American Superconductor®

REVOLUTIONIZING THE WAY THE WORLD USES ELECTRICITY®

Superconductor Electricity Pipelines

Carrying Renewable Electricity Across the U.S.A.

Out of Sight and Out of Harm’s Way

A White Paper
May 2009

The Challenge of Moving Renewable Power Long Distances

The U.S. is rich in renewable resources for electric energy production. Wind energy is already a significant source of electric power, and solar power is gaining traction. In order to continue developing these resources, the North American electric power grid must be expanded, reconfigured and/or modernized to facilitate the challenge of moving large amounts of electricity over very long distances. The inability of the existing transmission system to move electricity from the resource rich, but often sparsely populated, parts of the country to population centers remains a primary barrier in achieving the 20-30% renewable energy goals being put in place.[1]

The principal technology used today for long distance, high power transmission is high voltage overhead lines, whether alternating current (AC) or direct current (DC). However, a number of challenges have limited a wider application of this technology. These challenges can be addressed effectively by DC superconductor underground cables, which when coupled with voltage source converters (VSC), enable multi-terminal transmission over very long distances. Together, these technologies form Superconductor Electricity Pipelines, which offer an attractive new option for bringing large amounts of renewable power to market in a timely fashion.

Challenge 1: Siting

Siting of overhead power lines is generally regarded as one of the most difficult issues facing today's long-haul transmission projects. Public opposition to power lines that require hundreds of feet of right of way, battles over eminent domain, and concerns over aesthetics, real estate valuation, and electro-magnetic fields (EMF) are well known and documented. These issues can result in multi-year delays, high legal costs and poor customer relations. Underground DC superconductor cables require only a few feet of permanent right of way and can be sited in existing railroad and roadway paths. They are free of EMF and their deployment underground negates all concerns about aesthetics.

Challenge 2: Distance

The distance is growing between urban centers requiring more power and new sources of electricity generation. Renewable sources such as wind, solar, geothermal, and hydro are often quite distant from load centers. Distance is also becoming an issue when considering the construction of new power plants that depend upon more traditional sources of energy such as coal or nuclear. There is an increased desire to locate these plants further away from the end consumer of power, either to be closer to a source of cooling water,[2] closer to the energy source, or to a location where less public opposition is likely. This creates the need to move large amounts of power further than ever. With their very high power carrying capacity and exceptionally low power losses, DC superconductor cables provide a compelling new solution to the challenges associated with long distance transmission of electric power.

Challenge 3: Multiple Sources of Renewable Energy

Unlike traditional power plants, renewable energy sources are often distributed over a wide geography and are variable given the nature of the energy source. Aggregating geographically diverse renewable resources —wind and solar in particular —is key to reducing variability and uncertainty of the resource therefore facilitating integration with the grid. The transmission network must be able to support the connection of many renewable energy "farms" over a wide geographic area. Superconductor Electricity Pipelines have multi-terminal access, or "electricity on ramps," allowing many farms to be directly connected along the cable path, a feature shared with some other transmission technologies.

Challenge 4: Multiple Destinations

The demand for electricity from sources of renewable energy is rising dramatically in all regions of the country, and increasingly aggressive regional and national goals are being set to ensure that a large amount of the United States' electricity is produced from renewable resources. Though such sources are ostensibly available everywhere, population centers are generally geographically remote from locations that offer the highest quality resources. Just as the multi-terminal capabilities of Superconductor Electricity Pipelines allow for the connection of many renewable energy sources, they also offer "electricity off-ramps" to multiple population centers along the pipeline's path.

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[1] *"20% Wind Energy by 2030"*, U.S. Department of Energy Office of Energy Efficiency and Renewable Energy, July 2008, *"20% Wind Scenario: Major Challenges"* sidebar, p14. Note that Superconductor Electricity Pipelines address three of the four Major Challenges identified in this sidebar. In addition to transmitting wind energy to urban centers, Pipelines address larger load balancing areas (see page 14) and siting and environmental issues (page 12+).

[2] "Water Worries Shape Local Energy Decisions," Wall Street Journal, March 26, 2009.

Challenge 5: Cost Allocation

Cost allocation is frequently the most significant impediment to new transmission projects, often resulting in lengthy project delays while the cost sharing is studied and negotiated. There are many aspects of the cost allocation problem. One of the core issues is that while new transmission line projects provide significant benefits for consumers by reducing their electric bills, the physics of AC power transmission makes exact determination of the benefit each utility or region receives from a new line very difficult. Because DC transmission provides for very accurate control of electricity, the use of DC superconductor cables can simplify or eliminate key aspects of the cost allocation issue.

Challenge 6: Transmitting Across Interconnections

It would be very difficult or impossible to operate a single, synchronous AC power grid from coast to coast. As a result, the U.S. electrical grid is divided into three self-contained, large-scale power grids, or “interconnection areas.” These are the Eastern and Western Interconnections and the Electric Reliability Council of Texas (ERCOT), which operates the majority of the power grid in Texas. Electrical connection between these regions generally requires the use of DC power links to properly synchronize power flow between the regions. Power electronic AC to DC converters must be used to convert AC power from one region to DC power and then back to AC power in the adjacent region. The DC links employed in Superconductor Electricity Pipelines establish these interconnections seamlessly.

Challenge 7: Energy Losses

When electricity flows through a metal wire such as copper or aluminum, some of the electrical energy is transformed into heat because of the wire’s electrical resistance. This means that some of the electricity generated from renewable energy sources will be wasted in the power lines. The longer the power line, the more energy is wasted. If the source of electricity generation is fossil fuels, more fuel must be burned to make up for these electrical energy losses, thereby increasing the carbon footprint of the nation’s electrical energy system. Even if the fuel source is renewable, the losses are costly and result in less carbon-free energy for the consumer. These are major energy efficiency, energy independence and climate issues.

DC superconductor cables have no electrical resistance, and therefore cause no power losses by themselves; the only losses are associated with the cable’s refrigeration system. The result is that DC superconductor cables are significantly more efficient than conventional DC or AC overhead lines and cables, particularly at long distances. And by enabling wider use of renewable energy sources, they also promote energy independence.

