SUPERCONDUCTOR ELECTRICITY PIPELINES

A compelling solution to today's long-haul transmission challenges

BY NAREND REDDY

While the United States is rich in renewable resources for electric energy production, wind and solar power today account for only a relatively small portion of the country's electricity generation. That ratio, however, is set to rise rapidly as the U.S., like many other countries around the world, increasingly turns to renewable sources to meet higher power demands and reduce pollution.

The inability of America's existing transmission system to move clean electrical energy from the country's rural heartlands where it is generated to the high-demand urban load centers remains a primary challenge to achieving U.S. renewable energy objectives. In order to continue developing renewable resources, the North American electric power grid must be expanded and reconfigured to facilitate the challenge of moving large amounts of electricity over these very long distances.

The scope of this leading energy challenge will encompass the transmission of 100 gigawatts (GW) or more of green power. Networks of interstate, overhead 765 kilovolt (kV) power lines that would require rights of way hundreds of feet wide are one solution actively being considered to achieve this objective. In addition to the significant impact on the nation's aesthetic landscape, this traditional approach might not only require the use of eminent domain, but could take an environmental toll, as well.

A new option is now possible. Placed underground in existing rights of way, Superconductor Electricity Pipelines could carry many GWs of power more efficiently and at a similar cost to overhead lines, all in a pipe just three feet in diameter.

Superconductor Electricity Pipelines are uniquely and ideally suited to address all of the requirements to move renewable energy to distant load centers. With their very high power carrying capacity and exceptionally low power losses, DC superconductor cables provide a compelling new solution to the multitude of challenges associated with long distance transmission. Because they can be sited underground in new or existing rights of way, Superconductor Electricity Pipelines additionally offer aesthetic and security advantages by being safely 'out of sight and out of harm's way' from potential damage due to severe weather, lightning strikes or willful attack.

The principal technology used today for long distance power transmission is high voltage alternating current (AC) or direct current (DC) overhead lines. However, the challenges cited above have limited a wider application of this technology and can be addressed effectively by high capacity superconductor underground DC 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.

Resolving Key Transmission Challenges

Conventional overhead transmission lines require new corridors hundreds of feet wide with time-consuming and potentially litigious siting processes that can form a significant roadblock to developing new renewable power. Superconductor Electricity Pipelines are deployed underground utilizing conventional pipeline construction techniques. These systems require a corridor just 25 feet wide and can be located along existing transportation rights of way, thereby eliminating or greatly reducing the need for complex, contentious and costly siting procedures.

When compared to 765 kV overhead lines for long-haul transmission projects on the order of 1,000 miles and GWs of transmission load, Superconductor Electricity Pipelines:

- **Improve Aesthetics:** Superconductor Electricity Pipelines are out of sight, out of mind and, unlike overhead power lines employing towers over 100 feet tall, they are also free from electromagnetic fields.

- **Enhance Efficiency:** Superconductor Electricity Pipelines are able to cut power losses by two to three times compared to conventional transmission options.

- **Simplify Cost Allocation:** The power supplied to and delivered from Superconductor Electricity Pipeline DC-AC on- and off-ramps enables much simpler cost allocation, as the power flow in this system is fully controllable.

- **Are Cost Competitive:** When looking at the 1,000-mile, multi-GW transmission runs required to transport renewable energy from America's heartlands to its cities, Superconductor Electricity Pipelines are comparable in cost to 765 kV AC overhead transmission lines.

- **Increase Security:** Ice storms, hurricanes, tornadoes, vandalism and terrorism are just a few of the threats to overhead power lines. Given their underground location, Superconductor Electricity Pipelines are out of harm's way and safely shielded from these threats.

Superconductor Power 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 100 times the amount of electricity that can be conducted by copper or aluminum wires of the same size. Secondly, when transmitting DC power, superconductors have absolutely zero resistance to the flow of electricity, which means that DC superconductor cables introduce no electrical losses of the circuit.

