

NYSERDA PON 1208: Category D

Using Electric Pipelines to Create a Regional HVDC Grid

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Critical Issue Overview

The proposed project seeks to address the solicitation for the Policy Track of Advanced Concepts, to develop precommercial, enabling technologies necessary for practical investment in—and modernization of—the regional grid of which New York is a part, and upon which we rely for much of our electric power. Overhead transmission lines grow more controversial each year, while at the same time, the economic incentive to transport bulk power grows. It becomes increasingly more difficult to site new powerlines of any power rating, and it is particularly difficult to site new high voltage lines. The theoretical limit for conventional, overhead transmission has nearly been reached, yet there exists the need for more transfer capacity. Rethink Technologies, Inc. proposes to first explore, and then ultimately to develop a plan for a regional HVDC loop based on electric pipelines to provide a practical technology manufacturable in New York, with a regional implementation plan that will allow New York to effectively share power with the entire eastern US grid.

The types of electric pipelines that this proposal addresses (based on extruded aluminum conductors) could economically send 10-50 GW of power 2000 km, depending on how much aluminum is used per km. Table 1 shows the results of a simplified calculation of transfer capacity versus amount of aluminum used in the conductors for a ±800 KV, 2000 km linear design. For the 10 GW case, at 10% resistive loss and ±800 KV, a 2000 km HVDC electric pipeline would use 10.8 cubic meters of aluminum per mile. Based on the 1/16/2009 Commodity Exchange price for Aluminum of \$1.446/kg, this implies a direct cost for aluminum of \$39,500 per km. The preferred layout of such a high capacity HVDC powerline is a loop, which automatically provides redundant connections, as is required by contingency planning. Eventually, major power sources and sinks inside the loop could be tied in with power lines that cross between two different points on the loop, producing further redundancy if there is a break in the main loop. The more total capacity (both supply and demand) that is tied into the loop, the more power capacity that the loop per se requires to really stabilize the interconnected nodes. This is a part of the problem we will address with the help of Professor Chow, seeking to determine the optimized layout for the HVDC loop, and the most appropriate capacities for the taps and the loop itself.

Table 1: Characteristics of 2000 km Electric Pipelines With Varying Aluminum/km

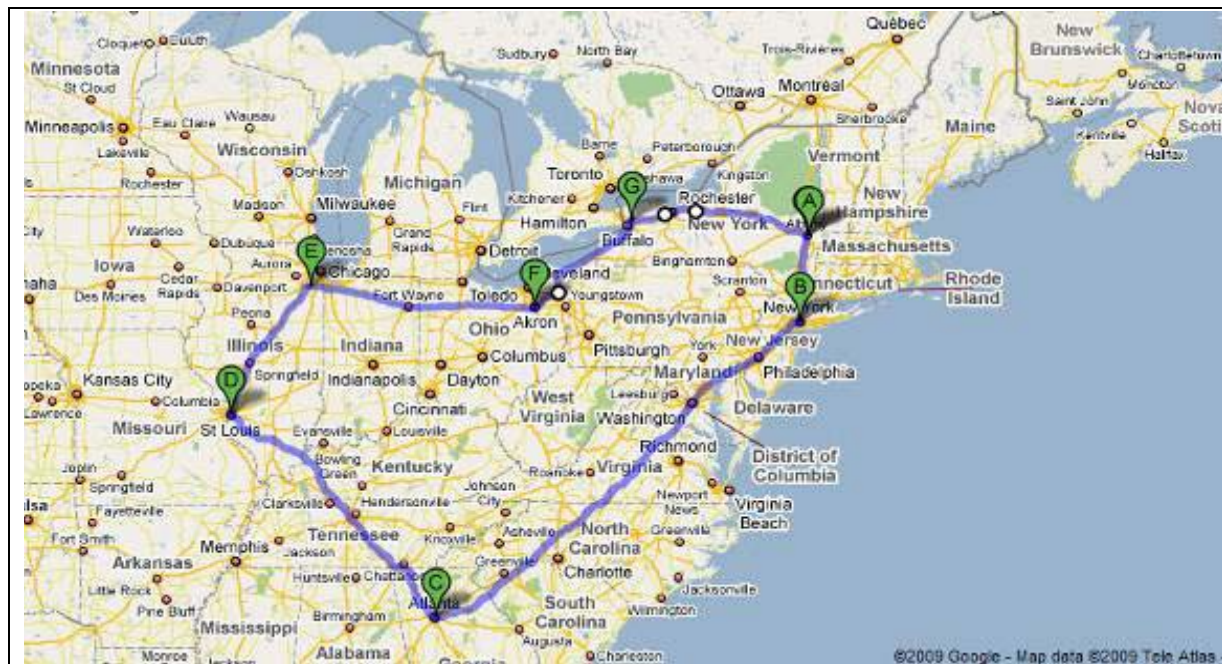
<u>cubic meters</u> <u>Al per km</u>	<u>conductor</u> <u>diameter, cm</u>	<u>2-way</u> <u>milliohm/km</u>	<u>metric tons</u> <u>Al per km</u>	<u>Aluminum</u> <u>\$/km</u>	<u>Ohms, 2000</u> <u>km line</u>	<u>Delivered</u> <u>GW</u>
1	2.52	138.80	2.73	\$ 3,948	277.6	0.83
5	5.64	27.76	13.65	\$ 19,738	55.52	4.15
10	7.98	13.88	27.30	\$ 39,476	27.76	8.30
20	9.77	6.94	54.60	\$ 78,952	13.88	16.60
30	11.28	4.63	81.90	\$118,427	9.25	24.90
40	12.62	3.47	109.20	\$157,903	6.94	33.20
50	13.82	2.78	136.50	\$197,379	5.55	41.50
60	19.54	2.31	163.80	\$236,855	4.63	49.80

(based on conductivity of pure aluminum at 100° C; conductivity & capacity 9.6% higher at 70°)

An HVDC loop system would have the maximum benefit if it were on the continental scale, and it is hoped that this proposed project is a step towards a continental scale HVDC grid. Before a continental scale loop can be contemplated, the concept must be demonstrated on a regional basis, and studying the regional, multi-terminal HVDC loop concept in detail is the subject matter of this proposal. (A few more innovations are probably needed before a continental scale, coast-to-coast HVDC loop becomes possible,

such as higher voltage and/or possibly use of a cheaper conductor, sodium, which is theoretically much cheaper per equivalent unit of conductivity than aluminum.) We can not presume the best route, nor size of the electric pipeline, nor size distribution of the many taps to the main loop in this proposal, since these are matters this proposal seeks to address. Defining a route for the HVDC loop is one of the main activities of the proposed project. However, just to illustrate the concept, without pulling in realistic route planning data, we present the idea conceptually in Figure 1, which shows a power-sharing HVDC loop stretching from Albany to New York City down to Atlanta then over to Saint Louis, up to Chicago, then through northern Ohio, up through the Buffalo and Niagara region, and then back across New York State to Albany. This loop is about 4250 km, and touches some of the most populated cities, and areas prone to transmission congestion, in the eastern US. We propose using existing powerline rights of way, which will simplify somewhat our modeling work, since those routes are very well known, and by definition they connect major nodes of our existing grid. Every tap to the main HVDC loop must be isolatable by a circuit breaker. I believe there also should be circuit breakers on the main loop, though figuring out in detail how many and where they should go is relegated to the future project per se.

Figure 1: Example of Proposed HVDC Loop (4250 km)



At 70° C aluminum, the minimum capacity (10% loss) between any two points on this HVDC loop is 85.5 GW

The above route would tie together areas with hundreds of GW of power production and consumption. According to ABB, redundant fiber optic communication now enables a multi-terminal HVDC transmission project of this type to be reliably controlled¹, and both ABB and Siemens have developed control mechanisms and circuit breakers for ± 800 KV HVDC transmission for their projects in China and India. Using rapid communication to achieve simultaneous firing of several parallel-connected ± 800 KV HVDC circuit breakers would enable circuit breakers on the main ± 800 KV HVDC loop, no matter how high the rated transfer capacity. (This may or may not be the most cost effective option, but it is comforting that an option exists for circuit breakers on a 100 GW HVDC transmission line.)

Consider the HVDC loop option represented in Figure 1, deploying 50 cubic meters of aluminum/km. This design would use 136.5 metric tons of aluminum/km, worth \$987 million for the entire 5000 km project at current prices. (The entire amount of aluminum required for the transmission project of Figure 1 is 682,500 metric tons of aluminum. Although that sounds like a lot, it would only be 2.45 years of production from Alcoa's aluminum smelter in Messina, New York, after the proposed plant upgrades called for in the Governor's deal with Alcoa to guarantee low cost electricity for the plant. This deal is contingent on Alcoa investing \$600 million on upgrading the facility; according to a January 13, 2009 Business Wire story.)

Extrusion of aluminum is a well developed and efficient process, costing only about \$.25/kg. Even if the total installed cost of the transmission line was ten times the cost of the aluminum, the resultant transmission project would be cost effective considering the dramatic improvement in efficiency of using the regional generation capacity (we deal with this in more detail in the Appendix). For the 4250 km HVDC loop of Figure 1 with 50 cubic meters aluminum per kilometer, the maximum resistance between two points on the loop (2.95 ohms) occurs where the clockwise distance between the points is equal to the counterclockwise distance between the points (2125 km); at ± 800 KV and 10% loss, this implies a transfer capacity between any two points on the loop of at least 85.5 GW (based on maximum aluminum temperature of 70° C, the maximum conductor temperature allowed by ABB in their XLPE insulated underground HVDC cables). This is definitely enough transfer capacity to stabilize the regional grid and allow for market access for power sales across the entire region. This is not an optimized design, but does show the potential of the proposed system. A major goal of the project is to optimize the route and the amount of aluminum used per km in a project similar to Figure 1.

The proposed system represents a paradigm shift for power transmission in several ways. First is the obvious movement from wires to solid conduits, "electric pipelines." This is an unavoidable consequence of the need for increased power transfer due to many factors, including deregulation of the power market, increased use of wind and solar energy, reduction of greenhouse gas emissions, increased power consumption, and increased sensitivity to the environmental and aesthetic consequences of overhead power transmission. There are many proposals for superconductor based supergrids² (a useful bibliography can be found at <http://www.w2agz.com/SG%20-Bibliography.htm>), yet it is amazing to the author (who has been promoting conventional conductor based electric pipelines since 1991³) that the totally obvious need to use more conductor to achieve the needed transfer capacity has not lead so far to widespread consideration of electric pipelines for long distance power transmission. Even if superconductors were deployed to create a supergrid^{4,5} (more on this in the Appendix), one would necessarily be looking at an underground installation option; it seems obvious that researchers studying this option would have run calculations on the conventional conductor based alternative, but this seems to have not been the case, although one high temperature superconductor concept⁶ uses superconductive tape wrapped around an aluminum core; in principle such a design could be used in superconducting wires so that if the temperature rises above the curie temperature, the aluminum core would be able to handle the shunted power. This seems not to have been the goal of this design, however; the aluminum is merely malleable core to use for wrapping the superconductor; its function is mechanical rather than electrical.

One particular "supergrid" concept involves superconductive cables for power transmission and combines this with cryogenic pipelines for liquid hydrogen or methane⁷, whereas Airtricity (a leading European wind energy developer) is promoting their own version of an HVDC "supergrid⁸;" as far as I know these designs do not envision a vast loop like the present proposal.

The other way that the proposed project represents a paradigm shift is that it would be the first HVDC transmission project ever built in the form of a loop, with many power taps. Loops occur quite naturally in the massively interconnected AC grid, but so far as the author is aware, a multi-terminal HVDC loop has never been proposed before. One of the main reasons is that AC grids are more readily controllable, via monitoring and controlling phase angles of the AC power. This would also be the first HVDC project with more than ten power taps. (In actuality, there would likely be around 100 power taps in the system of Figure 1 if it is built). The project would require either breakthroughs in controlling conventional thyristor-based rectifiers, or using either GTO (gate turn off thyristors) or IGBT (insulated gate bipolar transistor) voltage source converters, which are well suited to a multiple connection design, but are not as efficient nor (at present) capable of operating at the proposed design voltage (± 800 KV). IGBT and GTO converters are however undergoing rapid evolution and improvement. (Experts the author interviewed were mostly skeptical about using conventional thyristor-based converters in a multi-tap system, though by combining each thyristor tap with reinforcement of the AC grid connection points with synchronous condensers, flywheel fast acting storage, capacitors, or FACT power electronics for example, there is a chance that thyristors could be deployed in a multi-tap setup, perhaps in combination with IGBT and/or GTO taps.)

At ± 800 KV, it is not cost effective to have power taps allowing less than one GW of power injection or removal, because the cost of insulation is insensitive to the power level, and depends only on the voltage. Most power taps would probably be around two GW, as this is about the largest size that will integrate well with the existing AC grid node points. There are advantages for cost, stability, maintenance, and control if all the power taps are standardized. These are considerations the proposed study will examine in detail, with input from the project consultants, and the potential suppliers of converter technology, ABB and Siemens.

