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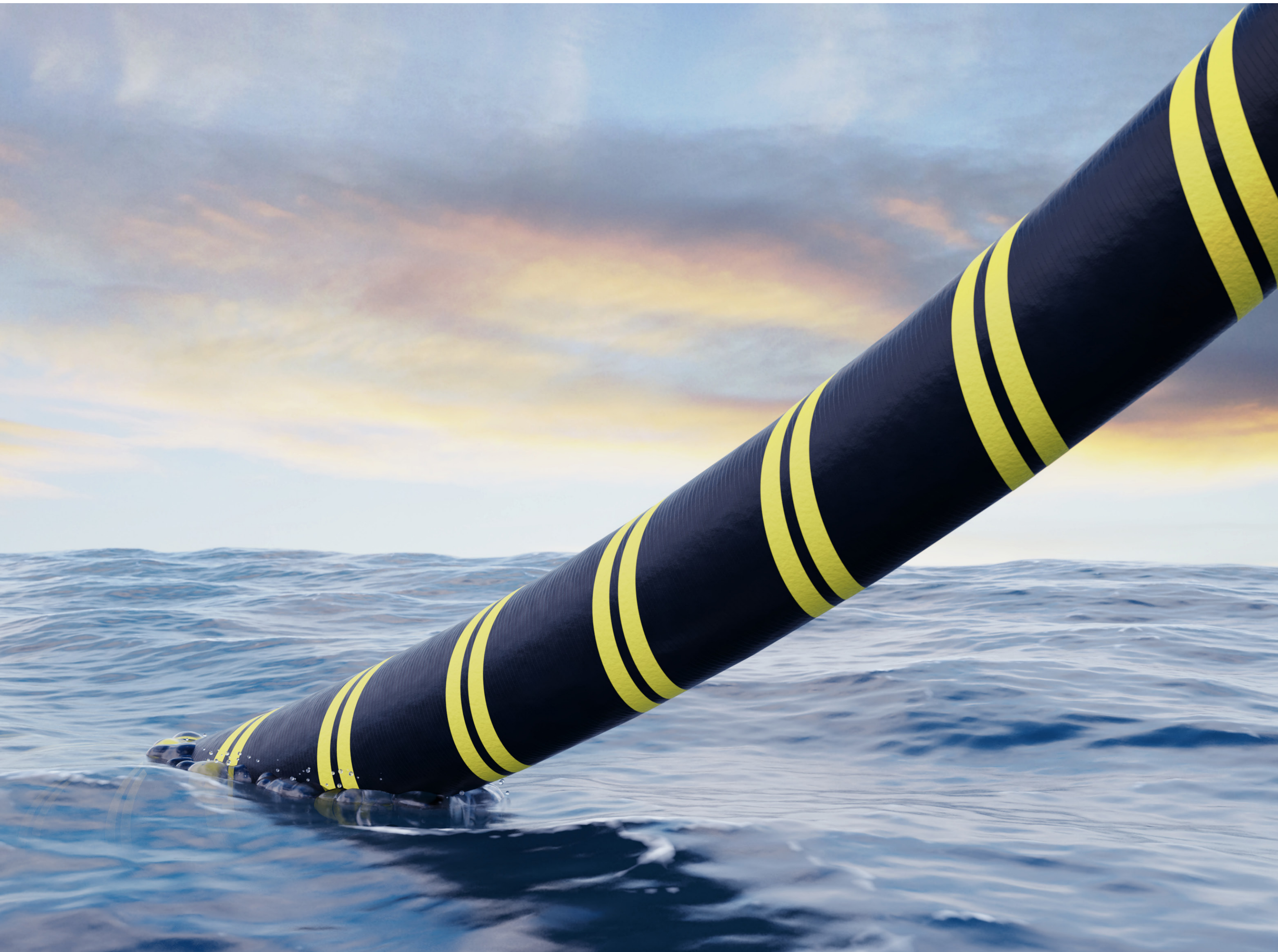
Building electricity bridges: The critical role of high-voltage direct current lines

Joseph Webster and Frank Willey



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CONTENTS

I. INTRODUCTION

High-voltage direct current (HVDC) electricity lines serve as electricity bridges, connecting previously untapped energy resources to distant demand centers. They also enable optionality for grid operators and, with more than forty-four international interconnections, connect grids across countries.[1] Consequently, HVDC lines are critical tools for improving energy security and lowering energy costs.

The scale and quantity of HVDC projects are growing rapidly. Indeed, HVDC lines are critical for meeting rising electricity demands across developed countries, emerging markets, and the developing world, as the growth in renewable energy generators increases the need to deliver electricity over long distances. The best renewable assets are often located far from demand, whereas most traditional power plants—such as coal, natural gas, and nuclear plants—have been built in relative proximity to load centers such as cities. Compared to high-voltage alternating current (HVAC) lines that connect traditional power plants to relatively close load centers, HVDC lines offer long-distance advantages such as lower energy loss and adaptable power flow. Without HVDC lines, the developed and developing worlds might not be able to provide the additional electricity generation needed for cooling, data centers, artificial intelligence, and other uses.

While HVDC lines present an exciting opportunity to advance several objectives simultaneously, obstacles loom as projects grow to unprecedented scope. Industry leaders and policymakers should grasp the scale of the HVDC opportunity and work in concert to remove unnecessary barriers to development; identify and mitigate potential supply chain shortages; ease trade and investment hurdles; strengthen certainty and predictability for investors; and foster international dialogues to establish the trust needed to conduct these projects.

Compared to high-voltage alternating current lines, HVDC lines offer long-distance advantages.
UNSPLASH/Julien Maculan

1 Jingxuan (Joanne) Hu, "DC and Power Electronics—Key Enablers of Flexible, Reliable, and Economic Future Networks," CIGRE, March 12, 2021, https://www.cigre.org/article/GB/dc-and-power-electronics---key-enablers-of-flexible-reliable-and-economic-future-networks.

