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Modernization of High-Voltage Transmission Networks for Grid Reliability: Lessons from Large-Scale Infrastructure Projects

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Abstract- National grid operators have few infrastructure investments of greater consequence than the modernization of large-scale high-voltage transmission. Still, when it comes to what these projects teach us about grid reliability, the record is more likely to be couched in technical jargon than in the realities of project delivery. To put this in perspective, the present paper takes a comparative look at two of the world's most thoroughly documented modernization efforts: China's ultra-high-voltage (UHV) program and India's Green Energy Corridor. Our analysis is based on an empirical study of power transmission delay factors as well as a review of peer-reviewed literature and the project files of governments and multilateral development banks. We find that while both programs made use of phased sequencing as a means of mitigating risk, their public records tell different stories. In the case of China, one can see the merits and the drawbacks of incremental technology validation; there is even a matter of record where underutilization of a demonstration line was linked to coordination issues on the generation side. India's documentation is more forthright in showing that the timeline for project delivery was held back by right-of-way acquisition and not the technology itself, something a wider empirical study has independently borne out. The conclusion to be drawn is that the reliability of a modernized grid hinges on the combined management of delivery and technical risk. And while lessons from one program may be instructive for another, they should not be applied wholesale without first considering if the structural nature of the reliability problem is in fact the same.

Keywords: high-voltage transmission; grid reliability; ultra-high-voltage; infrastructure project delivery; transmission modernization; right-of-way

I. INTRODUCTION

For modern grid infrastructure, the dependable conveyance of electrical power across great distances is an engineering problem of the first order. National utilities have turned to large-scale high-voltage transmission modernization as their main means of curbing losses, accommodating renewable sources and meeting rising demand. Among the most thoroughly chronicled examples of such work in the last twenty years are China's ultra-high-voltage (UHV) program and India's Green Energy Corridor; the technical and operational records for both are ample and in the public domain, making them well suited to a comparative analysis.

China's UHV initiative is perhaps the most expansive use of ultra-high-voltage alternating and direct current technology in the world. Launched in the early 2000s and growing ever since the 2009 commissioning of the Nanyang–Jingmen 1000 kV demonstration line, it was put in place to resolve the geographic disconnect between where China generates its energy and where it is needed (Huang et al., 2009). India's approach with the Green Energy Corridor is on a similar scale but driven by different imperatives. Formally put forward in 2012 and rolled out from 2015 onward, this project is intended to bring variable renewable generation into the national fold while bolstering system reliability (Government of India, Ministry of Power, n.d.; Asian Development Bank, 2021).

In the pages that follow, these two projects are considered as case studies in large-scale

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modernization. The intent is to cull practical lessons on grid reliability that have applicability outside of either country. This paper makes the case that one should not view transmission modernization in purely technical terms; the experience of both programs shows that how a project is delivered – be it through right-of-way management, sequencing or phased commissioning – is just as determinative of reliability as the technology employed.

There is value in the lessons from such undertakings because the fundamental challenges of delivery do not change from one nation to the next: the capital outlay, protracted construction, the coordination required with generation-side development and the complexities of land acquisition over several jurisdictions. A grid operator looking to make a major investment in some jurisdiction other than China or India may not be able to simply copy the technical specs of either program, but can look to the pattern of risks and mitigations that a side-by-side examination reveals. That is the contribution this paper sets out to provide. The discussion is structured as follows: Section 2 is a review of the literature on high- and ultra-high-voltage transmission and its modernization. Section 3 covers the methodology and case selection, after which Sections 4 and 5 detail the China UHV and India Green Energy Corridor cases in turn. A cross-case analysis of what can be learned for grid reliability is offered in Section 6. The paper then moves to a consideration of wider implications in Section 7 before concluding.