Superconductor materials must be refrigerated with conventional liquid nitrogen to exhibit their ideal electrical characteristics. While some power is required for the refrigeration – this system still has much higher overall efficiency than any other long-distance transmission system.

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. Three of these cables have been energized in the United States. Since April 2008, a 138 kV AC high-temperature superconductor transmission line has been operating successfully just outside of New York City on Long Island Power Authority's (LIPA) primary transmission corridor. At full capacity, the LIPA installation is capable of transmitting up to 574 megawatts (MW) of electricity in a right of way just one meter in width, and is the world's longest and most powerful superconductor cable system deployment to date (see Figure 1). Superconductor cable technology also is gaining traction abroad. Korea Electric Power Corporation (KEPCO) is now in the process of deploying the first of these systems in the grid outside the city of Seoul.

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

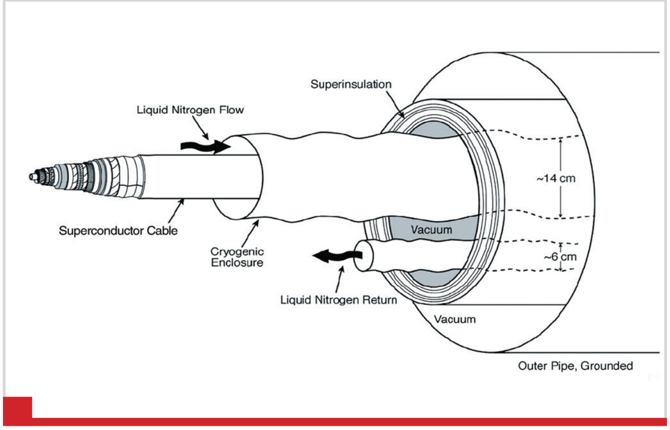

Figure 2: Superconductor Electricity Pipeline cross section (Figure courtesy Electric Power Research Institute).

While all previous installations have been AC applications, applying this established technology to DC transmission is fairly straightforward. Figure 2 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 shows the underground pipeline construction and burial methods that the Superconductor Electricity Pipeline will employ.

Figure 3: Typical underground pipeline construction methods can be used for Superconductor Electricity Pipelines.

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 have been difficult to implement. Recently, multi-terminal technology based on newer power electronic designs incorporating VSC has become available. This new technology provides greater control and flexibility and more simply enables DC lines to connect to multiple generation sources and multiple areas of electrical demand with ability to facilitate power flow in either direction as needed.

DC terminals employing VSC technology, however, are available only at relatively moderate (100-300 kV) voltages. By comparison, ultra-high voltages (+/- 800 kV) are required for conventional point-to-point DC transmission. To be used in the transmission of high power levels, the lower voltage levels require the use of very high currents; yet transmitting high current long distances through conventional aluminum or copper conductors results in considerable resistive losses. Superconductor power cables overcome these limitations by providing the ability to carry very high levels of current with zero electrical loss.

The VSC terminals are able to inject power onto the line, or pull power off the line in precisely controlled amounts, akin to valves on a gas pipeline or on- and off-ramps on a highway. For example, a 5,000 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 United States, and deliver 500 MW to each of ten cities that it passes on the way to the east or west coasts.

Figure 4 shows some areas most suitable for wind power production in the United States. The blue lines represent possible paths for a Superconductor Electricity Pipeline, and the white circles represent potential discrete points of connection to the pipeline. Traditional AC transmission would still be utilized to collect power from geographically adjacent wind farms and provide a common point of connection to the pipeline at the white circles. A looped configuration of the Superconductor Electricity Pipeline system provides a number of advantages including increased reliability, as maintenance work or unavailability to one section of the pipeline would not prevent power from flowing from one location to another.

Implementing the pipeline as shown would provide a 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.

