 percent at no cost to building owners and a profit to the

[162] LHB 2009 slides 7 and 9
[163] LHB 2009 slide 28
[164] Makhijani 2010 CFNF p. 81
[165] APS 2008 p. 60

> ESCO that paid for the upgrade [C40 Cities, 2008]. U.S. results are likely to be similar. Generally, it is easier to achieve efficiency gains in new buildings than in existing ones."

The role of building energy use is critical to the success of a fully renewable electricity system. The larger vision of zero energy homes and buildings are not impossible realities. The Science House in Minnesota provides insight into how the concept of a net zero energy house or building can function in Minnesota's climate. The 1,530 square-foot Science House was built in June of 2003 and is located in the "Big Back Yard" at the Science Museum of Minnesota in the heart of downtown St. Paul.[166] It is currently only available to the faculty of member school districts to learn about environmental and energy related topics, and provides a number of STEM (science, technology, engineering, and math) related equipment available to check out for use in the classroom. The building itself houses a classroom, a laboratory, an office, and restrooms.[167]

The building is 100 percent electric, and generates all of the energy it needs on-site with an 8.8 kW rooftop solar PV system. The solar panels actually produce 30 percent more electricity than the building uses annually. During the design phase, decisions were made based on a goal of creating a building that is 60 percent more energy efficient than was required by the then existing building code.[168] The central challenge during the design phase was how to accomplish the set energy efficiency goals with a limited budget. During construction, every decision was predicated on the anticipated impact on future energy performance of the building. While the building used commercially available renewable energy and energy efficiency technologies, it was innovative at the time for putting them all together into an integrated system including having many different trades (such as electricians, plumbers, carpenters, roofers) that might not have previously worked together to collaborate and share in communication and strategies.[169]

The building was designed to minimize maintenance, though it experienced some maintenance problems with both the geothermal heat pump and the solar panels in

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166 Science House 2008 Overview
167 Science Museum of Minnesota 2011
168 Science House 2008 Energy and Overview sections; Science Museum of Minnesota 2011. The electricity use and production information is based on the year February 2004 to February 2005 (Science House 2008 Energy section)
169 Science House 2008 Process section

the first year. Both problems were resolved and the equipment operated properly after the repairs. Additionally performance data is continually monitored to ensure that the performance criteria are met.[170]

The energy use of the building was a key component of all aspects of the design and construction phase. In Minnesota the climate often swings between extremes of cold and dry to hot and humid – the annual temperature range for Minnesota is 130˚F. The Science House was designed to function within these extremes, while maintaining a 60 percent reduction in energy use from the building code requirements. The orientation of the building allows for maximum solar exposure, while also providing a view of the Mississippi River. To protect it from the harsh winters, the building was set into the slope on the north side, and additional landscaping helps prevent heat gains in the summer and heat losses in the winter. The vestibule is non-air conditioned and instead uses a tower with windows to maximize natural ventilation.[171]

The building also benefits from an on-site ground-source heat pump which provides heat in the winter and draws heat away from the building's interior in the summer. Additional efficiency measures include low-density foam insulation, automated lights to shut off when rooms are unoccupied, and even paint colors chosen specifically for their light reflecting properties.[172] The total cost of the project, excluding the cost of the land, was $650,000 as of the date of completion.

A zero-energy building comes with design trade-offs. Perhaps most critical at the design stage is the size and capability of a solar PV system, which by its necessity of having access to good sun exposure directly impacts the location and shape of the building. Additionally, windows, rather than placed based on the view, might be placed to optimize passive solar heating and daylighting strategies.

B. Energy Efficiency and Demand Dispatch in a Fully Renewable System

The above discussion shows how energy efficiency can be used to lower the overall cost of energy services. As we will see in the next chapter, this lower cost efficiency can be combined with higher cost supply, in our case renewables, to maintain the overall cost of energy services about the same as at present. However, there are additional considerations in the context of a

[170] Science House 2008 Process section
[171] Science House 2008 Indoor Environment and Energy sections
[172] Science House 2008 Energy section

renewable energy system. As we have seen, when an attempt is made to meet the demand curve with a similarly inflexible approach as today, a fully renewable system results in a large amount of spilled energy, while the top 2,000 megawatts of capacity that is used for generation from storage is used less than one percent of the time (in our example 55 hours out of 8760 hours in the year). Actually, the top 1,000 MW of capacity is used for just 9 hours in the year (about 0.1 percent of the time), as shown in Table V-1. This is the renewable equivalent of a large amount of capacity that is idle for much of the year. Further, an inflexible approach that does not address the demand curve as it relates to the availability of renewable generation seasonally also makes the storage requirement larger.

As noted above, the average capacity factor in 2010 for Minnesota generation was just about 42 percent. The natural gas capacity factor was only 9.4 percent and the petroleum capacity factor was even lower at about 0.4 percent. This system can be made more economically efficient by targeted efficiency improvements coordinated with demand dispatch. Together they can help shape the demand curve to make the overall investment in the system more productive and more closely matched to the installed capacity. We will qualitatively address the issues related to building an economically efficient and reliable renewable system in Minnesota.

1. Targeted Efficiency Investments

Since the relational peaks occur in the summer in Minnesota (from about mid-June into the first part of September in the year modeled in this report) and just around or after sunset, residential sector efficiency improvements in lighting and certain appliances like televisions would appear to provide a significant benefit to the system so far as the residential sector is concerned. Air-conditioning efficiency improvements would also help in the residential sector though not for all of the times of the relational peaks (defined in our example as the top 55 hours, shown in Figure V-1 above), since residential air-conditioning use in Minnesota in the first part of September would vary a great deal from year to year. Typically, September is the month when a transition from air conditioning to heating takes place in the residential sector. In much of the commercial sector (restaurants, malls, many office buildings), air conditioning use would continue into the fall due to the heavy lighting loads. Hence improvement of efficiency in lighting and air conditioning (in certain cases appliances as well, such as refrigerators and freezers in the case of restaurants and food storage warehouses) could contribute to reducing relational peaks and system cost.

The summer and early fall are also periods when demand is frequently high *relative* to wind and solar generation, putting a strain on storage capacity. Hence, adopting efficiency measures that depress demand in these periods as opposed to during the spring and fall, when storage is most frequently full would also enable a reduction in storage cost.

Combined heat and power (CHP) systems in the commercial sector provide another way of dealing with the relational system peak. CHP systems are essentially like combined cycle natural gas generating plants that use natural gas to generate electricity and then also use the waste heat ejected from the turbine or (in the case of a small CHP system) a reciprocating gas engine. In the case of combined cycle power plants, the waste heat is used to make steam which drives a steam turbine to generate more electricity. In the case of CHP plants, the waste heat can be used to drive absorption air conditioners (which are similar to the natural gas/ammonia refrigerators of old times). The waste heat can also be used for heating in the winter as well as for hot water supply. CHP systems with absorption air conditioning could eliminate much or most of the relational system peak if judiciously employed in the commercial sector. CHP systems can use a variety of fuels – natural gas is the most common, but wood, waste, biogas, and hydrogen generated from excess renewable supply could also be used. CHP is a technology that combines efficiency and generation; since the generation is dispatchable, it provides flexibility to the system that complements its efficiency aspect and strengthens the renewable system's reliability.[173]

2. Demand Dispatch

Making efficiency improvements of the type discussed above would reduce the relational peak and possibly shift it. Indeed, with great efficiency improvements targeted at one season, it may shift it to winter. Theoretically, this could also happen in the present central-station dominated system, but it is more likely in a wind-solar renewable system, since solar generation is low in the winter both as regards average generation per day and the total number of hours for which the generation is available. The most flexible and economical way to structure a renewable system is to optimize generation, storage, efficiency, CHP capacity, and demand dispatch *together.* Among these five elements, demand dispatch, if available on a large enough scale (i.e., aggregated over a large enough number of residential, commercial, and industrial customers) can provide the greatest flexibility to a renewable system. Two elements already provide significant flexibility – air-conditioner cycling and interruptible industrial loads.[174]

But demand dispatch can and should become much more varied – including appliances such as dishwashers, clothes washers, the timing of the operation of the defrost cycle in residential or

[173] The use of CHP with an intelligent grid is illustrated with a case study in Nyquist 2009.
[174] It is common for industries placing a large demand on the system to agree to interruptible power – i.e., the utility can cut off the power supply in an emergency – for lower electricity rates.

commercial freezers, and even water and space heating systems. As noted above, excess energy supply can be used to cool commercial refrigerators and freezers to slightly below the normal operating range, which allows the compressor to be turned off during times of deficit supply. Electric vehicles and plug-in hybrids would greatly increase demand dispatch capability. With good enough batteries, they may even be able to feed power back to the grid, providing added compensation to the battery (vehicle) owner. The same arrangements can be envisioned for computers with batteries that are connected to the power supply.

Demand dispatch as a functional part of the grid on a significant scale requires a system with greater communication between consumers and producers, and different rate structure arrangements that also have privacy and security protections and consumer choice and override protections so that consumers could override their pre-selected options (at a cost). These technologies, and the smart appliances that would operate with them, are rapidly coming to the marketplace. Brooks et al. "have estimated that up to 33% of all loads could have at least some level of demand dispatch control without a significant impact on end users."[175] We can anticipate that at the very least, the most expensive parts of the system as modeled here, with a single storage technology, would be greatly reduced in scale. Demand dispatch, especially when applied to year round loads such as consumer electronics, freezer defrost cycles, or plug-in hybrids and electric vehicles, would provide the needed flexibility to deal with shifting relational peaks as the efficiency of the overall system is improved. Modeling the impact of deploying such demand dispatch is beyond the scope of this study, but should be attempted in the future on a state and/or regional level.

[175] Brooks et al. 2010 p. 23.

VI. Economic Considerations

The cost of electricity to any individual ratepayer depends on how much electricity is used and the costs to generate and deliver that amount of electricity. This can clearly be seen in the economics of a renewable electricity system. Our analysis shows it is technically feasible to meet Northern State Power-Xcel Energy's 2007 hourly demand using only renewable energy, combined with energy storage technology. Of course, we also need to be concerned with the cost of realizing such a vision and whether it can be done without significantly raising rates. In 2010, Minnesota residential ratepayers paid an average of 10.59 cents per kWh.[176] This charge includes the cost of generation of electricity as well as charges for transmission and distribution infrastructure. The transmission and distribution cost for residential customers is about 5 cents per kWh.[177]

While we have done the modeling for the demand of a single year – 2007 – the creation of a fully renewable electricity sector will take 25 to 40 years, depending on policies, prices of renewables, evolution of storage, and demand dispatch technologies. Costs of renewable energy technologies are expected to decline substantially, especially costs of solar PV but also including wind, even though it is a relatively mature technology. For instance, the California Energy Commission estimates that onshore wind (Class 5) costs will decline to about $1,500 per kW by about 2025. It also projects the costs of single axis solar PV to decline to about the same level by 2025.[178] Of course, since we assume fixed solar PV, the cost would be lower. The SunShot Initiative[179] of the Department of Energy aims to reduce the cost of installed solar photovoltaic systems to $1 per watt for central station plants, $1.25 per watt for commercial scale installations, and $1.50 per watt for small-scale residential installations by the year 2020.[180]

In this report we assume that technical progress will be somewhat slower than current estimates. Specifically, we assume that wind energy capital costs will remain about the same

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[176] EIA 2010 Minnesota Profile Table 8

[177] The residential rate of 10.59 cents per kWh includes generation, transmission and distribution costs. The industrial rate of 6.29 cents has no distribution costs, but only generation and transmission costs. (EIA 2010 Minnesota Profile Table 8). Transmission costs are usually in the 0.5 to 1.0 cent per kWh range, which allows us to infer a generation cost of about 5.3 to 5.8 cents per kWh. The transmission and distribution cost for residential customers is therefore about 5 cents per kWh ($50 per MWh).

[178] Klein 2011 Slide 6

[179] The name was selected as an analogy to the 1960s program to put human beings on the moon.

[180] DOE 2012 SunShot p. xix

(in constant dollars) and that solar PV costs will be on average about $2,000 per kW by about the middle of the period of transition. These are costs that are somewhat higher than presently expected for the middle of the decade of the 2020's, which is roughly the mid-point of a possible transition to a renewable electricity sector as envisioned here. We use a single cost in our cost estimation, since we have not attempted to make a detailed assessment of the evolution of the Minnesota electricity sector over time. As noted, the renewable resources are plentiful – far above any conceivable growth – and hence the main issues relate to policy, the evolution of technology, and economics, which are interrelated factors.

The costs of the hardware portions of a compressed air energy system are reasonably well-known since they consist of well-established technologies – compressors and expanders. The main uncertainty is in the cost of the cavern, which is site dependent. However, this uncertainty is lower than might be imagined at first since underground storage of compressed natural gas is a well-established technology.

We estimate costs in two steps. First, we estimate the overall costs per unit of supply – renewable generation plus storage, including the spare capacity needed to fulfill reliability requirements. Then we look at what impact reducing electricity demand through broad energy efficiency improvements will have on rates paid by customers.

The basic approach for estimating generation cost is to estimate unsubsidized levelized costs for each new power plant built. Levelized costs calculate the cost of building and operating a generating facility over its lifetime, including fuel, operations, and maintenance costs. Because the costs are adjusted for inflation, and because *no loan guarantees, production tax credits, or investment tax credits are taken into account in our analysis,* we can provide an "apples-to-apples" comparison of energy generation costs. But this approach is not without its problems and dilemmas. We exclude special tax treatment of different electricity sources, which have a large effect on practical decisions but which distort economic comparisons. For instance, wind energy project finance can benefit from a substantial production tax credit. This is not included in the calculations in the present study. However this basic framework should be sufficient to estimate the costs of a fully renewable electricity system in Minnesota.