II. ADVANTAGES OF HVDC OVER HVAC LINES

HVDC lines enjoy several technical and cost advantages over HVAC lines that render them appropriate for long-distance transmission of electricity. HVDC lines can carry higher voltages than HVAC lines, are more heat resistant, and have reduced line losses.[2] HVDC lines are thus more efficient at transmitting greater quantities of electricity over longer distances than HVAC lines, including underground or underwater.[3] HVAC lines have lower station costs because they do not need to convert between alternating current and direct current, but also have higher cable costs. Thus, while HVAC lines are suitable for short distances, their costs scale unfavorably as project scope and distance increase.[4] As an industry rule of thumb, HVDC system costs are higher than HVAC system costs for overhead lines of less than 600 kilometers (km) and for cables 64 km in length; for projects with greater distances, HVDC lines have more favorable costs.[5]

Another advantage of HVDC lines over HVAC is that the former can connect asynchronous grids, which enables subsystems of the grid to be split into smaller subsystems that operate separately and autonomously.[6] Transferring power between asynchronous regions—without disrupting frequency—is possible only with direct current lines.[7]

Additionally, HVDC lines expand access to diverse generation assets, especially because transmission lines can be bidirectional.[8] HVDC lines also reduce the need for the "spinning reserve"—the operating reserve needed to rapidly increase generation to meet changes in demand.[9] Finally, HVDC lines can provide faster grid restorations amid "black start" conditions in which the grid faces a blackout.[10]

Because of their superior technical and cost performance at long distances compared to HVAC lines, as well as their huge potential to unlock new clean energy resources, HVDC lines serve as the connective tissue for the power grid on which the success of the energy transition will hinge.

Opportunities for renewables-driven HVDC lines exist on every continent. The southwestern United States, for instance, has the greatest solar irradiance in the nation, while the closest large demand centers—such as Houston, Dallas, and Chicago—are hundreds of kilometers away.[11] The United States' large coastal cities are similarly far from the nation's best onshore wind resources. Europe's domestic renewable resources are relatively dispersed around the continent, but meeting European decarbonization ambitions could require HVDC connectivity with North African wind and solar. China has a wide array of projects linking its renewables generation in northern and western provinces with demand centers along its coastal regions, particularly in the south. Finally, western Australia has abundant solar and onshore and offshore wind resources that could be sent to population centers in eastern Australia, or even abroad.

2 "On the Road to Increased Transmission: High-Voltage Direct Current," National Renewable Energy Laboratory, June 12, 2024, https://www.nrel.gov/news/program/2024/on-the-road-to-increased-transmission-high-voltage-direct-current.html#:~:text=Second%2C%20HVDC%20lines%20can%20carry,power%20can%20be%20transmitted%20further.

3 Note, according to Diversegy: "capacitive losses arise from the capacitance between the transmission line conductors and the ground or the ability of the power lines to store and release electrical energy due to the electric field created between the lines and the ground. As the line's voltage alternates, energy is stored and released from the electric field created by this capacitance, leading to losses. These losses are more significant at higher voltages and frequencies." "Understanding Line Losses in Energy Transmission and How They Affect Your Electricity Rates," Diversegy, September 11, 2024, https://diversegy.com/understanding-line-losses-in-energy-transmission/; Erin Law, "The Benefits of HVDC Transmission Systems (High-Voltage Direct Current)," Cence Power, July 18, 2022, https://www.cencepower.com/blog-posts/hvdc-transmission-systems.

4 Athanasios Krontiris and Peter Sandeberg, "HVDC Technology for Offshore Wind Is Maturing," ABB, October 24, 2018, https://new.abb.com/news/detail/8270/hvdc-technology-for-offshore-wind-is-maturing.

5 ""High Volate Direct Current Transmission," Americans for a Clean Energy Grid, August 2014, https://cleanenergygrid.org/wp-content/uploads/2014/08/High-Voltage-Direct-Current-Transmission.pdf.

6 Ibid.

7 Ibid.

8 Aaron Larson, "The Future Electric Grid: How HVDC Could Transform the US Power System," *Power Magazine*, August 2, 2021, https://www.powermag.com/the-future-electric-grid-how-hvdc-could-transform-the-u-s-power-system/.

9 Johannes P. Pfeifenberger, et al., "The Operational and Market Benefits of HVDC to System Operators," Brattle Group and DNV, September 2023, https://acore.org/wp-content/uploads/2023/09/The-Operational-and-Market-Benefits-of-HVDC-to-System-Operators.pdf.

10 "ÅL-link," Hitachi Energy, last visited May 7, 2025, https://www.hitachienergy.com/news-and-events/customer-success-stories/aland#:~:text=The%20existing%20fossil%20fuel%20powered,cables%2C%20each%20158%20km%20long.

11 "Energy Data," Global Solar Atlas, last visited May 7, 2025, https://globalsolaratlas.info/map.

Table 1. Comparison of HVDC vs. HVAC transmission systems

Feature	HVDC	HVAC
Transmission efficiency	Lower energy losses over long distances[12]	Higher energy losses over long distances[13]
Distance suitability	Most efficient for distances of more than 600 kilometers (overhead) or more than 64 kilometers underground[14]	Best suited for distances of less than 600 kilometers.[15]
Power transfer capacity	Higher power transfer capability per conductor[16]	Power transfer capability per conductor decreases at long distances[17]
Grid interconnection	Can connect asynchronous grids[18]	Requires synchronous grids[19]
Cost considerations	Higher converter station cost, lower transmission line cost over long distances[20]	Lower station cost, higher transmission line cost[21]
Suitability for underwater/underground	Ideal for submarine and underground cables[22]	Less efficient for submarine and underground transmission[23]
Voltage stability	Stable voltage with no reactive power losses[24]	Voltage drops over long distances[25]
Operational flexibility	Precise control of power flow and direction[26]	Can only control power flow with specialized devices in a limited range[27]
Right-of-way requirements	Can use narrower corridors[28]	Requires wide corridors[29]
Reliability and maintenance	Higher maintenance costs due to complex converter stations	Lower maintenance costs
Application	Best for long-distance transmission, offshore wind, and interconnections[30]	Best for short-to-medium distances and local distribution[31]
Electromagnetic interference (EMI) energy storage and renewables integration	Minimal EMI with nearby communication lines[32]	Higher EMI with nearby communication lines[33]
Environmental impact	Lower infrastructure footprint and fewer transmission lines needed[34]	Higher infrastructure footprint with more lines required[35]