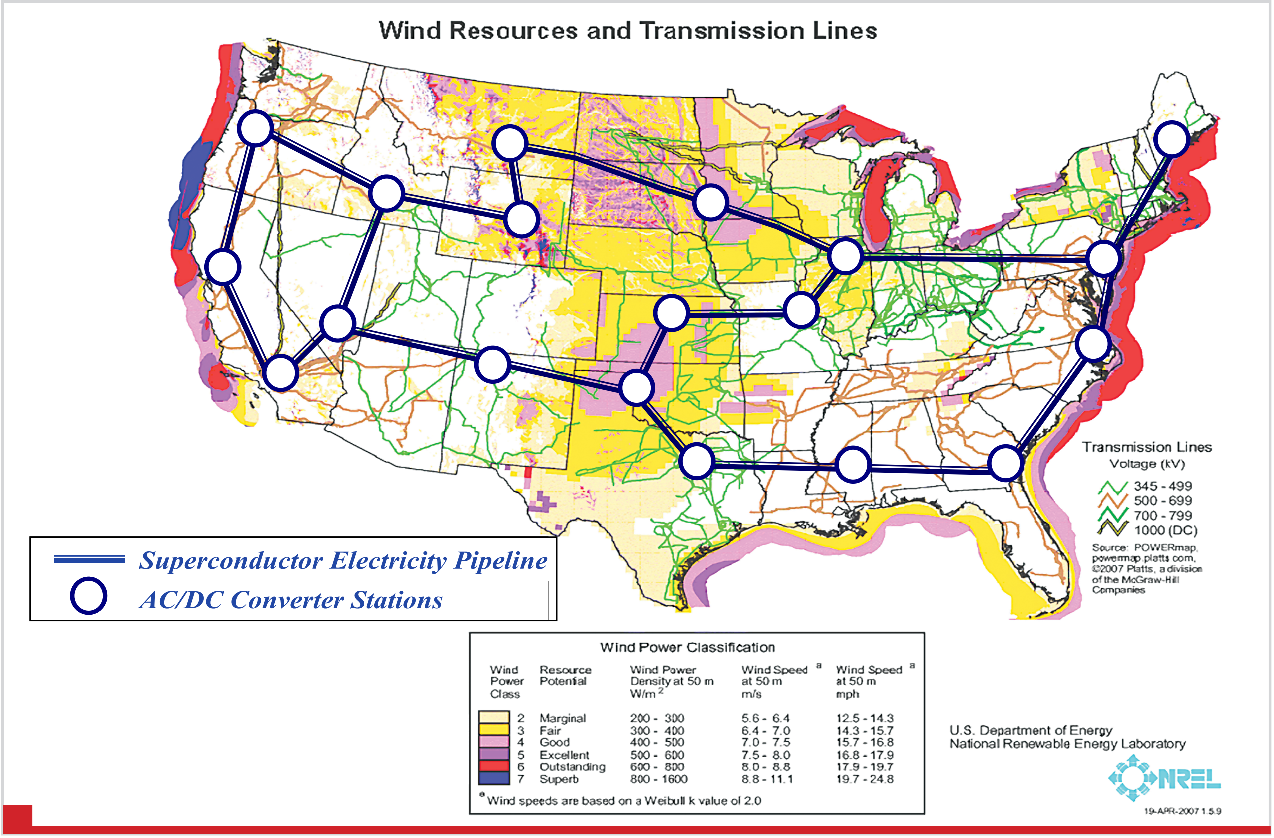

Figure 4: Potential Superconductor Electricity Pipeline system to connect renewable power.

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 longer distances 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 long distance AC lines are limited by basic electrical tenets, including:

- Higher electrical losses as distance from AC line increases.
- Reduced power transmission capacity with increasing length of transmission.
- Development of underlying secondary AC network needed to accommodate the EHV transmission lines.

AC underground transmission cables are also 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 over distances greater than 100 km.