> *"Levelized cost is often cited as a convenient summary measure of the overall competiveness of different generating technologies. Levelized cost represents the present value of the total cost of building and operating a generating plant over an assumed financial life and duty cycle, converted to equal annual payments and expressed in terms of real dollars to remove the impact of inflation."* (EIA 2010 Levelized costs)

Levelized costs are calculated in the usual way using the formula:

$$\textbf{Levelized cost} = \Sigma_T [(I_t + M_t + F_t)(1+r)^{-t}] / \Sigma_T [E_t*(1+r)^{-t}]$$

Where
I_t = Investment-related payments in the year t
M_t = Operations and maintenance expenditures in the year t
F_t = Fuel expenditures in the year t
E_t = Electricity generation in the year t[181]
r = Discount rate
T= lifetime, sum is from 1 to T years.

The following parameters and those listed in Table VI-1 were used for the levelized cost calculations:

- Inflation rate for fuel and O&M cost assumed = 2 percent
- Discount rate for calculating levelized cost = 8 percent.[182]

[181] Constant annual generation, E, is assumed in this study = installed capacity*capacity factor*hours in the year. This means that the denominator = $E*\sum_T(1+r)^{-t}$, where t goes from 1 to T. The capacity factor is different for the various technologies, as explained below, but in each case it is kept constant.
[182] The 8 percent discount rate is based on Xcel Energy's most recently authorized cost of capital of 7.47 percent. (Xcel 2010a p. 4-2)

Technology	All-in capital costs ($/kW)	Life, years	Capacity factor	Total O&M, including fuel, $/kW/year[183]	Levelized costs ($/kW-year)
Wind	$2,000[184]	25[185]	38 percent [186]	$40[187]	$187
Solar PV[188]	$2,000	25[189]	15 percent	$40[190]	$214[191]
Biomass	$1,500	30	60 percent	~$45 plus fuel costs per kWh[192]	$133
CAES - Compressor[193]	$200	20	75 percent (total CAES system)[194]	$1[195]	$45
CAES – Expander	$250	20		$1.25[196]	$25
CAES – Balance[197] **of System**	$500	-		-	$51
CAES - Cavern	$2/kWh	-	Variable	$2.5[198]	-

Table VI-1. Parameters used for economic evaluation of the different energy types in the study.[199]

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183 For O&M costs, the Energy Information Administration's *Annual Energy Outlook* input data and National Renewable Energy Laboratory data were consulted. (NREL 2008 p. 28 (for wind), EIA 2010a (levelized cost section – all types), Stoddard et al. 2006 Table 5-3 (for CSP), and CEC 2009(all types))

184 Based on Wiser and Bolinger 2011 p. 47

185 EWITS 2011 p. 97 for lifetime; for cost p. 209

186 Capacity factors are for the combination of sites selected. The value here is calculated from the wind generation derived in the model divided by the total potential generation if the full capacity had been operational for 8,760 hours per year. Minnesota has a large wind potential with capacity factors over 40% at a hub height of 100 meters. NREL estimates that potential to be about 1.5 billion megawatt hours, which is more than 20 times the 2007 sales of electricity in Minnesota. 100-meter wind data are from NREL and AWS Truepower 2011.

187 This is based on O&M costs of 2 percent of the wind capital costs.

188 Capacity factors are for the combination of sites selected. For PV, the value used is an average capacity factor for a horizontal fixed PV panel, the technology assumed in this study.

189 DOE 2012 SunShot p. 201 estimates 25 to 30 year lifetime. We have used 25 years. We have also reduced output by an average of 12.5% over 25 years – i.e. output reduction by 0.5 percent per year over the expected lifetime.

190 This is based on O&M costs of 2 percent of the solar PV capital costs.

191 The cost has been escalated by about 15% to account for a gradual deterioration of PV output by that amount of 30 years.

192 This is based on O&M costs of 3 percent of the biomass capital costs.

193 Costs for all components of the CAES system (compressor, expander, balance of system, and cavern) were derived from estimates found in the literature. See Succar and Williams 2008; Mason et al. 2008; and Greenblatt et al. 2007. Non-fuel O&M costs (fixed plus variable) vary by component, but overall are similar to single stage natural gas turbine power plant fixed O&M costs.

194 Based on NREL 2006.

195 Based on O&M costs of 0.5 percent of the CAES component capital costs.

196 Based on O&M costs of 0.5 percent of the CAES component capital costs.

197 This includes the cavern and can be expected to vary considerably by site and size of project.

198 Based on O&M costs of 0.5 percent of the CAES component capital costs.

199 EIA 2011 Assumptions p. 97

The overall cost of generation for the system modeled here, with a single type of storage, no demand dispatch, and no additional efficiency, would be about 13 cents per kWh, or slightly more than double the present average cost of generation. But a comparison to new nuclear power plants is instructive. As is well known, Wall Street simply refuses to finance new nuclear power plants because they are far too risky. Indeed, the CEO of General Electric said in 2007 that, if he were the head of a utility, he would build gas and wind power plants and would "never do nuclear."[200] In addition, utilities also seek funds from ratepayers, known as "Construction Work in Progress" (CWIP) under which ratepayers are charged for construction costs in their bills without any guarantee that projects will be completed and electricity actually provided. The arrangement for ratepayers is much like giving a contractor money to build a house with no guarantee that the house will be finished or, if not built, that a refund is provided.

In view of the inability of nuclear to obtain financing on the open market, a fair market-based costing of nuclear would assume the cost of capital to be in the range of low-grade bonds, also often called "junk bonds." These interest rates tend to be ten percent or more and even as high as 14 percent. Equity investors would demand even higher rates of return. Using a cost of capital of 12 percent and an all-in cost (including interest during construction) of $8,000 per Kw yields a nuclear electricity cost from new plants of about 15 cents per kWh. Given the uncertainties, a reasonable range would be from roughly 12 cents to over 20 cents per kWh.[201] Hence, we can see that even when renewables are made dispatchable with storage and with the same reliability criterion as present-day supply, the cost of renewables is at the lower end of the cost of nuclear, estimated on a market basis.

An electricity system based entirely on renewable energy generation will be more expensive because the cost of renewable energy technology is generally more expensive that the embedded cost of existing infrastructure (which does not include environmental and health externalities). However, when compared with other low- or zero-greenhouse gas emitting electricity generation options, renewable energy can actually be more cost effective. Table VI-2 shows this comparison for renewable generation with storage to make it dispatchable but without optimization, nuclear generation, and coal-fired generation with carbon capture and storage technology.

[200] McNulty and Crooks 2007

[201] This range corresponds to all-in capital costs of $7,000 to $10,000 per kW, cost of capital of 10 to 14% and O&M costs (including fuel) of 2 cents per kWh. For details as well as references see Makhijani 2010 eUtah pp. 68-74.

Electricity generation technology	Cents per kWh	Comments
Renewables	13	*Mix for Minnesota used in this report*
Nuclear	12-20+	*Note 1*
Coal with carbon capture and storage	15	*Assuming CCS = 5 cents/kWh (Note 2)*

Table VI-2. Comparison of low-CO2 electricity levelized generation costs (i.e., transmission and distribution costs not included).

Note 1: For nuclear cost estimation details see Makhijani 2010 eUtah, where details and references are provided.

Note 2: For coal with CCS see Interagency Task Force 2010.

When transmission and distribution costs are added to the renewable costs above, the costs for residential service are on the order or 18 cents per kWh compared to 10.6 cents per kWh in 2010, for Minnesota ratepayers. Of course, there would be efficiency increases well before such rate increases would take effect and demand dispatch would also come into play on a significant scale to reduce costs. As discussed in Chapter IV, a mix of appliance and building standards for the commercial and residential sectors, and market forces for the industrial sector would induce efficiencies over the few decades that the transition would take.

Using the residential sector as an example, we have shown, based on national estimates, that about one-third of the electricity can be saved at an average cost of about 3 cents per kWh. Since this is far below the cost of generation, additional efficiency improvements in the form of more advanced technologies such as LED lighting, very high efficiency air conditioners, combined heat and power systems – even on small scales – would be expected to be deployed. Table VI-3 shows the costs for three scenarios: without efficiency, with moderate efficiency and with high efficiency. We have assumed the high efficiency measures would, on average cost about $100 per MWh, which makes the average cost of reducing electricity consumption by half to be about $54 per MWh. Advanced passive construction can reduce energy consumption (overall including heating and cooling by non-electric means) by about 70 percent.[202]

[202] See discussion and references in Makhijani 2011 OCT Declaration pp. 15-22

	Base case	Efficiency Tranche 1	Efficiency Tranche 2
Level of efficiency	No efficiency change	Medium efficiency (33%)	High efficiency (additional 17%)
Cost, $/MWh	$176 for generation	$30 for efficiency Tranche 1	$100 for efficiency Tranche 2
Average cost of electricity services $/MWh at different efficiency levels	$176	$128	$115
Annual services supplied by generation, MWh	8.68	5.82	4.34
Annual services supplied by efficiency, MWh	0	2.86	4.34
Annual elec. bill for generation	$1,529	$1,024	$764
Annual cost of efficiency	$0	$86	$234
Total annual cost for residential electricity services	$1,529	$1,110	$998
2010 cost	$920	$920	$920
Annual cost difference	$609	$190	$78

Table VI-3.; Residential cost comparison 2010 costs with full renewable system at various levels of efficiency in Minnesota[203]

We have added $50 per MWh for transmission and distribution cost to renewable generation costs to reflect delivery of the power to the residential sector. This is likely to overestimate such costs, since distributed solar energy will not require transmission investments and will also lower transmission and distribution losses, since a large part of the energy generated is consumed on site. However, distributed solar will also require a strengthened distribution system and probably storage devices on the consumer side of the substations supplying residential power. There may well be a net cost decrease as a result of such factors, but we have not attempted to estimate that here. Note that the annual level of energy services remains the same, but the different efficiency scenarios provide varying levels of these services via improved end use technology. Hence in the 33 percent increase in the medium efficiency case, one-third of the total energy services of 8.68 MWh (8,680 kWh) per year is provided by efficiency, while the rest, about 5.8 MWh (5,800 kWh) is provided by generation. Similarly in the high efficiency case, half of the services come from efficiency and the other half from generation. We should note that the average costs of $100 per MWh (10 cents per kWh) are above the range of the most expensive technologies considered by the APS study cited in Chapter V, but the savings are also above that range.

[203] Calculations based on residential data for 2010 found in EIA 2010 Minnesota Profile.

The overall cost difference when efficiency improvements are taken into account is about $6 to $7 per household per month before any optimization to reduce spilled energy and manage relational system peaks. It is essential to note the difference between rates per kWh and total bill in this context. In the medium efficiency case, the electricity bill for the generation supplied will be moderately more than at present but there will be also a modest added cost of efficiency. In the high efficiency case, the electricity bills for supply would actually be lower by over $150 per year. Somewhat more than this would be needed for efficiency improvements. Thus, overall the reduction in the total bill due to lower electricity use more or less balances out the increased efficiency costs to achieve that level of efficiency.

The notion that electricity supply bills go down with increasing rates is more than theoretical. For instance, California has strong efficiency standards and its per-person electricity use has stayed constant for decades, in contrast to the rest of the country. Utility rates are far higher – closer to those estimated above for a fully renewable system, but overall bills are considerably lower than the rest of the country. Tables VI-4a and VI4-b compare bills, usage and rates in San Antonio, Texas, with the service area of PG&E in California. The rates in California are much higher, the usage is much lower and the bills are lower. Adjusting for air-conditioning use differences would likely make the bills about the same.

Table VI-4a	San Antonio CPS Energy Residential Rates, Use, and Bills			
	2006	2007	2008	2009
Annual Bill $	$1,195	$1,179	$1,104	$1,291
Average Monthly Bill $	$100	$98	$92	$108
Rate (cents/kWh)	8.18	7.88	7.90	9.06
Consumption	14,610	14,966	13,972	14,252
Table VI-4b	**PG&E Residential Rates, Use and Bills**			
	2006	2007	2008	2009
Annual bill	$1,017	$1,026	$1,037	$1,059
Average Monthly Bill $	$85	$86	$86	$88
Rate (cents/kWh)	14.48	14.87	14.80	15.24
Consumption	7,023	6,900	7,007	6,949

Table VI-4. Comparison of CPS Energy (Texas) and PG&E (California) Electricity Rates, Use, and Bills. Sources: Compiled and calculated from annual reports of CPS Energy for San Antonio and of Pacific Gas and Electric Company. (CPS Energy 2007-08 p. 18, CPS Energy 2009-09 p. 25, and PG&E Form 10-K, 2010)

The above calculations are based on wind and solar costs that are somewhat higher than is commonly assumed for a period ten to twenty years from now. Table VI-5 shows the cost estimates of a fully renewable system at various levels of efficiency assuming $1,500 per kW for Class 5 wind, with a 20 year lifetime, and $1500 for solar PV, with a 30 year lifetime. The solar PV estimates are approximately the goals of the SunShot Initiative for residential rooftop systems for the year 2020.

	Lower Cost Case	Efficiency Tranche 1	Efficiency Tranche 2
	No efficiency change	Medium efficiency (33%)	High efficiency (additional 17%)
$/MWh	$154	$30	$100
Average cost of electricity services $/MWh at different efficiency levels	$154	$113	$104
Annual services supplied by generation, MWh	8.68	5.82	4.34
Annual services supplied by efficiency, MWh	0	2.86	4.34
Annual elec. bill for generation	$1,336	$895	$668
Annual cost of efficiency	$0	$86	$234
Total annual cost for electricity services (generation plus efficiency)	$1,336	$981	$901
Total annual cost for in 2010	$920	$920	$920
Cost difference: renewables – 2010	$416	$61	($19)

Table VI-5: Cost estimates using $1,500 per kW for wind with a 20 year lifetime and solar PV with a 30 year lifetime

In this case, the high efficiency case is marginally cheaper than at the present case, though given the uncertainties, the residential bills in both the medium and high efficiency cases may be assumed to be about the same as at present.