In a typical overhead transmission project, only a small portion of the project expenditure goes towards the purchase of the conductor. That changes with electric pipelines; the conductors are relatively massive, and aluminum acquisition cost will intrinsically become a large fraction of the cost, as is true of the insulator cost as well. Compared to wire, the insulated extrusions will be much less expensive per unit mass of conductor. Since the volume of conductor used in the transmission project is the major determinant of line resistance (in this case, resistance of the HVDC loop), and since resistance determines transmission loss:

$$\text{Transmission loss (watts)} = I^2R = V^2/R;$$

A transmission line of length L, using a uniform cross-section conductor of area A uses a volume of conductor L·A; resistance in ohms for such a line is given by:

$R = \rho \cdot L/A$, where ρ is the resistivity. (We have used as a conservative value of resistivity for aluminum its value at 100° C, $3.47 \cdot 10^{-8}$ ohm-meter in the calculations for Table 1 and Figures 2-4 in the Appendix; the calculation of resistance of the loop design of Figure 1 uses the more realistic value of resistivity for aluminum its value at 70° C, $3.17 \cdot 10^{-8}$.)

Fractional transmission loss = $I^2R / V \cdot I$; setting this equal to 0.1 (10% resistive loss) means:

$V \cdot I = \text{power in} = (0.1)(V^2/R)$; delivered power is 90% of this = $(.09)(V^2/R)$. (This is the simple equation used to create Table 1.)

We have identified insulation, heat transfer, making joints between pipe conductor segments, terrorist resistance, main loop circuit breakers, and thermal expansion joints as key electric pipeline

design considerations to be studied. Professor Nelson will be our lead consultant on these electric pipeline design issues. Professor Chow will help us to address route and capacity planning, evaluation of system stability impacts, determining the most logical capacities for the many HVDC taps required to tie the proposed HVDC loop into the AC grid. Expert advice from Robert Lassiter (Professor Emeritus of Electrical Engineering at UW Madison) and Stig Nilsson (who is involved in a study of the superconducting supergrid for EPRI) indicates that current controlled, line commutated thyristors (which are most efficient in terms of energy transfer) probably cannot be used on the proposed HVDC loop, because of control problems. (It is possible that some thyristor-based converters could be on a multi-terminal HVDC system, provided that the AC power going into the converter is “cleaned up.” We have retained Professor Mariesa Crow, who is at the University of Missouri at Rolla to consult on this issue; she is a leading expert on flexible AC transmission technology, “FACTS.”) These experts agree however that the proposed multi-terminal power loop could work with newer, voltage source IGBT technology (which is slightly less efficient than thyristors, but is much better than thyristors at suppressing AC grid instabilities based on reactive power disturbances). Another intermediate option between thyristors and IGBT voltage source converters are the GTO (gate turn off thyristors) that have intermediate properties between conventional line commutated thyristors and IGBT voltage source converters. Professor Crow thinks it is possible that GTO rectifiers could also work in a multi-terminal HVDC grid. (The Appendix gives more details on thyristors, GTO, and IGBT AC/DC converters.)

We will also address regulatory issues, possible environmental concerns and paths to technology adoption; our consultants will contribute to this portion of the project somewhat, but in the main, we will seek input from industry insiders, FERC and DOE officials and scientists, federal EPA and state level environmental officials, environmentalists, and any other stakeholders we can identify to help us define regulatory and environmental barriers and/or impediments to adoption.

A key part of the project will be development of cost estimates for the electric pipeline. The only part of the pipeline design that is firmly established is that the conductors will be extruded aluminum. We will find New York manufacturers to work with on costing the extrusions, such as American Douglas Metals, Inc., which has a Buffalo area facility; Romco sales of the Bronx, or Forsythe Industries of Aurora, NY. It is likely that the crude extrusions will have to be polished to minimize surface defects which produce a locally increased electric field, and therefore cause breakdown of the insulation at lower voltage. We intend to make it clear to potential manufacturers that aluminum extrusions for this project must be produced in New York.

Another key part of pipeline design will be the insulation; we intend to compare polymeric insulation (key problems: heat dissipation, mismatch of thermal expansivity with aluminum) with fluid insulated designs (key problems: containment, possible leakage, inferior breakdown strength). Professor Nelson is an expert on high voltage insulation materials, and has done highly relevant work on insulation materials (polymeric nanocomposites)⁹. Roger Faulkner possesses potentially patentable designs for the electric pipelines that will be revealed to NYSERDA only if this proposal is accepted.

Nanocomposite reinforced crosslinked polyethylene (XLPE), invented in part by the project’s major consultant, Professor J. Keith Nelson of Rensselaer, represents a major advance over the insulation materials that are used at present for insulation of directly buried HVDC cables. (Two types of underground HVDC cables are used at present; oil impregnated paper insulated cables are the oldest and most mature technology, and this technology is proven for underground cables up to 600 KV DC. The newer technology is crosslinked polyethylene, which at present is only proven up to 320 KV.) Although this proposal is being funded under category D (policy track research studies), Rethink will accept

NYSERDA's standard terms on any electric pipeline IP that may be developed during the course of this project, but I must point out that Professor Nelson's IP is already assigned to Rensselaer and EPRI, so if electric pipeline designs are developed during the course of this project that use Professor Nelson's nanocomposite insulation materials, there will be a need to license that IP.

Consider the long term perspective: if it were possible to bring solar power from Arizona, New Mexico and Texas to North American East Coast cities, solar power would be cost competitive with daytime peak power generated by gas turbines today, with further cost improvements likely as solar technologies evolve. Solar power installations in the US southwest cannot presently send power east, which effectively rules out major (strictly economically-driven) development of solar power at present in the US. However, given present economics and solar technology, solar energy facilities would be built in the US southwest with private capital if the power could be sent east to be sold as "peak power."

As is well known, the availability of energy storage makes it possible for wind and solar power to contribute a larger fraction of total energy needs without negatively impacting system stability, and the regional HVDC grid is proposed in conjunction with a large pumped storage project involving lake Erie (as the elevated reservoir) and lake Ontario (as the lower reservoir), using the 99.4 meter difference of elevation between these two Great Lakes to provide vast pumped energy storage capacity, up to 1300 gigawatt-hours if the lake level in Lake Ontario is allowed to vary by 30 cm during a charge/discharge cycle (less than the typical seasonal variation of Lake Ontario's level). This storage potential is comparable to the installed energy storage capacity of all other pumped storage projects in the world, and although it would be a massive engineering project to realize the storage potential of these lakes, the cost savings for not having to purchase the land for the pumped storage project is also very large. Development of the enormous potential storage capacity between these two natural reservoirs would make it possible for wind energy to provide a large fraction of the electrical energy demand of the eastern US. (The proposal for a major pumped energy storage facility on the Isthmus of Niagara is detailed in a separate response to NYSERDA PON 1200 on energy storage, filed January 14, 2009. Copies can be provided upon request.)

The proposed regional HVDC power grid would decrease the total electric generating capacity and spinning reserves that would be needed to satisfy the region's electricity appetite, because demand peaks occur at different times in different places. Thus, if different regions share their generating capacity, less total capacity is needed. The potential capital savings from sharing generating capacity is immense, and could pay for the regional HVDC electricity grid.

Team Qualifications

The Principle Investigator is Roger Faulkner, the owner of Rethink Technologies, Inc. (“Rethink”), an R&D company in Cambridge, NY. Roger Faulkner is a polymer scientist by training (PH.D. 1984, University of Akron; chemical engineer as an undergrad). Most of the work performed by Rethink has been in the area of polymer science, formulations, and processes. Recently, Rethink completed a Navy SBIR contract (N-08-042) on development of an improved elastomeric barrier for sea water for a particular need on submarines. Rethink is also a subcontractor to Kazak Composites of Woburn, MA on two Phase 2 SBIR contracts, one for the Navy and one for the Air Force. Rethink also contracts to do industrial R&D for several companies, including Hyperion Catalysis International, Pacific Rubber, and Daikin America.

First and foremost, Roger Faulkner is an inventor. His first of four issued US Patents so far (6,197,438) is on cookware (the others are on fluoroelastomer technology), and he has filed more than 20 patent applications (mostly provisional), on products and devices. Two patents are now pending. The idea of using massive conductors deployed in “electric pipelines” is one of his inventions, although it is quite possible that such concepts were considered in the early days of DC power transmission, before Tesla’s breakthrough invention (the transformer) caused the shift to AC power for transmission and distribution.

Mr. Faulkner also has a long standing interest in renewable energy, and was a Full Party and a Public Intervenor before the 1991 Advance Plan 6 hearings of the Public Service Commission of Wisconsin (see <http://www.wsn.org/publicintervenor.html> for a description of what this entailed). In those hearings, he presented testimony on these topics: powerline EMF, siting of power plants, nuclear power, cogeneration, externalities, and he recommended an underground HVDC option based on electric pipelines for a major transmission line, the “Intertie.” (The testimony of Professor Willis Long, his expert witness on the Intertie is contained in the Appendix.) He also ran for office in Wisconsin (US Senate Republican primary, 1992) in an effort to advocate for environmental issues from a free market perspective. The concept of electric pipelines comes out of his interest in making renewable energy practical and reducing greenhouse gas emissions. Though not a specialist in electrical systems, he has enough engineering knowledge to understand the important issues, to talk to specialists, and to pull together an unbiased report that will show if, and at what power level a regional HVDC loop makes sense.

Other Rethink employees or associates include Ken Mumby and Rob Karnes. Ken is a full time Research Associate at Rethink; he has a recent math/chemistry degree from SUNY Albany. Ken has been intimately involved in the preparation of this proposal, and has found many very important leads and informative references through his web-savvy database searching. Rob Karnes is an experienced mechanical engineer who has worked closely with Roger Faulkner for years on many projects, and he will be consulting on mechanical aspects of the electric pipeline design.

In addition to Rethink staff and associates, there are three highly qualified professors who have generously agreed to take reduced fees for consulting to assist this project, which they think is both interesting and potentially important. Professor Keith Nelson has published numerous papers on high voltage insulation, which is a key consideration in design of electric pipelines. Keith is a professor of electrical engineering at Rensselaer Polytechnic, as is the second project consultant Joe Chow, who will be helping mainly with figuring out how to tie the proposed new HVDC loop into the regional grid to best enhance system stability, how to deal with contingencies, and what should be the target transfer capacities to enable economically meaningful capacity sharing. We also have arranged for consulting help from Professor Mariesa Crow, a well known power electronics specialist. The CVs of our consultants and their

commitment letters are contained in the Appendix. I am truly honored that these highly qualified scientists have agreed to assist with the proposed project.

I also wish to thank several people who gave very useful advice during the development of this proposal. All of these folks thought the concept advocated in this proposal is interesting, and quite possibly practical given recent advances in IGBT voltage source converters and other power electronics innovations. Professor Emeritus Willis (Bill) Long of UW Madison was my expert witness when I first advocated for an underground HVDC electric pipeline for a cross-state intertie in 1991 before the Wisconsin PSC. His testimony from that hearing process is reproduced in the Appendix, and my interaction with him got me going down the road towards advocating for an HVDC grid. Bob Degeneff, president of Utility Systems Technologies, Inc. of Latham, NY is also a former electrical engineering professor at Rensselaer, and before that he was for a time in charge of the HVDC group at GE Energy in Schenectady. Bob gave me encouragement (he actually said the concept of an HVDC grid based on electric pipelines is “a phenomenally interesting idea”) and helped me network with other power industry insiders. Professor Robert H. Lasseter is an Emeritus Professor of electrical engineering at the University of Wisconsin Madison, and a long time advocate of a superconductor based supergrid. He gave me about an hour of his valuable time, and then sent me to speak to Stig Nilsson, who also gave me valuable help on the phone. Stig was willing to join this project as a consultant, but said he had to check with his project manager on a large EPRI study in which he is engaged, to study the concept of a superconductor-based DC supergrid. The next day, Stig reported that the manager of the EPRI project, Steve Eckroad, told Stig he could not participate in this project until all possible invention disclosures are filed, so I began looking for another appropriate consultant. Matt Lazarewicz of Beacon Power then gave me the lead to Mariesa Crow, who agreed to consult on the project.

We anticipate that this project will result in several scientific papers. Roger Faulkner will be an author or co-author on each of these papers. The outside consultants will co-author papers on different aspects of the project, such as:

1. Overview of an Eastern US Regional HVDC Grid based on Electric Pipelines
2. Power Electronics Stabilized Many Terminal HVDC Grid Options
3. Implications of a Regional HVDC Grid on Network Stability and Spinning Reserve Requirements

These journal article titles are fictional at this stage. The point is that each of the project consultants will be expected to publish a scientific article on some aspect of the HVDC grid concept. I expect the authors to acknowledge support from NYSERDA. These published papers will be tangible results of this initial NYSERDA study, and besides showing NYSERDA in a good light, will reach a wider audience. If this project demonstrates theoretical economic viability (as I believe it will), and if a realistic way around the knotty problem of controlling an HVDC grid can be found, then I think this initial study will draw the attention of EPRI, DOE, FERC and other national-level organizations, and the project will move forward. If so, the small investment of NYSERDA in this project will have moved this important technology forward in such a way as to move forward the day of implementation; moving that day forward by a year will be worth many millions of dollars to New York rate payers, who will gain access to less expensive electric power as soon as the HVDC loop is completed (possibly sooner). This project will be most likely to advance the cause of building an HVDC grid if it raises the profile of the project in such a way as to make it interesting at the federal and public interest level. Of course, if our

findings do not indicate economic viability, we would say so, and even in this case we will publish articles, which will if nothing else have positive PR value for NYSERDA.

