



TECHNICAL REPORT

UNDERSTANDING THE COST OF TRANSMISSION INFRASTRUCTURE

Insights from World Bank Group-Financed
Transmission Projects



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The Energy Sector Management Assistance Program (ESMAP) is a partnership between the World Bank and over 20 partners to help low- and middle-income countries reduce poverty and boost growth through sustainable energy solutions. ESMAP's analytical and advisory services are fully integrated within the World Bank's country financing and policy dialogue in the energy sector. Through the World Bank Group (WBG), ESMAP works to accelerate the energy transition required to achieve Sustainable Development Goal 7 (SDG7) to ensure access to affordable, reliable, sustainable, and modern energy for all. It helps to shape WBG strategies and programs to achieve the WBG Climate Change Action Plan targets. Learn more at: <https://esmap.org>

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Abbreviations

AC	Alternating Current
ACCC	Aluminum Conductor Composite Core
ACER	Agency For the Cooperation of Energy Regulators
ACSR/TW	Aluminum Conductor Steel Reinforced / Trapezoidal Wire
CAPEX	Capital Expenditure
CBA	Cost-Benefit Analysis
COP21	21 st Conference of the Parties (UNFCCC)
COP28	28 th Conference of the Parties (UNFCCC)
DC	Direct Current
DS&I	Design, Supply, and Installation
EHV	Extra High Voltage
EMDE	Emerging Markets and Developing Economies
ESMAP	Energy Sector Management Assistance Program
FIRR	Financial Internal Rate of Return
FNPV	Financial Net Present Value
GHG	Greenhouse Gas
GWh	Gigawatt-Hour
HFO	Heavy Fuel Oil
HTLS	High-Temperature Low-Sag
HVAC/DC	High-Voltage Alternating Current / Direct Current
ICR	Implementation Completion and Results Report
IEA	International Energy Agency
IFIs	International Financial Institutions
IPP	Independent Power Producer
IRENA	International Renewable Energy Agency
kV	Kilovolt
kWh	Kilowatt-Hour
LCOE	Levelized Cost of Energy
LCOT	Levelized Cost of Transmission
MISO	Midcontinent Independent System Operator
MW	Megawatt
NCEP	National Council on Electricity Policy
NPV	Net Present Value
NZE	Net-Zero Emissions
O&M	Operation And Maintenance
OHGW	Overhead Ground Wire

OPEX	Operating Expenditure
OPGW	Optical Ground Wire
PAD	Project Appraisal Document
PPA	Power Purchase Agreement
PPP	Public–Private Partnership
PPP	Purchasing Power Parity
RETI	Renewable Energy Transmission Initiative
ROW	Right-of-Way
SCADA	Supervisory Control and Data Acquisition (Software)
TSO	Transmission System Operator
UF	Utilization Factor
UNFCCC	United Nations Framework Convention on Climate Change
WACC	Weighted Average Cost of Capital
WECC	Western Electricity Coordinating Council

All currency is in United States dollars (US\$) unless otherwise indicated.

Key Findings

Study Context

This technical report **provides a one-of-a-kind dataset and analysis of transmission infrastructure costs in developing economies**, highlighting its role in increasing energy access, enabling energy markets, and facilitating the energy transition. By creating and drawing on a newly created **Transmission Cost Database** from 74 World Bank Group-financed projects (2000–2024) totaling US\$ 21 billion, the analysis fills a critical gap in providing transparent, systematic cost data, that can guide economic analysis of transmission investments, power systems planning, and climate finance analytics to inform new grid investments to advance energy access and energy system decarbonization.

Global electricity demand is expected to double by 2050, requiring substantial investments in renewable generation and associated transmission grids.

Transmission grids are essential not only for improving reliability, reducing congestion, and enabling cross-border trade but also for energy security and for integrating variable renewable energy resources.

Transmission Cost and the Impact on Project Economics

As the expansion of future transmission grids will be financed through a variety of sources from IFIs to climate finance and private sector participation, it is important to ensure that public data on transmission cost is available. Yet timely, reliable, and harmonized transmission cost data for developing countries has historically been scarcely available.

This report leverages the Transmission Cost Database to address that gap to provide structured, comparable insights that enable transparent benchmarking and cross-project comparison to facilitate more accurate cost planning. By improving understanding of CAPEX, O&M, and project variability, the data is intended to help guide investment prioritization, optimize project design, and strengthen decision-making for efficient, reliable transmission infrastructure investments.

Analysis of the data shows that transmission capital costs vary widely by region, voltage, and project design. **Measured in US\$ million per kilometer, World Bank Group-financed projects in developing markets exhibit a slight downward trend over time.** Further, WB-financed transmission projects fall below benchmark data gathered in developed markets, with unit costs ranging from 1.56 to 4.35 times lower. Cost variability however remains high, with minimum-to-maximum ratios of 2 to 3, emphasizing the

importance of using cost ranges rather than single averages when planning and budgeting for new transmission investments.