We note here that this entire calculation is for the year 2007. In practice, the demand for energy services will grow beyond the present level as will the economy and along with it consumer income. Since both new generation and efficiency technologies can be applied to new uses and new buildings (especially in light of Minnesota's goals for net zero buildings), the expenditures on electricity services would grow but the fraction of income spent on electricity services (generation plus efficiency) should remain about the same.

A caution is in order. A renewable energy system with storage will work differently than the present system with a large amount of idle capacity in the form of natural gas fired power plants. We reproduce the figure that shows how relational peaks occur in the form of chart showing expander capacity use and the cost of the top tranches of the expander in Figure VI-1.

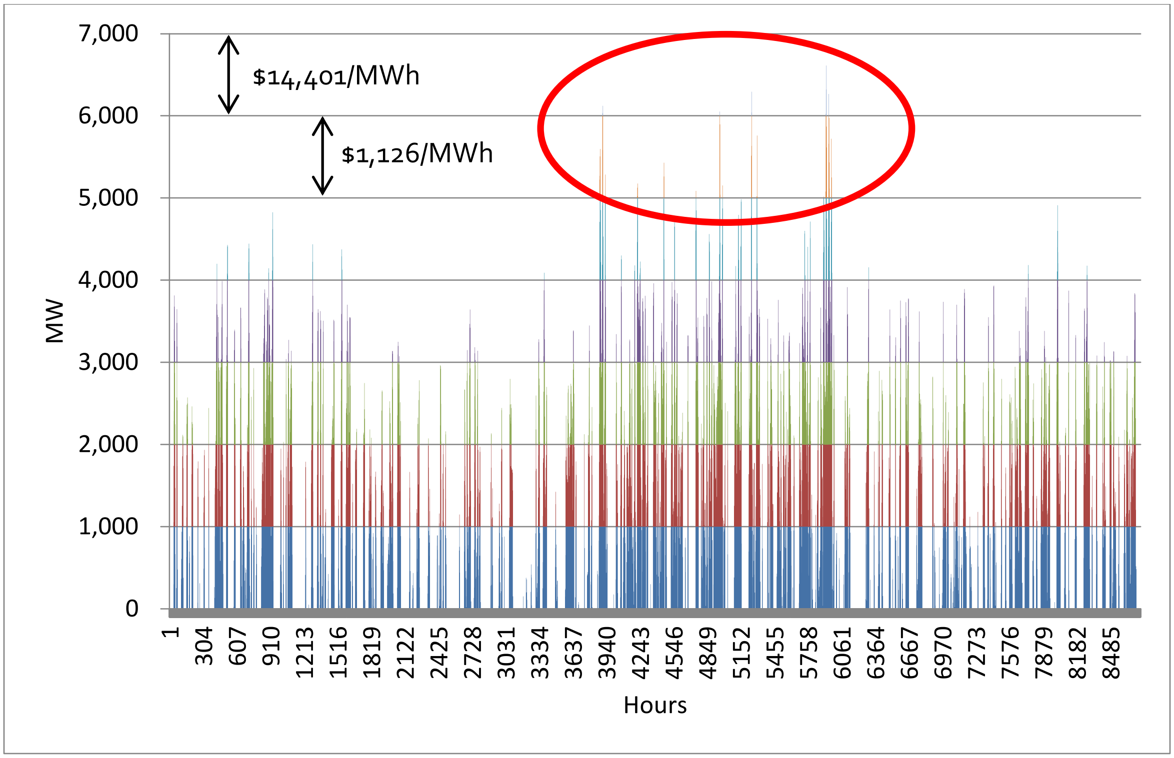

Figure VI-1. Expander capacity in MW needed to meet 2007 Xcel Energy hourly electricity demand with only renewable energy generation technology. Capital costs per MWh of generation for the CAES expander are shown for the top two tranches of storage capacity required. Source: IEER.

As we have discussed in the previous chapter, efficiency investments may shift the relational peaks. It will be essential to incorporate features such as demand dispatch and combined heat and power systems to allow for more flexible and economical operation of the system and to reduce the spilled energy. Reducing the spilled energy of 7.3 million megawatt-hours per year by 50 percent would save hundreds of millions of dollars, though of course it would also require corresponding investments. However, it is important to note that such investments in intelligent grids are needed in any case to make present-day grids more secure, reliable, and economical and to enable incorporation of distributed energy sources. Optimizing demand dispatch, efficiency, storage, solar and wind generation, and combined heat and power could result in a significant reduction in costs compared to the system modeled in Tables VI-3 and VI-5.

A. Jobs and Economic Development of a Renewable Minnesota

In addition to providing a clean and renewable source of energy, our 100 percent renewable energy-based electricity system would provide significant opportunities for economic development and job creation potential across the state.[204]

We will do a jobs estimate based on the investments in generation, storage, and efficiency taking very approximate (order of magnitude) account of the fact that only a portion of the jobs corresponding to those investments would be in Minnesota. This approach also makes it possible to integrate the storage element of the scenario created here. We first estimate the investments based on 2007 level of electricity services, if they were to be supplied by renewables plus efficiency, and then allow for a doubling of electricity services over 40 years (about 2 percent per year),[205] that has been typical of recent years (excluding the recession). Finally, we extend our calculation to cover the entire state since we have modeled just over two-thirds of the use by focusing on Xcel electricity demand data as reported to FERC. Combining growth up to 2020 at 1.9 percent per year and extending the model to the whole state results in a tripling of the investment figures.

First, we subtract the existing 2,733 MW of wind energy capacity from the 12,296 MW needed in our scenario to get roughly 9,500 MW of additional wind energy capacity needed for a 100 percent renewable energy system, which amounts to about $19 billion in investment. Solar at $2,000 per kW would amount to somewhat over $9 billion and hydro/biomass would be around $2 billion. In addition, there would be the jobs associated with energy storage, in our example compressed air energy storage, with a total capital investment of about $9 billion. The total investment in generation, if there are no efficiency improvements would be roughly $60 billion over about 40 years and would be about half that in the high efficiency case, or about $30 billion. Providing for growth and extending to the whole state triples this figure and gives an estimate of investment in generation and storage over 40 years in the high efficiency case of about $90 billion.

[204] The estimates in this section are very approximate and pertain to the jobs created in building an efficient, renewable electricity sector in Minnesota over the next 40 years with in-state renewable resources. They do not provide any comparison about the relative numbers of jobs that would be created with a different approach to the electricity sector in some other way. Since the overall costs per unit of electricity services (generation plus efficiency) in the high efficiency case are estimated to be about the same as at present (assuming that a similar level of efficiency is achieved in all sectors), there would be no net stimulatory or depressive economic effect of a change in electricity costs as a result of the transition to the efficient, renewable system.

[205] The electricity grow rate, excluding the recent recession has been about 1.9% per year. Estimated from EIA 2010 Minnesota Profile Table 8.

Efficiency investments would be on the order of $15 billion cumulatively in the residential sector and possibly on the order of the same amount for the commercial and industrial sectors combined. Adjusting these figures gives an efficiency investment on the same order as the generation plus storage investment – roughly $90 billion over 40 years. This means that, overall, the generation, storage, and efficiency would result in an investment on the order of $4 to $5 billion per year.

Jobs numbers per unit of investment are quite varied and there is considerable uncertainty. A survey by the New York Department of Transportation indicates that the construction sector creates 11,000 to 38,000 direct and indirect jobs per billion dollars of expenditures, with a median estimate of 24,000.[206] The Economic Development Research Group estimates that investment in public transport creates about 30,000 jobs per billion dollars in investment expenditures with a range of 24,000 to 41,000 jobs nationally "depending on the spending mix."[207] A University of Massachusetts study estimates direct job creation in clean energy to be about 9,350 jobs per billion dollars with about an equal amount created as secondary effects of investment.[208] The Center for American Progress estimates 16,700 jobs[209] per billion dollars invested in a mix of renewable energy and efficiency.

We will use a figure of 10,000 job-years per billion dollars invested in renewable energy and efficiency, which gives a total employment of 1.8 million job-years over the 40 years of transition to an efficient, renewable electricity sector. Since these jobs are over 40 years, there would be 45,000 people employed each year for 40 years on average in order to build a renewable and efficient electricity sector in Minnesota. In addition, the jobs in operating and maintaining the generating facilities in the high efficiency case would grow over time to about 5,000 jobs by 2050, assuming $30 per kW-year for non-fuel costs and $150,000 in expenditures per year per operating and maintenance job. In sum, our order of magnitude estimate is that there would be roughly 50,000 steady jobs created in the process of converting Minnesota to an efficient, fully renewable electricity state.

A commitment to a fully renewable or even a largely renewable energy system focused on wind and solar could also be leveraged to attract renewable energy manufacturing. For instance, CPS Energy, the utility of the City of San Antonio, Texas, decided to greatly increase its investment in solar PV, once it essentially abandoned its commitment to acquire 50 percent of a two-reactor nuclear project at the South Texas Plant. It was able to leverage

[206] NY DOT 2012
[207] Economic Development Research Group 2009 p. ii
[208] Pollin et al. 2008 p. 9
[209] DiPasquale and Gordon 2011

manufacturing facilities for the city and other benefits when it decided to install 400 megawatts of PV capacity.[210]

Germany also provides a useful example of the role of government leadership in creating a renewable energy economy. Germany's Renewable Energy Sources Act (EEG) has had a dramatic impact on the German economy and is directly responsible for 68 percent of the 300,500 jobs recorded in the renewable energy industry in 2009.[211] In fact, this represents a growth of jobs in the renewable energy sector of 8 percent since 2008 and over 87 percent since 2004.[212] This type of commitment to renewable energy installations as well as a commitment to manufacturing and production has played a critical role in establishing Germany's economy on the international stage. With no long-term commitment to renewable energy, the U.S. dropped from supplying 40 percent of the world's solar PV industry twenty years ago, to less than 10 percent today.[213]

Within the German solar PV industry, in 2008 there was a 75 percent export ratio to production – fueled by a growing international solar PV market.[214] This success is partly due to the German experience and expertise in related industries such as automobiles, glass, and the chemical industry.[215] On the international scale, solar PV production is dominated by China at 32.7 percent, and followed by Germany (18.5 percent) and Japan (16.0 percent).[216] These are also the three leading countries, as of 2009, with positive international trade balances – meaning that they export more than they import. The United States, on the other hand, had the highest international trade deficit in 2009 among the OECD list of 33 countries – meaning the US imports far more than it exports.[217] The US has a tough road ahead to regain leadership in renewable energy. According to a study by the Pew Charitable Trusts, the top ten leading world economies devoted a greater percentage of their gross domestic product to renewable energy than the U.S. did in 2009.[218] Yet, the size of the US economy is so much larger than the others, that it can, given the will and vision and actual implementation, regain that leadership.

The thing in common between the budding San Antonio example and Germany is that both have made very substantial commitments to renewable energy; that commitment has

[210] Montgomery 2012. The details of the various agreements are still being finalized.
[211] BMU 2010 p. 27
[212] BMU 2010 p. 27
[213] Runyon 2010 and Schott 2012
[214] Maiser 2010 p. 2
[215] Maiser 2010 p. 13
[216] Maiser 2010 p. 11, as of 2008
[217] OECD 2010
[218] Pew 2010 p. 5

leveraged and sustained manufacturing jobs in Germany and San Antonio seems embarked on the same direction. Minnesota has made significant commitments to renewable energy as well and has the beginnings of a manufacturing sector, but in order for it to be as steady and growing as it is in Germany, it will require a sustained commitment, independent of short-term ups and downs. The San Antonio example also indicates that investments in nuclear power plants and large scale investments in renewable energy are mutually exclusive. Germany has forsworn new reactors for quite some time and now is embarked upon phasing out existing ones.

A single new power reactor requires such a huge investment (sometimes comparable to or more than the entire market value of the company proposing it[219]) and such a long time to come to fruition, *that it tends to crowd out other* ***large-scale*** *investments.* While it is common to hear that "all options should be on the table" – this notion does not recognize that there is a limited amount of capital that can be invested in the electricity sector. It is not that there would not be renewable energy investments, but they would tend to remain at the margins and not move to the center of generation, which is the needed direction. In other words, there is a choice to be made between nuclear on the one hand and renewables and efficiency on the other as the main direction for the electricity system of the future.

[219] This is the reason that nuclear power reactors are sometimes called a "bet the company" or "bet the farm" risk.

VII. Conclusions and Recommendations

Minnesota has the ability to meet current and future electricity demand, using only in-state renewable energy resources. Our analysis has shown it is possible to meet the hourly electricity demand of the state's largest utility using a combination of wind energy, solar PV, and storage, at a manageable cost if it is combined with efficiency improvements. It is important to remember the caveat that a renewable system has relational system peaks that must be managed. Reducing spilled energy and making the system more economical will require the development of demand dispatch on a significant scale, and preferably also a variety of storage technologies as well as combined heat and power plants.

The cost estimates for the mix of renewable generation and storage considered here varies from 11 to 13 cents per kWh, compared to about 5.5 cents today. Nuclear and carbon capture with storage would generally be at least as expensive and probably much more expensive than this. As is well known, Wall Street will not touch new nuclear power plants and ratepayers and taxpayers are being asked to bear the risk. Nuclear carries significant risks in terms of investment and waste and is likely to crowd out *large-scale* investments in renewable energy and efficiency.

It will be necessary to combine new renewable generation with efficiency and demand dispatch to make it economical and manageable. If this is done, the total cost of electricity to households, including the cost of efficiency, transmission, distribution, and generation would be approximately the same as it is today. There is some uncertainty in this result of course, due to the uncertain future cost trajectory of wind and especially solar PV. Using a reasonable range of estimates as currently projected for the mid- to late-2020's, about the middle of a transition period to a fully renewable system, and with vigorous efficiency improvements, we estimate that the overall monthly cost for residential electricity services would go up or down by a few dollars compared to the present. Reducing spilled energy and the size of the relational peaks would produce further economies. It should be remembered that with appropriate efficiency investments, the bills for generation would go down but the balance would be spent on increasing efficiency as we have discussed in Chapter VI.

