Underground HVDC Supergrid Can Work in Europe

Roger W. Faulkner

Elpipes[1] are game-changing underground high-voltage DC (HVDC) power lines that will allow pipeline companies to compete in the power transmission market. Elpipe technology uses polymer-insulated underground HVDC conductors that are rigid (not wires, but sections of bus pipe). This allows much heavier conductors than are possible if they have to wrap on a reel. This greater capability means that they can carry more than twice as much power (more than 15 gigawatts) as the largest transmission line ever built, a 7.2-gigawatt, 800-thousand-volt overhead HVDC line in China built by ABB and State Grid Corp China.

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In order for us to have a future powered by renewable energy, the lowest-cost solution involves a supergrid, which the European Commission has recognized as a critical technology to accomplish a rapid reduction of greenhouse gas emissions.[2] Supergrids are important because they make it possible to trade electrical energy over a large (continental-scale) region (i.e., a big enough region to bridge between several weather systems). Wind and solar energy aggregated over an entire continent, as in **Exhibit 1** for Europe and North Africa, becomes far more reliable than any one wind farm or solar installation.

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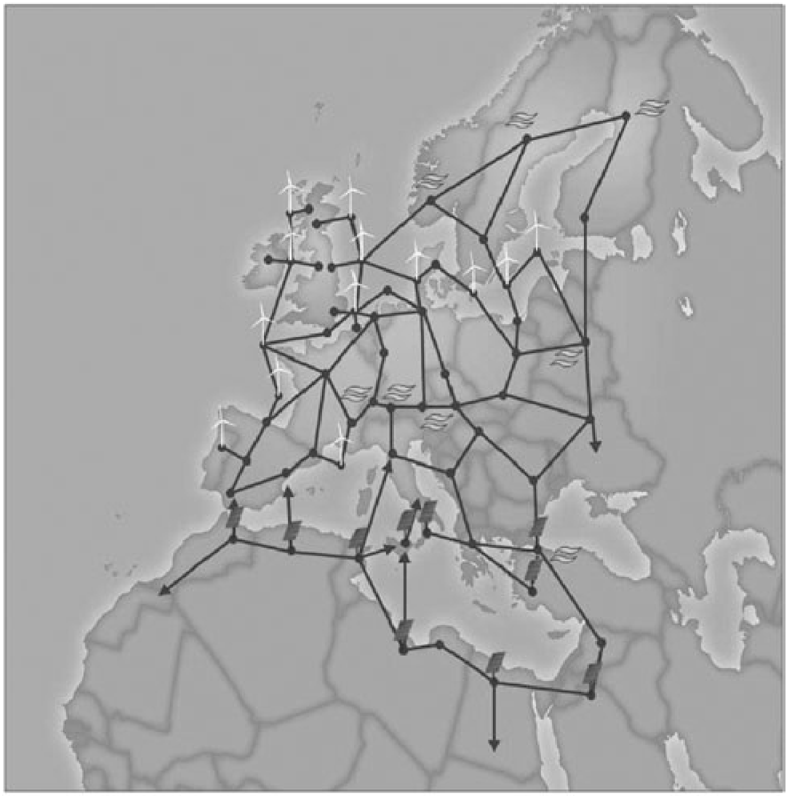
This greater expanse implies that less energy storage (typically pumped hydraulic storage) or dispatchable generation (typically gas turbines or dispatchable hydro power dams with large storage reservoirs) is needed to balance the unavoidable intermittency of wind, solar, or tidal energy. It has been shown that a renewable-energy-based electricity supply becomes economically feasible for Europe at the lowest aggregate cost if a supergrid allows long-distance capacity sharing. **Exhibit 1** illustrates a conceptual European supergrid, but the number of power lines shown is not adequate to move hundreds of gigawatts around Europe with current technology, as is needed to enable a transition to renewable energy.

Renewable-energy-based electricity supply becomes economically feasible for Europe at the lowest aggregate cost if a supergrid allows long-distance capacity sharing.

Roger W. Faulkner (roger@elpipe.com) is president of Electric Pipeline Corporation.

One major hurdle for a supergrid in Europe is the permitting of the power lines. We

Exhibit 1. European Supergrid



Source: Friends of the Supergrid; the connections shown would have to be higher capacity than any prior art powerline to move hundreds of GW around Europe.

simply will not be able to build a supergrid unless we can put it underground, because the political opposition to overhead lines is so strong (at least in North America and Europe). The difficulty of permitting new overhead transmission lines in the eastern United States or Europe is legend. At this point, every new overhead transmission project faces 5–15-year delays based on public opposition.