The actual detailed course of this project will probably be modified at a kickoff meeting that will be held either at Rensselaer or in a NYSERDA conference room. Roger Faulkner, Ken Mumby, and all of the outside consultants who can make it will be present. Any NYSERDA personnel or invitees will be welcome. The meeting will be kicked off by a presentation by Roger Faulkner, and each of the consultants will have a few slides on aspects of the project that seem important to them. I intend to tape this meeting and photograph anything put up on whiteboards during that meeting. If I planned this entire project by myself, and then set those plans in stone, when the outside consultants who have agreed to help have such impressive credentials, it would be a disservice to NYSERDA. To get the best service from this incredible team I have assembled, the consultants should have a major role in formulating the project. Therefore I expect that the detailed plans presented in the Statement of Work may be modified in our first meeting as a group.

Appendix A: The Detailed Technical & Policy Case for Electric Pipelines

(Portions of the text above have been extracted from this Appendix, which is adapted from a longer book chapter that the author Roger Faulkner wrote for a planned book, *Inventing Tomorrow*.)

Introduction

Electricity is one of the most transportable forms of energy. It is convenient and economical to convert many different forms of energy (wind, solar, hydro power, fossil fuels, nuclear energy) into electricity to facilitate transportation to market. Yet electricity is not nearly portable enough, since it is not yet practical to transport bulk electric power coast to coast within a continent, let alone between continents. Major advances in transporting electricity on a continental scale would make it practical for wind and solar energy to make a larger contribution to our energy economy, especially if this is combined with large scale energy storage. Though this proposal focuses on a regional application of high voltage DC (HVDC) underground powerlines, which because of their size and capacity we call “electric pipelines,” this technology is also applicable to creating a continental-scale HVDC grid. Now is the time to think out of the box on the critical issue of redesigning our electrical grid.

For reasons that are familiar to power system designers and engineers, any type of powerline capable of moving economically significant amounts of power (more than 100 gigawatts, GW) of electric power coast-to-coast in North America would necessarily be a DC powerline. In order to be politically feasible, such powerlines would have to be sited underground; thus the term “electric pipeline.” Pipelines are viewed differently than overhead powerlines by environmental activists and the general public, and usually do not provoke the magnitude of political opposition that typically arises in response to any new overhead powerline proposal in the North America or Europe. What we are proposing is in essence a regional pilot project to develop and demonstrate an underground HVDC grid in and around New York State that connects Niagara Falls to New York City, while also tying together most of the large power producing and power consuming regions of the Eastern US.

As is well known, the availability of energy storage makes it possible for wind and solar power to contribute a larger fraction of total energy needs without negatively impacting system stability, and the regional HVDC grid is proposed in conjunction with a large pumped storage project involving lake Erie (as the elevated reservoir) and lake Ontario (as the lower reservoir), using the 99.4 meter difference of elevation between these two great lakes to provide vast pumped energy storage capacity, up to 1300 gigawatt-hours if the lake level in Lake Ontario is allowed to vary by 30 cm during a charge/discharge cycle (less than the typical seasonal variation of Lake Ontario’s level). This storage potential is comparable to the installed energy storage capacity of all other pumped storage projects in the world, and although it would be a massive engineering project to realize the storage potential of these lakes, the cost savings for not having to purchase the land for the pumped storage project is also very large. Development of the enormous potential storage capacity between these two natural reservoirs would make it possible for wind energy to provide a large fraction of the electrical energy demand of the eastern US. (The proposal for a major pumped energy storage facility on the Isthmus of Niagara is detailed in a separate response to NYSERDA PON 1200 on energy storage, filed January 14, 2009.)

The proposed regional HVDC power grid would decrease the total electric generating capacity and spinning reserves that would be needed to satisfy the region’s electricity appetite, because demand peaks occur at different times in different places. Thus, if different regions share their generating capacity, less total capacity is needed. The potential capital savings from sharing generating capacity is immense, and could pay for the regional HVDC electricity grid.

The availability of such an HVDC grid would produce complex economic and political effects which would affect generation methods. For example, such a grid might alleviate many public concerns about nuclear reactors by allowing them to be sited far from population centers. At the same time, a regional HVDC grid would encourage solar, wind, and hydroelectric power development by greatly improving market access for power generated in remote areas. The proposed regional HVDC grid (and eventually, a continental grid) would enable not only increased efficiency but also decreased environmental impacts from power generation.

Such an interconnected regional electricity grid could decrease pollution if combined with tighter air pollution regulations and/or pollution taxes. Theoretically, the least efficient (and therefore most polluting) generators would tend to be shut down (completely or in part) by competition with more efficient generators, but only if there is consistent pollution regulation in different jurisdictions. The key missing element at present that prevents the development of continental scale strongly connected power grids is a practical means to efficiently transport tens to thousands of GW of electric power much further than is presently practical, with acceptable costs and environmental impacts.

We have nearly reached the theoretical limit of the conventional, overhead transmission line, and it is obvious that such lines will never be capable of linking the coasts of North America, let alone the Earth as a whole. The technology of electric power transmission is due for an overhaul. Overhead transmission lines grow more controversial each year, while at the same time, the economic incentive to transport bulk power grows each year.

For example, if it were possible to bring solar power from Arizona, New Mexico and Texas to North American East Coast cities, solar power would be cost competitive with daytime peak power generated by gas turbines today, with further cost improvements likely as solar technologies evolve. Solar power installations in the US southwest cannot presently send power east, which effectively rules out major (strictly economically-driven) development of solar power at present in the US. However, given present economics and solar technology, solar energy facilities would be built in the US southwest with private capital if the power could be sent east of the Mississippi River to be sold as "peak power."

Because of the strong economic incentive to transport western US electricity east (and similar incentives around the world), new technology is bound to arise that will make it possible to transport bulk electric power on a continental and eventually even on a global scale. The political question is, should this technical evolution be promoted and accelerated as a matter of policy? Would improved capability to transport electrical energy produce significant benefits for the US and world economies in the next several decades? I believe the answer to these questions is yes. Compared to many other major scientific and technical initiatives which the US government has undertaken since WW II, the development of very long distance powerlines would have far greater impacts on the overall economic health of the US. The present proposal amounts to a first step of this process that will in the end have to be a national program.

Any technology to transport massive amounts of electricity must be reliable, rapidly repairable, and redundant in order to guarantee continued supply in the face of possible accidents, geological events, or terrorism. Redundant implies that at least two independent powerlines must connect the major nodes of the grid. One desirable way to achieve redundancy is via a loop design. The proposed regional HVDC project would eventually become a part of a continental scale HVDC grid, but even at the regional level, there is a need for redundancy. Development of a realistic layout for the regional HVDC grid will be one aspect of the proposed project. The other aspects of the proposed project will be to address conductor design, thermal expansion of the electric pipelines, circuit breakers, and problems around designing a many-terminal HVDC grid that operates under voltage control rather than current control (as do present

HVDC transmission projects). It will not be possible to solve all these problems, but it is possible to advance the agenda of designing realistic electric pipelines that could serve as the basis for an HVDC grid.

AC versus DC & Overhead versus Underground Powerlines

Ever since the earliest examples of long distance electric power transmission, overhead transmission lines have been the preferred method for transporting large amounts of electric power. As the length of any conventional transmission line increases, both the energy transfer capacity of the line and the efficiency of energy transfer decrease. The main ways to fight this are to increase the transmission line voltage, and/or to increase wire diameter. Up until 1956, only AC power could be readily changed from one voltage to another (via transformers, which only work for AC power). In 1956, ABB built the first HVDC transmission line (which is still in service, though it has since been upgraded) between Gotland Island and the Swedish mainland, via a subsea cable.

There are different trade-offs for AC versus DC power transmission. Voltage can only be taken up to about 765,000 volts (765 KV) for an AC powerline because beyond that, power dissipation through dielectric loss becomes severe. Voltage for DC overhead powerlines can be taken up to higher voltage than the maximum AC voltage, to about ± 800 KV (the way in which voltage is reported for AC vs. DC powerlines is not identical; an 800 KV DC powerline has 1600 KV conductor to conductor, and 800 KV conductor to ground, whereas AC voltage refers to the conductor to conductor root mean square, or “rms” voltage); In effect, HVDC voltage can go about twice as high as HVAC voltage. Beyond these voltages, power dissipation via dielectric losses (for AC) and/or through corona discharge (for both AC and DC) becomes severe. Wire diameter is limited for AC transmission lines due to the “skin effect” that prevents an AC current from penetrating to the center of a large wire, whereas a DC line can be arbitrarily thick.

Dielectric losses are caused when dipoles in matter align with a changing local electric field. As the polar structures turn to follow the field, the movement causes local heating. The dielectric loss during transmission is equal to the total heat that is generated in materials around the powerlines due to induced motions of electric dipoles. Dielectric loss depends mostly on the changing voltage (there is a component due to induced electric fields, produced by changing magnetic fields).

In effect, energy for the dielectric heating effect is being sucked out of the AC transmission line. This effect is so strong for high voltage AC powerlines that fluorescent lights will glow under a high voltage AC powerline. Dielectric losses are negligible for a DC line, because the voltage is steady. Dielectric power dissipation scales with the square of the voltage times the frequency of voltage reversal (60 cycles per second or *hertz* in the US, 50 hertz in Europe). Dielectric loss becomes significant for AC powerlines above about 500,000 volts. Dielectric loss is negligible for DC powerlines, because the voltage does not reverse regularly.

Another way that energy is lost from powerlines is through varying magnetic fields; these changing fields lead to energy loss by two mechanisms: induction and magnetic hysteresis. Both types of magnetic loss from powerlines scale linearly with current (amperage) and the frequency of change of the field (hertz), and don't depend on voltage. Electric fields are produced or “induced” by changing magnetic fields, and this can cause a significant power drain if electrical conductors are near an AC powerline. Magnetization of ferromagnetic materials (such as steel) also leads to power dissipation as the magnetization changes directions (magnetic hysteresis). As with dielectric loss, magnetic losses are negligible for DC powerlines, because the current does not reverse direction regularly.

There are two additional causes of power loss from a powerline that apply equally to both AC and DC powerlines: corona discharge (relevant only at high voltage, and for overhead or gas-insulated powerlines) and simple power leakage between the conductors. Corona discharge occurs when a voltage gradient is high enough to ionize a gas, but not high enough to cause an arc. Corona discharge limits the maximum voltage of overhead HVDC powerlines to around two million volts between the conductors. All powerlines lose some power, usually a small amount, through direct leakage of current between the conductors. This type of leakage becomes more severe as the voltage and physical size of powerlines increases, and also depends on the properties of the insulators used to isolate the powerlines from each other.

At the time that power grids linking major cities were first built, there was no convenient way to convert AC power to high voltage DC power. Beginning in the late 1950s efficient AC/DC converters first became available which can convert AC power to high voltage DC power and back again to AC power after transmission. Today, all the highest capacity longest-distance power transmission lines in the world are overhead high voltage DC lines (HVDC).

Overhead HVDC powerlines can transport significantly more power for greater distances than AC lines, for several reasons. One reason is that higher maximum voltages can be used in HVDC than HVAC lines because DC lines do not have significant dielectric losses. Overhead HVDC powerlines run into problems with safety, environmental concerns, and wire weight that limit the practical line length to about 2,000 kilometers, and the maximum (differential) voltage to around two million volts. (In the jargon of conventional power transmission, such a powerline is called a \pm one million volt powerline, referring to the voltage difference between either conductor and the ground.) The highest voltage powerlines built or planned to date are two \pm 800 KV lines that will be built in China.

The heaviest set of conductors ever hung on a single row of support towers are contained in the huge Itaipu transmission lines from the foothills of the Andes to Rio De Janeiro. This pair of \pm 600 KV HVDC powerlines makes it possible to deliver about 6300 megawatts (6.3 GW) of power after transmission 800 kilometers at 18% line loss + ~4% converter loss. The towers are huge, and occupy a substantial right-of-way which cannot practically be used for anything else. It is not thought to be politically feasible to install such a powerline in New York State. This powerline does not have nearly enough transmission capacity to link the major eastern and western US power grids. In fact, it would require ~200 GW of transfer capacity to meaningfully interconnect the two coasts of the US. To accomplish a coast-to-coast North American interconnection with overhead powerlines similar to the Itaipu transmission project would require at least 50 separate coast to coast lines. Such a project, even if it was economically feasible, is not politically feasible in the US because of the environmental and aesthetic impacts.

Wheeling of Electric Power

There is another way that power can be (and commonly is among US utilities) transported across an interconnected grid. Wheeling of power doesn't require that individual bits of electricity need be sent very far; rather, next neighbor utilities accomplish a net movement of power by buying power from one neighbor and selling power to their neighboring utility in the opposite direction.

Wheeling of power occurs in a mesh of interconnected power sources (generator stations). Generator stations are usually served by several major powerlines which go off in different directions. In most cases, the total capacity of these major circuits (i.e., the powerlines) exceeds the generator station's

maximum power generation capacity. These major circuits usually connect to a neighboring electricity generating station, and the AC phase of neighboring generating stations are synchronized. Indeed, whole regions are synchronized. Power is wheeled when individual power stations send most of their power east (for example), allowing their western neighbor utilities to serve most or all of their western service territory. This method can in principle transfer net power coast to coast, though no electricity need be sent very far (no further than the maximum distance between next neighbor, interconnected power plants).

Wheeling would work better in North America if there was a string of major cities in and around the Rocky Mountains. As it is there is a band of very low power consumption (and production) across North America that drastically limits the amount of power which can be transferred by wheeling coast to coast. In this regard, Europe is (in principle) in much better shape than the US for wheeling power because its population and power consumption is more evenly distributed than that of the US. Note however that a series of electrical links between major Midwestern cities and the West Coast would, by filling in this gap, make it possible to wheel power coast to coast in North America.