Challenge 8: Security

Overhead AC and DC transmission lines are exposed to severe weather patterns such as ice storms, tornadoes and, more commonly, lightning. Trans-mission towers also are subject to acts of willful destruction (vandalism and terrorism). Incidents such as these can cut power supplies to distant cities for lengthy periods of time. Underground DC superconductor cables put the power link out of sight and out of harm’s way.

Challenge 9: Flow Control

The proper operation of a power system must also support the economic transactions between buyers and sellers of power. This requires management of many aspects of the power system itself to control power flow. DC terminals enable real-time control of power flows. In addition to providing the ability to improve the overall stability of the AC grid, the ability to change the direction of power flow very quickly provides numerous opportunities to enhance the operation of the grid.

The Solution: Superconductor Electricity Pipelines

The Concept

Superconductor Electricity Pipelines combine conventional underground pipeline construction techniques with two highly complementary electric power options: superconductor cables and multi-terminal (voltage-source converter-based) DC power transmission. The result is a high-capacity electric transmission “pipeline” that is underground, easy to site and access, highly efficient, controllable and offers greater security than competing technologies.

The Technologies

Superconductor Cables

As the name suggests, superconductor cables utilize superconductor materials instead of the copper or aluminum traditionally used to carry electricity in overhead power lines and underground cables.

Superconductor materials provide two major advantages. First, wires made from superconductor materials conduct well over 150 times the amount of electricity that can be conducted by copper or aluminum wires of the same size. This power density advantage drives system economics and is fundamental to the reason underground superconductor cables can achieve cost parity with overhead AC power lines over long distances. Second, when transmitting DC power, superconductors have absolutely zero resistance to the flow of electricity, which means that DC superconductor cables are literally perfect conductors and introduce no electrical losses of their own.

Superconductor materials must be refrigerated to exhibit their ideal electrical characteristics. The cables are cooled with conventional liquid nitrogen refrigeration systems that are widely used in a variety of industries. While some power is required for the refrigeration — lowering the overall system efficiency —superconductor power cable systems still have much higher overall efficiency than any other long-distance transmission system.

Figure 1: 138 kV AC superconductor power transmission cable operating since April 2008 in Long Island Power Authority' s grid.

Figure 2: Typical underground pipeline construction

The cables employ superconductor wires that are commercially well established and are available from multiple producers globally. Superconductor cable systems are now operating in multiple in-grid sites around the world, demonstrating their reliability and performance, as illustrated in Figure 1. While all previous installations are AC applications, applying this established technology to DC is straightforward. Figure 2 shows typical underground pipeline construction and burial methods and Figure 3 shows a cross section of one possible design of a Superconductor Electricity Pipeline. Because superconductor cables are compact, light, and emit no heat or electromagnetic fields (EMF), they are particularly easy to install, even in close proximity to other underground infrastructure.

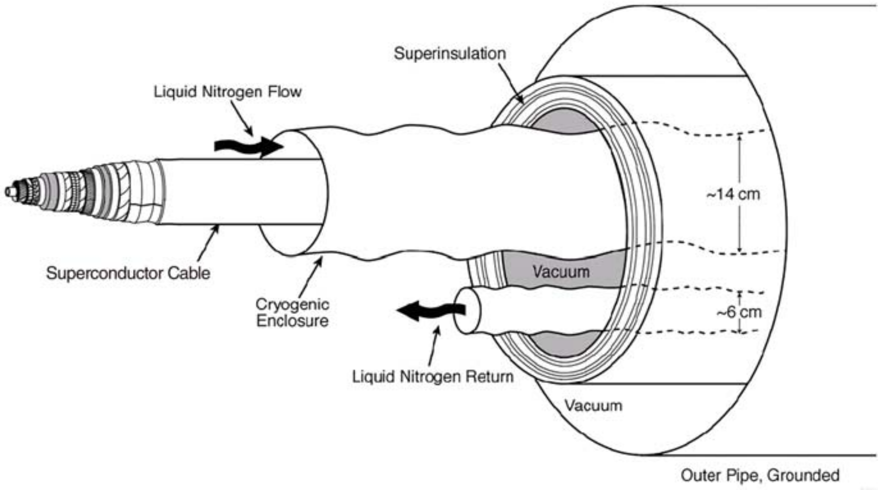

Figure 3: Superconductor Electricity Pipeline cross section (Figure courtesy Electric Power Research Institute).

Multi-Terminal DC Transmission

DC power transmission has been used for decades around the world to move large amounts of power from one source of power generation to one load center. While a few multi-terminal systems have been built, they were very difficult to implement. Recently, multi-terminal technology based on new power electronic designs incorporating so-called voltage-source converters (VSC) has become available. This technology provides greater control and flexibility and more simply enables DC lines to connect to multiple generation sources and multiple areas of electrical demand.

DC terminals employing VSC technology, however, are available only at relatively moderate (100-300kV) voltages. By comparison, ultra-high voltages (+/- 800kV) are required for conventional point-to-point DC transmission. To be used in high power transmission, the lower voltage levels require the use of very high currents. But transmitting high current long distances through conventional aluminum or copper conductors results in considerable resistive losses (discussed further on page 8). Superconductor power cables break through these limitations by providing the ability to carry very high levels of current with zero electrical loss. The combination of a VSC-based multi-terminal DC system and superconductor cables makes for a compelling new transmission option, uniquely suited to transmitting renewable energy over long distances with multiple collection and distribution points.

The Superconductor Electricity Pipeline System

The superconductor DC cable functions as a virtual bus-bar that can carry a set amount of power across its length. The VSC terminals are able to inject power onto the line, or pull power off the line in precisely controlled amounts. This would be akin to valves on a gas pipeline or on- and off-ramps on a highway. For example, a 5,000 megawatt (MW) superconductor DC cable may have 250 MW injected at 20 locations as it passes through the wind energy rich upper Midwest portion of the U.S., and deliver 500 MW to each of the ten cities that it passes on the way to the east or west coasts.