12 "High Volate Direct Current Transmission," Americans for a Clean Energy Grid, August 2014, https://cleanenergygrid.org/wp-content/uploads/2014/08/High-Voltage-Direct-Current-Transmission.pdf.
13 Ibid.
14 Ibid.
15 Ibid.
16 Ahmad Ezzeddine, "An in-Depth Comparison of HVDC and HVAC," EE Power, October 12, 2022, https://eepower.com/technical-articles/an-in-depth-comparison-of-hvdc-and-hvac.
17 Ibid.
18 Ibid.
19 Ibid.
20 Ibid.
21 Ibid.
22 "High Volate Direct Current Transmission."
23 Ibid.
24 Ezzeddine, "An in-Depth Comparison of HVDC and HVAC."
25 Ibid.
26 Caleb Jordache Pillay, Musasa Kabeya, and Innocent E. Davidson, "Transmission Systems: HVAC vs HVDC," Industrial Engineering and Operations Management Society, 2020, https://www.ieomsociety.org/detroit2020/papers/450.pdf.
27 Ibid.
28 Bob Hobson, "Why HVAC Cables Are Poised to Provide Valuable Alternatives," Utility Dive, June 5, 2023, https://www.utilitydive.com/spons/why-hvdc-cables-are-poised-to-provide-valuable-alternatives/651800.
29 Ibid.
30 Ezzeddine, "An in-Depth Comparison of HVDC and HVAC."
31 Ibid.
32 Ibid.
33 Ibid.
34 Ibid.
35 Ibid.

Regardless of geography, HVDC lines are uniquely suited for a particular type of renewable resource: offshore wind. While onshore technologies can use either HVDC lines or HVAC lines, electricity generated by offshore wind is most efficiently delivered through HVDC lines for technical reasons. HVDC's lower cable costs and lower weight per unit length enable the transport of longer sections, lower installation time, and easier maintenance.[36] These features make HVDC lines particularly advantageous for projects far from shore. The US Bureau of Ocean Energy Management points to HVDC lines as a superior technical solution for wind farms farther than thirty miles from shore—an important consideration given the "not in my backyard" backlash to visible wind turbines.[37] Significantly, the first US offshore wind project to employ HVDC lines has started fielding the associated electricity transformers.[38]

36 Krontiris and Sandeberg, "HVDC Technology for Offshore Wind Is Maturing."

37 Pamela Middleton and Bethany Barnhart, "Supporting National Environmental Policy Act Documentation for Offshore Wind Energy Development Related to High Voltage Direct Current Cooling Systems," US Department of the Interior, Bureau of Ocean Energy Management, Office of Renewable Energy Programs, April 2022, https://www.boem.gov/sites/default/files/documents/renewable-energy/state-activities/HVDC%20Cooling%20Systems%20White%20Paper.pdf#:~:text=A%20high%20voltage%20direct%20current,DC)%20for%20transport%20to%20shore; John Rather, "When Nimby Extends Offshore," *New York Times*, January 29, 2006, https://www.nytimes.com/2006/01/29/nyregion/nyregionspecial2/when-nimby-extends-offshore.html.

38 Adrijana Buljan, "Transformers for First US UVDC Offshore Wind Grid Connection Arrive in New York," OffshoreWIND.biz, May 3, 2024, https://www.offshorewind.biz/2024/05/03/transformers-for-first-us-hvdc-offshore-wind-grid-connection-arrive-in-new-york/.

III. ENHANCING ENERGY SECURITY IN DIFFERENT ECONOMIES

With projections showing that renewable energy technologies will represent 95 percent of new electricity generation globally through 2027, the HVDC lines required to connect much of this power to demand centers will significantly bolster the energy security and reliability that these new generators provide.[39] Connecting new energy sources diversifies and distributes the energy mix, including across national borders, while providing greater grid flexibility and load-balancing opportunities to keep prices steady and mitigate potential outages. These advantages will strengthen the resilience of the electricity grid in the face of rising temperatures, extreme weather events, and other grid-threatening events.

HVDC lines could also help expand access to natural gas production that complements renewables production. Gas-fired power plants, especially combined-cycle power plants that are more efficient because they have two electricity generating stages, are "dispatchable" generators, meaning they can increase or decrease their electricity production quickly to meet power demand when "intermittent" solar or wind resources are insufficient. In many cases, gas-fired power plants, either baseload or peaking, can improve HVDC project economics by enabling higher, steady electricity throughput on the line in addition to the electricity generated by renewables.

These enabling features of HVDC lines will play a major role in determining how—or even if—incremental electricity needs are met. Studies suggest that both the developing and developed world are likely to see massive increases in electricity demands in the coming decades, both to support economic imperatives and to meet decarbonization objectives. HVDC lines will be critical for ensuring that these growing electricity demands are met.

HVDC and electricity needs in the developed world

The developed world will likely see unprecedented growth in electricity demand from data centers, as well as the electrification of transport and heating. This will require new transmission infrastructure, with HVDC infrastructure being the most economical option for long distances. The International Energy Agency's (IEA) October 2024 "World Energy Outlook" projected global electricity demand to be 6 percent higher in 2035 than it forecast the prior year.[40] This might prove to be an underestimate, as there is considerable uncertainty regarding the electricity demands of data centers, whether they derive from traditional cloud computing requirements or from artificial intelligence needs.[41] Indeed, the IEA's "Electricity 2024" report estimated that data center demand could more than double in four years—from 460 terawatt hours (TWh) in 2022 to more than 1,000 TWh by 2026—with much of the increase occurring in the developed world, co-located with consumers.[42] US utilities, for instance, are already groaning under stress from data centers and new clean technology factories.[43] Some measures, such as reconductoring of existing power lines with advanced carbon-fiber wires, are vital for meeting demand.[44] But both Europe and the United States will need to connect load centers with distant renewables-rich regions. Electricity markets in developed economies will hinge, in large part, on greenfield HVDC lines.

HVDC lines' role in emerging markets

HVDC lines could also enhance energy security and promote decarbonization across emerging markets. In Latin America, for example, HVDC lines could connect renewables-rich regions, especially in Argentina and Chile, with other parts of the continent. Argentina's southern regions contain some of the world's highest onshore wind speeds, while the capital of Buenos Aires often schedules summer power outages.[45]

Similarly, HVDC lines offer intriguing possibilities for Turkey from both energy security and decarbonization perspectives. In 2023, Turkey's production of natural gas was minor, but it consumed 47 billion cubic meters; in the same year, it produced 0.58 exajoules of coal while consuming 1.65 exajoules.[46] Turkey is not only a major importer of natural gas and coal, much of which comes from Russia, but its domestic

39 Eren Çam, Marc Casanovas, and John Moloney, "Electricity 2025: Analysis and Forecast to 2027," International Energy Agency, February 2025, https://iea.blob.core.windows.net/assets/0f028d5f-26b1-47ca-ad2a-5ca3103d070a/Electricity2025.pdf.