II. LITERATURE REVIEW

The scholarship on high-voltage and ultra-high-voltage (UHV) transmission has evolved in two separate directions. On one side is a robust technical and engineering literature devoted to the technology; on the other, a more circumscribed body of work that looks at the policy and delivery aspects of large-scale projects. There is no shortage of established technical writing. In a foundational review for the Proceedings of the IEEE, Huang, Shu, Ruan and Hu (2009) laid out the history of China's UHV alternating and direct current program, from the design parameters of the first test lines to research on insulation coordination and the electromagnetic environment. That early groundwork was built upon by Shu and Chen (2018) in their review of the following ten years of UHV application in China, and by Liu et al. (2018), who put on record the key technologies behind the ±1100 kV UHVDC transmission then being developed as the world's highest voltage class. While this literature makes clear in some detail how UHV can cut losses and boost capacity over distance, it is aimed at a technical readership and gives short shrift to the institutional or financial realities of putting such systems in place at scale.

One will also find a parallel strand of technical work on the grid reliability and stability issues that come with modernizing transmission to accommodate renewables. For instance, Adetokun and Muriithi (2021) offer a thorough review in Heliyon of Flexible Alternating Current Transmission System (FACTS) devices for voltage stability in renewable-integrated grids, weighing the cost and performance of STATCOMs and SVCs. Such work is pertinent to efforts like India's Green Energy Corridor, yet it tends to view voltage stability as an isolated technical matter rather than part of a larger infrastructure delivery equation.

The policy and project-delivery side of things is not as well covered, though it is of direct interest to the present paper. A 2020 report by the Clean Energy Grid Initiative is useful for flagging non-technical impediments to U.S. high-voltage development – permitting holdups, cost-allocation spats between states, and disputes under FERC Order 1000 are all catalogued with reference to the TransWest Express line. But its narrow U.S. regulatory lens means it does not readily apply to the China and India cases we consider here. The Asian Development Bank (2021) is a rare source for a public, project-level account of outcomes in India's Green Energy Corridor and Grid Strengthening Project, noting for example delays stemming from right-of-way acquisition.

More to the point is the empirical study of Pall, Bridge, Gray and Skitmore (2020) in Energies. After surveying 311 stakeholders and sifting through 63 potential delay factors in ten categories, they found that right-of-way issues and changes to transmission routes were more critical to causing delays than many contractual or technical variables. This is a significant finding for our purposes: it shows via a broad empirical exercise, as opposed to a single project narrative, that right-of-way delay is a pattern to be expected in power transmission delivery, not an idiosyncrasy of any given country. It lends weight to the generalizable lesson drawn from the India case in Section 5.

What is missing from the existing scholarship, and what this paper sets out to fill, is a synthesis of these strands. One can find deep technical documentation of the technology, or aggregate data on delivery barriers in a U.S. context, but there is no work that brings together the documented lessons from the two most thoroughly recorded large-scale modernization programs, China's UHV and India's Green Energy Corridor, in a comparative framework with an eye to grid reliability.

III. METHODOLOGY: CASE SELECTION AND APPROACH

A comparative case study approach underpins the work in this paper, with an eye on two high-voltage transmission modernization programs of a magnitude and context that make them worthy of side-by-side examination: the ultra-high-voltage (UHV) program in China and India's Green Energy Corridor. The analysis is built from the ground up using publicly accessible material – technical literature, peer-reviewed engineering scholarship and the like, as well as government and multilateral project files – without any primary data collection of our own. To be consistent with the temporal scope of the analysis, every source has been verified as having been published no later than 2021.

Three considerations dictated the choice of cases. There is the matter of scale; at tens of billions of dollars in investment and thousands of circuit kilometers, these are among the most significant modernization undertakings in the world. Then there is the quality of the public record. In the case of China one can rely on a wealth of peer-reviewed technical writing, while for India there is detailed delivery documentation at the project level, such as an Asian Development Bank completion assessment that puts on record the causes of any delays or the outcomes of delivery. Finally, the programs offer complementary motivation. Both set out to enhance grid reliability but for different reasons: China's UHV effort was necessitated by the long distances between geographically distinct demand and generation hubs, whereas the Indian initiative was about bringing variable renewable sources onto the national grid (Government of India, Ministry of Power, n.d.). This distinction is useful for the cross-case analysis in Section 6, where we can separate lessons that apply to a given objective from those with more general relevance.