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 at distances typically greater than 400-500 miles. Additionally, traditional HVDC transmission 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 800 kV, have right of way requirements similar to those of a single 765 kV AC transmission line[1], 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 because DC cables are not available at the higher voltage ratings required for higher power capacities. Also, transmitting thousands of megawatts of power would require the use of many cables in parallel, increasing both power losses and right of way requirements.

TRANSMISSION LINE POWER AND DISTANCE REQUIREMENTS		SUITABLE TRANSMISSION SOLUTIONS: Overhead Solutions			Underground Solutions			
		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.

Superconductor Electricity Pipelines offer a cost effective option and a technology that has a unique fit for transmission of moderate to high levels of power over long distances (shown in Table 1).

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. Due to public opposition to the construction of new overhead lines, almost all new urban and suburban distribution circuit projects have transitioned from overhead to underground over the course of the past several decades. The ability of any AC overhead line to transmit power drops with distance.

Table 2 compares the right of way requirements for various types of overhead power lines and Superconductor Electricity Pipeline to move 5,000 MW of power over 1,000 miles.

Figure 5 compares the power transfer capability of a single 765 kV AC overhead line to that of a DC superconductor cable. From this chart, it can be seen that more than one AC line may be required to move power depending on the distance that the power needs to be transmitted.

Because superconductors have no electrical resistance, it is possible to construct DC superconductor cables with practically any desired power transmission capability. Figures 6 compares the right of way required for 765 kV AC overhead transmission lines or a Superconductor Electricity Pipeline for 5,000 MW of power. The example used throughout this article is 5 GW (5,000 MW), sufficient power for 2.5 million homes. It is possible to build the pipelines with even higher ratings (10 GW or more) with little to no additional loss penalty and without significant increase in cost. 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.

TYPE OF TRANSMISSION LINE	345 KV AC	500 KV AC	765 KV AC3,6	800 KV DC	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, 1,000 miles.[1]

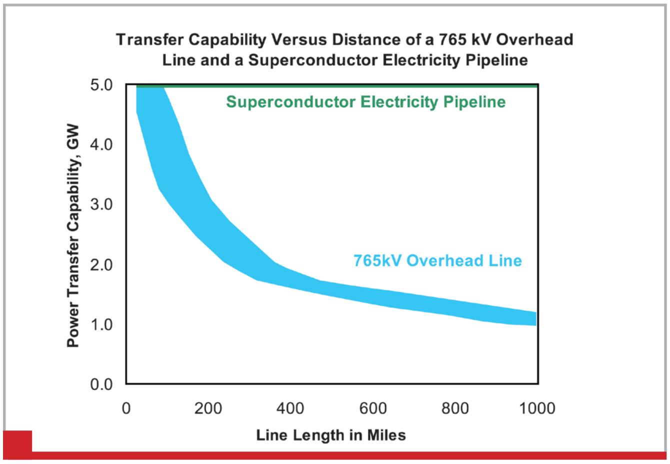

Figure 5: Comparison of power transfer capability versus distance of a single 765 kV AC overhead transmission line to a Superconductor Electricity Pipeline.

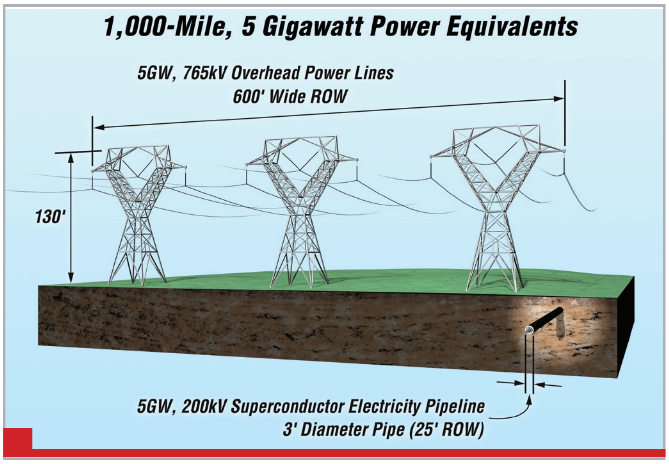

Figure 6: Aggregate right of way comparison to transmit 5 GW (5,000 MW) for 1,000 miles with three overhead AC lines with 8% power losses and DC superconductor cables.