40 Brad Plumer, "Global Electricity Demand is Rising Faster Than Expected, I.E.A. Says," *New York Times*, October 16, 2024, https://www.nytimes.com/2024/10/16/climate/global-demand-electricity-rising.html.

41 Çam, et al., "Electricity 2025."

42 Ibid.

43 Evan Halper, "Amid Explosive Demand, America Is Running out of Power," *Washington Post*, March 7, 2024, https://www.washingtonpost.com/business/2024/03/07/ai-data-centers-power/.

44 Shannon Osaka, "How a Simple Fix Could Double the Size of the US Electricity Grid," *Washington Post*, May 28, 2024, https://www.washingtonpost.com/climate-solutions/2024/05/28/reconductoring-us-electricity-grid-renewables/.

45 "Energy Data"; "Argentina to Schedule Power Outages over Summer, Francos Says," *Buenos Aires Herald*, September 23, 2024, https://buenosairesherald.com/business/energy/argentina-to-schedule-power-outages-over-summer-francos-says.

46 "Statistical Review of World Energy 2024," Energy Institute, last visited May 2025, https://www.energyinst.org/statistical-review/resources-and-data-downloads.

coal is of low quality.[47] Accordingly, Turkey's buildout of HVDC lines to renewables-rich and gas-rich regions in North Africa and the Caucuses could not only reduce its dependency on Russia, but also reduce overall carbon emissions.

Finally, Oman might ultimately employ HVDC lines to ship electricity to India or other countries in the Middle East. Oman enjoys some of the world's best solar and wind resources.[48] An Oman-to-India HVDC project would face economic, technical, geopolitical, and domestic political challenges, but the project is not far-fetched: India, Saudi Arabia, Oman, and the United Arab Emirates (UAE) are studying the technical feasibility of an undersea electricity connection.[49] Finally, Oman might be able to construct intra-Middle Eastern HVDC lines. While there has historically been limited appetite for advanced energy technologies such as wind and solar in the hydrocarbon-rich Middle East, the region's economies and grid resiliency would benefit from access to a diversified and low-cost fuel mix—and even the UAE and Saudi Arabia are increasingly embracing solar and electric vehicles.[50] Moreover, Oman's onshore wind speeds are among the highest in the region and blow consistently during the summer, when the region's electricity demand peaks.[51]

HVDC lines' role in the developing world

Developing countries could also benefit from HVDC lines, albeit for very different reasons. Developing economies, including those along the equator, will require vastly more electricity for industrialization, transportation, data centers, and, critically, air conditioning. The IEA's latest electricity demand forecast estimates that 85 percent of incremental electricity demand through 2026 will derive from outside advanced economies, with much of the rise driven by industry as well as electrification of the residential and transportation sectors.[52]

Developing economies' rising air conditioning needs should be of particular concern for policymakers because of the humanitarian and economic implications. Air conditioning needs are growing across the world due to higher temperatures, with extreme heat posing an ever-larger risk to equatorial populations. According to one study, cooling demand for electricity could reach as high as 22 TWh on peak summer days in India by 2050, accounting for roughly 1.8 percent of India's total annual demand in 2020.[53] For instance, the Indian city of Ahmedabad recently averages 164 days of temperatures above thirty-five degrees Celsius; that figure could increase to 225 days annually if global temperatures rise three degrees Celsius above pre-industrial averages.[54] Moreover, with peak temperatures rising around the world—especially near the equator—air conditioning could be the difference between life and death. To meet electricity needs for air conditioning, especially under net zero-aligned conditions, developing countries will likely require massive new long-distance HVDC line capacity.

Advancing such developmental objectives with HVDC lines will also involve natural gas markets in certain developing economies. While renewable energy generation is clearly preferable to natural gas from a decarbonization perspective, not every region enjoys abundant renewables potential and natural gas will be the most competitive electricity generation source in some markets. Most of South Asia and Southeast Asia, as well as parts of central and western Africa, have mediocre solar irradiance and weak onshore wind potential. These same markets are also developing economies with few financial resources and, in many cases, have few domestic alternatives to coal. For instance, India is the world's second-largest coal producer, while Indonesia is the third largest.[55] India has limited renewables potential, while Indonesia has some of the world's most limited solar and onshore wind resources, along with limited land availability. To meet both decarbonization objectives and energy security needs, many countries, including India and Indonesia, will require HVDC lines to connect to places with more favorable renewables, natural gas, or, most likely, both.

47 Bahadır Sercan Gümüş, "Domestic Coal Is Far from Providing a Baseload in Türkiye," Ember Energy, August 6, 2024, https://ember-energy.org/latest-insights/domestic-coal-is-far-from-providing-a-baseload-in-turkiye/; "Exclusive: Turkey Saves $2 Billion on Russian Oil as Imports Soar Despite Sanctions," Reuters, December 18, 2023, https://www.reuters.com/business/energy/turkey-saves-2-bln-russian-oil-imports-soar-despite-sanctions-2023-12-18/; Shivangi Mittal, "Turkey Data: Thermal Coal Imports Drop 11% on Month in Nov with Buyers on Sidelines," S&P Global, January 3, 2025, https://www.spglobal.com/commodity-insights/en/news-research/latest-news/coal/010325-turkey-data-thermal-coal-imports-drop-11-on-month-in-nov-with-buyers-on-sidelines.

48 "Energy Data"; Ilkka Hannula, et al., "Renewable Hydrogen from Oman: A Producer Economy in Transition," International Energy Agency, June 2023, https://www.iea.org/news/oman-s-huge-renewable-hydrogen-potential-can-bring-multiple-benefits-in-its-journey-to-net-zero-emissions.

49 "Power Grid Planning Rs 40,000-cr Subsea Interconnection with Middle East in 5 Yrs," *Economic Times*, July 29, 2024, https://economictimes.indiatimes.com/industry/energy/power/power-grid-planning-rs-40000-cr-subsea-interconnection-with-middle-east-in-5-yrs/articleshow/112114254.cms?from=mdr.

50 Dave Jones and Libby Copsey, "Saudi Arabia's Surprisingly Large Imports of Solar Panels from China," Carbon Brief, March 31, 2025, https://www.carbonbrief.org/guest-post-saudi-arabias-surprisingly-large-imports-of-solar-panels-from-china/#:~:text=It%20imported%2051GW%20of%20solar,%2C%20Malaysia%2C%20India%20or%20Cambodia.