In what follows, the paper does not try to put both cases through the same reporting template given the different nature of the source material. Instead, for each we have drawn on the public record to synthesize the technical scope of the infrastructure, the implications for grid reliability, and the documented realities of project delivery, be it in terms of phasing, timelines or complications. We have been rigorous in our source verification. No claim has been made on the basis of general familiarity with the subject; each has been traced to a checkable publication. Since the paper is framed around a 2021 cutoff, care was taken to confirm original dates rather than depend on a republished version that might fall outside the analytical window. If a date could not be put to rest with confidence, the source was left out. Table 1 provides a summary of the principal dimensions we have compared, and the full narratives for the two cases are set out in Sections 4 and 5, in keeping with a case-study logic that favors depth over a wider sample.

Table 1. Comparative Summary of the Two Case Studies

Dimension	China UHV Program	India Green Energy Corridor
Primary objective	Long-distance transfer between fixed generation and demand centers	Integration of variable renewable generation; reduced curtailment
Core technology	1000 kV UHV AC; ±800/±1100 kV UHV DC	765 kV / 400 kV AC; ±800 kV / ±320 kV HVDC terminals
Implementing body	State Grid Corporation of China (centrally coordinated)	POWERGRID (inter-state) + state transmission utilities (intra-state), ADB co-financed
Program origin	Early 2000s planning; NDRC approval 2005	2012 POWERGRID feasibility study
First major milestone	2009: Jindongnan-Nanyang-Jingmen 1000kV line energized	2015: Implementation begins
Documented scale	>30,000 km UHV lines; ~150 GW capacity; >400 billion yuan invested (by ~2020)	~3,200 ckm (Phase I ISTS) + HVDC terminals; ~US$7 billion interstate investment
Key documented lesson	Phased technology validation; demonstration-line underutilization risk (partner/generation-side dependency)	Right-of-way acquisition as primary delivery-schedule risk (within-budget, satisfactory post-commissioning performance)
Primary reliability mechanism	Reduced line losses; reduced dependence on local generation reserves	Reduced renewable curtailment; increased interregional transfer capacity

IV. CASE STUDY: CHINA'S ULTRA-HIGH-VOLTAGE TRANSMISSION PROGRAM

The impetus for China’s ultra-high-voltage transmission program can be traced to a structural disconnect between where the country’s energy resources are and where the demand for electricity is. Most of the nation’s coal, hydropower and, in recent years, wind and solar capacity are found in the west and north. Yet the heaviest concentration of demand lies in the eastern and coastal provinces, frequently at a distance of 1,000 km or more (Huang et al., 2009). Conventional extra-high-voltage (EHV) lines running at 500 kV were deemed inadequate to move the necessary volumes of power over such ground without incurring unacceptable losses; this gave rise to the need for new technology capable of 1,000 kV AC and ±800 kV (eventually ±1,100 kV) DC (Huang et al., 2009; Liu et al., 2018).

A demonstration phase put the technical foundation in place, culminating in the Nanyang–Jingmen 1000 kV UHV AC line which went into commercial service in early 2009 (Huang et al., 2009). As the technical literature makes clear, the project was meant to do two things: prove out UHV technology in the field and produce the kind of empirical data on lightning performance, insulation coordination and electromagnetic effects that would be required for the design of future, larger UHV lines.

Contemporaneous industry reports on the original demonstration line bear witness to the engineering scale involved. The Jindongnan–Nanyang–Jingmen line was put into operation in March 2009 with a transfer capacity of 5,000 megawatts. It ran for 650 km in all, crossing both the Yellow and Hanjiang rivers in two parts: 360 km from Jindongnan in Shaanxi to Nanyang and another 290 km on to Jingmen in Hubei (Global Transmission Report, 2009). State Grid Corporation of China completed the work in 28 months from its 2006 inception at an estimated 5.7 billion yuan, and after some 168 hours of testing it was cleared for commercial use. One finds this degree of construction detail in the documentation for the demonstration line but not so much for the program’s later expansion phases, a discrepancy in line with the literature gap noted in Section 2.