Economic and Environmental Advantages

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 power consumed by the cable's cooling system. Total system losses to move 5,000 MW are less than three percent 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 as shown in Figure 9 below.

Though cost allocation of transmission projects is complex, one key issue is that projects benefit many utilities as a result of a 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.

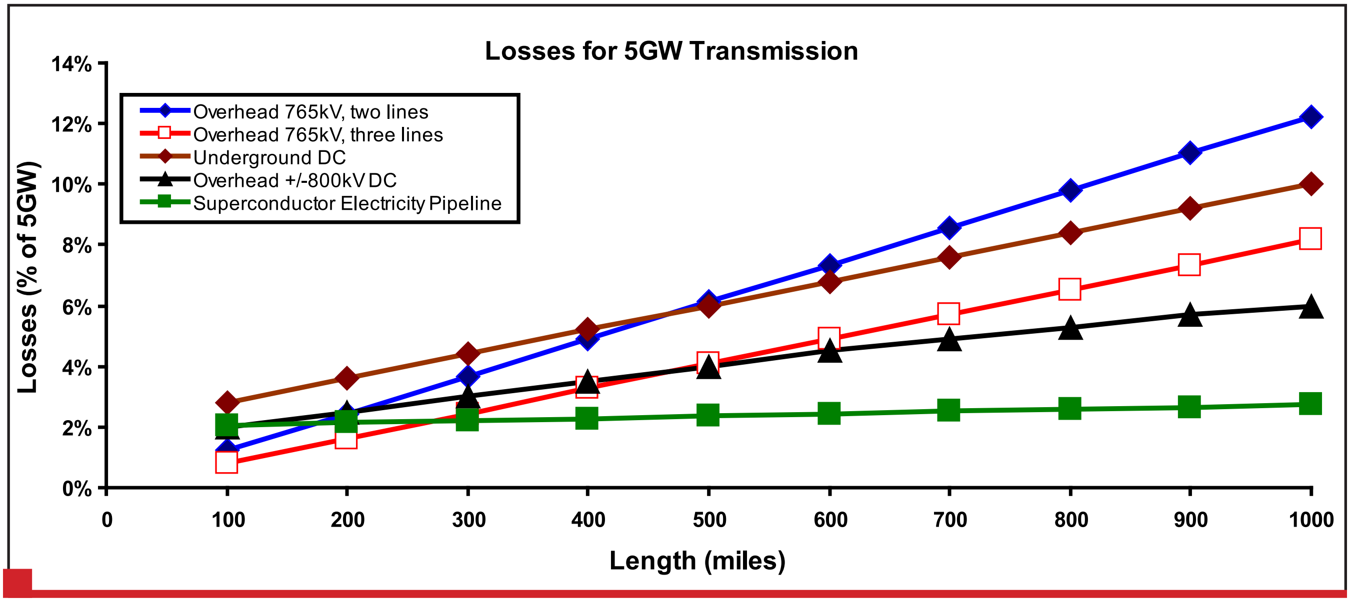

Figure 9: Efficiency of various transmission options.

Figure 8: Superconductor Electricity Pipelines can be located along existing transportation rights of way.

Improved Security and Operational Characteristics

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 use of DC also allows the transfer of power long distances across electrical regions without impacting the operation of the regional local grids. Being independent of the AC grid, the Superconductor Electricity Pipelines will be able to make power available from hundreds or thousands of miles away that can be used for black starting or rebooting of the local AC grid.

Cost Competitive

The estimated cost of a Superconductor Electricity Pipeline, which includes the cost of seven sets of 750MW DC converter stations, would be in the range of $8 - $13 million per mile fully installed for a 1,000-mile cable system. 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). This estimate is comparable to the $7 to $10 million cost per mile estimate 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.