Not only is this expensive due to direct litigation and delay costs, but also the uncertainty wreaks havoc with procurement, and other projects that depend on the transmission will be delayed, too. The delay ripples through the economy. By moving underground, the construction delays for elpipes will be more like a gas pipeline (2–5 years) than an overhead line (5–15 years).

The second major problem inhibiting development of supergrids is that we need higher-capacity power lines than exist today. Consider Exhibit 1: if this map showed the number of connections that would actually be needed for a European supergrid, around 10 times as many lines as are shown would be needed, given current technology. This would not be a good picture for selling the concept.

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Given current technology, most of those lines would have to be new overhead HVDC lines,

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which would certainly be opposed wherever they are proposed. Elpipes could reach high-enough capacities that a supergrid resembling Exhibit 1 would be possible. Elpipes answer these two issues (the need for higher capacity and underground siting).

Elpipes (**Exhibits 2** and **3**) are arguably the only practical option for undergrounding the high-capacity backbone of an HVDC supergrid. Even at 600,000–800,000 volts, the most likely operational voltage for a Eurasian supergrid, conductors capable of carrying tens of thousands of amps will be needed for the supergrid, which implies either superconductors or high-cross-section metallic conductors such as in the elpipes of Exhibits 2 and 3.

The full benefits of a supergrid require it to be completed before it is fully functional. During construction, the maximum capacity of any one part of the supergrid can be severely limited by reliability and redundancy requirements, rather than pure transmission capacity from an engineering point of view. Redundancy is not affected by whether the power lines are overhead or underground, and it must be addressed well before the entire supergrid is finished. Thus, the full transmission capacity must be usable for portions of the supergrid during construction.

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Exhibit 2. Hollow Keystone Extruded Elpipe Conductors

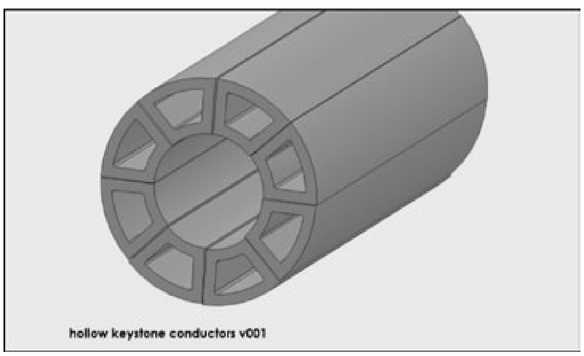
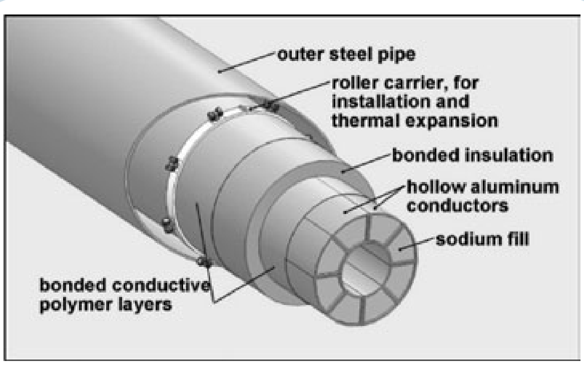


Exhibit 3. Elpipe Cross-Section, Optional Sodium Fill



The smallest shape that provides full redundancy for all connected nodes is a multiterminal HVDC loop. (The nodes are AC/DC converters that interface the HVDC loop with the AC grid.) Such a loop is self-redundant,[3] because each node on the loop is connected to every other node on the loop in two independent directions: clockwise and counterclockwise. HVDC circuit breakers are also needed between each set of next-neighbor AC/DC converter station nodes in order to achieve full redundancy for every node. ABB made a recent breakthrough on HVDC circuit breakers,[4] but these are likely going to be quite expensive,[5] and thus something less than full redundancy may be used in practice, as suggested in a recent patent.[6]

CURRENT EUROPEAN CONFIGURATION ALLOWS REDUNDANCY IN COUNTRIES

HVDC loops are the logical "unit cells" of the supergrid.[7] This configuration creates an intrinsic redundancy within the loop as described earlier and enables portions of the supergrid to be highly useful long before the entire supergrid is complete. In the European context, this loop concept fits very well with the boundaries of some existing European countries, including at least Germany and France.