Given that an efficient renewable energy future can create tens of thousands of steady, well-paid jobs, and maintain the overall cost of electricity services at about the present level, a decision about a renewable energy future need not be linked to the issue of when and how utilities will be required to account for their greenhouse gas emissions. A 100 percent renewable energy-based electricity system in Minnesota is technically feasible and if joined with efficiency economically sound, without taking into account the benefits of reducing greenhouse gases, air pollution, and nuclear waste. Of course, it is all the more important in the context of Minnesota's goal of reducing greenhouse gas emissions by 80 percent by 2050.

A. Specific Recommendations

In order for Minnesota to economically achieve the 80 percent reduction in greenhouse gas emissions (the target for 2050 mandated by Minnesota's 2007 Next Generation Energy Act), it will take an almost complete elimination of emissions from the electricity sector. Policy makers can make significant strides towards that by creating an official state policy of achieving a 100 percent renewable energy-based and efficient electricity system by 2050. This will set a direction for the electricity sector and serve as a component of the state's greenhouse gas policy, as well as support economic development opportunities across the state.

The main next step needs to be an official detailed model of the state's electricity sector that would include:

1. A detailed analysis of energy efficiency in the context of relational system peaks;
2. An analysis of the role and extent of combined heat and power in a renewable electricity system;
3. The extent and phasing-in of demand dispatch, its ability to deal with relational system peaks and provide flexibility and reliability to the system as the renewable component grows;
4. The role that plug-in hybrids and electric vehicles could play in a renewable electricity sector and the infrastructure needs of both for the vehicles themselves and for the grid;
5. A detailed exploration of the feasibility for compressed air energy storage and pumped hydro energy storage (both natural and human constructed) sites in Minnesota;
6. The ways in which various levels, types, and scales of storage could be joined to generation, efficiency, combined heat and power, and demand dispatch to reduce spilled energy and system costs.
7. An econometric model that reliably couples electricity rates and demand that would be a macro-economic complement to the micro-technical assessments of efficiency on which costs are usually estimated.

A demonstration project, at the level of a university or small community utility, joining the various elements of fully renewable electricity system is highly desirable. Such a project should include various levels of storage, demand dispatch, an intelligent grid and combined heat and power. It should be appropriately instrumented so that the performance of the various elements can be measured and a future, larger scaled project could be better optimized.

The Public Utilities Commission might consider initiating and participating in a similar project at the regional Midwest Independent Transmission System Operator (MISO) level to study a renewable and distributed grid. This would allow an exploration of the ways in which a project for a fully renewable, efficient, and reliable system covering the entire MISO system could be made more economical than a state-by-state approach.

References

AIA 2011	American Institute of Architects. *AIA 2030 Commitment: Why Commit?* Washington, DC: AIA, 2011. On the web at http://www.aia.org/about/initiatives/AIAB081490 (accessed April 29, 2011). The commitment letter is at http://www.aia.org/about/initiatives/AIAB079567.
Alberta Innovates 2011	Alberta Innovates – Technology Futures. *Energy Storage: Making Intermittent Power Dispatchable: Final Report*. Version 1.0. Edmonton, AB: AITF, October 17, 2011. On the web at http://www.albertatechfutures.ca/RDSupport/CarbonCaptureStorageandCleanEnergy/CleanEnergy/LinkClick.aspx?fileticket=ODSKXehVJ18%3d&tabid=680%20%28page%207%29.
AP 2011	Luke Meredith. "Iowa wind energy storage project scrapped: APNewsBreak: Plans for $400 million wind energy storage project in Iowa scrapped", *The Associated Press*, July 28, 2011. On the web at http://finance.yahoo.com/news/Iowa-wind-energy-storage-apf-1259789282.html?x=0&.v=2.
APS 2008	American Physical Society. *Energy Future: Think Efficiency: How American Can look Within to Achieve Energy Security and Reduce Global Warming*. College Park, MD: APS, September 2008. On the web at http://www.aps.org/energyefficiencyreport and http://www.aps.org/energyefficiencyreport/report/aps-energyreport.pdf
Apt 2007	Jay Apt. "The spectrum of power from wind turbines", *Journal of Power Sources* 169 (2007):369-374.
Architecture 2030 FAQ	Architecture 2030. *FAQ*. Santa Fe, NM: Architecture 2030, viewed on October 4, 2011. On the web at http://architecture2030.org/about/faq.
AWEA 2011	American Wind Energy Association. *U.S. Wind Industry Fourth Quarter 2011 Market Report*. Washington DC: AWEA, January 2012. On the web at http://awea.org/learnabout/publications/reports/upload/4Q-2011-AWEA-Public-Market-Report.pdf.
AWEA 2012	American Wind Energy Association. *Industry Statistics.* Washington DC: AWEA, [2012?]. On the web at http://awea.org/learnabout/industry_stats/index.cfm. Accessed February 2, 2012.
Bélanger and Gagnon 2002	Camille Bélanger and Luc Gagnon. "Adding wind energy to hydropower", *Energy Policy* 30 (14) (2002):1279-1284.
BMU 2010	Germany. Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU). *Renewable Energy Sources in Figures: National and International Development.* Berlin, Germany: Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, June 2010. On the web at http://www.bmu.de/files/english/pdf/application/pdf/broschuere_ee_zahlen_en.pdf.
Braun 2012	Will Braun. "Hydro deal raises questions", *Winnipeg Free Press*, February 14, 2012. On the web at http://www.winnipegfreepress.com/opinion/westview/hydro-deal-raises-questions-139271273.html.

Brooks et al. 2010	Alec Brooks, Ed Lu, Dan Reicher, Charles Spirakis and Bill Weihl. Demand Dispatch: Using Real Time Control of Demand to Help Balance Generation and Load, *IEEE Power & Energy Magazine* 8 (3) (May/June 2010): 20 29. On the Web for members at http://www.ieee.org/organizations/pes/public/2010/may/index.html. The index to the issue is at http://www.ieee.org/organizations/pes/public/2010/may/index.html.
Brower 2009	Michael Brower. *Development of Eastern Regional Wind Resource and Wind Plant Output Datasets: March 3, 2008 — March 31, 2010.* (NREL/SR-550-46764) Golden, CO: National Renewable Energy Laboratory, December 2009. On the web at http://www.nrel.gov/wind/integrationdatasets/pdfs/eastern/2010/aws_truewind_final_report.pdf.
California 2008	Arnold Schwarzenegger. *Executive Order S-14-08 by the Governor of the State of California*. [Sacramento]: Office of the Governor, California, November 17, 2008. On the web at http://gov38.ca.gov/index.php?/executive-order/11072.
California 2009	Arnold Schwarzenegger. *Executive Order S-21-09*. [Sacramento]: Office of the Governor, California, [September 15, 2009]. On the web at http://gov.ca.gov/news.php?id=13269.
California 2010	California. *Assembly Bill No. 2514: AB 2514, Skinner. Energy storage systems*. Signed into law on September 29, 2010. On the web at http://www.leginfo.ca.gov/pub/09-10/bill/asm/ab_2501-2550/ab_2514_bill_20100929_chaptered.pdf. Chaptered by Secretary of State - Chapter 469, Statutes of 2010.
Carter 2011	Conversation with Rick Carter of LHB Inc. Conducted by Christina Mills, May 25, 2011, Minneapolis, MN.
Cavallo 1995	Alfred J. Cavallo. "High-Capacity Factor Wind Energy Systems", *Journal of Solar Energy Engineering* 117 (2)(May 1995):137-143. Link on the web at http://scitation.aip.org/getabs/servlet/GetabsServlet?prog=normal&id=JSEEDO000117000002000137000001&idtype=cvips&gifs=yes&ref=no. "Transactions of the ASME"
Cavallo 2001	Alfred J. Cavallo. "Energy Storage Technologies for Utility Scale Intermittent Renewable Energy Systems", *Journal of Solar Energy Engineering* 123 (4)(November 2001):387-389. Link on the web at http://asmedl.org/getabs/servlet/GetabsServlet?prog=normal&id=JSEEDO000123000004000387000001&idtype=cvips&gifs=Yes&ref=no. "Transactions of the ASME"
CEC 2009	California Energy Commission. *Comparative Costs of California Central Station Electricity Generation.* (CEC report number CEC 200-2009-17-SD) Sacramento: CEC, August 2009. On the web at http://www.energy.ca.gov/2009publications/CEC-200-2009-017/CEC-200-2009-017-SD.PDF.
Chen et al. 2009	Haisheng Chen, Thang Ngoc Cong, Wei Yang, Chunqing Tan, Yongliang Li, and Yulong Ding. "Progress in electrical energy storage system: A critical review", *Progress in Natural Science* 19 (3)(2009):291-312.

Ciborowski and Claflin 2009	Peter Ciborowski and Anne Claflin. *Greenhouse Gas Emissions in Minnesota: 1970-2006.* St. Paul, MN: Minnesota Pollution Control Agency, June 2009. On the web at http://www.pca.state.mn.us/index.php/view-document.html?gid=9230.
CPS Energy 2007-08	CPS Energy. *Generations: CPS Energy 2007-08 Annual Report*. [San Antonio, TX: CPS, 2008]. Formerly on the web at http://www.cpsenergy.com/files/annual_report_web%200708.pdf.
CPS Energy 2008-09	CPS Energy. *Transformations: CPS Energy 2008-2009 Annual Report*. [San Antonio, TX: CPS, 2009]. On the web at http://www.cps-satx.com/files/2009CPSEnergyAnnualReport.pdf.
CSBR 2009a	Center for Sustainable Building Research. *Minnesota Sustainable Building 2030: Phase One and Two/Year 1 - Final Report*. (09 - 0892) Minneapolis: CSBR, [University of Minnesota, College of Design], July 15, 2009. On the web at http://www.leg.state.mn.us/docs/2009/mandated/090892.pdf. "Consultant's Report."
CSBR 2009b	Center for Sustainable Building Research. *Notification of SB 2030.* [Memorandum] to: All Minnesota Building Owners and Designers, from: Center for Sustainable Building Research, on the behalf of the Department of Commerce, State of the of Minnesota, re: Sustainable Building 2030. July 31, 2009. On the web at http://www.mn2030.umn.edu/notice.html.
DeCarolis and Keith 2006	Joseph F. DeCarolis and David W. Keith. "The economics of large-scale wind power in a carbon constrained world", *Energy Policy* 34 (4)(2006):395-410.
DiPasquale and Gordon 2011	Christina C. DiPasquale and Kate Gordon. *Top 10 Reasons Why Green Jobs Are Vital to Our Economy: Millions of Competitive Jobs Created and Sustained*. Washington, DC: Center for American Progress, September 7, 2011. On the web at http://www.americanprogress.org/issues/2011/09/top_ten_green_jobs.html.
DOE 2008 20% Wind	U.S. Department of Energy. *20% Wind Energy by 2030: Increasing Wind Energy's Contribution to U.S. Energy Supply.* (DOE/GO-102008-2567) Golden, CO: DOE, Office of Energy Efficiency and Renewable Energy, July 2008. On the web at http://www.nrel.gov/docs/fy08osti/41869.pdf. Prepared by the National Renewable Energy Laboratory.
DOE 2010a	U.S. Department of Energy. *Grid Storage Report: Report to Congress*. Washington DC: DOE, July 2010. On the web at http://wyden.senate.gov/imo/media/doc/grid_storage_report.pdf. Formerly at http://science.energy.gov/~/media/s-4/pdf/presentations/doe_grid_storage_report_final_with_wyden_transmittal_letter.pdf.
DOE 2010b	U.S. Department of Energy. *Pacific Gas & Electric Company: Advanced Underground Compressed Air Energy Storage*. [Washington, DC?]: DOE Office of Electricity Delivery and Energy Reliability, December 2010. On the web at http://www.smartgrid.gov/sites/default/files/pge-oe0000198-final.pdf, from link at http://www.smartgrid.gov/project/pacific_gas_and_electric_company_advanced_underground_compressed_air_energy_storage.