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 cost breakdown of a Superconductor Electricity Pipeline varies with the line length and DC converter ratings required. DC converter costs are based on total MW rating and are independent of line length. Figure 10 shows the estimated cost breakdown of a 5,000 MW, 1,000-mile Superconductor Electricity Pipeline.

For conventional transmission technologies, the cost of building underground transmission is generally higher than overhead, 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. Building a Superconductor

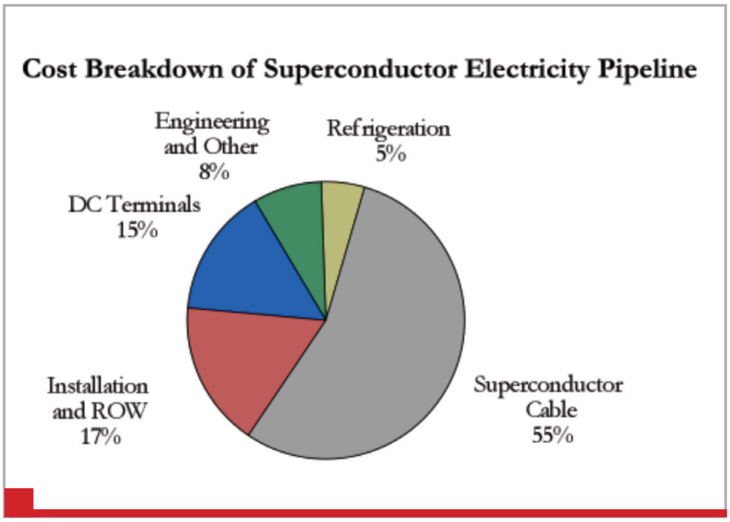

Figure 10: Cost analysis of a 5,000 MW, 1,000 mile Superconductor Electricity Pipeline.

CHARACTERISTICS FOR LONG DISTANCE, HIGH POWER TRANSMISSION (more than 500 miles and more than 5000 MW)	Overhead Solutions			Underground Solutions			
	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 5,000 MW 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 5,000 MW or more							✓

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

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

Electricity Pipeline with a higher capacity will only result in a marginal increase in costs. Doubling the above example to a 10,000 MW, 1,000-mile application only increases the cost by about one-third, and the losses drop to 2.4%, further demonstrating the economies of scale inherent with Superconductor Electricity Pipelines.

Table 3 summarizes the characteristics of Superconductor Electricity Pipelines and conventional transmission solutions.

Conclusion

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. With the ability to utilize existing rights of way, these pipelines also minimize the impact on public lands, including national parks, wilderness areas or other environmentally sensitive areas, in addition to populated areas.

Because superconductors have no electrical resistance, it is possible to construct DC superconductor cables with practically any desired power transmission capability with little to no additional loss penalty. This essentially unlimited design capability is not possible with any other type of power transmission. Superconductor Electricity Pipelines can also be over-designed to accommodate future growth without significant increase in cost.

In essence, Superconductor Electricity Pipelines are uniquely and ideally suited to address all of the issues associated with moving renewable energy to distant load centers and offers a new, optimal solution for long haul transmission.

References

The text is principally from American Superconductor's White Paper titled "Superconductor Electricity Pipelines; Carrying Renewable Electricity Across the U.S.A. Out of Sight and Out of Harm's Way." To request a free copy, visit www.amsc.com/powerpipes.

[1]"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.

Narend Reddy

Director of Network Planning and Applications at American Superconductor Corporation, Narend joined the company in 2001 as a Transmission and Distribution Planning Engineer. He previously worked for Fiji Electricity Authority in the generation and network planning divisions. Narend is a Registered Professional Engineer, a member of IEEE and holds a bachelors degree in Electrical Engineering and Computing and a masters in business administration. Email nreddy@amsc.com.