AC/DC Converters

AC/DC converters which can efficiently transfer large amounts of power from HVAC to HVDC and back again were not available until the late 1950s (when they were first developed by Asea Brown-Boveri (ABB), the Swedish electrical equipment manufacturer). Since then, these devices have become more efficient (98% efficiency is now common), and more reliable.

Each converter station costs about \$50/kilowatt of capacity (\$50 million/gigawatt of capacity). Two converter stations are needed to transfer power, one to convert AC to DC power, and one to convert DC back to AC. Luckily, the same equipment can be used in either direction, so a single converter station can feed excess power back into the grid sometimes, or remove power at other times. (For comparison, new generating capacity typically costs between \$600 to \$2000 per kilowatt of capacity, depending on the type of generators.)

In 1956, ABB built the first HVDC transmission line (which is still in service, though it has since been upgraded) between Gotland Island and the Swedish mainland, via a subsea cable insulated with “mass impregnated non-draining” (MIND) cable (basically oil saturated paper insulated) unipolar cable and sea electrodes for the return current. At that time, conversion from high voltage AC (HVAC) to HVDC was accomplished using mercury arc valves. HVDC has gone through three stages of evolution since then; thyristor valves became the state of the art method to do the conversion of AC to DC and back again from about 1970 to the present (the last of the old mercury arc valves were removed from service in 2004), and remain the only proven method for voltages above 400 KV. (I will not use the term UHVDC, meaning “ultra-high voltage DC” for such lines even though it is often used in practice; herein HVDC refers to any DC transmission project with voltage above 100 KV.)

Thyristor based AC/DC converters are still used by all HVDC suppliers in the very highest voltage installations, such as the two +/- 800 kV HVDC lines being built in China (one with ABB technology, the other with Siemens technology). Two newer technologies for high power, high voltage AC/DC converters have been developed since the advent of line commutated thyristor converters. GTO (gate turn off) is a faster responding thyristor technology using different semiconductors, and capable of faster switching (up to ~400 hertz) than conventional thyristors. GTO converters can also be self commutating, meaning they can switch

modes while current is flowing; though this results in switching losses that are not experienced with line commutated thyristors, this ability improves the ability of GTO converters to stabilize the connected AC grid. The newest state of the art AC/DC converters are known as voltage source or IGBT (insulated gate bipolar transistors), and these devices are capable of switching at frequencies > 1000 Hz, which greatly aids the function of stabilizing the connected AC grid. Both ABB and Siemens presently offer IGBT HVDC systems of this type. In terms of energy efficiency, line commutated thyristors are most efficient, followed by GTO, and then IGBT. (GE sold its HVDC transmission technology to Areva in the 1980's; Areva does not yet offer IGBT technology for HVDC converters.)

New York has two HVDC undersea connections. ABB supplied all the technology for the Cross Sound project (New Haven to Shoreham), including IGBT based voltage source converters and polymeric insulated cables (+/- 150 kV, 330 MW). The Neptune project between New Jersey and Long Island (500 kV, 660 MW) uses thyristor based (current source) HVDC converters from Siemens and MIND cable from Prysmian (one MIND cable rated +/- 500 kV and a medium voltage cable for the return current).

The most recent type of AC/DC converters (IGBT) has not yet been constructed at the very highest HVDC voltages. At this time, the highest commercially available HVDC technology based on IGBT converters is rated 640 kV (± 320 kV). Also, IGBT based converters are not yet as efficient (~1-1.1% power loss per converter station) as thyristor based converters (~0.7-0.8% power loss per converter station). According to ABB USA, there is no fundamental reason that IGBT technology cannot go to much higher voltages. It is mainly an issue with experience and confidence; the electric power transmission industry is highly conservative, and being a new technology, IGBT based converters are presently offered at lower power ratings than thyristor based AC/DC converters. (Thyristor-based technology has been gradually evolving into larger and larger unit sizes since the 1970s.) In particular, both thyristors and IGBT converters involve stacked water-cooled component modules that are connected in series to achieve high voltages. The main difference in efficiency between the two types of converters has to do with how many component modules have to be series connected to achieve the desired voltage. In the 1980s, thyristor based converters had about the same efficiency as present day IGBT units but as thyristors have continuously increased their voltage capability, the conversion losses have dropped proportionately. There is every reason to expect that IGBT based converters will undergo a similar evolution in the next 5-10 years.

HVDC Grid: General Considerations

Inclusion of HVDC interconnects between portions of an AC grid makes the AC grid more resistant to the upsets that occur when a powerline is suddenly removed from service, as by an accident. Sudden removal of a powerline in an interconnected AC grid causes the phase of power arriving by two different routes to a single point to become asynchronous; if asynchronicity is bad enough, the initial upset can cause circuit breakers to blow at remote sites which share several interconnections to the powerline which was removed from service. This can sometimes bring down the whole grid in a much larger area than that directly served by the powerline that crashed (this happened in the 1964 East Coast

Blackout, and was a contributing factor in the 2004 blackout). Unlike HVAC interconnections, HVDC interconnections are asynchronous, and tend to stabilize a primarily AC grid when a powerline is suddenly removed from service, as by an accidental short or a broken line.

HVDC powerlines require a nearly instantaneous synchronization of power injection and power removal between all the AC/DC converters connected to the grid. This requires nearly perfect communication between all the converters connected to a single powerline. Up until the 1990's, it was believed that this becomes an unmanageable control problem above about 5 AC/DC converters connected to a single line. More recently, through the use of fiber optic communication links that run in the same corridor as the HVDC connections, and through new control protocols and software, this has become a manageable problem for multi-terminal HVDC powerlines containing up to a hundred or so terminals, according to ABB. Fast-responding energy storage devices connected to an HVDC grid (such as capacitor banks and/or flywheels) can stabilize an HVDC grid for a few seconds to allow more time to adjust to system upsets without crashing the whole system. In order to build the sort of regional (or eventually continental-scale) HVDC energy grid visualized, it will be essential to operate the grid under an advanced control system. Energy storage devices connected to the grid will probably be an essential feature of such a control scheme. These storage devices can either inject or remove power nearly instantaneously to maintain stable operating conditions (local voltage) for the grid; however it is essential to detect powerline outages or shorts before injecting stored power into the grid to support a fantastic arc. A byproduct of such a control scheme is added reliability due to the presence of the storage capacity.

Several different kinds of storage capacity would be ideal, ranging from very fast capacitor-based storage to slower flywheel or superconducting inductors to very slow hydroelectric pumped storage or electrochemical storage (batteries or fuel/electrolysis cells). The storage capacity of an HVDC grid should ideally be adequate to compensate for simultaneous outages of several connected transmission lines or power plants.

Superconductor Based Power Transfer Options

At present, the main option being considered for very long distance (continental scale) power transmission involves superconducting powerlines (superconductors have zero electrical resistance). This option entails some major technical hurdles, and is discussed in this section.

Two types of superconductors have received the greatest attention as potential means to accomplish the goal of very long distance bulk power transportation. "Conventional" superconductors are cooled by liquid helium and can carry very high current densities (as high as 100,000 amps/square centimeter). "High temperature" superconductor powerlines could in principle be cooled by liquid nitrogen or liquid hydrogen, but must be much thicker to carry equivalent amperage to a helium-cooled superconductor. (Room temperature superconductors, even if they are perfected, cannot carry enough amperage to be competitive in this application.)

Conventional helium-cooled superconductors are a proven but expensive technology (several large particle accelerators use miles of helium-cooled superconductor cable). High temperature superconductor powerlines cooled by liquid hydrogen or even liquid methane or liquid nitrogen may be practical within a few decades, but are not ready for application to a continental-scale HVDC grid at present. (Problems with the high temperature superconductors primarily involve the relatively low current carrying capacity and poor manufacturability of presently available materials; also the brittleness of these materials is a problem, as is the need to maintain reliable cooling.)

Most experts and advocates of superconductive powerlines agree that we should wait to see what may come out of the next decade of research on liquid nitrogen-cooled superconductors before we plunge ahead to develop liquid helium cooled superconductor cables. In any case, the development of a practical superconducting long range cable will eventually occur if sustained research is diligently pursued in this area. This is an area of research deserving of increased research funding. (There are several demonstration projects in which relatively short superconducting powerlines have been used to interconnect urban substations, including a project in Albany.)

A particularly intriguing option for superconductor-based powerlines is to couple such lines with liquid hydrogen pipelines. Hydrogen is a clean energy carrier that can easily substitute for natural gas and to some extent for electricity as well. The boiling point of hydrogen is less than half that of liquid nitrogen, the coolant most often mentioned in relation to high temperature superconducting powerlines. Lower temperatures make it more likely that technologists can find improved superconductors to operate at liquid hydrogen temperatures that will ultimately prove capable of carrying the high current densities that will be needed to transfer hundreds to thousands of GW through superconducting powerlines. Insofar as hydrogen itself is a desirable means to store and transport energy, it seems natural to couple a superconducting powerline with a liquid hydrogen pipeline¹⁰.

However the final design of a superconducting powerline comes out, many of its basic characteristics won't depend at all on the composition or temperature of the superconductor or the identity of the coolant used to maintain that temperature. Let us consider some of these general features.

Any superconducting powerline must have a cooling system. The energy consumption for cooling will be the main transmission loss, and is expected to be comparable to the conversion losses at the ends of the powerline, which are required to link to the existing conventional grid. Total energy loss for transmission on the order of 4% is thought to be realistic. Cooling is critical because if the conductor temperature rises above its curie temperature, it ceases quite abruptly to be a superconductor. If a high current continues to flow after the conductor warms above the Curie temperature, the conductor is very rapidly heated and can become plasma so fast that an explosion occurs. Therefore maintenance of the cooling system will be of paramount importance for any superconducting powerline.

A feature shared by all superconductor cable designs is that to insure reliability, it must be possible to gain rapid access to the line anywhere along its course to perform repairs (for example, to repair a coolant leak or to replace a compressor or sensor). This essentially requires that a superconductive cable be installed in a service corridor, rather than being directly buried. Such a high capacity, cross continental (or even global) power link would become so important that it would be intolerable to have the link out of service for a sustained time for repairs. The service corridor per se is a major portion of the total projected cost of a long distance superconductive powerline project.

(The preferred installation option for electric pipelines also entails service corridors, though electric pipelines do not absolutely require service corridors as would superconducting powerlines. The same service corridor used for a conventional conductor based electric pipeline could later be used for a superconductor based transmission line. This option has the great advantage that the conventional conductor could later constitute a backup circuit for the superconductor-based line. In case of a cooling system failure, it would in this case be possible to shunt the energy transfer from the superconducting line to the more reliable though less efficient conventional conductor based electric pipeline.)

It is highly probable that at some future time, superconducting transmission lines will become practical. One might therefore logically question whether we should wait until superconducting

powerlines become practical before investing in conventional metal conductor-based electric pipelines. One reason that electric pipelines are practical is that they are simple and robust. I predict they will be more reliable than superconducting powerlines. Consider for example the relative chance for a massive electricity pipeline to survive an earthquake or a terrorist attack compared to a superconducting line; superconductors are quite brittle, and must be kept very cold. It is easy to see that a superconducting line would be more likely to break than a thick-walled aluminum pipe. Cryogenic lines would have to be built and monitored for years before they could be trusted to deliver power reliably, and the complexity (cooling, brittleness of the superconductor for example) of the superconductor pipeline guarantees a higher rate of faults on a superconductor grid, so such a grid may never become reliable enough for transmission, and cannot be said to be reliable until field reliability is proven in service. So, even if testing started tomorrow, and went perfectly, it would be at least 5 years before a realistic probability of failure, and actual data on recovery time would be obtained. Superconducting powerlines will never be reliable, I predict. That does not mean they are worthless, or unworthy of being pursued. If a superconducting line is only “up” 98% of the time, that is fine if the superconducting line has a conventional conductor-based backup circuit to which the current can be harmlessly shunted when anything takes the superconductor out of service. This would result in up to a 10% loss of delivered power as the power is shunted over from the superconductor to the electric pipeline. The resultant 10% reduction of transmitted power could be accommodated at the receiving end much better than a total loss of power.

I believe that the combination of a brute force electric pipeline with a superconducting powerline is highly synergistic. Consider thee facts:

- Either a superconductor circuit or an electricity pipeline needs a backup circuit to be reliable
- Failure modes will be different between the two systems
- The electric pipeline has the higher materials cost, so building a backup circuit of the same kind could be more expensive that a superconductor backup circuit.
- The cost of an electric pipeline will not come down much with experience and improved designs, but superconducting powerlines will definitely come down in price as technology improves.
- Superconducting lines are not lossless. The energy input to maintain cooling, and to replace components (there will be millions of moving parts in the system to cool the superconducting line) is a loss deducted from transmitted power. Unlike resistive losses from conventional conducting lines, these cooling losses barely increase with increasing transfer capacity (they do increase a little, because the diameter of the cryogenic cylinder through which the superconducting wire must pass increases as more superconductor is required to carry the current). This means that a one GW superconducting line will have about the same line loss as a 100 GW line. And when the 100 GW line carries only a GW, its loss will be just as high as when it carries 100 GW.
- By contrast, line losses in an electric pipeline are a constant fraction of transmitted power at the full rated power, and when a 100 GW line carries only one GW, line losses become very low.
- The superconducting system will have much higher maintenance cost.

- Every cooling system on the thousands of kilometers of the superconducting system must work perfectly for the system to work.
- When the superconductor does work, it saves 5-10% of the input energy (at typical loads).