DOE 2011	U.S. Department of Energy. *Solar Radiation Basics*. (Energy Savers) Washington, DC: DOE; [Office of] Energy Efficiency and Renewable Energy, last updated February 9, 2011. On the web at http://www.energysavers.gov/renewable_energy/solar/index.cfm/mytopic=50012.
DOE 2012 Electricity	U.S. Department of Energy. *Electricity 101*. Washington, DC: DOE, Office of Electricity Delivery and Energy Reliability, accessed February 27, 2012. On the web at http://www.doe.gov/oe/information-center/educational-resources/electricity-101.
DOE 2012 SunShot	U.S. Department of Energy. *SunShot Vision Study*. (DOE/GO-102012-3037) [Golden, CO]: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, February 2012. On the web at http://www1.eere.energy.gov/solar/pdfs/47927.pdf, from links at http://www2.eere.energy.gov/solar/sunshot/vision_study.html. Prepared by the National Renewable Energy Laboratory.
E.ON Kraftwerke 2010	E.ON Kraftwerke. *Introducing the Huntorf site*. Wilhelmshaven, Germany: E.ON Kraftwerke, viewed on December 1, 2010. On the web at http://www.kraftwerk-wilhelmshaven.com/pages/ekw_en/Huntorf_Power_Plant/Overview/index.htm. Facts and figures, at http://www.kraftwerk-wilhelmshaven.com/pages/ekw_en/Huntorf_Power_Plant/Facts_%26_Figures/index.htm. History, at http://www.kraftwerk-wilhelmshaven.com/pages/ekw_en/Huntorf_Power_Plant/History/index.htm.
Economic Development Research Group 2009	Economic Development Research Group, Inc. *White Paper: Job Impacts of Spending on Public Transportation: An Update*. Boston: EDRG, April 29, 2009. Prepared for American Public Transportation Association, Washington, DC. On the web at http://www.apta.com/gap/policyresearch/Documents/jobs_impact.pdf.
EIA 2010 Minnesota Profile	U.S. Department of Energy. Energy Information Administration. *Minnesota Electricity Profile.* (DOE/EIA-0348(01)/2) Washington, DC: EIA, Assistant Administrator for Energy Statistics, Office of Electricity, Renewables, and Uranium Statistics, January 2012. On the web at http://www.eia.gov/electricity/state/minnesota and http://www.eia.gov/electricity/state/minnesota/pdf/minnesota.pdf. Chapter of *State Electricity Profiles 2010.* Links start at http://www.eia.gov/electricity/state. Full report at http://www.eia.gov/electricity/state/pdf/sep2010.pdf. • Table 3. Top Five Retailers of Electricity, with End Use Sectors, 2010 • Table 4. Electric Power Net Summer Capacity by Primary Energy Source and Industry Sector, 2000 and 2004 Through 2010 • Table 5. Electric Power Net Generation by Primary Energy Source and Industry Sector, 2000 and 2004 Through 2010 • Table 8. Retail Sales, Revenue, and Average Retail Prices by Sector, 2000 and 2004 Through 2010

EIA 2010 Levelized costs	U.S. Department of Energy. Energy Information Administration. *Levelized Cost of New Generation Resources in the Annual Energy Outlook 2011*. Washington, DC: EIA, November 2010. On the web at http://www.eia.gov/oiaf/aeo/electricity_generation.html, with link to http://www.eia.gov/oiaf/aeo/pdf/2016levelized_costs_aeo2011.pdf.
EIA 2010a	United States. Department of Energy. Energy Information Administration. *Annual Energy Outlook 2010 with Projections to 2035: Electricity Demand*. (DOE/EIA-0383(2010)) Washington, DC: EIA, May 11, 2010. On the web at http://www.eia.gov/oiaf/archive/aeo10/electricity.html, from links at http://www.eia.gov/oiaf/archive/aeo10/index.html. The Main report is at http://www.eia.doe.gov/oiaf/aeo/pdf/0383%282010%29.pdf.
EIA 2011 Assumptions	U.S. Department of Energy. Energy Information Administration. *Assumptions to the Annual Energy Outlook 2011*. (DOE/EIA-0554(2011)) Washington, DC: EIA, July 2011. On the web at http://www.eia.gov/forecasts/aeo/assumptions/pdf/0554(2011).pdf, from link at http://www.eia.gov/forecasts/aeo/assumptions/.
EIA 2011 FAQ	U.S. Department of Energy. Energy Information Administration. *Frequently Asked Questions: How much carbon dioxide (CO_2) is produced per kilowatt-hour when generating electricity with fossil fuels?* Washington, DC: EIA, December 6, 2011. On the web at http://www.eia.gov/tools/faqs/faq.cfm?id=74&t=11.
EIA Electric Power Annual 2009	U.S. Department of Energy. Energy Information Administration. *Electric Power Annual 2009.* (DOE/EIA-0348(2009)) Washington, DC: EIA, Assistant Administrator for Energy Statistics, Office of Electricity, Renewables, and Uranium Statistics, released: November 23, 2010; revised: January 2011, April 2011. On the web at http://www.eia.gov/electricity/annual/archive/03482009.pdf.
EIA Electric Power Annual 2010	U.S. Department of Energy. Energy Information Administration. *Electric Power Annual 2010.* [(DOE/EIA-0348(2010)) Washington, DC: EIA, [Assistant Administrator for Energy Statistics, Office of Electricity, Renewables, and Uranium Statistics], tables released November 9, 2011. On the web at http://www.eia.gov/electricity/annual. Full text not yet available. Table 1.2 Capacity by Energy Source, 2010
EIA Natural Gas 2004	U.S. Department of Energy. *The Basics of Underground Natural Gas Storage*. Washington, DC: EIA, latest update: August 2004. On the web at http://www.eia.gov/pub/oil_gas/natural_gas/analysis_publications/storagebasics/storagebasics.html
Elliott, Wendell, and Gower 1991	D. L. Elliott, L. L. Wendell, and G. L. Gower. *An assessment of the available windy land area and wind energy potential in the contiguous United States*. (PNNL-7789) Richland, WA: Pacific Northwest Laboratory, August 1991. Link on the web at http://www.osti.gov/energycitations/product.biblio.jsp?osti_id=5252760.
EnerNex 2004	EnerNex Corporation and Windlogics, Inc. *Xcel Energy and the Minnesota Department of Commerce Wind Integration Study – Final Report.* Knoxville, TN: EnerNex, September 28, 2004. On the web at http://archive.leg.state.mn.us/docs/2004/mandated/040541.pdf

EPRI-DOE 2004	*EPRI-DOE Handbook Supplement of Energy Storage for Grid Connected Wind Generation Applications. Technical Update.* (1008703) Palo Alto, CA: EPRI; Washington DC: U.S. Department of Energy, December 2004. On the web at http://mydocs.epri.com/docs/public/000000000001008703.pdf.
Ever-Green 2008	Ever-Green Energy. *St. Paul Cogeneration*. [Web page]. St. Paul, MN: Ever-Green Energy, 2008. On the web at http://www.ever-greenenergy.com/clients/cogeneration.html (accessed April 29, 2011). Main page and photo are at http://www.ever-greenenergy.com/solutions/powerplant.html.
EWITS 2011	EnerNex Corporation. *Eastern Wind Integration and Transmission Study.* Rev. (NREL/SR-5500-47078) Golden, CO: NREL, February 2011. On the web at http://www.nrel.gov/wind/systemsintegration/pdfs/2010/ewits_final_report.pdf.
EWITS Dataset	National Renewable Energy Laboratory. *[Eastern Wind Integration and Transmission Study: Time-Series, Land-based Dataset]*. [Golden, CO: NREL, no date]. On the web at ftp://ftp2.nrel.gov/pub/ewits/TimeSeries/LandBased, from links at http://www.nrel.gov/wind/integrationdatasets/eastern/data.html (NREL 2010).
Farrell 2010	John Farrell. *Community Solar Power: Obstacles and Opportunities.* Minneapolis, MN: The New Rules Project, September 2010. On the web at http://www.newrules.org/sites/newrules.org/files/communitysolarpower.pdf.
Farrell and Morris 2010	John Farrell and David Morris. *Energy Self-Reliant States*. 2nd & expanded ed. Minneapolis, MN: The New Rules Project, May 2010. On the web at http://www.newrules.org/sites/newrules.org/files/ESRS.pdf.
FERC 2010 Chippewa	U.S. Federal Energy Regulatory Commission. "Riverbank Minnesota, LLC; Notice of Preliminary Permit Application Accepted for Filing and Soliciting Comments, Motions to Intervene, and Competing Applications: Project No. 13654-000", *Federal Register* 75 (68) (April 9, 2010):18193. On the web at http://www.gpo.gov/fdsys/pkg/FR-2010-04-09/pdf/2010-8074.pdf. Accepted by the Commission on April 2, 2010.
FERC 2010 Granite	U.S. Federal Energy Regulatory Commission. "Riverbank Minnesota, LLC; Notice of Preliminary Permit Application Accepted for Filing and Soliciting Comments, Motions to Intervene, and Competing Applications: Project No. 13655-000", *Federal Register* 75 (68) (April 9, 2010):18189-18190. On the web at http://www.gpo.gov/fdsys/pkg/FR-2010-04-09/pdf/2010-8065.pdf. Accepted by the Commission on April 2, 2010.
FERC 2012 Chippewa	U.S. Federal Energy Regulatory Commission. "Riverbank Minnesota, LLC Project No. 13654-000: Order Cancelling Preliminary Permit", 138 *FERC* ¶ 62,038 (January 18, 2012). On the web at http://elibrary.ferc.gov/idmws/common/opennat.asp?fileID=12868366.
FERC 2012 Granite	U.S. Federal Energy Regulatory Commission. "Riverbank Minnesota, LLC Project No. 13655-000: Order Cancelling Preliminary Permit", 138 *FERC* ¶ 62,039 (January 18, 2012). On the web at http://elibrary.ferc.gov/idmws/common/opennat.asp?fileID=12868371.

FERC 2012 Permits	U.S. Federal Energy Regulatory Commission. *All Issued Preliminary Permits*. Washington, DC: FERC, updated 02/06/2012. On the web at http://www.ferc.gov/industries/hydropower/gen-info/licensing/issued-pre-permits.xls, from link at http://www.ferc.gov/industries/hydropower/gen-info/licensing.asp.
FERC Form 714	U.S. Federal Energy Regulatory Commission. *Form No. 714 - Annual Electric Balancing Authority Area and Planning Area Report*. Washington, DC: FERC, data accessed in 2009. Overview on the web at http://www.ferc.gov/docs-filing/forms/form-714/overview.asp and links to Data at http://www.ferc.gov/docs-filing/forms/form-714/data.asp.
Fink et al. 2009	S. Fink, C. Mudd, K. Porter, and B. Morgentern (Exeter Associates, Inc.). *Wind Energy Curtailment Case Studies:* May 2008 — May 2009. (Subcontractor Report NREL/SR-550-46716) National Renewable Energy Laboratory, U.S. Department of Energy, Golden, CO: NREL, 2009. On the web at http://www.nrel.gov/docs/fy10osti/46716.pdf.
Fosnacht 2010	Donald R. Fosnacht. *Pumped Hydro Energy Storage (PHES) Using Abandoned Mine Pits on the Mesabi Iron Range of Minnesota*. [presented at E3 Conference, St. Paul, MN, December 1, 2010.] [Duluth: Natural Resources Research Institute (NRRI), UMN Duluth, 2010]. On the web at http://www1.umn.edu/iree/e3/archive/archive_2010/E3_Fosnacht.pdf.
Fthenakis, Mason, and Zweibel 2009	Vasilis Fthenakis, James E. Mason, and Ken Zweibel. 2009. The technical, geographical, and economic feasibility for solar energy to supply the energy needs of the US. *Energy Policy* 37 (2):387-399.
Gandy 2000	Simon Gandy, *A guide to the range and suitability of electrical energy storage systems for various applications, and an assessment of possible policy effects, A report submitted in partial fulfillment of the requirements for the MSc and/or the DIC*, Imperial College of Science, Technology and Medicine (University of London), September 2000. Link on the web at http://www3.imperial.ac.uk/portal/pls/portallive/docs/1/7294737.PDF.
Giramonti et al. 1978	Albert J. Giramonti, Robert D. Lessard, William A. Blecher, and Edward B. Smith. "Conceptual design of compressed air energy storage electric power systems", *Applied Energy* 4 (4)(1978):231-249.
Greenblatt et al. 2007	Jeffery B. Greenblatt, Samir Succar, David C. Denkenberger, Robert H. Williams, and Robert H. Socolow. "Baseload wind energy: modeling the competition between gas turbines and compressed air energy storage for supplemental generation", *Energy Policy* 35 (2007): 1474–1492. "Available online 9 June 2006."

Hall et al. 2006	Douglas G.Hall, Kelly S.Reeves, Julie Brizzee, Randy D. Lee, Gregory R. Carroll, Garold L. Sommers. *Feasibility Assessment of the Water Energy Resources of the United States for New Low Power and Small Hydro Classes of Hydroelectric Plants.* (DOE-ID-11263) Idaho Falls: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Wind and Hydropower Technologies Program, Idaho Operations Office, January 2006. "Idaho National Laboratory." Links on the web at http://hydropower.inel.gov/prospector/index.shtml. Main report and Appendix A at http://hydropower.inel.gov/resourceassessment/pdfs/main_report_appendix_a_final.pdf and Appendix B Part 1 at http://hydropower.inel.gov/resourceassessment/pdfs/appendix_b_1_final.pdf and Appendix B Part 2 at http://hydropower.inel.gov/resourceassessment/pdfs/appendix_b_2_final.pdf.
Hawaii 2009	Hawaii. *Renewable Energy; Energy Efficiency*. Hawaii HB 1464 C.D. [Conference Draft] 1, signed into law in June 25, 2009. On the web at http://www.capitol.hawaii.gov/session2009/bills/HB1464_CD1_.htm or at http://www.capitol.hawaii.gov/session2009/Bills/HB1464_CD1_.pdf. Date signed from http://www.pewclimate.org/print/node/6694.
Interagency Task Force 2010	Interagency Task Force on Carbon Capture and Storage. *Report of the Interagency Task Force on Carbon Capture and Storage*. [Washington, DC: U.S. Department of Energy and U.S. Environmental Protection Agency, and others, August 2010. On the web at http://fossil.energy.gov/programs/sequestration/ccstf/CCSTaskForceReport2010.pdf and also at http://www.epa.gov/climatechange/downloads/CCS-Task-Force-Report-2010.pdf. Links to related documents at http://www.epa.gov/climatechange/policy/ccs_task_force.html.
ISEP Press Release 2011	Iowa Stored Energy Plant Agency. *Study Finds Iowa Stored Energy Park Cost Effective [Press Release]*, Des Moines, IA: ISEPA, January 17, 2011. On the web at http://www.isepa.com/ISEP%20Econ%20Study%20Press%20Release.pdf.
ISEP Study Summary 2011	Iowa Stored Energy Plant Agency. *Iowa Stored Energy Project (ISEP) Economics Study Summary*. Des Moines, IA: ISEPA, January 14, 2011. On the web at http://www.isepa.com/ISEP%20Economics%20Study%20Summary.pdf.
Kahn 1979	Edward Kahn. "The reliability of distributed wind generators", *Electric Power Systems Research* 2 (1)(1979):1-14.
KEMA 2007	Gerard Thijssen and Johan Enslin. *Cost Comparison for a 20 MW Flywheel-based Frequency Regulation Power Plant*. Final Report. Prepared by KEMA Inc. for Beacon Power Corporation. Raleigh, NC: KEMA Inc., September 12, 2007. On the web at http://www.beaconpower.com/files/KEMA_Report.pdf.