By utilizing the Transmission Cost Database, the technical report further provides a **Levelized Cost of Transmission (LCOT)** framework that complements traditional US\$/per-kilometer metrics with expressing transmission costs in **US\$ per kWh transported**, integrating CAPEX, OPEX, discount rates, and energy flows over the project lifetime. The LCOT establishes the cost of the preferred technical transmission solution through option screening and cost input preparation, which can feed directly into a broader cost-benefit analysis (CBA), thereby avoiding systematic over- or under-costing at the project preparation stage. Running both in parallel, with LCOT sensitivity analyses feeding directly into CBA cost inputs, represents a good practice for credible transmission project planning.

In this report, the LCOT has been applied to the Transmission Cost Database and tested with case studies, providing a benchmark reference. Together, they offer stakeholders a practical tool for analyzing transmission cost, assessing investment efficiency, and informing economic analysis of project planning.

Recommendations for Future Investment and Planning

Transparent, reliable, and standardized transmission cost data is critical for guiding investment decisions. By introducing the LCOT framework and the Transmission Cost Database, this report provides a foundation for evidence-based planning, cost benchmarking, and informed transmission investment decisions.

To further inform future grid investments, **the Transmission Cost Database could be used as a model for expanded data collection beyond WB-financed projects** to other financial institutions or grid types, thereby strengthening the coverage of the database and enhancing its comparability, transparency, and analytical depth. Applied alongside the database, the LCOT provides a practical framework for initiating broader cost-benefit analysis by integrating CAPEX, OPEX, discount rates, and energy flows. These tools are intended to help improve investment planning, assess cost efficiency more accurately, and guide informed decision-making for transmission infrastructure development.

Analysis also shows that **cost-reduction opportunities** can be found beyond individual line design, through optimized system integration, procurement strategies, and effective operational practices, which has allowed some projects to close below initial cost estimates even in complex conditions. Further, with **rapidly evolving generative AI tools** there will be opportunities to leverage the Transmission Cost Database for rapidly developed analytics and increasingly complex use cases to support cost optimization and evidence-based investment decisions.

Executive Summary

Access to affordable, reliable, and sustainable electricity is central to economic development and global energy transition. Following the adoption of the Paris Agreement, countries have pledged to significantly reduce greenhouse gas emissions and transition toward low-carbon energy systems. As the energy sector accounts for roughly three-quarters of global emissions, decarbonization requires a rapid expansion of renewable energy and accelerated electrification of end uses.

Transmission systems play a pivotal role in enabling this transition. They enhance grid reliability, facilitate large-scale integration of renewable energy, support cross-border power trade, and reduce overall power system costs through coordinated planning and expansion. Robust transmission networks can allow countries to capture economies of scale and manage variability in renewable generation to improve energy security. Conversely, underinvestment in transmission infrastructure may lead to congestion, reliability challenges, and higher system losses.

Despite their strategic importance, transmission investments remain insufficient globally, particularly in developing economies. Moreover, reliable and transparent cost data are limited, and cost benchmarks are fragmented. While generation costs are widely tracked, transmission cost developments—across capital expenditure (CAPEX), operational expenditure (OPEX), discount rates, and implementation timelines—are less systematically documented. Strengthening this understanding can yield critical knowledge for decision-makers to generate informed assessments for transmission project investment.

This technical report and database seek to provide specialists engaged in transmission investment, energy transition, and power systems planning. This report addresses the data gap by compiling and analyzing a transmission cost database based on 74 World Bank Group-financed projects between 2000 and 2024. It examines and compares cost expressed in US\$ per kilometer across regions and at time while also assessing O&M expense levels and applied discount rates. The findings indicate that most projects achieve competitive expenditure under diverse implementation conditions. However, analysis also documents that conventional cost metrics expressed in US\$ per kilometer do not fully capture the economic value, system benefits, or technical complexity of transmission investments.

To provide a more comprehensive assessment framework, the report introduces the Levelized Cost of Transmission (LCOT). By expressing transmission costs in US\$ per kWh transported, LCOT integrates CAPEX, OPEX, discount rates, and energy flows into a single metric. This approach enables more robust cost-benefit analysis and provides consistent benchmarks for investment decisions, and an input to comprehensive cost-benefit analyses. Beyond financial evaluation, the LCOT framework helps assess technical optimization strategies and financing structures to enhance system performance.

Strengthening transmission systems and improving cost transparency are critical to achieving global net-zero pathways. Data-driven investment frameworks such as LCOT can support better decision-making, mobilize financing, and ensure that transmission infrastructure effectively underpins the expansion of renewable energy and the electrification of the global economy.





ONE INTRODUCTION

In 2015, the international community agreed to a coordinated solution to address climate change and its negative impacts. World leaders ratified the historic “Paris Agreement” at the United Nations Climate Change Conference (COP21), setting the path towards global greenhouse gas (GHG) emissions reduction to keep global temperature below 2°C above pre-industrial levels and pursue efforts to limit it to 1.5°C above pre-industrial levels. This implies a reduction in emissions by 45% by 2030 and the attainment of net-zero emissions by 2050.