Then there is the matter of the line’s early operating record, which provides a counterpoint to any notion that the program’s phased approach has been unalloyed success. Caixin Global has reported that even after a capacity boost two years post-commissioning allowed for a stable annual throughput of 25 billion kilowatt-hours, the Jindongnan–Nanyang–Jingmen line did not come up to those figures for more than ten years. A senior engineer with the Electric Power Planning and Design General Institute put the shortfall down to a lack of a generation partner with the steady supply to make use of the line's capacity (Caixin Global, 2021). In fact, work on a facility to provide that supply was put on hold in 2017 and only picked up again in 2019, for an investment of some 8 billion yuan (Caixin Global, 2021). The underutilization on record serves as a telling caveat to the demonstration-phase lesson set out above. In the case of this line, for instance, it is true that the project produced the technical validation data needed to guide later UHV development; yet it also shows that one cannot assume a demonstration will see its full designed capacity put to work simply because it is a technical success. This is all the more so when the asset's worth is contingent on complementary generation-side investment that is planned and bankrolled in isolation.

After the demonstration phase the program grew in scope, encompassing both AC and DC. Over the next decade, Shu and Chen (2018) chronicled the way UHV research and application were extended to a number of corridors linking China's key demand and generation areas. The direct current side of the effort moved with particular speed. Once ±800 kV UHVDC was an established operational reality, Chinese grid operators set about developing transmission at ±1,100 kV. Liu et al. (2018) have put on record the technical work involved in making the step up in voltage, from the insulation design to the lightning arrester configuration and switching overvoltage margins. One can see in the move from 800 to 1,100 kV a pattern of incremental escalation at the program level, where each new voltage class is built on the empirical and technical ground of the last.

Industry reports from the time give some sense of the investment scale beyond the solitary demonstration line. An issue brief from 2018 for the Clean Energy Grid Initiative puts it at several billion U.S. dollars per line for the 19 UHV lines China has put in place since 2006. At the time there were also 10 UHV DC and 27 UHV AC lines in various stages of development or construction. The brief specifically cites the Changji–Guquan 1,100 kV UHV DC line with a 12,000 megawatt capacity (Clean Energy Grid Initiative, 2018). When a single corridor can handle the output of some dozen large power plants, the stakes of getting the design and construction right are high; any failure or period of underuse like that seen on the original line means a loss of capacity that would be far more consequential than with conventional lower-voltage options.

There are two mechanisms at play in the UHV program's rationale for grid reliability. For one thing, UHV transmission is more efficient over long distances, cutting line losses in a way that lower-voltage systems cannot (Huang et al., 2009). For another, by moving very large volumes of power on a few high-capacity corridors, the program lessens the need for regions to hold sizeable local generation reserves to keep the balance, and they can source from further afield (Shu & Chen, 2018). While these points are relevant to the matters of grid reliability addressed here, the technical literature tends to frame them in engineering terms. There is not much in the public domain regarding the institutional or cost challenges of putting individual lines in the ground, nor the delivery timelines, which is in keeping with the gap we noted in Section 2.

V. CASE STUDY: INDIA'S GREEN ENERGY CORRIDOR

Where China's UHV program was driven by the need to span long distances between fixed points of generation and demand, India's Green Energy Corridor had a different impetus. The initiative was put in place to tackle the grid integration issues that come with variable renewable capacity which is both geographically scattered and growing at pace. One can trace its provenance in the records of the Indian government: a 2012 study by the Power Grid Corporation of India Limited (POWERGRID) revealed that the transmission infrastructure near the country's most promising wind and solar locations could not handle the expected output from renewables. In response, POWERGRID put forward a report on the Green Energy Corridor later in the year, and after the necessary approvals were in order, implementation got under way in 2015 (Government of India, Ministry of Power, n.d.).