Klein 2011	Joel Klein. *Overview of the Energy Commission's Cost Of Generation Model*. [Presented at the] Cost of Generation Modeling Workshop, May 16, 2011. [Sacramento]: California Energy Commission, 2011. On the Web at http://www.energy.ca.gov/2011_energypolicy/documents/2011-05-16_workshop/presentations/Overview_of_Commission_COG_model.pdf.
Kueck et al. 2008	John D. Kueck, Brendan J. Kirby, Moonis R. Ally, and C. Keith Rice. *Using Air Conditioning Load Response for Spinning Reserve.* (ORNL/TM-2008/227) Oak Ridge, TN: Oak Ridge National Laboratory, 2008; published Feb. 2009. On the web at http://certs.lbl.gov/pdf/air-conditioning-load.pdf.
Lang 2010	Final Notes of conversation, 29 July 2010: Arjun Makhijani with Dr. William Lang, Strata Power Company, Yorkville, Illinois, reviewed and corrected by Dr. Lang. See Appendix to this report.
Lessons from Iowa 2012	Lessons from Iowa. *Lessons from Iowa.* Des Moines, IA, LFI, accessed February 7, 2012. On the web at www.lessonsfromiowa.org, with links to various materials, including: Robert H. Schulte, Nicholas Critelli, Jr., Kent Holst, and Georgianne Huff. *Lessons from Iowa: Development of a 270 Megawatt Compressed Air Energy Storage Project in Midwest Independent System Operator A Study for the DOE Energy Storage Systems Program*. (Sandia Report; SAND2012-0388) Albuquerque, NM: Sandia National Laboratory, January 2012. On the web at http://www.lessonsfromiowa.org/download.php?id=86.
LHB 2009	*Minnesota Sustainable Buildings 2030: Case Studies Metrics.* [Presentation to SB 2030 Advisory Board June 15, 2009.] [Minneapolis]: LHB, [2009]. On the web at http://www.mn2030.umn.edu/download/4-LHB-Draft%20Presentation%20Revised.ppt, from link at http://www.mn2030.umn.edu/presentations.html.
Lincoln Journal Star 2011	Algis J. Laukaitis. "NPPD plans to store compressed air underground for energy use", *Lincoln Journal Star*, October 14, 2011. On the web at http://journalstar.com/news/local/article_b37791e4-2198-5789-a795-d97d7869f209.html.
Maiser 2010	Eric Maiser. *Photovoltaic Production Equipment - Market and Technology Drivers.* Berlin: Federal Ministry of Economics and Technology, 2010. On the web at http://www.renewables-made-in-germany.com/fileadmin/termine/Messetermine/Presentations_Messetermine/SolarEnergy2010_Maiser.pdf
Makhijani 2010 CFNF	Arjun Makhijani. *Carbon-Free and Nuclear-Free: A Roadmap for U.S. Nuclear Policy.* 3rd printing. Takoma Park, MD: IEER Press, 2010. On the web at http://www.ieer.org/carbonfree/CarbonFreeNuclearFree.pdf. (First published in 2007. Reprinted in 2010, including the corrections made in the 2008 printing)
Makhijani 2010 eUtah	Arjun Makhijani. *eUtah: A Renewable Energy Roadmap*. Salt Lake City: HEAL Utah, December 14, 2010. On the web at http://www.ieer.org/reports/eUtah2010.pdf.

Makhijani 2011 OCT Declaration	Arjun Makhijani. *Declaration of Arjun Makhijani, Ph.D., In Support of Plaintiffs' Motion for Preliminary Injunction*. Signed September 26, 2011. On the web at http://www.ieer.org/comments/Makhijani_Declaration.2011.09.26-efficient-renewable-energy-system.pdf. Filed in United States District Court Northern District of California. Case No. C11-02203 EMC. Alec L., et al., Plaintiffs, vs. Lisa P. Jackson, et al., Defendants. November 21, 2011. Read more at: Our Children's Trust, at http://ourchildrenstrust.org/legal-action/lawsuits.
Mandel 2010	Jenny Mandel. "DOE Promotes Pumped Hydro as Option for Renewable Power Storage", *New York Times*, October 15, 2010. On the web at http://www.nytimes.com/gwire/2010/10/15/15greenwire-doe-promotes-pumped-hydro-as-option-for-renewa-51805.html (accessed April 29, 2011)
Mason et al. 2008	James Mason, Vasilis Fthenakis, Ken Zweibel, Tom Hansen and Thomas Nikolakakis. "Coupling PV and CAES Power Plants to Transform Intermittent PV Electricity into a Dispatchable Electricity Source", *Progress in Photovoltaics: Research and Applications* 16 (2008):649–668.
McNulty and Crooks 2007	Sheila McNulty and Ed Crooks, US Utilities Sceptical over Nuclear Plants, *Financial Times*, November 18, 2007.
Mills and Wiser 2010	Andrew Mills and Ryan Wiser. *Implications of Wide-Area Geographic Diversity for Short-Term Variability of Solar Power.* Berkeley, CA: Lawrence Berkeley National Laboratory, Energy Analysis Department, September 2010. On the web at http://eetd.lbl.gov/ea/emp/reports/lbnl-3884e-ppt.pdf. Presentation based on LBNL-3884E. Full report at http://eetd.lbl.gov/ea/emp/reports/lbnl-3884e.pdf.
Minn. Stat. § 216B.241, 2011	Minnesota. Office of the Revisor of Statutes. "216B.241 Energy Conservation Improvement", *2011 Minnesota Statutes*. On the web at https://www.revisor.mn.gov/statutes/?id=216B.241#stat.216B.241. Original 2008 text is at https://www.revisor.mn.gov/statutes/?id=216B.241&year=2008#stat.216B.241.9 . Subd. 9.Building performance standards; Sustainable Building 2030, at https://www.revisor.mn.gov/statutes/?id=216B.241#stat.216B.241.9.
Minn. Stat. § 216B.1612, 2011	Minnesota. Office of the Revisor of Statutes. "216B.1612 Community-Based Energy Development; Tariff", *2011 Minnesota Statutes*. On the web at https://www.revisor.mn.gov/statutes/?id=216b.1612.
Minn. Stat. § 216B.1691, 2011	Minnesota. Office of the Revisor of Statutes. "216B.1691 Renewable Energy Objectives", *2011 Minnesota Statutes*. On the web at https://www.revisor.mn.gov/statutes/?id=216b.1691.
Minn. Stat. § 216H.02, 2011	Minnesota. Office of the Revisor of Statutes. "216H.02 Greenhouse Gas Emissions Control", *2011 Minnesota Statutes*. On the web at https://www.revisor.mn.gov/statutes/?id=216H.02.
Minnesota 2003	*Minnesota Session Laws 2003, 1st Special Session, Chapter 11* [St. Paul]: Minnesota Office of the Revisor of Statutes, signed by the Governor May 29, 2003. On the web at https://www.revisor.mn.gov/bin/getpub.php?pubtype=slaw_chap&year=2003&session_number=1&chapter=11.

Minnesota PUC 2011	Minnesota Public Utilities Commission. *Before The Minnesota Public Utilities Commission: In the Matter of a Petition by Northern States Power Company d/b/a Xcel Energy For Approval of Power Purchase and Diversity Exchange Agreements with the Manitoba Hydro Electric Board, Order Approving Agreements*. (Docket No. E-002/M-10-633) St. Paul, MN: PUC, May 26, 2011. Search at https://www.edockets.state.mn.us/EFiling/edockets/searchDocuments.do?method=showeDocketsSearch&showEdocket=true. Document ID: 20115-62931-01.
Minnesota Transmission Owners 2008	Minnesota Transmission Owners. *Dispersed Renewable Generation Transmission Study*. (Docket Number E999/DI-08-649) Saint Paul, MN: Minnesota Department of Commerce, Office of Energy Security, June 16, 2008. Links on the web at http://www.state.mn.us/portal/mn/jsp/common/content/include/contentitem.jsp?contentid=536916459 (Use Internet Explorer to access.) [Phase I]
MIT 2006	Massachusetts Institute of Technology. *The Future of Geothermal Energy: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century: An Assessment by an MIT-led Interdisciplinary Panel*. Jefferson W. Tester, Chair. (INL/EXT-06-11746) Cambridge: MIT, 2006. On the web at http://geothermal.inel.gov/publications/future_of_geothermal_energy.pdf. Slide show based on this study is at www.nrel.gov/analysis/seminar/docs/2007/ea_seminar_mar_1.ppt.
MN DOC 2004	Minnesota. Department of Commerce. *Average solar radiation in Minnesota 1998-2002*. St. Paul: DOC, [2004?]. On the web at http://www.state.mn.us/mn/externalDocs/Commerce/MN_Solar_Map_110802025502_solarmap5.pdf, from link at http://www.mngeo.state.mn.us/chouse/utilities.html (*Public Utilities Infrastructure Information for Minnesota*, Minnesota Geospatial Information Office.) Accessed November 21, 2011.
MN DOC 2006	Minnesota. Department of Commerce. *Wind Maps*. St. Paul: DOC, maps published January 2006; accessed October 14, 2011. On the web at http://www.state.mn.us/portal/mn/jsp/content.do?contentid=536887066&contenttype=EDITORIAL&agency=Commerce. • 80-meter 2006 wind speed map, at http://www.state.mn.us/mn/externalDocs/Commerce/80_Meter_Wind_Speed_013106115153_80MeterWindSpeed.pdf • 100-meter 2006 wind speed map, at http://www.state.mn.us/mn/externalDocs/Commerce/100_Meter_Wind_Speed_013106115814_100MeterWindSpeed.pdf.
MN DOC 2009	Minnesota. Office of Energy Security. *Minnesota Solar Electric Rebate Program Report 2002-2008*. St. Paul, MN: Minnesota Department of Commerce, April 8, 2009. On the web at http://www.state.mn.us/mn/externalDocs/Commerce/MN_Solar_Electric_Rebate_Report_040809051301_MinnesotaSolarElectricRebateProgram.pdf.

MN DOC 2010a	Minnesota. Office of Energy Security. *Report on the Cost Effectiveness and Progress of the Sustainable Building 2030 Standards: Report to the Minnesota Legislature Submitted Pursuant to Minnesota Statute §216B.241, Subd. 9*. St. Paul: Minnesota Department of Commerce, Februray 18, 2010. On the web at http://www.state.mn.us/mn/externalDocs/Commerce/Sustainable_Buildings_2030_CostEffectiveness_Report_021810031731_SB2030_Cost_Effectiveness_Report.pdf.
MN Exec. Order 11-14	Minnesota. Executive Department. *Executive Order 11-14: Continuing the Office of Energy Security as the Division of Energy Resources Within the Department of Commerce* / Mark Dayton, Governor. St. Paul, Governor, April 8, 2011. On the web at http://mn.gov/governor/multimedia/pdf/EO-11-14.pdf.
MN Solar Guide 2001	*Small Solar Electric Systems: A Minnesota Guide*. [St. Paul: Minnesota Department of Commerce?, 2001?]. On the web at http://www.state.mn.us/mn/externalDocs/Commerce/Small_Solar_Electric_Systems_A_MN_Guide_032103025940_GuidetoSolarElectric.pdf.
Montgomery 2012	James Montgomery. "CPS Energy Partners with OCI Solar Power on 400-MW Project", *RenewableEnergyWorld.com*, January 12, 2012. On the web at http://www.renewableenergyworld.com/rea/news/article/2012/01/cps-energy-partners-with-oci-solar-power-on-400-mw-project.
MSBG 2009	*The State of Minnesota Sustainable Building Guidelines: Buildings, Benchmarks & Beyond.* Version 2.1. Minneapolis: Center for Sustainable Building Research, College of Design, University of Minnesota, December 21, 2009. Links on the web at http://www.msbg.umn.edu/guidelines.html. PDF at http://www.msbg.umn.edu/downloads_v2_1/B3-MSBG_V2-1.pdf.
NAS 2010	*Electricity from Renewable Resources: Status, Prospects, and Impediments*. America's Energy Future Panel on Electricity from Renewable Resources; National Academy of Sciences; National Academy of Engineering; National Research Council. Washington, DC: National Academies Press, 2010. On the web at http://www.nap.edu/openbook.php?record_id=12619.
New York 2010	New York (State). Public Service Commission. *Case 03-E-0188 - Proceeding on Motion of the Commission Regarding a Retail Renewable Portfolio Standard. Order Establishing New RPS Goal and Resolving Main Tier Issues* (Issued and Effective January 8, 2010). "At a session of the Public Service Commission held in the City of Albany on December 16, 2009." On the web at http://documents.dps.ny.gov/public/Common/ViewDoc.aspx?DocRefId={30CFE590-E7E1-473B-A648-450A39E80F48}, from link at http://www3.dps.ny.gov/W/PSCWeb.nsf/All/1008ED2F934294AE85257687006F38BD?OpenDocument.
Next Generation Energy Act of 2007	Minnesota. Office of the Revisor of Statutes. *Laws of Minnesota for 2007, Chapter 136–S.F.No. 145.* On the web as https://www.revisor.mn.gov/data/revisor/slaws/2007/0/136.pdf. Cited as Next Generation Energy Act of 2007.