Figure 4 shows some of the areas most suitable for wind power production in the United States. The blue lines represent possible paths for a Superconductor Electricity Pipeline, and the blue circles represent discrete points of connection to the Pipeline. Traditional AC transmission would be utilized to collect power from geographically adjacent wind farms and provide a common point of connection to the Pipeline at the blue circles. Connecting the Superconductor Electricity Pipeline in loops as shown increases reliability, as maintenance work or unavailability to one section of the Pipeline would not prevent power from flowing from one location to another.

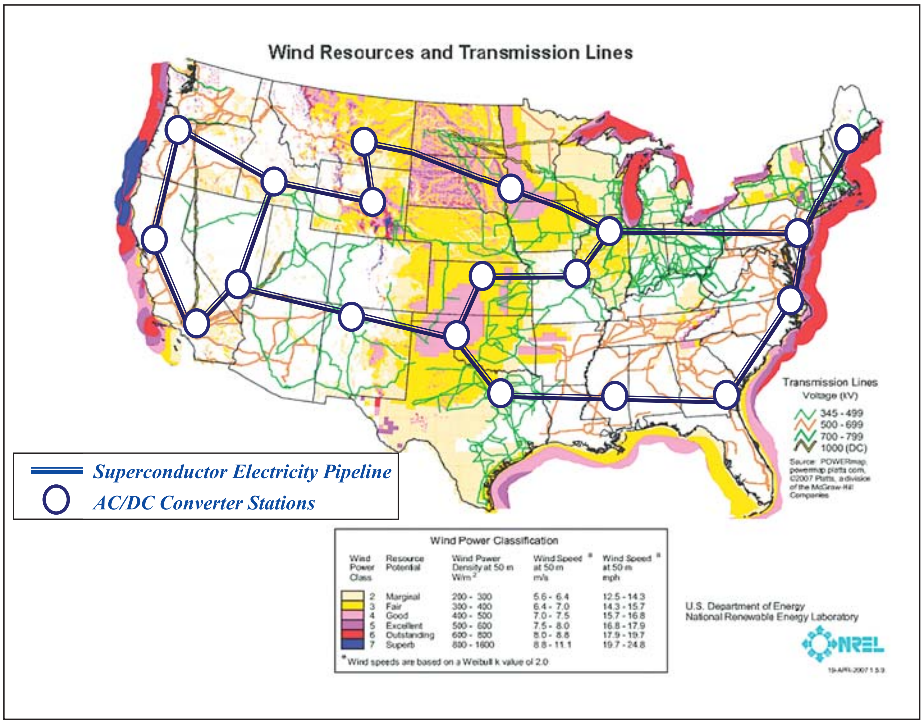

Figure 4: Sample Superconductor Electricity Pipeline paths to connect renewable power

Implementing the Pipeline as shown would provide a straightforward means to:

- Collect wind energy from both onshore and offshore wind farms;
- Collect renewable energy from solar and geothermal rich areas;
- Enable the delivery of renewable power to major population centers, including regions that have less productive renewable resources; and
- Transfer power from region to region to take advantage of seasonal and daily power generation and load profiles.

Comparision of Transmission Options

DC superconductor cables are not optimal for all forms of electric power transmission, but are uniquely well suited for moving renewable power long distances from multiple sources to multiple destinations while also addressing various technical and commercial concerns. The shortcomings of conventional forms of electric power transmission for this specific purpose are detailed below.

AC Overhead Transmission Lines

Overhead AC transmission lines form the overall skeleton of today's electric power grid. This grid was largely designed and constructed at a time when utilities generated their own power, transmitted the power over their own system and then distributed it to their own customers. The length of transmission lines was limited, and each system was tightly integrated. Over time, transmission lines were built to provide connections with other utilities, but those were primarily for reliability-based reasons.

Moving more power further with AC overhead transmission lines requires the use of higher voltage lines. Besides the obvious impacts of larger towers and increased right-of-way requirements, these lines are limited by basic electrical tenets, including:

- The further an AC line moves power, the higher electrical losses become.
- The amount of power that can be moved along an overhead AC transmission line drops with distance.
- When a network of new AC power lines is applied at a voltage higher than the existing system, much of the existing system may have to be modified or rebuilt to support it. This is akin to constructing a new superhighway to accommodate ten times the traffic. These highways may move bulk traffic (electricity) more effectively, but when the road is closed (i.e., a fault occurs on the power system) all the additional traffic must exit the new highway and go on to existing roads. Just as the existing road system would have to be rebuilt to accommodate the additional traffic, so would part of the existing electrical grid. This can require significant additional costs and impact the time required to implement the new system.
- It is not possible to precisely control how or where power flows on an AC electrical grid, making it difficult to determine which utility should pay for what part of a new transmission line. Technology advances like Supercon-ductor Electricity Pipelines will help transition to the grid of the future.

AC Underground Transmission Cables

AC underground transmission cables are widely used in urban environments and have the advantage of being out of sight and out of harm's way. However, unavoidable electrical characteristics of traditional underground AC cables make them less than ideal for moving very large amounts (more than 1,000 MW) of AC power. Moreover, these characteristics dramatically limit the distance that this power can be carried. Moving large amounts of AC power underground much further than 100 km (60 miles) in a single cable link is not technically practical.

Overhead and Underground Point-to-Point HVDC Transmission

The use of high power electronics to convert AC power to very high voltage DC power overcomes many of the issues associated with AC transmission. High Voltage DC (HVDC) or Ultra High Voltage DC (UHVDC) overhead transmission lines provide a relatively efficient means to move power very long (1000+ miles) distances. Power losses are typically lower for DC than with AC overhead or underground lines. Traditional HVDC transmission[3],

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[3] Conventional HVDC systems employing line commutated converters.

however, is typically limited to the transfer of power from only one point to one other point. This "point-to-point" transmission system is commonly used where power must be moved from a large power generation source, such as a hydro-electric dam, to a single point of power consumption, such as a single metropolitan area. Overhead HVDC lines, which go up to 800kV, have right-of-way requirements similar to those of a single 765kV AC transmission line[4], and with it, share the same siting and security challenges.