51 "Energy Data"; Simon West, "Gulf State Targets Five-Fold increase in Renewable Energy Capacity," Breakbulk Magazine, August 12, 2022, https://breakbulk.com/Articles/oman-plots-greener-future.

52 Eren Çam, et al., "Electricity 2024: Analysis and Forecast to 2026," International Energy Agency, May 2024, https://iea.blob.core.windows.net/assets/18f3ed24-4b26-4c83-a3d2-8a1be51c8cc8/Electricity2024-Analysisandforecastto2026.pdf.

53 Peter Sherman, Haiyang Lin, and Michael McElroy, "Projected Global Demand for Air Conditioning Associated with Extreme Heat and Implications for Electricity Grids in Poorer Countries," *Energy and Buildings* 268 (2022), https://www.sciencedirect.com/science/article/pii/S0378778822003693#:~:text=Demand%20for%20AC%20electricity%20in,larger%20than%20those%20experienced%20today.

54 Eric Mackres, et al., "The Future of Extreme Heat in Cities: What We Know—and What We Don't," World Resources Institute, November 29, 2023, https://www.wri.org/insights/future-extreme-heat-cities-data.

55 "Statistical Review of World Energy 2024."

IV. COMMERCIAL DEVELOPMENTS: THE LAY OF THE LAND

Greater HVDC buildout is already taking shape, as substantial new capacity is being deployed, under construction, or under consideration. There are dozens of planned HVDC projects, with many of them located in China. The Zhundong-Wannan project, with planned transmission capacity of 12 GW, claims to constitute "the world's highest voltage level, largest transmission capacity, and farthest transmission distance ultra-high-voltage project."[56] Indeed, China's "clean energy bases" aim to move solar and wind electrons from far-flung inland provinces, such as Xinjiang and Inner Mongolia, to densely populated urban coastal areas.[57] While China is aiming to construct a large number of HVDC lines, it is a closed market in many respects. The rest of the world is also eyeing its own HVDC projects, as the below table demonstrates.

An HVDC power station that supported the 2022 Winter Olympic Games in China.
REUTERS/Tingshu Wang

56 Aaron Larson, "High-Voltage Power Transmission Projects Are Booming Around the World," *Power Magazine*, June 26, 2024, https://www.powermag.com/high-voltage-power-transmission-projects-are-booming-around-the-world/.

57 Lauri Myllyvirta and Xing Zhang, "Analysis: What Do China's Gigantic Wind and Solar Bases Mean for Its Climate Goals?" Carbon Brief, March 5, 2022, https://www.carbonbrief.org/analysis-what-do-chinas-gigantic-wind-and-solar-bases-mean-for-its-climate-goals/.

Table 2. Proposed, under construction, and completed HVDC lines*

Status	Actual or expected end date	Project name	Countries involved	Project value	Land cables (km)	Sub-sea HVDC (km)	GW Capacity
Planning	early 2030s	Xlinks Morocco-UK Power Project	Morocco-United Kingdom (UK)[i]	£22–24 billion ($28–30 billion)[ii]	0	3800 (x2 cables)[iii]	3.6[iv]
			Note: considering route to Germany as well				
	2030	Western Isles HVDC Connection Project	United Kingdom[v]	£1.2 billion[vi]	80[vii]	81[viii]	1.8[ix]
	2030	Marinus Link	Australia (Northwest Tasmania-Latrobe Valley in Victoria)[x]	$3–3.3 billion[xi]	90[xii]	250[xiii]	0.75[xiv]
	2028	Tyrrhenian Link	Italy (Sicily to Campania, Sicily to Sardinia)[xv]	€3.7 billion[xvi]	0	970[xvii]	1[xviii]
	2027[xix]	The Australia-Asia PowerLink	Australia – Southeast Asia	US$24 billion (AUS $31.6 billion)[xx]	800 (within Australia)	4300[xxi]	1.75 to Singapore[xxii]
Under construction	2031	Nederwiek 2 HVDC Project[xxiii]	Netherlands	$2.1 billion	0	95	2
	2028	NeuConnect Power Project[xxiv]	Germany-UK	€2.8 billion ($3.1 billion)[xxv]	725	Combined	1.4
	2025	ADNOC-TAQA Project Lightning	United Arab Emirates	$3.8 billion[xxvi]	0	264[xxvii]	3.2[xxviii]
	2025	Shetland HVDC Link[xxix]	Scotland	£660 million ($871.9 million)[xxx]	10	253[xxxi]	600 MW
	2025	SuedLink[xxxii]	Germany	$11B[xxxiii]	700[xxxiv]	0	4[xxxv]
	2025	Saudi Arabia-Egypt Electricity Interconnection Project[xxxvi]	Saudi Arabia-Egypt	Phase 1: $1.8 billion[xxxvii]	1350[xxxviii]	22[xxxix]	3
Completed	2023	Viking Link	Denmark-UK[xl]	£1.7 billion ($1.84 billion)[xli]	0	765[xlii]	1.4[xliii]
	2022	Ethiopia–Kenya HVDC Interconnection Project	Ethiopia-Kenya[xliv]	$1.3 billion[xlv]	1045[xlvi]	0	2[xlvii]

*Sources for table 2 are listed starting on page 16.

V. CHALLENGES TO HVDC DEPLOYMENT

While HVDC lines are making substantial commercial progress across the world, significant political economy challenges remain. As with all transmission projects, cost allocation remains a significant hurdle. When transmission projects cross several jurisdictions, none wants to bear more than its "fair" share of the costs. Negotiations over cost allocation can slow, or often derail, project development. Furthermore, international transmission projects often suffer from a lack of bilateral or multilateral trust. Russia's invasion of Ukraine and weaponization of energy interlinkages with Europe have sparked a re-emphasis on energy security and self-sufficiency, limiting appetite for some long-distance (and international) HVDC projects. Economic hurdles also exist, as HVDC projects are capital intensive and, consequently, pressured by interest rates. If interest rates persist in a higher-for-longer steady state, HVDC development will be adversely impacted. Furthermore, a lack of strong policies and regulations can lead to difficulty securing financing. Finally, private enterprises and governments will need to secure stable supply chains. Overcoming these challenges to HVDC lines will require forging sustainable political buy-in, strengthening supply chains, and assuring investors, including by demonstrating commitment to the rule of law.