NHA 2011	National Hydropower Association. "NHA applauds Administration funding announcement to increase hydro development." *Press Release.* Washington, DC: NHA, April 7, 2011. On the web at http://hydro.org/wp-content/uploads/2011/04/110407-DOE_DOI-Funding-Final.pdf.
NREL 2006	Paul Denholm. *Creating Baseload Wind Power Systems Using Advanced Compressed Air Energy Storage Concepts*. CU Energy Initiative/NREL Symposium, University of Colorado, Boulder. (NREL/PO-640-40674) Golden, CO: National Renewable Energy Laboratory, October 3, 2006. On the web at http://www.nrel.gov/docs/fy07osti/40674.pdf.
NREL 2008	National Renewable Energy Laboratory. *Annual Report on U.S. Wind Power Installation, Cost, and Performance Trends: 2007.* (DOE/GO-102008-2590) U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, May 2008. On the web at http://www.nrel.gov/docs/fy08osti/43025.pdf.
NREL 2011	*Wind Systems Integration – Energy Storage and Wind Power*. [Web page]. Golden, CO. National Renewable Energy Laboratory, updated July 19, 2011. On the web at http://www.nrel.gov/wind/systemsintegration/energy_storage.html.
NREL and AWS Truepower 2011	National Renewable Energy Laboratory and AWS Truepower. *Estimates of Windy Land Area and Wind Energy Potential by State for Areas*. [Golden, CO]: NREL; [Albany, NY]: AWS Truepower, February 4, 2010, updated April 13, 2011 to add Alaska and Hawaii. On the web at http://www.windpoweringamerica.gov/docs/wind_potential.xls, with link from http://www.windpoweringamerica.gov/wind_resource_maps.asp?stateab=mn. See various tabs for 80m or 100m heights.
NREL and LBNL 2012	Ryan Wiser, Eric Lantz, Mark Bolinger, and Maureen Hand. *Recent Developments in the Levelized Cost of Energy from U.S. Wind Power Projects*. Golden, CO: National Renewable Energy Laboratory; Berkeley, CA: Lawrence Berkeley National Laboratory, February 2012. On the web at http://eetd.lbl.gov/ea/ems/reports/wind-energy-costs-2-2012.pdf.
NRRI 2011	Donald R. Fosnacht and PHES Study Team. *Pumped Hydro Energy Storage (PHES) Using Abandoned Mine Pits on the Mesabi Iron Range, Minnesota: Final Report*. (NRRI/TR-2011/50) Duluth: Natural Resources Research Institute (NRRI), University of Minnesota, Duluth, November, 2011. Links to 8 parts on the web at http://www.nrri.umn.edu/egg/REPORTS/TR201150/TR201150.html. Part 1 is at http://www.nrri.umn.edu/egg/REPORTS/TR201150/Part1_NRRITR201150.pdf.
NSRDB 1991-2005	National Renewable Energy Laboratory. *National Solar Radiation Data Base 1991-2005 Update: Typical Meteorological Year 3.* Golden, CO: NREL, [2006?]. On the web at http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/by_state_and_city.html, from link at http://www.nrel.gov/rredc/solar_data.html.
NWCC 1997	National Wind Coordinating Commitee. "Wind Energy Resources", *Wind Energy Series* no. 4 (January 1997). On the web at http://www.nationalwind.org/assets/archive/Issue_Paper_4.pdf.

NY DOT 2012	New York (State). Department of Transportation. *Jobs Created and Employment Reporting*. [Albany?]: DOT, accessed March 7, 2012. On the web at https://www.dot.ny.gov/recovery/jobs. At head of title: Recovery Act: Economic Recovery.
Nyquist 2009	Thomas Nyquist. *Princeton University and Smart Grid, CHP, and District Energy*. [Presented at the U.S. EPA Combined Heat and Power Partnership 2009 Partners Meeting & NYSERDA CHP Roundtable, October 1-2, 2009, New York, NY.] [Princeton]: Facilities Engineering, Princeton University, [2009]. On the web at http://www.epa.gov/chp/documents/meeting_100209_nyquist.pdf, from link at http://www.epa.gov/chp/events/meeting_oct0109.html.
NYT 2011	Todd Woody. "Solar on Water", *New York Times*, April 19, 2011. On the web at http://www.nytimes.com/2011/04/20/business/energy-environment/20float.html?scp=1&sq=floatovoltaics&st=cse.
NYT 2012	Peter Applebome. "Drilling Critics Face a Divide Over the Goal of Their Fight", *New York Times*, January 9, 2012 (printed January 10, 2012, p. 17). On the web at http://www.nytimes.com/2012/01/10/nyregion/gas-drilling-critics-in-new-york-face-a-divide-over-their-goal.html.
OECD 2010	Organisation for Economic Co-operation and Development (OECD). "Balance of Payments (MEI) – Current Account Balance", *OECD.StatExtracts*, data accessed November 3, 2010. On the web at http://stats.oecd.org/Index.aspx. Go to tab for "International Trade and Balance of Payments."
Parker 2001	Carl D. Parker. "Lead-acid battery energy-storage systems for electricity supply networks", *Journal of Power Sources* 100 (1-2)(2001):18-28.
Peabody Net-Zero	David Peabody. *How to Build a Net-Zero House*. Alexandria, VA: Peabody Architects, March 24, [year?]. On the web at http://www.greenhaus.org/blog/building-a-net-zero-house.
Pew 2010	Pew Charitable Trusts. *Who's Winning the Clean Energy Race? Growth, Competition and Opportunity in the World's Largest Economies: G-20 Clean Energy Factbook.* Washington, DC: Pew, 2010. On the web at http://www.pewtrusts.org/uploadedFiles/wwwpewtrustsorg/Reports/Global_warming/G-20%20Report.pdf.
PG&E 2009	Jonathan Marshall. "PG&E Opts for Energy Storage", *Next 100 – A Dialogue on the Next Century of Energy*. San Francisco, CA: Pacific Gas and Electric Co., August 26, 2009. On the web at http://www.facebook.com/note.php?note_id=118611308007. Formerly at http://www.next100.com/2009/08/pge-opts-for-energy-storage.php (accessed May 2, 2011).

PG&E Form 10-K, 2010	PG&E Corporation and Pacific Gas and Electric Company. *Form 10-K*: For the Fiscal Year Ended December 31, 2010. Annual Report Pursuant To Section 13 Or 15(D) of the Securities Exchange Act of 1934. Submitted to the United States Securities and Exchange Commission. San Francisco: PG&E, February 17, 2011. On the Web at http://www.sec.gov/Archives/edgar/data/1004980/000119312511038959/d10k.htm. Also available from a link at http://investor.pgecorp.com/phoenix.zhtml?c=110138&p=irol-sec (search Annual Filings, for PDFs and Excel files).
Pollin et al. 2008	Robert Pollin, Heidi Garrett-Peltier, James Heintz, and Helen Scharber. *Green Recovery: A Program to Create Good Jobs and Start Building a Low-Carbon Economy*. Amherst: Political Economy Research Institute (PERI), University of Massachusetts; Washington, DC: Center for American Progress, September 2008. On the web at http://www.peri.umass.edu/fileadmin/pdf/other_publication_types/peri_report.pdf, from link at http://www.peri.umass.edu/green_recovery.
Reichling and Kulacki 2008	J. P. Reichling and F. A. Kulacki. "Utility scale hybrid wind-slar thermal electrical generation: A case study for Minnesota." *Energy* 33 (4)(2008):626-638.
Rosenfeld 2008	Arthur Rosenfeld. *Energy Efficiency: the first and most profitable way to delay Climate Change: The Indus Entrepreneur.* Sacramento, California Energy Commission, July 21, 2008. On the web at http://www.energy.ca.gov/2008publications/CEC-999-2008-017/CEC-999-2008-017.PDF.
Runyon 2010	Jennifer Runyon. "Will Clean Energy Manufacturing Create US Jobs?" *RenewableEnergyWorld.com*, November 1, 2010. On the web at http://www.renewableenergyworld.com/rea/news/article/2010/11/will-clean-energy-manufacturing-create-us-jobs.
Sandia 2001	Sandia National Laboratory. *Sandia assists with mine assessment: Solution to some of country's energy woes might be little more than hot air*. (News Releases) Albuquerque, NM: Sandia, April 24, 2001. On the web at http://www.sandia.gov/media/NewsRel/NR2001/norton.htm.
Schott 2012	Matthew Kraft (Schott North America). "Solar PV manufacturing jobs." Email to Lois Chalmers, February 24, 2012, 11:04 AM.
Science House 2008	U.S. Department of Energy. Office of Energy Efficiency and Renewable Energy. Building Technologies Program. *Science House at the Science Museum of Minnesota*. [Washington, DC: DOE, EERE, BTP, October 30, 2008. Web page banner: Zero Energy Buildings Database. Overview, at http://zeb.buildinggreen.com/overview.cfm?ProjectID=284. Process, at http://zeb.buildinggreen.com/process.cfm?ProjectID=284. Finance, at http://zeb.buildinggreen.com/finance.cfm?ProjectID=284. Energy, at http://zeb.buildinggreen.com/energy.cfm?ProjectID=284. Indoor Environment, at http://zeb.buildinggreen.com/indoorenv.cfm?ProjectID=284.

Science Museum of Minnesota 2011	Science Museum of Minnesota. *Science House: A Resource for Educators*. St. Paul: SMM, 2011. On the web http://www.smm.org/sciencehouse. (all accessed on November 9, 2011). Also: "How Science House Works", at http://www.smm.org/sciencehouse/about. "District Membership to Science House", at http://www.smm.org/sciencehouse/members.
SEIA and GTM Research 2011	Solar Energy Industries Association and GTM Research. *U.S. Solar Market Insight Report, Q3 2011. Executive Summary*. [Washington, DC]: SEIA; [Boston?]: GTM Research, [2011?]. On the web at http://www.seia.org/galleries/pdf/SMI-Q3-2011-ES.pdf.
Smith et al. 2007	J. Charles Smith, Michael R. Milligan, Edgar A. DeMeo, and Brian Parsons. "Utility Wind Integration and Operating Impact State of the Art", *IEEE Transactions on Power Systems,* 22 (3) (August 2007):900-908.
Sobieski and Bhavaraju 1985	D. W. Sobieski and M. P. Bhavaraju. "An Economic Assessment of Battery Storage in Electric Utility Systems", *IEEE Transactions on Power Apparatus and Systems* PAS-104 (12)(December 1985):3453-3459.
Sørensen 1978	Bent Sørensen. "On the fluctuating power generation of large wind energy converters, with and without storage facilities", *Solar Energy* 20 (4)(1978):321-331.
Sovacool 2009	Benjamin K. Sovacool. "The intermittency of wind, solar, and renewable electricity generators: Technical barrier or rhetorical excuse?" *Utilities Policy* 17 (3-4) (2009):288-296.
St. Cloud 2008	City of St. Cloud Public Utilities Department. "Hydroelectric Generation Facility." St. Cloud, MN, June 2008. Formerly on the web at http://www.ci.stcloud.mn.us/Utilities/docs/Hydro-FINAL080611.pdf.
Stoddard et al. 2006	L. Stoddard, J. Abiecunas, R. O'Connell. *Economic, Energy, and Environmental Benefits of Concentrating Solar Power in California: May 2005 – April 2006*. (NREL/SR-550-39291) Golden, CO: National Renewable Energy Laboratory, April 2006. On the web at http://www.nrel.gov/docs/fy06osti/39291.pdf.
Stodola and Modi 2009	Nathan Stodola, and Vijay Modi. 2009. Penetration of solar power without storage. *Energy Policy* 37 (11):4730-4736.
Succar and Williams 2008	Samir Succar and Robert H. Williams. *Compressed Air Energy Storage: Theory, Resources and Applications for Wind Power*. Princeton: Energy Systems Analysis Group, Princeton Environmental Institute, Princeton University, 8 April 2008. On the web at http://www.princeton.edu/pei/energy/publications/texts/SuccarWilliams_PEI_CAES_2008April8.pdf.
Šúri et al. 2007	Marcel Šúri, Thomas A. Huld, Ewan D. Dunlop, and Heinz A. Ossenbrink. "Potential of solar electricity generation in the European Union member states and candidate countries." *Solar Energy* 81 (2007):1295-1305. On the web at http://re.jrc.ec.europa.eu/pvgis/doc/paper/2007-se_suri_etal_pv_in_eu.pdf.

TVA Hydro	Tennessee Valley Authority. *Hydroelectric Power*. Knoxville: TVA, [undated]; accessed November 22, 2011. Links on the web at http://www.tva.gov/power/hydro.htm, to the image at http://www.tva.gov/power/pumpstorart.htm.
UPI 2009	"Study: Sunlight can turn CO_2 into methane", *UPI.com*, March. 5, 2009. On the web at http://www.upi.com/Science_News/2009/03/05/Study-Sunlight-can-turn-CO2-into-methane/UPI-53941236265473/.
Walawalkar, Apt, and Mancini 2007	Rahul Walawalkar, Jay Apt, and Rick Mancini. "Economics of electric energy storage for energy arbitrage and regulation in New York", *Energy Policy* 35 (4)(2007):2558-2568.
Wind Integration 2006 v.I	EnerNex Corporation. *Final Report – 2006 Minnesota Wind Integration Study Volume I.* Knoxville, TN: EnerNex, November 30, 2006. On the web at http://archive.leg.state.mn.us/docs/2007/mandated/070001/volumeI.pdf. Prepared for the Minnesota Public Utilities Commission, in collaboration with the Midwest Independent System Operator.
Wind Integration 2006 v.II	WindLogics. *Final Report – 2006 Minnesota Wind Integration Study Volume II: Characterizing the Minnesota Wind Resource.* St. Paul, MN: WindLogics, November 30, 2006. On the web at http://archive.leg.state.mn.us/docs/2007/mandated/070001/volumeII.pdf. Prepared for the Minnesota Public Utilities Commission.
Wiser and Bolinger 2011	Ryan Wiser and Mark Bolinger. *2010 Wind Technologies Market Report*. (DOE/GO-102011-3322; LBNL-4820E) Golden, CO: National Renewable Energy Laboratory; U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, June 2011. On the web at http://www1.eere.energy.gov/wind/pdfs/51783.pdf or http://eetd.lbl.gov/ea/emp/reports/lbnl-4820e.pdf. From http://eetd.lbl.gov/ea/emp/re-pubs.html.
WWSIS 2010	GE Energy. *Western Wind and Solar Integration Study*. (Subcontractor Report NREL/SR-550-47434). Golden, CO: National Renewable Energy Laboratory, May 2010. On the web at http://www.nrel.gov/wind/systemsintegration/pdfs/2010/wwsis_final_report.pdf, from link at http://www.nrel.gov/wind/systemsintegration/wwsis.html.
Xcel 2007	Xcel Energy. *2007 Resource Plan*. (Docket No. E002/RP-07-1572) St. Paul, MN: MN Public Utilities Commission, December 14, 2007. Search at https://www.edockets.state.mn.us/EFiling/edockets/searchDocuments.do?method=showeDocketsSearch&showEdocket=true. Document IDs: 4870622 RP Xcel Energy Initial Filing--Resource Plan - Section 1 4870625 RP Xcel Energy Initial Filing--Resource Plan - Section 3