Conventional underground HVDC transmission has the advantages of overhead HVDC lines but with a more limited power transfer capacity. This is because DC cables are not available at the higher voltage ratings required for higher power capacities. Transmitting thousands of megawatts of power would require the use of many cables in parallel, increasing both power losses and right of way requirements.

Multi-Terminal Overhead and Underground HVDC Transmission

Multi-terminal HVDC transmission systems have been built using conventional converter technologies but are limited to only a few terminals. Newer HVDC systems employ a special type of AC to DC VSC terminals. VSC terminals operate at lower voltages than do conventional HVDC terminals (+/-200kV DC instead of +/-800kV DC). When using conventional copper conductors, it is important to limit electrical losses to reasonable levels by keeping current levels low. When used with conventional conductors, the lower voltage VSC terminals ultimately place bounds on both the amount of power and the distance the power can be moved.

Table 1 summarizes the various transmission power-distance scenarios and which transmission method is best suited to each. Note the unique advantages of Superconductor Electricity Pipelines.

The Advantages of Superconductor Electricity Pipelines

Simplified Siting

Avoiding Public Oppositions

The ability to construct the entire DC superconductor cable underground addresses significant issues associated with new overhead transmission line construction: public opposition to new high voltage power lines that interrupt the horizon require clear cutting of broad right-of-ways, permanently co-opt real estate (whether public or private) and creates public health and environmental concerns (whether justified or unjustified). This type of opposition results in lengthy construction delays - sometimes lasting years - and high legal expenses while the numerous community group challenges are addressed. For these reasons, almost all new urban and suburban distribution circuit projects have transitioned from overhead to underground over the course of the past several decades. In fact, the desire for underground transmission has led at least one community to pay their local utility to cover the cost of converting overhead transmission to underground.[5]

Reduced Right-of-Way Requirements

Overhead transmission lines require substantial rights of way to accommodate the necessary air clearances needed to support the voltage being used. The ability of any AC overhead line to transmit power drops with distance. Figure 5 compares the power transfer capability of a single 765kV AC overhead line to that of a DC superconductor cable. From this, it can be seen that more than one AC line may be required to move power long distances.

In comparison, DC superconductor cables are highly compact, requiring at most a 25-foot permanent right-of-way for a 3-foot pipe. And their power transfer capability does not diminish with distance. All other transmission technologies will require larger rights of way to move similar amounts of power. Table 2 compares the right of way required for various types of overhead power lines, and Figures 6 and 7 depict the equivalent right-of-way required to move 5,000 MW, 1,000 miles using 765 kV AC overhead transmission lines or a Superconductor Electricity Pipeline.

		SUITABLE TRANSMISSION SOLUTIONS						
		Overhead Solutions			Underground Solutions			
TRANSMISSION LINE POWER AND DISTANCE REQUIREMENTS		AC	Point-to-Point HVDC	Multi-terminal VSC HVDC	AC	Point-to-Point HVDC	Multi-terminal VSC HVDC	Multi-Terminal Superconductor Pipeline
Low Power (<1GW)	Short (<100 mile) lines	✓		✓	✓	✓	✓	
Low Power (<1GW)	Moderate (100-400 mile) lines	✓	✓	✓		✓	✓	
Low Power (<1GW)	Long (>400 mile) lines	✓	✓					
Moderate Power (1-5GW)	Short (<100 mile) lines	✓						
Moderate Power (1-5GW)	Moderate (100-400 mile) lines	✓	✓	✓		✓	✓	
Moderate Power (1-5GW)	Long (>400 mile) lines		✓			✓		✓
High Power (>5GW)	Short (<100 mile) lines	✓						
High Power (>5GW)	Moderate (100-400 mile) lines		✓					✓
High Power (>5GW)	Long (>400 mile) lines		✓					✓

Unique fit of Superconductor Electricity Pipelines for Long Distance, High Power, Multi-terminal transmission

Table 1: Comparison of best fit transmission methods for different power capacities and distances

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[4] "Ultra High Voltage DC Systems", ABB, Pamphlet no. POW-0043, p3.

[5] "LIPA working overtime to finish new lines," Young, B., *The Southampton Press*, June 30, 2008

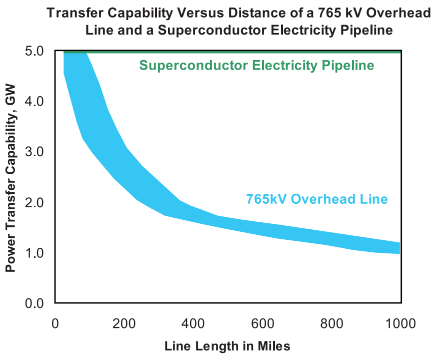

Figure 5: Comparison of power transfer capability versus distance of a single 765kVAC overhead transmission line[6] to a Superconductor Electricity Pipeline.

Re-use of Existing Infrastructures Right-of-Ways

The highly compact nature of DC superconductor cables and the resulting minimal right-of-way requirements enables the reuse of existing infrastructure rights of way.

For example, railroads, gas pipelines and the medians of interstate highways can all easily accommodate the co-location of DC superconductor cables. This can eliminate or greatly reduce the need for complex, contentious and costly siting procedures. These pipelines also minimize the impact on public lands, including national parks, wilderness areas or other environmentally sensitive areas, in addition to populated areas. See Figure 8.