Let us take Germany as an example, because the government there has agreed to shut down its nuclear industry. Thus, there is greater urgency to do something soon about grid connectivity in Germany to allow better nationwide sharing of generation and demand-side management resources. **Exhibit 4** shows the locations of existing nuclear power stations in Germany. There are also many other major AC nodes with transformer capacity of more than 500 megawatts (0.5 gigawatts) within Germany that are not shown. Such nodes are found near large generators (not just the nuclear plants shown on the map) and major cities.

Germany has agreed to shut down its nuclear industry. Thus, there is greater urgency to do something soon about grid connectivity.

The HVDC loop of Exhibit 4 passes within 50 kilometers of most of the generating capacity and most of the power demand in Germany. This loop is not meant to suggest a realistic path for the elpipe loop, but rather to show the concept. An optimized version of this loop would be tied into the AC grid at 50 or more places, and in effect enable transmission from any node to any other node.

Sharing of capacity reduces costs, in part because less total generation capacity can meet the needs for power.

Such a single HVDC loop completely within Germany would enable near-perfect capacity sharing throughout Germany, provided that the capacity of the loop itself and the AC/DC converters at the nodes is adequate. Sharing of capacity reduces costs, in part because less total generation capacity can meet the needs for power. Contrast that with the weak power-line upgrades announced recently by Germany,[8] which purport to represent bold engineering steps but are really just minimal upgrades constrained by the impossibility to build a new overhead power line in Germany. The obvious way around this impasse is to use elpipes.

Exhibit 4. German Nuclear Power and Notional Elpipe Loop

The value of each loop in a supergrid is magnified when another loop connects with it, increasing the effective distance over which electricity can be traded. This tends to make aggregated wind more reliable, and to reduce spinning reserve requirements over the whole region served. In the case of Europe, there would be great value in connecting a German HVDC loop as in Exhibit 4 with a French loop that networks in France's nuclear generators, or to a Scandinavian HVDC loop for its dispatchable hydro capacity.

Germany could give up on the huge nuclear power projects of the past (as the government has committed to do) but not give up on nuclear power, by using barge-mounted modular nuclear reactors along its North Sea coast. The Russian nuclear company Rosatom recently launched a 35-megawatt unitized nuclear power station on

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a barge, and it is highly likely that more efficient and higher-capacity units will be available soon. I mention this because either North Sea wind power or North Sea nuclear power could be used to power Germany via the HVDC loop of Exhibit 4. Eventually, such a German HVDC loop would become one of the unit cells of the European supergrid and perhaps later a unit cell of a Eurasian supergrid, but it also makes sense as a strictly national investment, even if the European supergrid never gets built.

ELPIPE SYSTEM MAKES MANY CLEAN ENERGY PROJECTS VIABLE

The uncertainty of getting energy to market devalues investments in remote wind power and makes it more expensive to raise money. Providing a secure means for wind farms to export their energy throughout Europe could greatly incentivize wind power construction in high wind areas, and the same could also apply to other forms of remote-site energy development, including solar, nuclear, geothermal, tidal, or pumped hydro energy storage, for example. Even remote mine-head coal projects could be incentivized, with or without carbon dioxide capture (depending on the regulatory and tax policy), by the existence of transmission if a supergrid is built. (I mention this to show that to accomplish the desired environmental effects, a supergrid will need a carbon tax or some other mechanism to price out mine-site coal generation.)

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What is most needed for supergrids is a readily installable long-distance underground transmission option that can also be conveniently inspected, maintained, and upgraded after it is in service. Elpipes can do all that.

It is much easier to install gas pipelines in terms of obtaining permits and rights-of-way compared to overhead power lines. The installation of an elpipe looks to local residents like laying two side-by-side pipelines. The inner part, the elpipe that makes the gas pipeline into a power line, rolls into the pipeline after it is completed and inspected.

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The regulatory hurdles for long-distance gas pipelines are much simpler than for long-distance transmission lines crossing state boundaries. It is reasonable that the resistance to the installation of elpipes will be much less vociferous than opposition to a power line that could be visible 10 kilometers away from the line, simply because the aesthetic effect of an elpipe or a gas pipeline is much less than that of an overhead line, and thus the number of people impacted by any buried line is much smaller.

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ELPIPE TECHNOLOGY ENABLES BETTER INSPECTION AND REPAIR

The real innovation of elpipes is to combine together three old ideas into one product: a pipeline, a power line, and a train. Elpipes are like low-speed electric trains that run on a track that is the inside of a gas pipeline, in which the cars of the train are polymer-insulated bus pipe, and the flexible couplers between the cars are made of copper and elastomer. Elpipes are fabricated from several separately manufactured components, which is quite different than cables: a single cable may be a kilometer long for a land cable, or 100 kilometers for a sea cable.