From the start the project was of considerable technical scope. The Inter-State Transmission System

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(ISTS) for Phase I of the Green Energy Corridor alone entailed some 3,200 circuit kilometers of line and 17,000 MVA of substation capacity before being commissioned in March 2020 (Government of India, Ministry of Power, n.d.). With some funding from the Asian Development Bank, the wider Green Energy Corridor and Grid Strengthening Project incorporated 765 kV and 400 kV high-voltage lines and an associated substation, as well as four high-voltage direct current terminals (two at 800 kV and two at 320 kV) to better connect the power grids of western and southern India (Asian Development Bank, 2021).

The size of the investment speaks to the importance of the corridor in India's national transmission programme. The component under review here is part of a roughly 7 billion U.S. dollar outlay by POWERGRID to upgrade the interstate grid and get renewable energy from source to consumer despite the intermittency of the supply. While this is an order of magnitude less than the hundreds of billions of yuan China has put into its UHV programme (see Section 4), it is still among the most substantial dedicated investments in renewable-integration transmission made by any national operator in the period in question (Asian Development Bank, 2021).

There is also a matter of documentation. Public literature on the China UHV case is replete with detail on technology but offers little on delivery; the India case is more forthcoming on lessons at the project level. An assessment by the Asian Development Bank notes that while right-of-way problems caused some subcomponents to be "commissioned with delays", they came in at the estimated cost and have been running satisfactorily since (Asian Development Bank, 2021). For the purposes of this paper's cross-case analysis, that is a telling distinction: it puts land acquisition and right-of-way, not the technology, as the constraint on the schedule, with no similar compromise on cost or operational performance. Full commercial operations were up and running by October 2021, so the delays did not preclude a successful outcome (Asian Development Bank, 2021). Technical studies corroborate the value of the work done. A 2020 paper by Percis et al. looked at the 400 kV system in Tamil Nadu, then home to the most installed wind and solar in India, and found that such dedicated corridors are key to large-scale integration without the curtailment that results when there is not enough capacity to evacuate the power. It is a clear empirical tie-in to the Green Energy Corridor's objective of putting in the transmission capacity needed to avoid wasting renewable output (Percis et al., 2020).

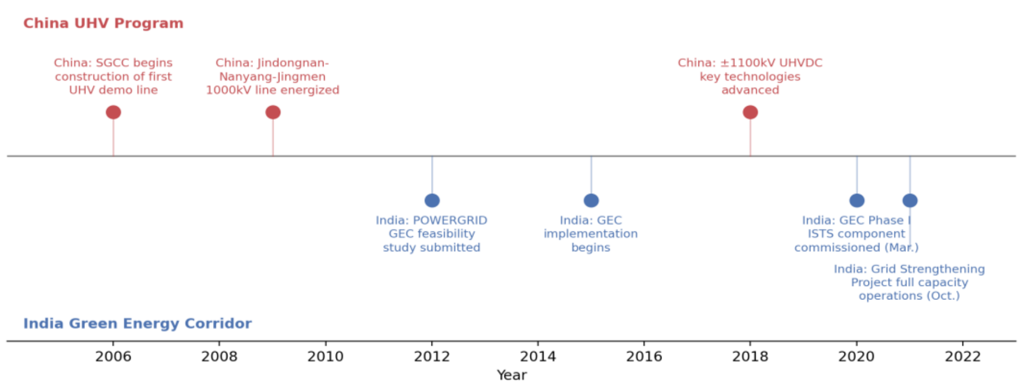

Figure 1. Timeline of Key Milestones, China UHV Program and India Green Energy Corridor. Source: compiled from Huang et al. (2009); Global Transmission Report (2009); Government of India, Ministry of Power (n.d.); Asian Development Bank (2021).