Aesthetic and Environmental Advantages

By utilizing DC power and taking advantage of other characteristics of superconductor materials, DC superconductor cables have minimal to no external electrical or magnetic fields (EMF). The significantly higher current handling capabilities of superconductors allow operation

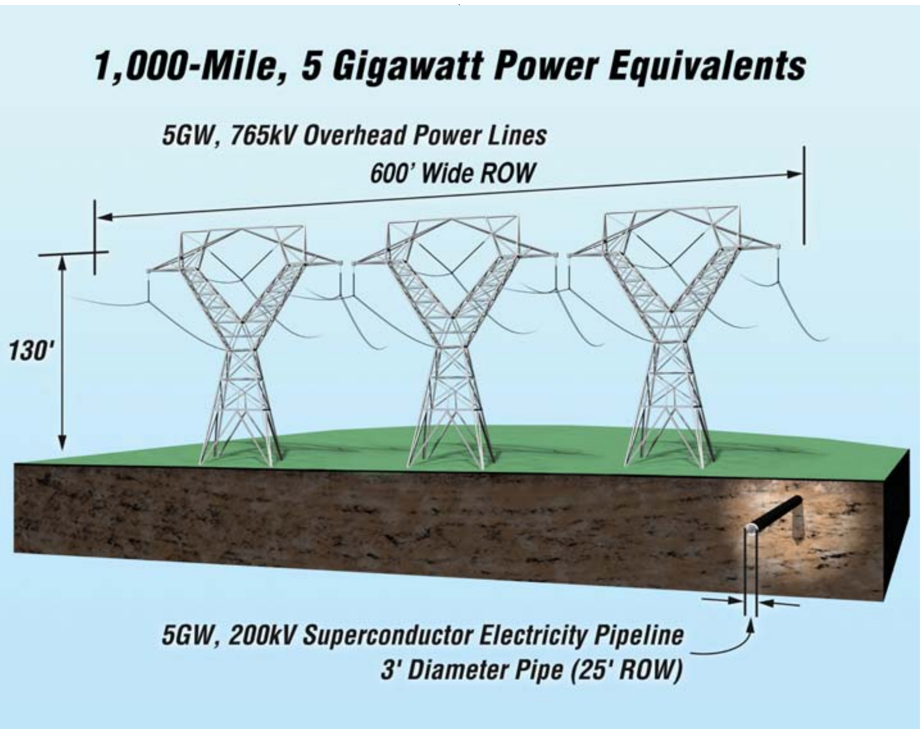

Figure 6: Aggregate right of way comparison to transmit 5 GW (5,000 MW) for 1,000 miles with three overhead AC lines with 8% power losses and DC superconductor cables[9].

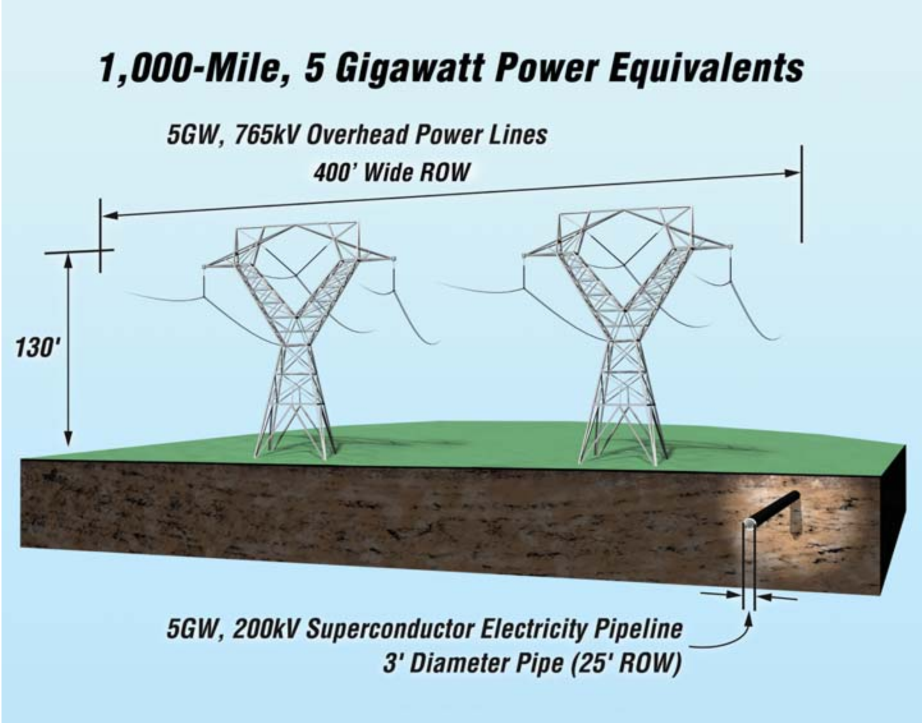

Figure 7: Aggregate right of way comparison to transmit 5 GW (5,000 MW) for 1,000 miles with two overhead AC lines with 12% power losses and DC superconductor cables[10].

Type of Transmission Line	345kV AC[7]	500kV AC[8]	765kV AC[4,7]	800kV DC[9]	Superconductor Electricity Pipeline
Right-of-Way Requirement	1350'	1000'	600'	270'	25'

Table 2: Transmission line right of way requirements to transmit 5,000 MW, 1000 miles.

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[6] "Analytical Development of Loadability characteristics for EHV and UHV Transmission Lines", Dunlop, R., Gutman, R., and Marchenko, P., *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-98, No.2 March/April 1979. Line represented in figure has a Surge Impedance Loading (SIL) of 2400MVA.

[7] "AEP INTERSTATE PROJECT: 765 kV or 345 kV Transmission", *American Electric Power*, April 24, 2007, p 8. Right of way based on three, 765kV lines, and nine, 345kV lines.

[8] Potomac-Appalachian Transmission Highline FAQ , http://www.pathtransmission.com/faqs/default.asp, *Potomac-Appalachian Transmission Highline*, LLC, 2009. Right of way based on five 500kV lines.

[9] Ibid, ABB, p3.

[10] Two and three line designs based on 765kV line design of 2400kV SIL, using 6-conductor bundle of Drake ACSR conductor with compensation every 200 miles.