Domestic political challenges

Transmission lines, especially those with international dimensions, are perhaps the most politically difficult critical infrastructure projects to realize. Intra-country projects also have their fair share of obstacles. They are subject to intense bargaining from sub-national actors, with each locality demanding fair compensation for transmission lines crossing its jurisdiction.

Building long-distance transmission projects within a single country is complicated, as the US experience demonstrates. Russell Gold's examination of a clean energy transmission line, as told in the book Superpower, illustrates the perils of inter-state transmission projects in the United States.[58] The clean energy company Clean Line was ultimately forced to abandon a plan to site five HVDC lines connecting wind (and solar) energy production in the heartland states with consumers on the East and West Coasts, and the industrial Midwest.[59] Clean Line's primary project, an HVDC line from Oklahoma to Tennessee, floundered amid opposition from local landowners and the challenges of dealing with multi-state permitting. Additionally, some environmental groups blamed weak commitments from offtakers.[60] When it comes to US transmission projects, more is less. Increasing the number of stakeholders in a project increases the number of potential veto points, complicates negotiations, and often leads to schedule slippage and cost overruns. Similar difficulties are found outside the United States. Renewable project developers around the world routinely complain about how slow bureaucracies are to approve or reject proposed projects.

Geopolitical challenges

The challenges facing long-distance HVDC transmission projects are amplified when projects cross international borders. Not only must these projects satisfy domestic, sub-national stakeholders within each country, but they must also receive approval from national governments. The inherently geopolitical nature of international transmission projects makes them more brittle.

Even countries with strong political ties experience difficulties approving HVDC projects. This dynamic holds in the US-Canada relationship, for example. Historically, the two countries have mutually benefited from extremely close ties, but international transmission projects spanning the US-Canada border have faced significant opposition, even in the most collaborative environments. For example, in 2021, Maine voters voted against a 1,200-megawatt HVDC transmission project that would have transported clean hydropower electricity from Quebec to Massachusetts.[61] While the project is now moving forward after court challenges, the initial ban caused major cost and schedule overruns.[62]

Building transmission lines across borders also poses challenges for projects within the European Union, which enjoys a high degree of mutual political trust. In the words of a 2023 European Investment Bank study, challenges in cross-border infrastructure projects can include "regulatory uncertainty, regulatory fragmentation, multiple permitting procedures, uncertainties connected with construction and levels of supply and demand, asymmetric prioritisation on either side of the border, complexities involved in coordinating funding sources, and other complications in planning, preparing and implementing projects. This means that cross-border projects often have longer lead times and encounter cost overruns."[63]

58 Russell Gold, *Superpower: One Man's quest to Transform American Energy* (New York: Simon & Schuster, 2019).

59 Ros Davidson, "Ambitious Clean Line Energy 'Wrapping Up,'" *Wind Power Monthly*, February 1, 2019, https://www.windpowermonthly.com/article/1523646/ambitious-clean-line-energy-wrapping-up.

60 Stephen Smith, "Clean Line: A TVA Failure of Clean Energy and Environmental Leadership," Southern Alliance for Clean Energy, January 8, 2019, https://www.cleanenergy.org/blog/tvacleanline/.

61 "Maine Voters Reject Quebec Hydropower Transmission Line," Reuters, November 3, 2021, https://www.reuters.com/world/americas/maine-voters-reject-quebec-hydropower-transmission-line-2021-11-03/; "New England Clean Energy Connect," Central Maine Power, last visited May 8, 2025, https://www.energy.gov/sites/prod/files/2020/09/f79/EXHIBIT%20O%20-%20PUBLIC%20OUTREACH%20MATERIALS%20%28W6270305x7AC2E%29.pdf.

62 Johanna Knapschaefer, "Embattled Maine Power Line Restarts as Cost Ballons to $1.5B," Clean Energy Construction, August 3, 2023, https://www.enr.com/articles/56895-embattled-maine-power-line-restarts-as-cost-balloons-to-15b. Marc J. Dunkelman, "Progressives Say They Want Clean Energy. They Held Up This Hydro Project for Years," *Politico Magazine*, February 23, 2025, https://www.politico.com/news/magazine/2025/02/23/massachusetts-clean-energy-00204964.

63 "Cross-Border Infrastructure Projects: The European Investment Bank's Role in Cross-border Infrastructure Projects," European Investment Bank, 2023, https://www.eib.org/attachments/lucalli/20230107_cross_border_infrastructure_projects_en.pdf.

Table 3. Supply chain and material needs for HVDC projects

Material/product	Use in HVDC	Key suppliers	Supply risks
Copper	Conductors in cables	Chile, Peru, China, United States	Price volatility
Aluminum	Alternative conductor material	China, Russia, Canada, Australia	Processing constraints
Steel	Towers and support structures	China, India, United States	Rising demand, raw material costs
Transformers	Voltage conversion	Germany, United States, China	Production bottlenecks, long lead times
Insulators	HVDC cable insulation	Global suppliers	Raw material shortages

Accordingly, even intra-EU transmission lines that cross borders can be subject to intense wrangling over who pays for what. For countries and regions that enjoy less mutual trust, "getting to yes" can prove even more difficult and complicated.

Supply chain challenges

In addition to their unique political economy challenges, HVDC lines are confronted with standard commercial problems facing other energy projects. Capital expenditures for HVDC lines are large; accordingly, they rise in tandem with interest rates. If the United States and the world have entered into a world of higher-for-longer interest rates, then the financing challenges of HVDC line projects will become even more difficult to overcome. Other cost drivers for HVDC lines—materials, labor, land acquisition, and more—rise or fall in line with broader inflation trends.[64]

Key cost drivers for transmission and HVDC lines include materials such as steel, copper, and aluminum. A single large (640-kilovolt) HVDC single-circuit steel tower, using an angled dead-end structure, uses more than 113,000 pounds of steel.[65] Consequently, steel prices are a major cost driver for transmission projects. Meanwhile, cable transmission lines also require massive quantities of copper or, less frequently, aluminum.[66] Bauxite—the principal aluminum-bearing ore—is plentiful and globally distributed, with leading production in Australia and Guinea .[67] While aluminum is typically less expensive than copper and lighter, it is also less conductive than copper.[68] Additionally, copper has a lower thermal expansion than aluminum, making it less likely to degrade or break during periods of heat.[69] For these reasons, most cable manufacturers prefer copper over aluminum, although there are exceptions.[70] Accordingly, ensuring reliable and robust copper supply chains will be critical to the success of cabling—and of HVDC lines—but copper supply chains face challenges and potential shortages.[71] Like other energy technologies, HVDC lines will be exposed to resource and supply chain constraints.