Therefore, an alternative scenario for implementation of a superconductive powerline is in conjunction with a conventional electric pipeline, with the cost justification for the superconducting line being based on energy savings. This scenario relaxes the reliability concerns that will otherwise keep superconducting lines from being implemented for a very long time.

Electric Pipelines

The simplest way electric power could be sent coast to coast is to build powerlines based on conventional conductors with much lower electrical resistance than any long distance powerlines in service today. These "electric pipelines" can be either conventional conductor or superconductor-based, in principle. The superconductor approach to electric pipelines has gotten significant press and research interest, but is not technically ready to deploy yet. There is also a more pedestrian way to decrease the electrical resistance of a power transmission line: use more conductor.

A long range transmission project today typically will use around 1 to 3 cubic meters of aluminum per kilometer in the transmission wires themselves. The largest elevated transmission project to date is the Itaipu project, which uses about 7 cubic meters of aluminum per kilometer in two parallel sets of towers. The aluminum acquisition costs per se amount to less than 5% of the total cost for most long distance power transmission projects. Using a lot more aluminum (10-100 cubic meters of aluminum/kilometer) makes sense economically if energy savings and transfer capacity increases can finance the acquisition and installation of the extra aluminum. (Insofar as there are plans afoot to build a trillion dollars worth of new electric generating capacity in North America in the next twenty years, and long-range transmission capacity will reduce demand, it is worth considering alternatives such as a continental power grid.)

Overhead powerlines of the present design simply could not carry the weight of aluminum that this type of "brute force" conventional conductor design requires. Heavy conductors are more feasible for buried lines than for overhead lines, so conventional conductor-based electric pipelines would probably be underground. The conductors would probably resemble pipelines more than wires. (An alternative vision is that numerous directly buried HVDC cables could provide the same low resistance as a pipeline-shaped powerline. Such cables are much more expensive than the conductors used in them (especially if the conductor is aluminum); the crux of the electric pipeline concept is to produce a relatively low cost massive conductor in which a large fraction of the total cost of the conductors is for the metal per se.

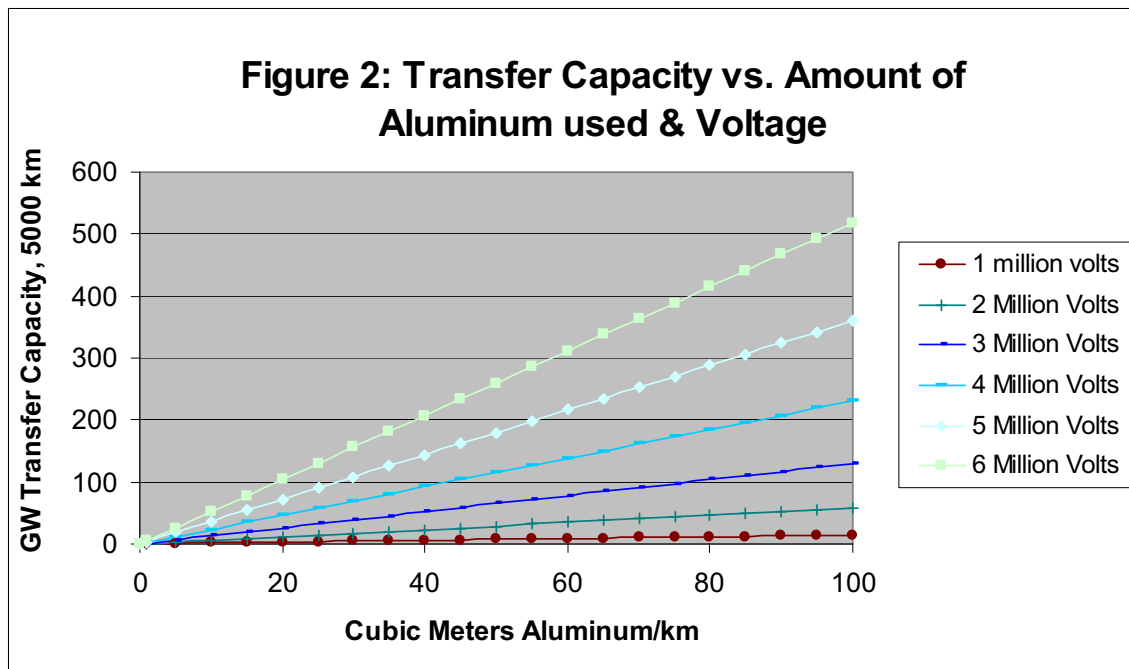
A long distance, high-capacity powerline should be highly reliable and readily repairable. Also, there must be redundant connections, otherwise an entire power-consuming region could face a blackout in case of an outage of one line. In the case of a continental grid, reliability requires multiple, redundant lines. Rapid reparability may require placing the conductors in special, maintenance-accessible corridors rather than direct burial of the line.

Electric pipelines are far more compatible with multiple uses of the transmission corridor than are overhead transmission lines. Route planning for electric pipelines could allow for simultaneous uses for the right of way that would not be practical or desirable for overhead transmission lines, such as bike trails or future high speed rail lines. The greatly reduced EMF from underground DC powerlines also

implies that electronic telecommunications wires and occupied buildings can be in close proximity to the transmission line without electromagnetic interference or health concerns based on alternating magnetic field effects. Note though, that the most likely scenario for electric pipelines is to follow existing rights of way for other powerlines that are already in service, so this potentiality for dual use of the corridor is probably a moot point for the most likely corridors.

An electric pipeline can cost effectively contain up to about 70 times as much aluminum per mile as the heaviest conventional high voltage overhead transmission lines, while occupying a right of way which can be narrower than the right of way for a single high voltage overhead transmission line. Particularly large projects, with more than 20 GW of transfer capacity, must be highly reliable & repairable, which may require placing them in access corridors, rather than directly buried.

Figure 2 illustrates the relationship between transfer capacity and conductor volume (cubic meters of aluminum) used per km in regard to a large coast-to-coast HVDC project. The lines in Figure 2 show the 5000 kilometer (3125 miles) transfer capacities of various feasible HVDC electric pipelines. The six lines represent different design voltages, from one to six million volts (this is the conductor-to-conductor voltage; thus the design voltage of ± 800 KV that we have adopted would be 1.6 million volts in Figure 2). The horizontal axis represents the actual amount of aluminum in the pipeline (including both the positive & negative conductors), expressed as cubic meters of aluminum/kilometer. The vertical axis represents transfer capacity in GW; in this case the amount of power that can be transmitted 5000 kilometers with 10% line loss. Note that much less aluminum is required to transmit a given amount of power as increasing voltage is used.



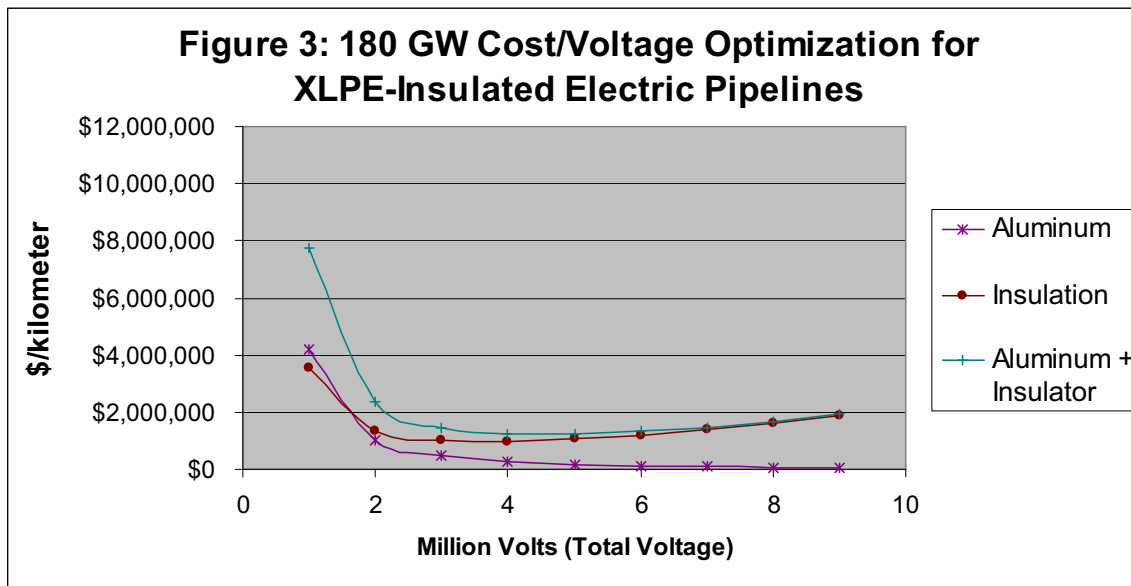
Notes;

These assumptions apply to Figures 2-4:

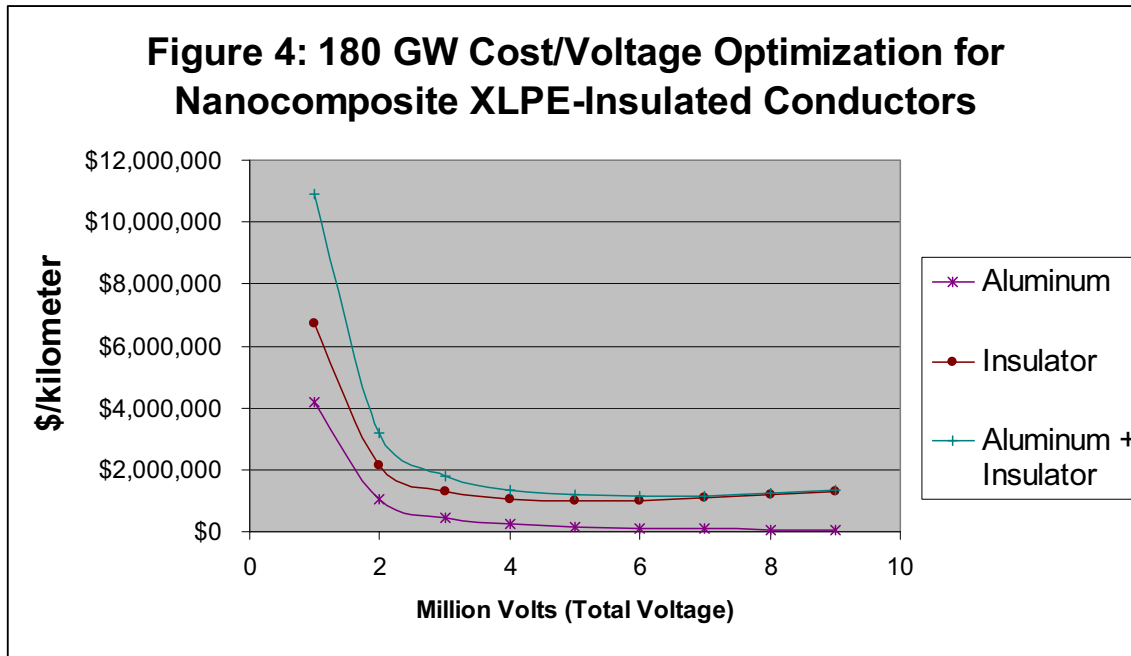
1. Assumes conductors are at 100° Celsius (temperature affects aluminum conductivity slightly); a conservative assumption, since under normal operating conditions, the aluminum will be cooler.

- Based on 90% transfer efficiency (10% line loss) for a 5000 kilometer powerline; line loss is less at lower transfer rates.

Figure 3 and Figure 4 show estimated cost of the two major cost contributors to electric pipelines per kilometer: aluminum (conductor) and insulator (XLPE in Figure 3, nanocomposite XLPE in Figure 4), and the sum of both versus voltage for the simplest possible design of a 5000 kilometer, 180 GW (delivered power) electric pipeline as a function of design voltage. (Simplest case means that the aluminum conductor is a circular cylinder; in the more general case, it can be hollow tube.) Although the particular values for cost of aluminum and polyethylene are up to date as of 1/15/2009, these are subject to market fluctuations. However, the main implications of Figures 3 and 4 do not change much with feasible changes of component (conductor & insulator) cost. Figure 3 shows an important feature of electric pipelines, that an optimum design voltage range exists which minimizes the cost of the electric pipeline. This optimum is a broad plateau from about 4 million to 6 million volts; the overall cost/mile of the conductor + insulator for an 180 GW coast-to-coast electric pipeline is estimated to be \$1.23 million for the XLPE insulated electric pipeline, compared to \$1.17 million per kilometer using nanocomposite- reinforced XLPE (minimum cost occurs at ~5 million volts for both these cases). Considering that the transfer capacity of this powerline is enough to create a coast-to coast connection in North America, this is a reasonable cost.



Basis: Same assumptions as Figure 2 plus the following estimated commodity prices for conductor & insulator: aluminum (conductor) costs \$1.446/kg; electrical-grade XLPE (insulator) costs \$2.20/kg; these were realistic prices on January 15, 2008.



Basis:

Same assumptions as Figure 2 plus nanocomposite XLPE insulator costs \$4.40/kg

Both Figure 3 and Figure 4 show how as voltage increases, the amount of aluminum needed to transfer a given amount of power goes down, while the thickness and cost of insulation required on the conductors goes up. From low voltage up to about 2 million volts between the conductors, the cost efficiency of the power transmission improves rapidly with increasing voltage, because of the rapid decrease of the amount of aluminum required. From 4-9 million volts, the total cost for conductor + insulator are nearly constant, and the insulator costs more than the conductor. The least expensive transmission line (given the particular assumptions of Figures 3 and 4) occurs around 5 million volts line-to-line (2.5 million volts from ground potential). Other factors, especially the cost of the converter stations, imply that an operating voltage around 2-3 million volts would probably be preferred for a continental grid based on HVDC electric pipelines.