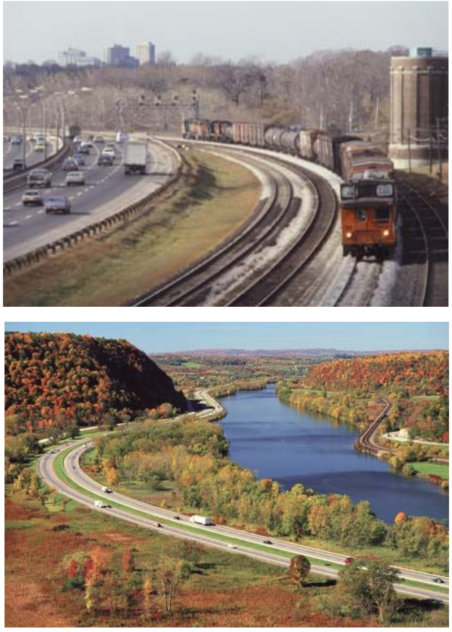

Figure 8: DC superconductor cables can be located along existing transportation rights-of–way.

at lower voltages (200 kV) than other high capacity transmission technologies that require voltages as high as 1000 kV. Underground construction is also less environmentally intrusive, reducing visual pollution of the landscape.

Economic Benefits

Efficiency

DC superconductor cables have zero electrical losses as a result of superconductors' zero resistance to DC current flow. The only losses in a Superconductor Electricity Pipeline will be associated with the conversion losses of the AC/DC terminals and the losses of the cable's cooling system. Total system losses to move 5,000 MW are less than 3% at 1,000 miles. This is roughly one-quarter to one-half that of other point-to-point conventional transmission technologies. The result is the most efficient method available to transmit large amounts of power long distances. See Figure 9.

Cost Allocation

Though cost allocation of transmission projects is complex, one key issue is that projects benefit many utilities as a result of the new line's construction. Yet the nature of AC transmission makes exact determination of the benefit each customer of the transmission line receives very difficult, often resulting in project delays while the cost sharing is studied and negotiated. This problem becomes more pronounced the longer and more extensive the AC transmission line project becomes, and is further complicated when additional AC lines are built, changing the power flows once again.

The precise control and measurability of the power supplied to and delivered from the DC on- and off-ramps simplifies determination of cost allocation as the beneficiaries of power sales and purchase will be clearer.

High Power

Because superconductors have no electrical resistance, it is possible to construct DC superconductor cables with practically any desired power transmission capability. The example used throughout this white paper is 5GW (5,000 MW), sufficient power for 2.5 million homes. It is possible to build the pipelines with even higher ratings (10GW or more) with little to no additional loss penalty. This essentially unlimited design capability is not possible with any other type of power transmission.

Over-designing a Superconductor Electricity Pipeline to accommodate future growth and changes in power flow is readily achieved without significant increase in cost. This is important as transmission lines have lifetimes of 50 years or longer. Planning for the future by designing in additional capacity can be a prudent method of capturing the economies of scale that Superconductor Electricity Pipelines can uniquely offer.

Enhanced Market Dynamics

The precision and flexibility in power collection and delivery provided by Superconductor Electricity Pipelines provide opportunities to exactly match purchases of energy generated to sales of energy delivered.

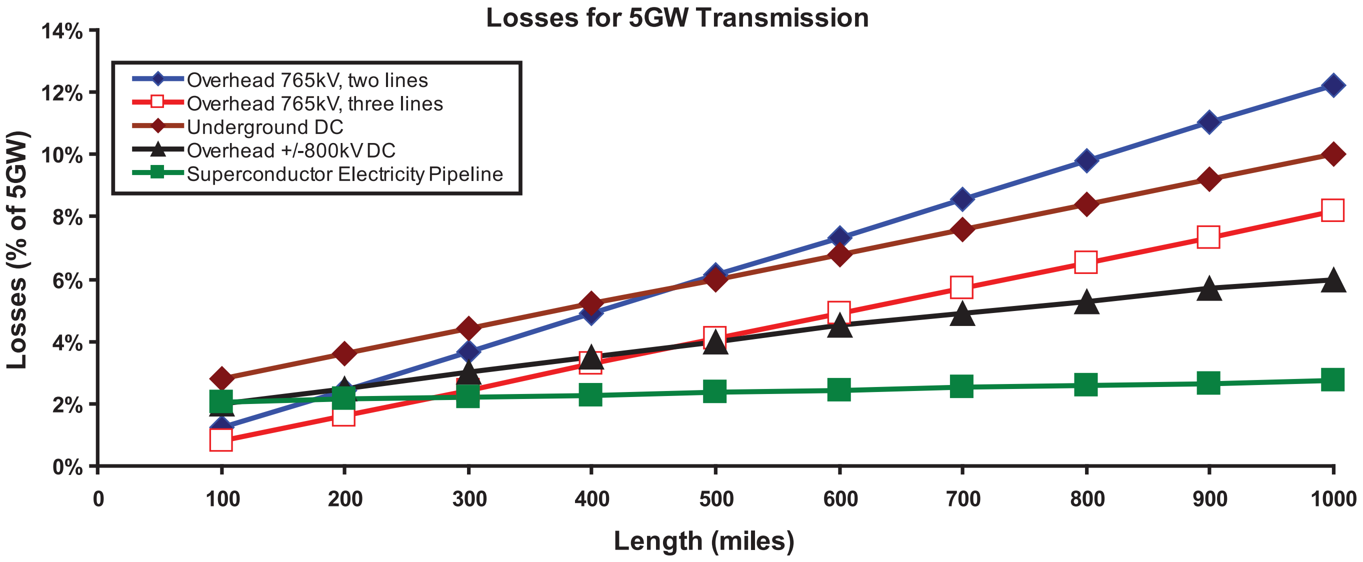

Figure 9: Efficiency of various transmission options[11]

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[11] Losses estimated as follows: Conventional underground HVDC: *"HVDC with Voltage Source Converters And Extruded Cables For Up To ±300 kV and 1000 MW"*, Jacobson, B., Jiang-Häfner, Y., Rey, P., Asplund, G., et al, CIGRE 2006 Conference, Table 3; Overhead 765kV AC, two lines: two lines of 2400MVA SIL using 6-bundle conductors with compensation every 200 miles; Overhead 765kV AC, three lines: three lines of 2400MVA SIL using 6-bundle conductors with compensation every 200 miles; Overhead HVDC: "HVDC and FACTS Economical complements to AC Transmission", Bahrman, M, DOE Concepts of Future Electric Transmission, March 4, 2009, slide 11; Superconductor Electricity Pipelines, VSC converter losses of 2% plus 35kw/mile refrigeration losses

This can be seen as a path to implement one of the goals of the Smart Grid: that of enabling new products, services and markets, or in "creating new opportunities and markets by means of its ability to capitalize on plug-and-play innovation wherever and whenever appropriate."[12]

The control capability also provides improved ability to integrate with the grid by reducing the variability of output from renewable sources (such as wind farms) by aggregating the output of numerous farms.