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Being made of numerous separately manufactured components creates both complexity and opportunities for improved quality control. In a cable, the conductor and insulator are bonded; thus, any flaw in either means both have to be thrown out or recycled, whereas in elpipes, the elastomer sleeves used for electrical insulation can be tested before installation, and if a flaw is found, the sleeves are cheap to replace. This can lead to high reliability compared to kilometer-plus-long cables, because testing standards for the insulating sleeves can be far more aggressive than would be economical for cables.

The train-like features of an elpipe also greatly improve reliability and repairability, especially compared to other underground transmission options. The "elpipe train" moves during installation, which means that all the (critical) electrical junctions can be formed in a clean room, at one end of the line. No field splices yields much better reliability, plus the way the splices are made also results in better reliability.

They are still a formidable development challenge although with enormous rewards for our energy future.

The on-board sensors and intranet not only enable coordinated motion of long sections of the elpipe (up to hundreds of kilometers), but also alert operators to impending failures before they happen. The modularity of elpipes means that they can be repaired by swapping out components in the regularly spaced repair vaults (about every 10 kilometers). The modularity and the fact that elpipe conductors are normally hollow also means that elpipes can be upgraded so as to increase transmission capacity by swapping out modules at night or in low-usage times.

No fundamentally new engineering principles are required for elpipes; they are an old-fashioned combination invention.

This ability to upgrade transmission capacity without a daylong outage is unique among all power lines. Elpipes are both conceptually simple and revolutionary. They do not require any fundamentally new technology to be developed. Yet they are still a formidable development challenge, although with enormous rewards for our energy future and our ability to break our addiction to fossil fuels in the long run.

No fundamentally new engineering principles are required for elpipes; they are an old-fashioned combination invention. I recently received notification that my US patent on elpipes will be granted.[9] This grant is evidence of the novelty of elpipes (regardless that they are made up of prior-art components).

ELPIPES MOVE MORE ENERGY FOR SAME DIAMETER AS GAS PIPELINES

It is interesting to realize, insofar as natural gas can be used to generate electricity, that a gas pipeline is a virtual power line. A paper by ABB researcher Alexandre Oudalov and coauthors[10] compared the overall energy efficiency of bulk transfer of energy by gas pipeline, oil pipeline, coal unit trains, and HVDC power lines, and concluded that at voltages above 400,000 volts, HVDC is the most efficient way to move bulk energy. To bring that down to a specific example, a 36-inch gas transmission pipeline with a design pressure of 10 megapascals will support a maximum flow rate of (at most) 28 million cubic meters a day. If all this gas is run through state-of-the-art combined-cycle gas turbines at 53 percent conversion efficiency, this amount of gas would generate 6.5 gigawatts of power (baseload basis), or 13 gigawatts per pair of pipelines.

In fact, though, average power output would be less than that because simple-cycle gas turbines (which are much less efficient, about 30 percent) are used for peak power, and there is also an energy penalty for "spinning reserve" requirements (needed for stable operation of the grid). After accounting for these factors, the average efficiency of gas generation, using today's best practices, would be about 40 percent, in which case average power production that could be supported by a pair of 36-inch gas pipelines would be 10 gigawatts. Elpipes deployed inside two 36-inch pipelines could deliver greater than 20 gigawatts, at better transmission efficiency than gas.

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HEAT CAN BE DISSIPATED SAFELY UNDERGROUND

The power transfer capacity of any conventional underground power line (both cables and elpipes) is limited by the need to dissipate waste heat. Underground power lines in general have lower ampacity (amps per square centimeter, perpendicular to current flow) than an overhead line, which has much easier ways to shed waste heat (radiation and convection) that do not apply underground. Elpipes will use more metal per ampere than cables, simply because the amount of metal is governed by economics rather than the mechanical limitations imposed by the need to wrap cable on a reel. As a result, 15–25 percent of the total project cost of an elpipe power line is for aluminum conductor per se (assuming aluminum is used), compared to less than 2 percent of the total project cost for a conventional power line using wires or cables. The more metal used, the lower is the resistance, and the lower is the waste heat production. Elpipes allow any economically desirable amount of conductor to be used, without requiring multiple power lines to move the energy.

Exhibit 5 shows a typical cross-section for the aluminum conductors of an elpipe. The required cross-section of aluminum to make a 10-gigawatt elpipe that loses 50 watts per meter at 6,250 amps is 202 square centimeters. At an operating voltage of 800 kilovolts, this corresponds to 1 percent of transmitted power per thousand kilometers (three times lower than the best power lines of today), considering the loss in both polarity elpipes.