Economic Value of Electric Pipelines

Conventional electric pipelines can transport bulk electrical power on a continental scale, for example around North America, Europe, or Asia. A continental grid of such electric pipelines would enable the efficient transfer of electrical energy all around North America (for example), while at the same time significantly improving the efficiency of relatively local electrical energy transfer. The present proposal is aimed at further studying the concept, and crystallizing a plan that specifically addresses New York’s needs for improved reliability, saving capital costs for new power plants, and reducing greenhouse gas emissions from electric power generation.

Unlike superconductor-based options, the proposed electric pipelines are based on engineering principles and fabrication techniques that are well understood. Though construction of an electric pipeline network would indeed be a major undertaking, there is no doubt that the project is doable without

developing fundamentally new technology. Such a project could obviate the need for numerous new power plants, by allowing more efficient sharing of present resources. And, as mentioned earlier, such a grid would make certain environmentally desirable electricity generation methods much more feasible. As such, it would represent a large step towards reducing emissions from power plants.

Control and Reliability Concerns

A high voltage DC (HVDC) grid with numerous connection points or “power taps” to the conventional AC grid would have to be controlled qualitatively differently from the HVDC projects of the past. Past projects operate under current control; this means that each converter station linking HVDC to the local AC grid has a target amount of current to inject or withdraw from the system. Under current control, the various converter stations must communicate, and precisely synchronize their actions. This becomes difficult with more than 5 or so converter stations on a common DC powerline, especially in the case of system upsets, like downed powerlines. Therefore, current control as it has been practiced in the past will not work for a large grid with many interconnections to the AC grid because of control problems.

A current-controlled HVDC powerline is analogous to a high pressure pipeline with multiple pumping stations operating to inject or remove water from the pipe; the amount of water going in and coming out must be kept very constant, or else the pressure (analogous to voltage) within the pipe can change very quickly. It gets to be an impossible coordination problem when thousands of pumping stations move water in/out of the pipe.

The alternative to current control of an HVDC grid is voltage control. Voltage controlled DC grids can have many taps (AC/DC converter stations). A voltage-controlled grid should also incorporate storage of electrical energy to even out voltage fluctuations. Communication is still vital, because even with online storage capacity, power in cannot be different than power out for very long before something will break down. Each AC/DC converter station need not have local energy storage; rather large storage plants could serve a whole region with hundreds of individual taps. A voltage controlled HVDC grid is analogous to a high pressure pipeline with multiple pumping stations operating to inject or remove water from the pipe; but with the additional feature that pressure-buffering reservoirs (such as elevated water tanks and/or standpipes) are also linked to the pipeline. In this case, the reservoirs keep the pressure nearly constant, even when injection and removal of water through the pumping stations and outlet taps is temporarily out of balance. There is still a need for maintaining a balance of power in/power out, but the control does not need to be nearly instantaneous, as is the case in a typical present day current controlled HVDC transmission project.

In the voltage controlled HVDC scenario with energy storage, additional generation capacity can be brought online when needed by the grid, but the storage or “energy buffer” gives enough time for the system to respond; this has the effect of decreasing the requirement for “spinning reserve” capacity, which saves energy. For the regional plan that will be developed for New York as a result of the proposed research, the potential impact will be greatly increased if the HVDC grid extends beyond the borders of New York State, as indicated in Figure 1. The proposed HVDC loop would come close to wind hotspots in the Great Plains, and to Hydro Quebec hydropower, and would probably be tied into these resources ultimately. As sketched in Figure 1, it also ties into major power nodes all across the eastern US; if constructed in this way the proposed grid will reinforce the existing AC grid powerfully, making electric power more reliable throughout the region, while also allowing power sales to be transacted over distances around 2000 km. Once there is a commitment to build the proposed HVDC grid, neighboring states and provinces will have a large economic incentive to also tie in.

Conductor Selection for Electric Pipelines

The first issue that must be settled in the design of an electric pipeline is the identity of the conductor. In principle, the least expensive conductor would be sodium. (Sodium, being extremely weak, would necessarily be deployed within an outer pipe for strength, such as steel.) Sodium has numerous disadvantages, however, including its reactivity, low melting point, and limited commercial availability. Sodium may be the most economical conductor when and if conventional (i.e., non-superconducting) electric pipelines having an order of magnitude lower resistance than the range needed for the proposed eastern US regional HVDC loop are ever constructed. At the present time though, aluminum is strongly preferred as the conductor for regional electric pipelines for the following reasons.

Aluminum is commercially available in enormous quantities. Aluminum is readily extrudable, and extruded aluminum pipes up to 30 inches in diameter are commercially available. The electrical conductivity of aluminum is excellent, better than one-half that of copper on an equal volume basis and better than copper on an equal mass basis. (On an equal cost basis, aluminum is far better than copper, but not as good as sodium.)

Aluminum is not highly reactive with air (due to the formation of a passivating surface oxide layer), and surface hardening of aluminum can be readily achieved via anodization, a well-established industrial process. Although rather weak, pure aluminum is strong enough to be self-supporting (sodium is not). Also, unlike sodium, aluminum will not melt under ordinary (or slightly abnormal) operating conditions of an electric pipeline.

Another benefit of using aluminum as the conductor is that there are well-developed technologies for welding, extruding, and anodizing aluminum, for adhering tough coatings to aluminum and for making electrical splices in aluminum conductors. Consequently, extruded aluminum has been adopted as the basis for the proposed electric pipelines.

Aluminum is perhaps more closely linked to electricity than any other common material. Metallic aluminum is in a sense stored electricity, since electricity is the most expensive "raw material" used to produce aluminum. At the same time, much of the world's electricity is transmitted over aluminum powerlines. The overall efficiency of electric power transmission is strongly dependent on the total amount of conductor "invested" in the transmission lines themselves. The present proposal represents an order of magnitude or greater increase in the direct investment in aluminum for conductors for long distance electric power transmission.

Size of the Pipelines

The transmission losses of any powerline depend on the electrical resistance of the line. The resistance per unit length for conventional conductors depends inversely on the amount of conductor actually used per unit length in the transmission line:

$$R = \rho L/A$$

Where R is resistance in ohms, L is the length of the conductor, in both directions, out and back, and A is the cross-sectional area of the wire. In the case of prior art underground HVDC cables, the maximum cross-sectional area of the wire is limited by the need to maintain a certain minimum flexibility (so the wire can be rolled up a reel for delivery); the maximum cross sectional area of the conductor portion of a wire (whether copper or aluminum) is about 2500 square millimeters (25 cm²). An HVDC direct buried powerline based on this type of wire would use 5 cubic meters of aluminum per kilometer. A powerline

with one cubic meter of aluminum per kilometer corresponds to a pair of aluminum wires, each 5.0 square centimeters in cross section, 2.52 cm diameter, and has 0.127 ohm resistance per km at 70° C. Using ten times as much aluminum makes the resistance one tenth as much, and so on.

Consider the case of electric pipelines capable of carrying 20 GW of electricity from wind farms in South Dakota to New York City, with no more than a 10% transmission loss, by way of Niagara Falls (to make use of the pumped energy storage potential, load leveling, and constant voltage support of the proposed pumped storage facility operating between Lake Erie and Lake Ontario, as suggested described in my PON 1200 application). This route would be about 1700 miles long (2720 km). To meet the 90% efficiency target at 1.6 million volts conductor-to-conductor (the current state of the art) would require 22 cubic meters of aluminum per kilometer, which implies a solid conductor diameter of 12.0 cm. By comparison, to meet this target at four million volts conductor-to-conductor would require only 3.6 cubic meters of aluminum per kilometer, which implies a solid conductor diameter of 4.8 cm. These conductor diameters are quite small compared to a typical oil or gas pipeline, though after accounting for insulation, the diameters would be considerably larger.

Why Electric Pipelines Must Carry DC Power

DC powerlines can transport significantly more power than AC lines, for several reasons, one of which was mentioned previously, that DC lines do not have significant dielectric losses. A more important factor is that the voltage is constant (or nearly so) in an DC line, so the maximum voltage is equal to the average voltage of the line; this is very different than is the case for AC lines, where the average voltage of an AC line (root mean square average voltage, relevant for calculation of transmission capacity) is less than the maximum voltage. Since any powerline's maximum voltage is limited by its insulation, transfer capacity is reduced for AC powerlines compared to DC powerlines:

- the insulator thickness fundamentally limits the maximum voltage;
- the instantaneous rate of power transfer is proportional to voltage squared;
- the voltage in DC power transmission is always near to the maximum design voltage;
- In AC transmission, the voltage changes with time, and is actually near the maximum voltage for only a small fraction of the time. The correct "average voltage" to use in calculating AC energy transfer is known as the "root mean square" voltage, which is significantly less than the maximum voltage.

There is also a built-in advantage for DC lines that require only 2 conductors per powerline compared to three-phase AC, which requires 3 conductors per powerline. (Single phase AC is used only for local power transmission, for example distributing power on a residential street.)

Another significant advantage of DC power transmission is that DC power can penetrate the entire depth of an arbitrarily thick conductor, whereas AC power only flows on the outer perimeter of a thick conductor, due to the "skin effect."¹¹ The fact that AC power only flows on the outer perimeter of a thick conductor means that thick AC lines have greater electrical resistance than do DC lines that contain the same mass of conductive metal. This "skin effect" is frequency dependent; at 60 Hertz (standard US AC power frequency), round conductors with diameter greater than about two centimeters are affected significantly.

DC conductors can be quite thick. The entire cross-section of even a very thick electric pipeline can efficiently transport a DC current. If such a thick electric pipeline were used for AC power transmission however, the current would not permeate the entire conductor, but would instead be concentrated near the outer surface (the "skin") of each conductor. For the massive conductors of electric pipelines, the AC resistance would be more than twice as much as the DC resistance due to the skin effect.

These facts are especially relevant for electric pipelines, where the insulator is a major cost. For overhead AC lines, designers merely move AC lines further apart on their towers (compared to DC lines with the same energy carrying capacity) to provide adequate insulation, which is rather inexpensive. For an electric pipeline, the increased maximum voltage of an AC design to carry the same total power as a DC design would entail a major increase in the cost of insulator.

Therefore (and for other more esoteric reasons as well), electric pipelines are necessarily DC transmission lines.

Electromagnetic Field (EMF) Minimization

An important feature of an electric pipeline is that such powerlines will emit essentially zero changing electromagnetic fields (EMF). Such powerlines will however produce local magnetic effects. Superconducting powerlines would produce stronger magnetic fields than those of electric pipelines based on conventional conductors, since most proposed designs for superconducting lines involve lower voltage (~20-200 KV) than that being proposed for conventional electric pipelines (~1600-6000 KV between the conductors). Lower voltage means more amperage would be required for superconducting lines to transmit the same power as a multimillion-volt conventional HVDC powerline, which implies stronger magnetic fields. Some proposed superconducting powerline designs would deploy magnetic shielding based on room temperature superconductors, which can contain the entire magnetic effect of the powerline within a superconductive sheath. In principle HVDC electric pipelines could also be shielded magnetically, either with high temperature superconductors or more conventional means.

To minimize local electrical effects around the electric pipeline (including both electric fields and ground currents), the outermost layer of the pipeline or pipeline corridor should be as near to ground potential as is practical. One way to minimize ground currents & local electric fields is by insulating the outer (presumably steel) jacket of each electric pipeline from ground, and linking the leakage flows from the positive & negative conductor jackets together, through amp meters so that the local leakage flow can be monitored. Monitoring these flows would give early warning of numerous kinds of faults, and would be a valuable part of a preventative maintenance program. Such a system would keep both conductor jackets at or near ground potential, and would assure that leakage to ground is nearly zero.

It is believed to be more practical to shield the magnetic effects of an electricity pipeline from the environment via design features, such as magnetic shielding in the corridor, or by installation choices (depth of burial, corridor layout) rather than by deploying a coaxial design of the conductors.

Selecting the Design Voltage

In selecting the design voltage for a proposed electric pipeline project, the sensitivity of the total cost and capabilities to the design voltage should be considered. Figure 3 shows that there is a broad optimum of design voltage between 4-9 million volts (conductor to conductor), but this is only part of the puzzle. The main factors limiting the design voltage are the thickness and cost of the required insulation layer, and the cost/availability of the converter stations.

It seems obvious that the design voltage should be as high as practical, insofar as the cost of the transmission lines per GW of capacity goes down dramatically up to 3 million volts between the conductors. For this project, we adopt ± 800 KV because that is the highest proven voltage for high voltage DC power transmission projects around the world today. Overhead HVDC powerlines run into major problems with corona discharge above two million volts; for this reason it is unlikely that overhead transmission lines with voltage between the conductors greater than 2 million volts will ever be built. Corona discharge is irrelevant for fluid-insulated or solid-insulated electric pipelines. Therefore, electric pipelines may perhaps be able to operate at voltages above two million volts; however there is another effect, the "volume effect" that tends to limit voltage in fluid-insulated or polymer-insulated electrical equipment such as transformers (for example) that needs to be addressed (see below). The author was not aware of the volume effect until he met with Professor Nelson to propose this project in November of 2008.