In addition, it would be possible for operators of the Superconductor Electricity Pipelines to sell so-called "ancillary services" such as regulation, spinning reserve, non-spinning reserve and supplemental operating reserve. The Superconductor Electricity Pipeline would also permit two transmission balancing areas to share the variability within each area and therefore reduce the balancing requirements of both, effectively creating larger load balancing areas.

Improved Security and Operational Characteristics

Low Impact on Underlying Grid

The use of a completely separate superconductor DC transmission cable that supports multiple source and load connections —on-ramps and off-ramps so-to-speak —leaves it decoupled from the underlying AC transmission network. Faults on the underlying AC power system are isolated from the larger amount of power flowing on the DC cable. The flexibility of the DC terminals allows the system operator to determine how the power on the DC cable interacts with the AC system during faults, and may even allow for faster recovery of faults on the AC grid.

The use of DC also allows the transfer (so-called "wheeling") of power long distances across electrical regions without impacting the operation of the regional local grids.

Storm and Outage Resiliency

Overhead transmission lines are subject to damage from a variety of weather-related causes, including ice, snow, lightning, wind storms, hurricanes and tornadoes. As an example, one ice storm in 1998 toppled 1,300 transmission line towers[13] in North America, causing widespread power outages. The time involved to replace or repair that number of transmission towers and bring power back online extends long after the storm has passed. In addition, overhead lines are subject to damage by vehicles and interruption caused by animals and birds. By being placed underground, DC superconductor cables are inherently immune to such events. The result is a more reliable and secure power network.

While carrying 5,000 MW of power over a single transmission pipeline raises questions about system security, redundancy can be provided by multiple parallel branches or a loop network of the type envisioned in Figure 4. This is similar to what would typically be proposed on a high voltage overhead AC network. Overall system architecture is important in any cable system since, while power outages are much less frequent, underground construction does result in lengthier repair times. Loss of power to one of the Superconductor Electricity Pipeline refrigeration systems would be addressed by providing redundant power supply to the cooling system as is done on existing AC superconductor cable installations.

Security from Willful Attack

As with weather-related events, overhead transmission lines are more susceptible to damage from willful attack. Overhead transmission lines and towers are easy to locate and are vulnerable to a variety of methods of attack. The underground nature of DC superconductor cables makes them harder to locate, more difficult to damage and easier to harden against attack. The latter can be accomplished with more damage-resistant pipeline materials or simply through deeper burial of the pipeline. Note that the self-contained refrigeration inherent in superconductor cables eliminates depth-of-burial concerns associated with conventional cable technology[14].

Black Start Capability

Black start capability describes the ability to supply power to a portion of the power grid that has completely collapsed and experienced a blackout. Though AC grids can inherently provide black start capability, it is not always possible to depend upon its availability and the required controllability of the generation necessary to do so. Being independent of the AC grid, the Superconductor Electricity Pipelines will be able to make available power from hundreds or thousands of miles away that can be used for black starting, or rebooting, the local grid[15]. This is true of any VSC-based DC system[16]. Sources of black start power are often eligible for payments from the connected utilities to which the black start capability is provided.

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[12] *"The Smart Grid: An Introduction,"* U.S. Department of Energy, 2008, p17.

[13] "El Niño, Ice Storms, and the Market for Residential Fuelwood in Eastern Canada and the Northeastern U.S.", P. Jagger, W. White, R. Sedjo, Resources for the Future Discussion Paper 99-44, Washington, DC, 1999, Table 1, p 3.

[14] Conventional cables generate heat as they carry current. A combination of factors, ranging from the soil's thermal resistivity to the depth at which the cables are buried, require them to be de-rated. The refrigeration system used with DC superconductor cables removes these thermal constraints associated with burying conventional conductors, allowing them to be buried deeply in the ground if required without any need for special considerations on the pipeline's performance.

[15] The VSC converter technology used with DC superconductor cables can produce the AC voltage necessary to facilitate black start. Black start capability requires the terminals to be equipped with suitable auxiliary power facilities.

[16] *"HVDC with Voltage Source Converters – A Powerful Standby Black Start Facility"*, Jiang-Hafner, Y., Duchen, H., Karlsson, M., Ronstrom, L., Abrahamsson, B., IEEE/PES Transmission & Distribution Conference & Exposition, 2008, p8.

Cost Competitive

For a 1,000 mile cable system, it is estimated that the cost of a Superconductor Electricity Pipeline would be in the range of \$8 - \$13 million per mile fully installed.[17] The estimates include the cost of 7 sets of 750 MW DC converter stations. The low end of this estimate is based on a single 5,000 MW pipeline while the upper end is based on a fully redundant 5,000 MW system (two cables). That is in the same general range as the \$7 to \$10 million cost per mile estimate[18] for two to three 765 kV transmission lines complete with required substations, which is what would be required to carry 5,000 MW for 1,000 miles. Importantly, this aforementioned cost for 765 kV does not include investments that may be required to upgrade the underlying transmission infrastructure to support any type of 765 kV AC line overlay. Some upgrades may also be necessary for Superconductor Electricity Pipelines but are not anticipated to be as extensive as those required for an AC overlay.

While conventional point-to-point overhead UHVDC transmission lines are generally less than \$5 million per mile, they lack the distributed on- and off-ramp capability, have higher losses, require a greater right-of-way, and do not alleviate the serious aesthetic, security, environmental and political issues associated with overhead lines. The longer the run, the more cost competitive become DC options like the Superconductor Electricity Pipeline. This is because the DC converters are largely a fixed cost based on the total MW power rating of the converters, and are not affected by line length.