In addition to cabling, the entire transmission industry—of which HVDC lines are a part—has been impacted by the global transformer shortage. Transformers are used to increase or decrease the voltage of electricity. Decreasing electricity voltage—or "stepping down" voltage—makes electricity safer and more usable for consumers.[72] Conversely, increasing electricity voltage (or "stepping up" voltage) allows for long-distance transmission, as this technique limits energy losses from resistance.[73]

Transformers have emerged as a critical bottleneck for transmission projects in general, and for HVDC projects in particular.[74] Because HVDC lines require both stepping up and stepping down voltage, transformers are integral for long-distance transmission. Recent reports, however, have shown that utilities' lead time for procuring new transformers has doubled to 120 weeks or more in recent years.[75]

A *Financial Times* analysis found that demand for HVDC lines outstrips supply by two and a half times.[76] There are additional reports of HVDC system manufacturers running factories at 130 percent of their intended capacity, with tender teams prioritizing only the most strategic of customers, such as utilities.

64 "Transmission Cost Estimation Guide," Miso Energy, March 15, 2023, https://cdn.misoenergy.org/20230315%20PSC%20Item%205e%20Transmission%20Cost%20Estimation%20Guide%20for%20MTEP23628223.pdf.
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66 Rachel Millard, "Will There Be Enough Cables for the Clean Energy Transition?" *Financial Times*, July 30, 2023, https://www.ft.com/content/c88c0c6d-c4b2-4c16-9b51-7b8beed88d75.
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76 Simeon Kerr, "Scotland Bets on Supply Chain Growth with Subsea Cable Investment," *Financial Times*, January 30, 2025, https://www.ft.com/content/8ce06f13-c09c-42b4-ba65-d29d4983d60d.

While these reports were unable to be confirmed independently, they are highly plausible.

Financing challenges

The need for new long-distance HVDC transmission infrastructure brings with it significant financing needs. BloombergNEF estimated that the global grid network will need to double in length from 2023 to 2050, requiring around $21 trillion in investment over the same period, though this also includes short-distance distribution lines.[77] The financing challenges confronting HVDC lines are complex, although schedule delays often make or break investment viability.

The fundamental challenges in securing financing for long-distance HVDC transmission lines are easy to identify: large upfront costs; lengthy development timelines; regulatory complexity and uncertainty; and, in many cases, the additional risks that accompany an international infrastructure project, such as currency risk or intergovernmental relations. Investors can be deterred from investing in long-distance HVDC transmission projects because they are long-term, capital-intensive investments in complex projects with significant regulatory risks.

Regulatory risks are compounded because long-distance HVDC lines typically cross jurisdictions, which can complicate cost recovery and make it difficult to secure financing. Disputes over regulated cost recovery and merchant revenues—the revenue attained by selling transmission line capacity to the market rather than through regulated tariffs—threaten project cash flows. Without regulatory certainty, investors cannot anticipate the expected timeline of a project or how the project will recover costs, escalating project risks and the cost of financing. HVDC projects often face difficulties securing sustainable sources of revenue from regulated and merchant line capacity. Project delays can also necessitate restructuring, additional capital raises, and other contingency planning mechanisms that further harm the viability of the deal.

Indeed, project delays might be the largest threat to financing long-distance HVDC transmission infrastructure. When an HVDC line's development is delayed, the project's financial conditions can erode. Delays can produce cost overruns due to rising labor and material prices, as well as additional interest payments for debt servicing; project delays also postpone revenues and can potentially threaten a project's viability. For instance, the proposed HyLinks Morocco-to-UK HVDC megaproject would constitute nearly one-quarter of Morocco's gross domestic product. If interest rates spike, project costs could balloon, and, in a worst-case scenario, lead to project cancellation. At a minimum, long-distance HVDC lines take about five years to develop and construct; the SunZia Wind and Transmission project only received approval to build after seventeen years.[78] In sum, project delays erode confidence in future HVDC deals and raise the cost of capital. Time is an enemy of financing long-distance HVDC lines.

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VI. OVERCOMING HURDLES TO HVDC DEPLOYMENT

The challenges facing HVDC lines are complicated and often downstream of larger forces across politics, regulation, economics, and supply chains. Consequently, addressing these challenges will require multiple lines of effort across different verticals.

As is often the case for energy infrastructure, politics is perhaps the primary challenge confronting HVDC projects. Building foundational bilateral and multilateral political trust needed for cross-jurisdictional HVDC projects is difficult, and will require patience and a keen understanding of the domestic and international political economy challenges transmission lines face. Of course, the world's energy security and decarbonization needs are urgent. Consequently, policymakers must pursue a difficult path of acting quickly but not rashly.

The most important way for countries to enable the construction of HVDC lines is to accelerate the time for approval, both domestically and internationally. With energy projects, time truly is money. Transmission plans dragging on for years raises capital expenditures, delays payback period, and prevents staff from identifying new opportunities. These measures consequently deter overall investment, including for new entrants. Accordingly, accelerating international HVDC lines will require greater action within countries and greater cooperation between them.

Measures to support the domestic deployment of HVDC lines

Within countries, the importance of speeding up project assessments—and quickly delivering go or no-go decisions—cannot be overstated and are foundational for international cooperation. Given the enormous social returns on HVDC projects, especially for low- or no-carbon generation sources, there is a highly compelling case for national and state policymakers to put in place a policy and regulatory environment that addresses challenges facing HVDC projects.

- Policymakers should expand funding for permitting authorities to conduct proactive planning assessments that would deliver a high social rate of return on investment. This would require increasing the budgets of regulators; incorporating more artificial intelligence where appropriate; and bolstering the talent pipeline by ensuring more regulators are hired and sending a strong demand signal to higher education enrollees.
- Regulators should identify areas or methods by which HVDC projects would be determined to have minimal adverse environmental or social impacts, indicating an accelerated project approval timeline.[79]
- Other measures that cut red tape, such as rapidly adjudicating lawsuits, would also accelerate HVDC projects and enable more investor certainty.
- US and European policymakers should engage with major copper producers, especially Chile and Peru. They should also consider siting refining and processing capabilities within their own countries. These actions would ensure that HVDC lines have secure and reliable supply chains, while avoiding sole-supplier dependency.
- Policymakers should ensure stable commodity and HVDC-related materials prices—especially for copper, but also for steel, aluminum, and other materials. They should do so through robust upstream production of commodities; creative market mechanisms, such as financing hedging instruments and creating new benchmarks; stockpiling strategic reserves; and monitoring supply chains.[80]
- Policymakers should concentrate on transformer shortages, which immediately threaten the viability of HVDC lines and electricity supply chains more broadly due to strains on the grid, rising electricity demand, and increasingly frequent and severe weather disasters. They should focus on providing stronger fiscal incentives, relaxing regulatory burdens, and standardizing transformers at the international, national, or even local levels.