In the range of 0.5 to 2.0 million volts (differential voltage) converter station costs are not highly sensitive to the design voltage (for the high capacity converter stations that are relevant for the proposed project). If this trend (i.e., cost nearly independent of voltage for large AC/DC converters) holds up to four million volts, then the design voltage should be pushed up to around four million volts (for a continental scale HVDC grid), unless there are complications with the insulation. (The exact relationship of operational voltage to cost of converter stations is not known for very high voltage projects.)

Electric pipelines have a minimum feasible size that is largely determined by the voltage of the pipeline (because the voltage determines the minimum thickness of the insulating layer). The smallest practical (i.e., self-supporting and robust) HVDC electric pipeline for long distance power transmission is about as heavy (aluminum/km) as the heaviest feasible overhead transmission project (the previously mentioned Itaipu HVDC powerline, which uses about seven cubic meters of aluminum/km). This is within the range of conductor lineal densities calculated to be required for moving 20 GW from South Dakota to NYC with no more than 10% loss (3.6-14.4 cubic meters aluminum/km, depending on voltage).

For a continental grid an operating voltage of at least two million volts and preferably four to six million volts appears to be optimal, provided that polymeric and/or fluid insulators can be developed that are reliable at these voltages, and provided that no unforeseen obstacles occur in increasing operational voltage of converter stations. At a design voltage of 1.6 million volts DC an electric pipeline would not be plowing new ground in respect to the vital converter stations and circuit breakers, yet this voltage is high enough to demonstrate economic feasibility for the project. (If a coast-to-coast electric pipeline were actually built, design phase research could be expected to increase the operating voltage beyond two million volts.) However, for the present proposal, 1.6 million volts is adequate for reinforcing the eastern US regional grid, and for importing wind power from the Great Plains, for example.

Insulation of Electric Pipelines

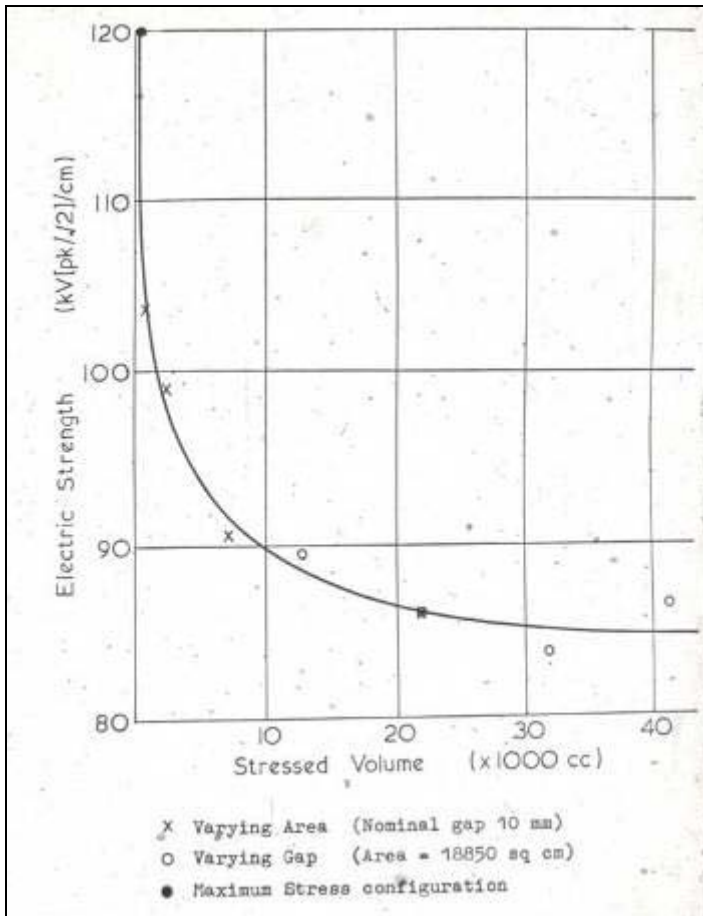
The design voltage implies a particular minimum insulator thickness. A thick insulation layer (as required by the high operating voltage) implies that a critical issue for electric pipelines will be heat transfer; in fact heat transfer often limits the maximum steady current carrying capacity of present day subsea HVDC cables (which are buried deep in ocean bottom sediments). The maximum short term transfer capacity is limited by the capacity of the converter stations and the adiabatic heating rate, while the steady state transfer capacity is often determined by the rate at which heat can be dissipated. Fluid insulators have the major advantage that free convection of such insulators greatly improves heat removal from the inner conductor. Effective heat transfer due to convection of fluid insulators also helps to minimize both the temperature and the maximum temperature change of the conductors. (The change of temperature sets requirements on the design of expansion joints.)

Aluminum has a fairly high rate of change of conductivity with temperature; the conductivity changes 30% from 20° C to 100° C. In MIND insulated HVDC cables, the maximum rated temperature for the conductor is 50° C, whereas in XLPE, steady temperatures as high as 70° C can be tolerated. This maximum temperature is determined mainly by long term stability and reliability but also somewhat by the changing conductivity of aluminum.

Electrical grade white mineral oil, castor oil, and pressurized SF₆ have been considered for the insulation. White mineral oil was selected for the preliminary design based on its good insulator strength, favorable environmental profile, and low cost. This type of oil is non-toxic and thermally stable for long-term use at 100° C under anaerobic conditions. An unreasonably liberal value of insulator strength (270 KV/cm) was adopted¹² based on thin film measurements of mineral oil electrical breakdown, and used to calculate an approximate thickness of the insulator layer, about ten cm at two million volts. Those calculations were made before I met Professor Nelson, who explained the volume effect¹³ in insulators to me. Figure 5 (from one of Professor Nelson's publications) shows the volume effect for mineral oil. I used a literature value for mineral oil insulation strength that was measured in a small gap, in a short term experiment. My estimate of breakdown strength was wide off the mark, as can be seen from Figure 5.

According to Professor Nelson, my assumed voltage breakdown strength for mineral oil in a large gap between an inner conductor and a steel inner pipe wall was too high by a factor of 130, because of the "volume effect." The volume effect is particularly strong in fluid insulators; as a result, for the time being we will set fluid insulators aside as an option.

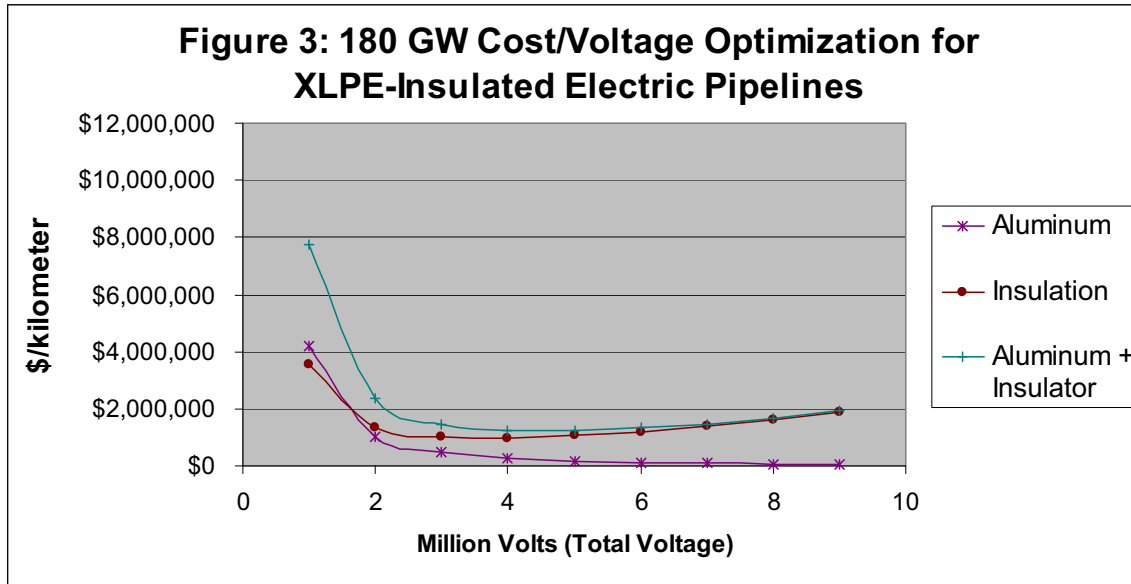
Figure 5: Breakdown Strength of Mineral Oil as a Function of Stressed Volume



The electrical strength above is for AC power, but is qualitatively similar to the observed behavior for DC liquid breakdown.

I have re-worked my calculations to be more reasonable according to the actual engineering breakdown strength of XLPE that is used by ABB in their 150 KV HVDC light cable (15 mm). Figure 3 (reproduced below for convenience) uses this realistic value of DC breakdown strength. The qualitative nature of the cost/km curve for the sum of the two major components, conductor + insulator, will look the same for any conventional conductor and any insulator. A broad range of economically optimum design voltage exists for each pair of one particular conductor and one particular insulator, the exact location of this optimum will vary with the properties (conductivity, density, cost, and DC voltage strength) of the conductor and the insulator. For the particular cases we evaluated (Figure 3, XLPE insulation, and Figure 4 nanocomposite reinforced XLPE insulation), the theoretical optimum operating voltage for the preferred conductor (aluminum) and PE-based insulators is around 5 million volts (total voltage), which means the HVDC transmission system would operate at ±2.5 million volts, for both XLPE and nanocomposite reinforced XLPE. This is a factor of three higher voltage than the presently proven HVDC technology. I do not advocate waiting until this optimum transmission voltage becomes

practical. This proposal instead recommends setting the voltage standard for electric pipelines at the new voltage standard created by the two recent ±800 KV projects being built in China.



Although there is only a small advantage seen for nanocomposite XLPE over conventional XLPE in terms of cost of the insulating layer per the assumptions I made (I took the nanocomposite to be twice as expensive as the standard XLPE), the nanocomposite XLPE has a very important advantage in terms of heat transfer out of the electricity pipeline because it need only be half as thick as an XLPE layer at the design temperature of 70° C.

This project if funded will engage Professor Nelson of Rensselaer Polytechnic to model proposed baffling methods (using the cumulative stress method) to predict and improve the performance of the fluid insulating layer in mineral oil insulated electric pipelines so as to refine estimates of the actual thickness of fluid insulator required for reliable insulation of the inner conductor, while still allowing efficient cooling of the conductor by convection of the oil. We will also model electric pipelines insulated both by standard XLPE and the nanocomposite-reinforced crosslinked polyethylene insulators that Professor Nelson and coworkers have developed. In order to achieve adequate heat dissipation, we anticipate that the conductor may have to take the form of a pipe, which increases the available surface area for heat dissipation through the low conductivity polymeric insulator. In general, the better the heat transfer, the smaller the diameter of the inner conductive aluminum tube can be, which saves money on the insulator.

Corridor and Installation Options

The electric pipeline installation method must allow for rapid repair in case of a fault condition, and must also provide a backup circuit to handle the load during repair of a particular circuit. The backup circuit can be parallel, but preferably would follow a completely separate path. Direct burial may be ruled out if one demands that the circuit be rapidly repairable, because of the impossibility of making rapid repairs on a buried line.

Several installation options are possible for electric pipelines. Overhead, buried, and siting the line in an accessible (probably mostly underground) service corridor are recognized options. Elevating the electric pipeline has advantages in terms of accessibility for maintenance and repair compared to burying the line. An elevated line would, however, have the greatest aesthetic impact and would also be at greater risk of accidental damage than the underground options. An elevated line would also experience greater temperature variations than the other proposed methods, which could cause several complications.

Buried lines have well known problems with maintainability and time required to repair a fault condition. Their reliability is generally good, however. Also, buried lines experience surface shear loads due to thermal expansion and contraction that could lead to fatigue problems. (This is more of a problem for electric pipelines than for gas or oil pipelines since fairly large daily temperature swings can be anticipated.) Buried rigid lines would require close-spaced expansion joints to overcome this difficulty. Finally, buried lines are subject to surface corrosion and damage during installation that may go undetected and cause problems later.

The preferred installation method for electric pipelines is to mount the electric pipelines in an accessible partially underground service corridor. The roof of the service corridor should ideally be rapidly removable to allow for access by cranes to the pipeline itself for repairs, if this should be required. (A fully buried corridor is less desirable because cranes could not be effectively used in construction and repair of the electric pipeline.) If two circuits (i.e., 4 electricity pipelines) share the same corridor, then it would be essential to guarantee that no feasible accident could simultaneously knock both electric circuits out of service simultaneously. (One implication of this is that parallel lines would have to be split so as to cross navigable rivers at different points, because of the possibility of damage to the bridge structure by a barge, for example.)

The design requirements outlined above for the electric pipeline service corridor are highly compatible with dual use of the corridor roof as a bike trail. Bikes, unlike trucks or trains, are incapable of experiencing violent accidents that could damage the corridor or the pipeline. Most routine maintenance and inspections would occur inside the corridor, with the roof on. The waste heat escaping from the electric pipelines in such a corridor is significant, and would have to be removed to allow the temperature inside the corridor to be controlled. This could be accomplished by mostly passive means, and it is also feasible to provide shelters along a bike path that are heated by waste heat from the electric pipeline(s).

Such a low aesthetic impact, environmentally benign installation method for an electric pipeline project increases the possibility of gaining the support of environmentalists and outdoor enthusiasts for the concept of electric pipelines. At the same time, the very low electrical resistance and high reliability of the pair of electric pipelines, and the maintainability due to placing the pipeline in an accessible service corridor, are advantageous from the utilities' point of view (and from the point of view of national energy policy).