Elpipes could be a windfall for aluminum producers. Aluminum all by itself can be used for elpipes, as in Exhibit 2, or the hollow spaces inside each keystone can be filled with sodium, as in Exhibit 3. Exhibit 5 shows equivalent-resistance elpipes based on copper, aluminum, and sodium.

Sodium is by far the lowest-cost conductor. A sodium conductor would be about one-fifth as expensive as an aluminum or magnesium one, and these in turn are about one-tenth as expensive as a copper conductor of equal resistance. Using steel pipes filled with sodium is by far the cheapest way to conduct electricity; a 24-inch steel pipe filled with sodium could carry 62.5 gigawatts of power at 800 kilovolts (1 percent loss at 1,000 kilometers), with a cost of conductor of only \$2.5 million a kilometer.

This sort of magnitude elpipe may be practical in the future. However, for the first projects, the size will likely be around 10-gigawatt capacity (at 800 kilovolts), as shown in Exhibit 5. If the initial voltage was 320 kilovolts, the capacity of the lines of Exhibit 3 would be reduced to 4 gigawatts, still greater power transfer capacity than the largest subsea HVDC cables (2.1 gigawatts at 600 kilovolts).

Elpipes can be fully underground and, as mentioned, resemble a pair of side-by-side gas pipelines. A recent paper[11] shows that a 10-gigawatt elpipe (as in Exhibit 5) can be buried two meters deep and still shed its waste heat through dry soil. Placing the elpipes at the surface increases transmission capacity by increasing the amount of waste heat that can be dissipated to the environment.

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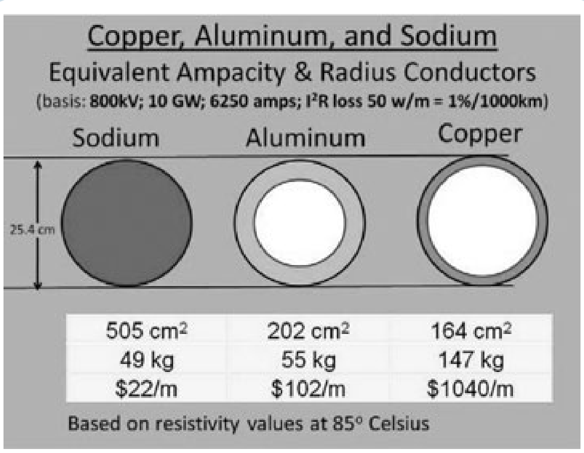
Because of the low ampacity and high mass of the elpipe conductors, elpipes can tolerate

Exhibit 5. Comparison of Equal Conductivity Bus Pipes



temporary excursions to much higher currents better than cables. To be specific, a buried cable can carry twice its rated current (100 percent overload) for 10 minutes at the most, before the temperature of the cable insulation rises above its maximum safe limit of 100 degrees Celsius, whereas an aluminum elpipe would take an hour to heat up to its maximum safe temperature at 100 percent overload. A sodium-based elpipe would take about four hours to reach its maximum temperature at 100 percent overload, because the melting of the sodium absorbs a significant heat of fusion.[12]

CONCLUSION

There is simply no other transmission technology that combines the security and aesthetics of underground siting with a very high transmission capacity (more than 10 gigawatts through a single pair of conductors) and rapid repairability (due to the train-like mobility of elpipes). This all needs to be proven, however.

There is simply no other transmission technology that combines the security and aesthetics of underground siting with a very high transmission capacity.

I expect that the first elpipe projects will probably be built in the Middle East/North Africa or in China in the next decade. I hope I am wrong about that, and the elpipe concept is piloted in the United States or Western Europe. I doubt that sodium will be used in the first elpipe projects, though I believe it can safely be used if it is contained inside strong metal pipes that are sealed at each end. Most likely, the first projects will be rated for 320 kilovolts but will be designed to be upgraded to 800 kilovolts.

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It is a unique feature of elpipes that modules are both repairable and replaceable. Modules can also be taken offline and modified; for example, an elpipe that was initially installed based on hollow keystones as in Exhibit 2 could be removed from service and disassembled, and then the hollow places in the keystones could be filled with a conductive metal (not necessarily sodium as in Exhibit 3; it could also be pure aluminum or magnesium). Not all the hollow keystones would have to be filled. Thus, the resistance of the line could be fine-tuned during reconductoring, which could occur without taking the line out of service beyond a few hours each night to swap out modules (cars in the elpipe train).

NOTES

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