Measures to enable cross-border HVDC projects

While cross-border HVDC projects are even more politically and technically challenging than intra-state transmission lines, nations can ease these burdens by fostering a collaborative political and economic environment.

- Countries should hold formal and informal—e.g., unofficial Track 1.5 or Track 2 dialogues—discussions on electricity interconnections and resilience, including for long-distance projects. This could help achieve two critical goals: fostering mutual political trust and de-linking energy and resilience issues from geopolitics. Compartmentalizing energy and resiliency issues from geopolitical questions is especially challenging in the wake of Russia's invasion of Ukraine and the growing weaponization of energy. Still, Cold War arms control negotiations offer a template for

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de-linking existential (or, in the case of the trend of changing weather patterns, near-existential) risks from broader geopolitical questions. By holding electricity interconnection dialogues with public- and private-sector actors in private settings, transmission stakeholders can identify potential roadblocks and mitigate challenges.

- To address the significant and growing trade and investment hurdles to HVDC development, policymakers should carefully consider the impact of import tariffs on energy supply chains, not only for HVDC lines but also for other related items, such as pipelines and raw materials.
- Turning to investment, predictability afforded by the rule of law has historically provided a huge boon to constitutional democracies. Policymakers should strengthen the rule of law, ensure the equality of citizens before the law, and provide protections for domestic and international investors to foster conditions for greater cross-border investments, including for HVDC projects.
- Additionally, policymakers should consider using creative private-public partnerships, and public financing where appropriate, to scale up manufacturing. A Scottish subsea cable factory provides a successful example. The project relied, in part, on £24.5 million of public-sector funding.81 Strategic, targeted public-sector participation could help address market failures, including for key manufacturing nodes. Concretely, governments could commit to long-term contracts, or provide a guaranteed offtaker. This might offer fruitful synergy with efforts to build a national transformer reserve, a long-standing topic of discussion in the United States, including when Vice President-elect JD Vance called for a strategic transformer reserve on the Joe Rogan podcast in November 2024.[82]
- Finally, for HVDC lines to achieve their promise, fiscal and monetary policymakers will need to keep real interest rates as low as possible and provide credible assurances to investors and partner governments that they will remain sustainably low.

Project financing solutions for HVDC infrastructure

To attract financing for HVDC infrastructure projects, developers should seek out effective deal structures, financing mechanisms, and risk mitigating strategies that align developers, investors, and regulators to enhance HVDC project bankability, widen the pool of potential investors in the asset class, and increase HVDC deal volume. Hybrid deal structures that take advantage of both regulated and merchant revenue streams within the same project enable: a wider distribution of nonpayment risk; additional eligible equity and debt investors with different risk appetites; and diversified revenue streams, including from tax benefits, all contributing to enhancing project bankability. Project developers can seek lower-cost debt financing to cover upfront capital costs, while equity can be used to cover unforeseen risks such as project delays or regulatory barriers.

The hybrid structure of public-private partnerships enables diverse investor classes to invest in HVDC projects, lower the cost of capital, and thus crowd in investment in HVDC infrastructure. For example, the regulated revenue could be used to secure lower-cost debt while merchant revenue can attract higher-risk equity capital in exchange for higher risk.[83] Revenues can also be used in cost-sharing agreements so that stable, regulated revenues can support construction, operation, and maintenance of the line, while the additional merchant revenues help reduce financing costs for the overall project.

Projects should leverage additional financing instruments such as green bonds, project bonds, sovereign loan guarantees, third-party loan guarantees, letters of credit, securities, and tax incentives to secure financing. Merchant line developers often employ non-recourse project financing, in which the project's assets and revenue are used to secure loans, which limits financial exposure for investors and can be particularly effective for large-scale infrastructure like HVDC lines. Leveraging an assortment of financing tools can help HVDC developers optimize their capital structure and attract sufficient financing, lowering their cost of capital and improving bankability.

Finally, risk mitigation strategies are crucial for improving HVDC project bankability and securing financing. Hedging mechanisms such as power purchase agreements (PPAs) or capacity contracts—agreements in which an entity such as a utility, grid operator, or industrial consumer buys the right to use a specified amount of transmission capacity or generation capacity over a set time period—with utilities or large industrial consumers provide long-term stable cash flows and shield the project from market risk. Additionally, political risk insurance and guarantees from multilateral development banks and financial institutions can help mitigate geopolitical risks for cross-border lines. Meanwhile, grid stability insurance and performance guarantees can protect investors from a project's operational failures, while credit enhancement tools—such as the letters of credit and third-party guarantees mentioned above—or currency hedging instruments, as needed, can reduce credit risk. These risk mitigation strategies address an assortment of technical, financial, and regulatory risks to make HVDC projects more attractive to both lenders and equity investors, ultimately increasing the volume of deal activity and accelerating the pace of deployment.

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VII. CONCLUSION

HVDC lines hold significant promise but also face complicated, cross-cutting challenges spanning politics, regulation, economics, and supply chains, all of which are subject to larger forces. Instead of being overwhelmed by the scale and complexity of the challenge, however, policymakers who recognize the value of HVDC lines should take key steps.

Policymakers should signal their support for, and commitment to, HVDC lines via both public and private statements. While this measure must be accompanied by tangible policies, sending a positive signal will help galvanize actors across industry, regulatory bodies, and the political system. Additionally, policymakers should routinely hold technical discussions with industry regarding key "pain points" facing project developers. While many of the macro challenges cannot be resolved at the technical level, policymakers might be able to address some discrete challenges. Finally, policymakers must improve the broader political, macroeconomic, regulatory, and supply chain challenges facing industry. While this process will not be easy, the benefits are potentially enormous. If their promise is realized, HVDC lines can bridge electricity supply and demand.

HVDC lines are well suited to connect long-distance offshore wind turbines.
Christian Charisius/Pool via REUTERS

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