The service corridor itself would be a major cost, if used in the proposed project; net cost over direct burial of the line is estimated to be about \$550,000/kilometer, or about \$2.75 billion for a the proposed 5000 km HVDC loop powerline (this portion of costs is not very sensitive to the size of the electric pipeline at all in the size range we are considering here). To put this in perspective, this amounts to less than the cost of two modern one GW power plants whereas the proposed HVDC loop pipeline could carry around 50 times this amount of power. (Such a HVDC loop would delay the need for at least 20 GW of new power plant capacity by allowing sharing of existing capacity.)

A service corridor has the advantage of a very long useful life compared to most other utility investments, such as power plants. Such a corridor would remain a valuable resource long after the electric pipeline per se is obsolete. The existence of such a service corridor would substantially reduce the future cost of creating parallel lines of all kinds, including telecommunications and superconductive grid lines.

Thermal Expansion of Pipeline

Thermal expansion of the conductors in the proposed (rigid) electric pipeline must be carefully considered. The compressible aluminum "accordion" shaped expansion joints preferred by Baker, Carlson, and Ouyang¹⁴ appear to be one suitable type of expansion joint. Another means by which thermal expansion and contraction could be allowed would be to allow the entire electric pipeline to expand and contract unencumbered. Within a service corridor an electric pipeline could be mounted on roller bearing supports so that lengthwise motion is not restricted. Such a mounting scheme would allow an increased length between expansion joints. Since the expansion joints will be quite expensive, mounting the electric pipeline in a service corridor on roller bearing supports may allow a cost savings over a buried system with regard to the cost of expansion joints.

Contingency Planning

No US utility planner would normally be willing to depend on power from one source through one line. The power must still be deliverable in a single contingency condition, such as outage of any particular powerline. Therefore, the huge energy transporting capability of an electric pipeline will never be used at full potential capacity unless at least two pipelines are built for reliability.

A particularly efficient way to provide double circuit service to numerous locations is to construct an electric pipeline loop system (as in Figure 1). Such a system has built in redundancy, even without a second parallel line, since power can be moved around clockwise or counter clockwise. A single break in such an HVDC loop circuit would not completely cut off any converter station (provided that circuit breakers can isolate the fault; however since main loop circuit breakers are sure to be quite expensive, it is doubtful that there would be more than a few main loop circuit breakers in such a system). It is vital that each tap be isolatable from the main loop by a circuit breaker to prevent a severe local disturbance from crashing the HVDC loop.

Also, it is conventional for large bipolar HVDC projects to be designed so that they can operate for a time in unipolar mode, with ground return. This could also be a feature of the proposed system, in which case, for contingency planning purposes, the bipolar system can be thought of as two independent circuits.

Useful Life of the Proposed HVDC Pipelines

It is certainly worth considering the life expectancy and ultimate fate of the electricity pipeline. The metal content of the pipeline is certainly recyclable. The insulation is not recyclable as a melt-processable plastic, since it is crosslinked in an irreversible way, but it can be recycled as a particulate (like finely ground tire rubber). If protected by an outside shield, and if the conductor and insulator are kept dry and not exposed to oxygen, the conductors would probably continue to work for thousands of years. Bearing this in mind, it is logical to mount the electric pipelines in a long lasting protective sheath.

Steel pipe will work, but will probably not last for thousands of years in soil unless it is coated with a tough water and oxygen barrier material.

Wisconsin PSC Advance Plan 6 Planning Docket, 1991/92

I introduced the concept of extruded aluminum electric pipelines as an alternative to overhead powerlines in a report and testimony I presented to the Wisconsin Public Service Commission (Advance Plan 6 planning docket, 1991/92). On the subject of proposed transmission options for linking western Wisconsin to eastern Wisconsin more strongly, I noted that:

" All the utility proposals involve overhead transmission lines. Overhead transmission lines have always been controversial, and have become more so because of increased public concern about EMF (electromagnetic fields). Overhead transmission lines also have numerous technical problems which have tended to be accepted as unavoidable consequences of transmitting bulk power."

This report went on to develop the concept of DC coaxial electric pipelines for Wisconsin's specific case. My testimony was politely received, but had little effect on that proceeding. This Appendix comes from a book chapter I wrote based on my presentation in the Wisconsin Public Service Commission's Advance Plan 6 Docket. (The author is greatly indebted to Professor Willis Long of UW Madison, who served as the author's expert witness in the AP6 Docket, and Paul Nonn of the UW Nuclear physics support staff, who aided in the preparation of my AP6 testimony.)

The following excerpt is taken from the testimony of Professor Bill (Willis) Long of UW-Madison in the Wisconsin Public Service Commission's Advance Plan 6 (AP6) hearings in 1991; it summarizes several important features of HVDC grids succinctly and with authority. (The support document cited in Professor Long's testimony, AP7 Exhibit 175, is essentially a similar document to the preceding Appendix, but was written from a state utility planning perspective rather than the regional/continental scale of the proposals above.)

- Q.: Do HVDC transmission links contribute to system stability and reliability?
- A.: Yes, particularly under contingency conditions such as when a major transmission line or generating station has been taken out of service for maintenance, an HVDC link can improve overall system stability in case of an unplanned system disturbance, such as may occur due to lightning, for example.
- Q.: Why have HVDC transmission systems not seen greater application as of yet?
- A.: Probably the major negative factor is the relatively high cost of the AC/DC converter stations. These converter stations have been coming down in price for decades, but still cost much more than comparable AC transformers. The cost of such converter stations would probably come down significantly in price if a larger market developed. At present, only a few large AC/DC converter stations are built each year.
- Q.: Please define the concept of an AC synchronous area.
- A.: AC grids normally operate as a large area in synchronization. This does not imply that all generating plants are in exactly the same phase at a given time, but rather that the various

generating plants have a stable phase relationship. An AC grid of infinite expanse could be kept in synchronization, but only if it were not disturbed. Real electrical grids must withstand various kinds of disturbances, and this requirement limits the maximum size of an AC grid. The North American Continent is too large to operate effectively as a phase-linked AC grid. There are in fact three large synchronous AC areas in the continental US, consisting of the East (includes Wisconsin), the West, and Texas AC grids.

Q.: Can these synchronous areas be interconnected by AC lines?

A.: Under stable conditions, it would be possible to interconnect the various AC grids in the US. Under disturbance conditions, however, this interconnection will prove unstable and unreliable.

Q.: Can different AC synchronous areas be interconnected by DC linkages?

A.: Yes, they can, and improved reliability of both systems will generally result from such an interconnection. The degree to which reliability is improved for such an HVDC intertie between asynchronous areas depends on how powerfully the end-points of the HVDC link are tied into the AC grid. Tying the HVDC link in at two or more key points in each of the asynchronous AC grids will improve the stability enhancement due to the HVDC intertie considerably over a two-terminal design in which each of the AC grids is only connected to the HVDC link at a single point. The value of DC interties is well recognized by system planners; in fact, such DC interties are often referred to as "asynchronous links."

Q.: Can you cite a few examples of AC/DC converters being used as an asynchronous link between two synchronous AC systems?

A.: Yes; for example in Japan there are different areas that operate at 50 Hertz (the European standard frequency) and at 60 Hertz (the North American standard). These two areas are tied together through back to back AC/DC converters. Another example occurs near the Austria/Czechoslovakia border across the former iron curtain, where an asynchronous link is used to connect the two synchronous AC areas.

Q.: Would it be fair to say that the reliability of both the Eastern and Western USA grids would be improved by a strong asynchronous DC intertie between these grids?

A.: Yes. There would also be a decrease of spinning reserve and reserve margin requirements, though it is impossible to quantify these effects without detailed modeling which I have not performed. I should note, however, that there was a DOE-sponsored study of this issue in approximately 1978.

Q.: What is the largest DC multi-terminal system that has been designed to date?

A.: The question of multi-terminal DC lines and the control aspects thereof, is one that's gotten a lot of attention in the literature in the last five years or so. The system being built now between Quebec and New England has five terminals, one of which will not be operated under normal conditions. This system starts at James Bay, drops part of its power at Montreal through two stations, one a little north and one a little south of Montreal, then continues to a terminus west of Boston. The fifth terminal was added after

- the system was initially engineered because of political considerations, and is not expected to operate much, if at all.
- Q.: Would you say that a five terminal HVDC transmission project is a proven technological option at this point?
- A. Yes; it's been studied extensively by computer simulation. The people who are studying it are people who used to work for me, and are extremely good at what they are doing. The James Bay to Boston system is designed to operate either with full communication through a central computer, or in the absence of communication. When communication is lost, the system remains stable and functional, though without communication the operation is somewhat less optimal. The specific problem encountered with the fifth terminal in the Hydro Quebec system came about because of a capacity mismatch with the other terminals, and because the system was originally designed as a four terminal system.
- Q.: What is the status of DC breaker development?
- A.: DC breakers have been developed for 400 KV service, and have been tested at field currents of 2000 amps and laboratory currents of 4000 amps. The people that developed this device would claim it is commercially available. No one has bought it and installed it on a commercial power system yet, however, so most power system engineers remain skeptical about the reliability of these breakers, as they have not seen large scale commercial installation of such breakers yet.
- Q.: Would the DC breaker problem prevent the construction of any of the project proposals cited in AP6 Exhibit 175?
- A.: No.
- Q.: Do you believe that two electric pipelines in the same service corridor can be considered for reliability purposes as two independent circuits?
- A.: With several caveats, the answer is yes. However, the corridor system must be so designed that a worst-case short circuit in one electric pipeline cannot damage the other pipeline. Also, the two pipelines would have to be separated at high-risk crossings, such as some highway crossings and any crossings over navigable rivers.
- Q.: Do you think that AP6 Exhibit 175 presents a reasonable case for HVDC electric pipelines as an appropriate means to interconnect the three US AC synchronous regions?
- A.: Yes. I would like to amplify on the notion which is contained in AP6 Exhibit 175 but not really emphasized, that conventional aluminum electric pipelines installed in an accessible service corridor would make the future upgrade of that transmission line to superconductive transmission both easier and less costly. Superconductive cable will almost surely be installed in a service corridor, since refrigeration equipment will be required to keep the line cold. In the future eventuality that a superconductive line would be installed in the same corridor as one or a pair of conventional aluminum electric pipelines, this would not necessarily imply that the aluminum electric pipelines would lose their value, since in that case the electric pipeline backups would significantly

improve the safety and reliability of the linkage since loss of cooling for the superconductive line will always be a possible fault mode.

Q.: Does this conclude your direct testimony?

A.: Yes, it does.

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- ¹ Consider for example: "Challenges with Multi-Terminal UHVDC Transmissions;" by Victor F. Lescale, *Member, IEEE*, Abhay Kumar, Lars-Erik Juhlin, *Member, IEEE* Hans Björklund, *Senior Member, IEEE*, and Krister Nyberg; Presented at: POWERCON2008 & 2008 IEEE Power India Conference October 12-15, 2008, New Delhi, India <put in standard format>
- ² R. L. Garwin and J. Matisoo, "Superconducting Lines for the Transmission of Large Amounts of Electrical Power over Great Distances," *Proc. IEEE* **55**, 538 (1967).
- ³ Testimony of Willis Long to Wisconsin PSC Advance Plan 6 hearings (Wisconsin Public Service Commission (Advance Plan 6 planning docket, 1991/92); appears in Appendix
- ⁴ National Energy SuperGrid Conference, Palo Alto November 6-8 2002 papers; note especially "The National Energy SuperGrid-Value & Implementation" by Chaim Braun (a copy will be supplied with the PON application)
- ⁵ SuperGrid 2 Conference: October 25-27, 2004, Levis Faculty Center University of Illinois at Urbana-Champaign (http://www.w2agz.com/SG%20-20SuperGrid%202.htm#Overview_&_Agenda): note especially "Superconducting Grid" by Bob Lasseter (Professor, UW Madison (a copy will be supplied with the PON application)
- ⁶ The Energy SuperGrid: Tech Stuff, <http://www.w2agz.com/SG%20-%20Tech%20Stuff.htm>, Accessed 1/20/09
- ⁷ For example, see papers from: SuperGrid 2 Conference: October 25-27, 2004, Levis Faculty Center University of Illinois at Urbana-Champaign:
- ⁸ http://www.airtricity.com/ireland/wind_farms/supergrid/
- ⁹ see for example: Internal Charge Behavior of Nanocomposites, by J. Keith Nelson and John C. Fothergill, *Nanotechnology* 15 (2004) 586-595 (there are many other articles on this subject by Professor Nelson; for full details refer to his CV which is included in the Appendix.
- ¹⁰ A Power Grid for the Hydrogen Economy: Overview/A Continental SuperGrid
By Paul M. Grant, Chauncey Starr and Thomas J. Overbye (*Scientific American*, June 26, 2006).
- ¹¹ Central Station Engineers, Electrical Transmission and Distribution Handbook, pg 34, Westinghouse Electric Corp, East Pittsburg PA, 1964.
- ¹² G. Luoni, D.A. Morello, and D.A. Silver (Pirelli Cable Co.), "HVDC Underground Cables for Large Urban Systems: Types, Voltages, Transmissible Power," pages 149-165 in *The Proceedings of the Symposium in Urban Applications of HVDC Power Transmission*, October 24-26, 1983 in Hershey, PA; Conference Sponsored by The Division of Electric Energy Systems, US DOE.
- ¹³ "Internal Charge Behavior of Nanocomposites" by J. Keith Nelson and John C. Fothergill, *Nanotechnology* 15, 2004 pp 586-595
- ¹⁴ **Ibid.**, page 167: by M. Ouyang, L.E. Carlson, and M.A. Baker "A ±600 KV HVDC Gas Insulated Transmission Line."