Cost Breakdown of Superconductor Electricity Pipeline

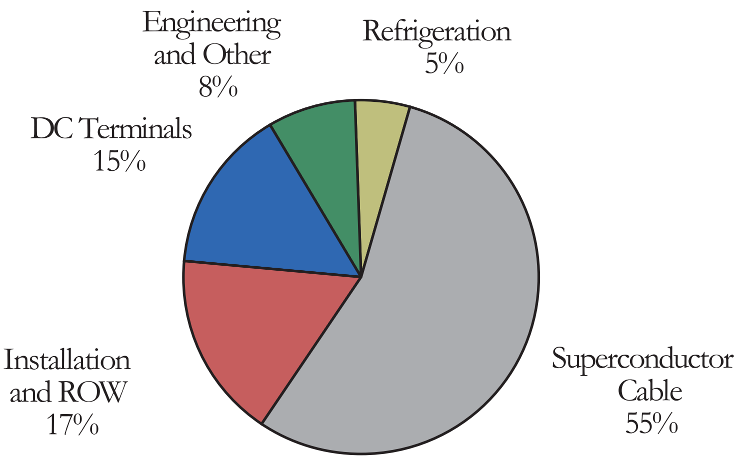

Figure 10: Cost Analysis of a 5,000 MW, 1,000 mile Superconductor Electricity Pipeline

The cost breakdown of a Superconductor Electricity Pipeline varies with the line length and DC converter ratings. Generally, the cable length and associated costs such as refrigeration, installation, and right-of-way, vary with the line length. DC converter costs are based on total MW rating and are independent of line length. Figure 10 shows the estimated cost breakdown[19] of a 5,000 MW, 1000 mile Superconductor Electricity Pipeline.

For conventional transmission technologies, the cost of building underground transmission is generally considered to be higher than overhead transmission, particularly for lower voltage transmission systems. This is primarily due to the cost of construction and permitting in high cost urban areas. By comparison, the distance traversed by Superconductor Electricity Pipelines will result in significant lengths being installed in cross country environments, where lower construction costs will prevail. It should be noted that even for conventional transmission technologies, at the power levels being considered, the difference in costs between overhead and underground lines diminishes significantly.

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[17] Mature cost.

[18] *"MTEP08: The Midwest ISO Transmission Expansion Plan,"* Midwest ISO, November 2008, p108. Cost estimate based on three times the cost estimate of \$3.125 million/mile.

[19] Mature system cost including appropriate contingencies based on AMSC analysis and adaptation of EPRI conceptual design, presented in: *"The Superconducting DC Cable: Enabling Technology for the Hydrogen-Electric SuperGrid, Program Design Review Meeting Cable Conceptual Design AC System Integration,"* Eckroad, S., Hassenzahl, W., et al, Electric Power Research Institute, July 25, 2008, pp 17-55, web link http://mydocs.epri.com/docs/public/SuperGridJuly08.pdf (publicly available).
Cable, cryogenic refrigeration, DC terminal, and engineering costs are from AMSC internal estimates from past project work and supplier quotes for Superconductor Electricity Pipeline components and systems.
Right of way and installation cost data sources:

- "DOMINION ESTIMATED TRANSMISSION COSTS OVERHEAD VS. UNDERGROUND COST COMPARISON 5 MILE, 230kV SINGLE CIRCUIT LINE EXAMPLE", Dominion Resources, July 2006, web link http://jcots.state.va.us/pdf/CostAnalysis.pdf
- PSCW Docket No. 05-CE-113 Thomas M. Finco Direct Testimony July 3, 2003 Official Filing before the Public Service Commission of Wisconsin Arrowhead Weston 345 kV transmission line project, web link http://www.arrowhead-weston.com/pdf/200307/Finco/Testimony/Finco.pdf

Doubling the example to a 10,000 MW, 1000 mile application only increases the cost by one-third, and the losses drop to 2.4%. This demonstrates the cost effective nature of transmitting large amounts of power via Superconductor Electricity Pipelines.

Given their efficiency advantages over all competing solutions, Superconductor Electricity Pipelines are expected to provide the fastest return on investment and represent the “greenest” transmission option available. Table 3 summarizes the characteristics of superconductor pipelines and conventional transmission solutions.

Summary

Superconductor Electricity Pipelines are uniquely and ideally suited to address all of the requirements to move renewable energy to distant load centers:

- Highest power capacity
- Highest efficiency (lowest power losses) of any transmission technology
- Ideal for very long distances
- Capable of transferring power across the three U.S. interconnections
- Able to accept power from multiple distributed sources, and precisely deliver power to multiple distributed destinations
- All underground construction with very small (25’) right-of-way requirement
- Simplified cost allocation due to precise controllability of DC terminals
- Minimizes interaction with existing AC grid, reducing costs and increasing operational flexibility

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	Overhead Solutions			Underground Solutions			
CHARACTERISTICS FOR LONG DISTANCE, HIGH POWER TRANSMISSION (more than 500 miles and more than 5000 MW)	AC	Point-to-Point HVDC	Multi-terminal VSC HVDC	AC	Point-to-Point HVDC	Multi-terminal VSC HVDC	Multi-Terminal Superconductor Pipeline
Capable of carrying 5000MW or more, 500 miles or more	✓	✓			✓		✓
Cost competitive	✓	✓		✓	✓		✓
Simplifies cost allocation		✓	✓		✓	✓	✓
Low impact on exisiting transmission grid		✓	✓		✓	✓	✓
Minimizes public siting opposition					✓	✓	✓
Can reuse exisiting transportation corridors					✓	✓	✓
Increased security from willfull attack					✓	✓	✓
Enhanced storm and outage resiliance					✓	✓	✓
Enhanced market dynamics						✓	✓
No electro-magnetic fields (EMF)							✓
Highest efficiency (lowest losses, lowest carbon footprint)							✓
Small (25 feet or less) right of way required for 5000MW or more							✓

Unique fit of Superconductor Electricity Pipelines for Long Distance, High Power, Multi-terminal transmission ↑

Table 3: Comparison of characteristics of various transmission technologies when transmitting 5,000 MW more than 500 miles

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