VI. CROSS-CASE ANALYSIS: LESSONS FOR GRID RELIABILITY

While the cases put forward in Sections 4 and 5 are quite different in terms of their motivation, geography and the public documentation on file, placing them side by side offers a number of instructive lessons for grid reliability as large-scale transmission modernization is undertaken. One such lesson is to be found in the merits of a phased approach to project sequencing that is driven by evidence. The UHV program in China, for instance, did not move straight from the drawing board to a nationwide rollout. It was preceded by the Nanyang–Jingmen 1000 kV line, a demonstration project whose purpose was to put the technical performance data on the table for any larger deployment to follow (Huang et al., 2009). India's Green Energy Corridor has a similar if less overtly technology-centric phasing: the ISTS component of Phase I was brought online in March 2020 before the Grid Strengthening Project was fully completed some 18 months later, with later corridor phases making use of the operational experience gained earlier (Government of India, Ministry of Power, n.d.). In either case, it seems prudent to sequence major transmission investments in such a way that early operational realities can mitigate risk in the design and execution of later ones, irrespective of the technology at hand.

Then there is the matter of distinguishing between technical and delivery risk. The literature on China's UHV transmission tends to frame it as an engineering problem; the reliability gains come from having successfully put in place higher-voltage, lower-loss corridors (Huang et al., 2009; Shu & Chen, 2018; Liu et al., 2018). The India case tells a different story. Documentation shows that what held up project delivery was not the transmission technology but the non-technical hurdle of right-of-way acquisition. This land-related risk put off the commissioning of some subcomponents but left the final cost and post-commissioning performance unscathed (Asian Development Bank, 2021). Taken together, the two cases indicate that one cannot assume good results on the technical front will translate to good results on the delivery front; both must be managed as separate concerns. The wider applicability of this point is borne out by other studies. An empirical review of 311 power transmission stakeholders by Pall et al. (2020) puts right-of-way issues and site accessibility at the top of the list for delay factors, no matter the country or technology. This lends weight to the finding in the India Green Energy Corridor case: it is not an isolated incident but part of a pattern well attested to in the project management literature. It would be wise for utilities and grid operators to view land acquisition and right-of-way management as a first-order risk in any future modernization effort, given that such problems are near-universal and not bound to a particular regulatory environment.

A third lesson pertains to how the mechanism of reliability aligns with the transmission objective. China's UHV program reduces reliance on local generation adequacy by making long-distance transfer between fixed centres more efficient (Shu & Chen, 2018). The Green Energy Corridor in India works to improve reliability in another way: by curbing the curtailment of variable renewables and boosting interregional capacity to handle that variability, as the Tamil Nadu example shows (Percis et al., 2020; Asian Development Bank, 2021). Both may be called improved grid reliability, but the former is dealing with a static geographic mismatch while the latter is responding to dynamic generation.

There is also the question of institutional capacity. China's State Grid Corporation of China has been able to implement its UHV program as a single, centrally run entity with direct say over generation-side coordination. India's approach required POWERGRID to coordinate with state-level transmission utilities and an outside financier in the form of the Asian Development Bank (Asian Development Bank, 2021; Government of India, Ministry of Power, n.d.). One can see how this might have made the right-of-way negotiations in the India case more arduous, since they involve state and local processes that are harder to wrangle in a multi-agency setup than within a vertically integrated utility. The sources at hand do not allow for a definitive test of this, but it is a plausible link between institutional structure and the delivery risk observed, and one worth further study.

Finally, the comparative evidence itself has its limitations. The China case is to be found in technical engineering papers while the India case is documented in development finance records; the asymmetry of the material available for each program constrains the cross-case analysis here, as will be discussed in Section 7.

VII. DISCUSSION

Section 6's comparative analysis has implications for the planning, evaluation and study of large-scale high-voltage transmission modernization that extend well beyond the particular findings for China and India. In terms of project planning practice, there is a clear lesson to be had. Both cases point to phased sequencing as a way to mitigate risk irrespective of the transmission technology at hand. It follows that utilities and grid operators with future modernization in their sights – be it UHV corridors, renewable integration or something else – would be wise to put their investments into demonstrable phases even if the technology in question is already proven in other quarters.