Xcel 2010a	Xcel Energy. "2010 Resource Plan (Docket No. E002/RP-10-825)." St. Paul, MN: MN Public Utilities Commission, August 2, 2010. Also available as *Application for Resource Plan Approval 2011 – 2025 Application. Docket Number: EOO2/RP-1O-. Northern States Power Company-Minnesota, an Xcel Energy Company.* On the web at http://www.xcelenergy.com/staticfiles/xe/Regulatory/Upper_Midwest_Resource_Plan.pdf.
Xcel 2010b	Xcel Energy. "Petition for Approval of Power Purchase And Diversity Exchange Agreements With Manitoba Hydro (Docket No. E002/M-10-633)". Minneapolis: Xcel, June 10, 2010. Available through the Minnesota Public Utilities Commission. Search at https://www.edockets.state.mn.us/EFiling/edockets/searchDocuments.do?method=eDocketsResult&userType=public#. Document I.D: 20106-51457-02 (Public)
Xcel Saver's Switch 2011	Xcel Energy. *Saver's Switch for Residences – MN*. [Minneapolis]: Xcel, 2011. On the web at http://www.xcelenergy.com/Save_Money_&_Energy/Find_a_Rebate/Saver%27s_Switch_for_Residences_-_MN. Formerly at http://www.xcelenergy.com/Save_Money_&_Energy/For_Your_Home/Heating_&_Cooling/Saver%27s_Switch_-_MN. (accessed September 23, 2011).
Yang and Jackson 2011	Chi-Jen Yang, and Robert B. Jackson. "Opportunities and barriers to pumped-hydro energy storage in the United States", *Renewable and Sustainable Energy Reviews* 15 (2011):839-844. On the web at http://www.duke.edu/~cy42/PHES.pdf.
Zeller 2010	Tom Zeller Jr. "Can We Build in a Brighter Shade of Green?" *New York Times*, September 25, 2010. On the web at http://www.nytimes.com/2010/09/26/business/energy-environment/26smart.html (accessed April 29, 2011)

Appendix

Final Notes of Conversation, 29 July 2010:
Arjun Makhijani with Dr. William Lang, Strata Power Company, Yorkville, Illinois
(reviewed and corrected by Dr. Lang)

Dr. Lang: I have been a geological consultant since the 1960s. I started working on the Iowa compressed air storage theme in 1985 and brought it under the Iowa association of municipal utilities in 2003. I had a patent issue with aquifer storage in as far back as 1970. I spent years dealing with turbomachinery manufacturers modifying their equipment for CAES. I have spent a lot of time chasing reservoirs for CAES all over, but I have spent the most time in Indiana, Illinois and Iowa. I have also worked on aquifer natural gas storage.

Arjun: Please tell me about compressed air storage in aquifers. It seems the Iowa project is in an aquifer.

Dr. Lang: It has to be a high permeability, very clean aquifer to give the deliverability of the air needed. I had located aquifers in Indiana and Illinois and acquired several of them for development. There was one in Indiana, but it turned out to have oil in it. In fact, several have turned up having oil-- that disqualifies them. If they have natural gas it can be displaced but for oil if it cannot be displaced; you can get reactions and oxidation. If you want to store air you have to find and test the reservoir and make it ready to go. It costs about $20 million and takes 5 years to do that.

I dealt with CAES in the 1970s with the AEC – they were looking at peak shaving. I had a deal with the AEC – if we could get a utility to agree to use it, the AEC would chip in 15%. But then ERDA was formed and it confused the whole matter.

TVA was looking at storage issues with the Gas Research Institute. They concluded it would be a problem if there was oil in the aquifer but natural gas would not prevent CAES use. The water does not become contaminated as a result of gas storage because the gas bubbles off with short term surface storage. The formation water in most of the natural gas storage reservoirs is not polluted but is generally non potable because of salinity or a high level of dissolved solids. If and when it comes along with the gas production it is reinjected into other formations with non potable water

In any case, the site at Vincent, Iowa is a super clean site. There is sandstone and no clay. There is a problem if there is too much clay since it reduces the permeability. You need a minimum permeability of 1,000 millidarcys. With today's technology you could be go down to 600. The Iowa sedimentary formation has a permeability of 9000 to 12,000 millidarcys. It is better than any that I have run into.

For a private developer to develop a storage site at reasonable cost you need good subsurface information. Most states don't have good records for subsurface. But Illinois has a high level of underground knowledge. In fact I was the first chair of Illinois Map Advisory Committee. Then it became a multistate program. There is a five-state geological advisory group in this region now.

A gas company agreed to sell me the Vincent reservoir with some natural gas in it. I bought it for CAES and started to put the utilities together. I had Betchel and AEP and Siemens and they were ready to buy it in 2000. But they did not want to develop it. Rather they planned to flip it in a year at a high profit. I didn't go along with that so I got 40 municipal utilities together to contract to go ahead with it. We started work and they put a couple million dollars into it and Strata Power about the same into drilling, rock testing, seismic work and reservoir modeling.

There is vast experience with storage of natural gas in aquifer formations. There are 20-some in this area that have big amounts of storage in them. Redfield in Iowa has 129 billion standard cubic feet of natural gas in it. There is a big one, Manlove in Illinois that has 160 billion cubic feet. There are many others. But you can't withdraw the total stored gas. Typically, in aquifer storage, the working gas is only 30% of the total. So In an aquifer they average 70 percent non-recoverable pad gas. The worst of them go up to 80 per or even 87 percent non-recoverable pad gas. In salt domes only about 1/3 is pad gas.

It is the same in Iowa. The non-working gas is part of the capital investment. This may be as much as a third of the cost of developing a natural gas storage field in aquifers. So that is the bad part – you need two feet of pad gas for every one foot of working gas. The rest may be unrecoverable. For instance, one reason for loss of gas is if there are clays in the formation which won't let the gas return.

Water in the Vincent reservoir in Iowa that I want to develop for CAES is exceedingly pure. It is even better than the Jordan formation, which is well known for purity. The St. Peter Formation at Vincent has only 1100 ppm TDS (total dissolved solids). And they would not let you inject natural gas in there today. (Air might be different). The Vincent Formation is so clean that you can get 65 percent working gas. Most of the gas people have not done gravel packed wells and horizontal wells. They would get a larger percentage of working gas that way. I worked on a well near Washington, D.C. We put inert gas and we got 80 million standard cubic feet per day (scf/d) because we completed the well with gravel packing.

Lang: The storage pressure depends on the virgin pressure of the aquifer [the pressure before gas is put into it.] There must be a delta-P above the aquifer pressure. It is potentially a variable volume-constant pressure storage system. Like a balloon in the deep sea. Even if you withdraw gas, it stays at a constant pressure but shrinks in volume.

The delta-P is typically 80 psi or 60 psi. The aquifer I am working with has a 465 psi virgin pressure. But I can pull the gas pressure below that down 300 psi when withdrawing gas. In storing the gas, you may have to go only 60 psi above the virgin pressure depending on how many wells you have.
In Illinois natural gas storage they typically go 100 psi over and that much under the virgin pressure.

Arjun: Is the Vincent, Iowa, site different than the one the Iowa Energy Storage Project is now looking at?

Dr. Lang: Yes, Vincent is different from Dallas County. Vincent is near Fort Dodge. The west boundary of the field has a fault and they thought that if they let the bubble get big enough it might hit the fault and leak. But they drilled a well on the other side of the fault to see if it leaked up the fault; it did not. Lots of natural gas storage wells have faults near them and they do not leak. The utilities have selected Dallas County but it has not been thoroughly tested and drilled yet.

So now I am looking at air storage again. I have worked with the McIntosh, Alabama plant and know it well. They have a salt cavern. But our aquifer would work about the same. They are now using the McIntosh plant as a balancing plant and not for peak shaving. It has much higher value that way. The plant can go from cold start to full power in seven minutes, and so it is extremely flexible. High temperature gas turbines cost 30,000 to 40,000 dollars to start up. CAES is cheap. It is worth a lot more for ancillary properties than for day-night arbitrage.

The Midwest ISO is oriented to green energy. They have taken over lines of MidAmerican and Xcel. They have an awful lot of wind generation. Wind needs storage to be efficient and useful. Because winds can be regional they can fall out on everybody at the same time and need expensive backup if there is no storage. And CAES could be used in the Midwest ISO region.

I have talked to several utilities; MidAmerican and Xcel said they are interested [in the Vincent reservoir]. But they say they are pretty well fixed up until 2015. But now ISEP is also saying 2015. The Midwest ISO is going to have ancillary nightmares. They will deal with independents. You can buy electricity off their lines and then sell it back to them. The value of balancing will be much greater than overnight arbitrage. I think we can buy and sell within the state so we don't have to deal so much with the Federal Energy Regulatory Commission. Perhaps there might be interstate transmission issues.

For overnight arbitrage services, we could go up to 800 MW of capacity with 10 to 15 hours of storage per day. If you wanted baseload type of supply – you would have to increase storage to 30 or 40 hours or more. We could probably go up to 2,000 MW for ancillary services at Vincent. We can have regulation output and hot spinning reserves. These do not require much volume. Moreover, aquifer storage can be expanded very easily. You can drill to enlarge the bubble by longer charging cycles and then add new wells in short order within the expanded bubble. In contrast, open caverns are a nightmare to expand.

Right now I am thinking of doing CAES as an independent with private financing. Some banks have expressed interest in it. I think I could put in an adiabatic system faster and cheaper than anyone might imagine

Arjun: What would it cost to build the system?

Dr. Lang: If it were set up for ancillary services the installed cost per kW probably would be about $1,200-1400 per kW. But you have to start with geological knowledge. National Wind is doing projects in North Dakota and Deutsche Bank is financing them. But the underground information there is so limited. It would cost a fortune to develop the UG information and take five years. So I said I wouldn't go there. Illinois has all the records.

Arjun: How about Minnesota aquifers?

Dr. Lang: You start running into hard rock there. Minnesota has a small aquifer natural gas storage facility – very small. They had a bigger potential site that crossed state lines and they decided they could not live with two jurisdictions.

Minnesota doesn't have so many prospects because the sediments are thin, but there are possibilities there. It takes sophisticated exploration techniques.

Arjun: Have there been environmental problems with compressed gas storage in aquifers?

Dr. Lang: Not really. There are water disposal problems in some cases. Water comes up at the end of the season, not regularly. At the end of the second season it is typically much less. They like to pump the natural gas down to the last bit of gas at the end of the winter season, but with CAES you don't have to pump it down.

You get water mostly when you get toward the end of the working gas. If the water is of poor quality – for instance, if it is less than potable and has more than 9000 ppm total dissolved solids, then you have to consider how you are going to dispose of it.

The company I acquired the Vincent field from were simultaneously developing Vincent and Red Field and they wanted 36 billion cubic feet at this Vincent. The sand at Vincent was so clean at that after they perforated the casing and acid treated the well to remove the drilling mud they also removed the small amount of calcite cement. That leaves the gas coming out at a high volume and they were pulling sand out. And they did not like that. Baker Hughes had a new sand consolidation treatment which was tried and reduced the per well deliverability by about 90%. This led to plans to abandon the field and resulted in Strata Power purchasing it.

In Minnesota the water is generally good. So you will not be disposing off polluted water or brackish water or oily water. So this would not be a problem. But they don't have to store green energy in Minnesota when the major markets are to the east . They can store it in places along the transmission lines. My reservoir [in Iowa] is along the way. Xcel had an RFP for load following for 1000 MW in 2002. Strata Power and Ridge Energy prepared a response for using Vincent but withheld it at the last minute because we did not feel that it fit the RFP objectives close enough and we thought it wouldn't get the proper evaluation.

Arjun: What about seismicity? Do you induce it if you build compressed air storage in aquifers?

Dr. Lang: No. Aquifers are funny – half a mile away there is no influence on water pressure or anything else. The storage space is created largely by the compression of millions of gallons of surrounding water by only a few parts per million. Water is compressible but only slightly. They have had extremely low problems with natural gas storage. Some have leaked. The Herscher Dome supplying Chicago used to leak 17 % per year. I worked on this problem with a consulting firm and mitigated the problem. The main problem may be the formation water that comes with the gas, as I've said. Normally this water is injected into underground formations that also have non potable water. But with sedimentary formations which have pure water, there would be no problem. Webster County, Iowa Conservation Department wants to use any excess water we have for a new duck pond which may go dry in the fall.

We take a lot of precautions. You have to put telescoping casing to protect all the groundwater zones along the way to the storage site. The first casing is 20 inches in diameter; the next is 10.5 inches, and then it gets smaller. You cement at each stage. This protects the groundwater zones along the way. I would be glad to send you the well designs to show you how they protect the ground water.

Arjun: How about the drilling mud? Does it have toxic chemicals?

Dr. Lang: Drilling mud is not a problem in this kind of work because you don't have to have complicated drilling muds. I have many patents in drilling muds. In this case it is not a problem. We sent drilling mud at Vincent to the local landfill and they were happy to have it to help seal the floor of the landfill.

Arjun: Thanks ever so much for your time. I will send you a copy of my book, Carbon-Free and Nuclear-Free as a token of my appreciation for your time and expertise and send you my notes for correction.

Dr. Lang: It was good to talk to you.