Then there is the matter of risk assessment. The distinction made in Section 6 between technical and delivery risk should prompt a more explicit separation of the two in any framework for large-scale projects; "project risk" ought not to be treated as an undifferentiated whole. A project can be soundly engineered from a technical perspective, as the literature on China's UHV lines indicates, yet still be subject to the kind of schedule risk from non-technical sources like land acquisition that was on display in the India case. At the same time, one should not mistake strong delivery-process management for technical rigor.

How grid reliability is measured and reported in the wake of such modernization is another consideration. In our examination of these cases, reliability gains were put on record by means of indirect proxies: in China through lower transmission losses and greater transfer capacity, in India via reduced curtailment of renewables. One will not find the direct, standardized metrics of utility reporting here, such as SAIDI or SAIFI. For the evidentiary basis of claims regarding the benefits of transmission modernization to be put on firmer ground, future research and project documentation would do well to make a more explicit link to those standardised metrics rather than relying on capacity-based figures alone.

These lessons are also of practical import to grid operators in developing economies contemplating similar investments. The examples in this paper come from large, populous nations with the wherewithal for state-directed investment, China via its State Grid Corporation and India with POWERGRID and multilateral co-financing. A smaller or less well-off economy may encounter the very same technical and delivery risks but have far less institutional capacity to make up for cost overruns or delays of the sort we have documented. For such operators the value of a modest demonstration phase to gain operational learning, as advocated in Section 6, may be all the more important before committing capital to an untested programme of full scale.

Finally, some caution is warranted in generalising from any one large-scale case to another. China's UHV and India's Green Energy Corridor were driven by different reliability imperatives – long-distance transfer between fixed points versus the vagaries of variable renewables – so practitioners should ensure the problems being addressed are structurally alike before drawing parallels. There are limitations to what this analysis can claim. For one, the public sources for the two cases are of a different character: largely technical engineering papers for China and project-level development finance records for India, which may colour the apparent differences between them. Moreover, while these are among the most thoroughly documented programmes in the world, a comparison of only two cannot tell us how widely the lessons apply. Nor can we yet judge the long-term reliability outcomes of the investments in question, given both are still expanding. And although Pall et al. (2020) give confidence that the right-of-way lesson is not unique to India, the international nature of their respondent base does not necessarily represent every geographic context evenly. We have not independently verified the proportion of South or East Asian projects in their work, so the right-of-way finding should be taken as broadly, if not uniformly, generalisable to the national contexts at hand.

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VIII. CONCLUSION

In the way of comparative case studies on what large-scale infrastructure can teach us about grid reliability, this paper has put under the microscope two of the most sizeable and well-documented high-voltage transmission modernization efforts in the world: China's ultra-high-voltage program and the Green Energy Corridor in India. Our analysis shows an apparent risk-mitigation strategy in the form of phased project sequencing at work in both. Yet the public record tells a different story for each when it comes to the lessons on offer. The UHV program in China is put forward in technical engineering literature as an example of how incremental validation of technology can yield the kind of reliability one would want from long-distance, low-loss power transfer; at the same time it makes clear that even a successful demonstration line is no assurance of full capacity utilization without the right sort of coordination on the generation side. For its part, the Indian initiative is documented more by way of development finance records at the project level. Here one sees the reliability to be had from dedicated renewable-integration capacity, but also the considerable non-technical delivery risk inherent in right-of-way acquisition, a point that a wider empirical study of transmission delays would confirm.

Taken together, these cases point to the conclusion that the reliability of a modernized grid hinges on the combined management of technical and delivery risk. It would be unwise to take a lesson from one modernization program and apply it to another without first ascertaining if the structural nature of the reliability problem is the same. Looking at the matter more broadly, there is room for a more systematic approach to documenting project delivery outcomes in tandem with the voluminous technical writing on transmission technology. One might look to the model set by Pall et al. (2020) and their focus on delay factors. Their work indicates that right-of-way issues are a primary cause of hold-ups in power transmission projects the world over, irrespective of the specific instance at hand. That is a finding worth heeding for any future research intent on generalizing what we know about grid reliability beyond the confines of a single national programme.

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