The energy sector is the source of about 75% of GHG emissions today. By replacing polluting coal, gas, and oil-fired power with energy from renewable sources, carbon emissions could be dramatically reduced. Electrification of end-uses will accelerate and therefore the global electricity demand is expected to double by 2050, driven by the industry and transport sectors. To remain sustainable, the increased electricity demand should primarily be met by renewable sources. This scenario will require the tripling of renewables and doubling in energy efficiency targeted by COP28 (IEA 2021). Further, transmission infrastructure must evolve to support growing electricity demand while integrating an increasing share of renewable energy generation.

Transmission grids have a critical role in enabling the energy transition. They facilitate the transport of large power flows across regions and connect geographically dispersed renewable resources to demand centers. Expanded transmission capacity enhances system reliability, reduces congestion, and facilitates the integration of variable renewable energy, reducing overall system cost by enabling access to least-cost generation, reducing curtailment, and fostering cross-border market integration. Transmission grids are enablers of regional integration, both for power trade and export, benefiting consumers and economies while enhancing energy security. Adequate transmission infrastructure can play a significant role in enabling private capital for electricity generation through independent power producers (IPPs). Increased transmission capacity also boosts renewable energy penetration while limiting backup capacity needs. Interconnections across regions increase security of supply through the aggregation of power systems to meet the demand (IRENA 2022). Overall power system costs can also be reduced through the coordination of transmission expansion plans, optimized investments in generation capacity, and reserve requirements. For example, the pan-Arab electricity market would significantly decrease the total capacity needed and decrease total power system costs by 8 to 13% (World Bank 2021). In addition, stronger transmission networks enhance the stability and reliability of regional power markets through improved cooperation between operators (e.g., emergency supply, scheduled outages, and spinning reserves).

Financing transmission grids should therefore take a central part of the global efforts to facilitate the energy transition and expand energy access. The International Energy Agency (IEA) estimates that achieving 2030 Net Zero targets will require global grid investment to nearly double to US\$ 600 billion per year, with emerging markets and developing economies (EMDEs) needing about US\$ 220 billion annually—almost triple current levels (IEA 2023). Large investments will therefore be required to close the investment gap in transmission infrastructure.

Underinvestment in transmission infrastructure may lead to system congestion, curtailment, reduced asset utilization, lower capture prices, negative pricing in energy markets, and compromised system reliability. For example, network losses averaged 15% across Africa in 2020, almost twice the global average due to aging infrastructure and inefficient grid management (IEA 2022). Other factors, such as regulatory uncertainty, economic constraints, and a shortage of skilled staff, also inhibit investments in transmission grids. Underinvestment in transmission infrastructure can delay the energy transition if new renewable energy assets cannot effectively deliver low-carbon electricity to users.

Reliable and accessible data on transmission costs can help inform investment decisions on transmission infrastructure and power systems planning. However, whereas cost data on renewable energy generation are widely covered and reported, trends in transmission cost are less extensively documented. Analysis of capital expenditure (CAPEX) and operational expenditure (OPEX) has thus far been partially monitored, and the publicly available information remains fragmented and limited.

This report aims to address some key questions to support the global discussions on energy transmission costs in the developing economies:

- What analytical findings can be drawn from the cost data of World Bank Group transmission projects, and how can these complement global benchmarks that are already available?
- How can transmission cost data from World Bank Group projects inform decision making and planning of new transmission infrastructure?

The value of this technical report lies in the novelty of data sources supporting the analysis. It relies on a new dataset compiled through a curated Transmission Cost Database (the Database) based on 74 transmission projects financed by the World Bank Group during the period from 2000 to 2024. The Database contributes to improving global knowledge and transparency on cost data, particularly in developing countries. These 74 projects were data-mined from 469 World Bank Group energy projects and represent the most complete and relevant data available, with a total investment of US\$ 21 billion and over US\$ 13 billion in World Bank Group lending.

On this basis, this report first introduces trends and indicators on the cost of transmission infrastructure from the Database, illustrating CAPEX, O&M rate variations, discount rates, and providing temporal and geographical comparisons.

The analysis shows that World Bank Group projects consistently achieve competitive unit costs (in US\$ million of investment per km)—typically 1.56 to 4.35 times below analyzed benchmarks. In the data sample, higher unit costs are seen in Eastern and Southern Africa and lower ones in Western and Central Africa. Operation and maintenance expenses generally range from 2 to 3% of capital costs—below literature averages—and discount rates cluster between 6 to 12%, consistent with the recourse to concessional financing. Nearly 70% of projects faced delays, mainly due to procurement or land issues, yet around

half still closed below their initial cost estimates. These findings highlight that World Bank Group projects effectively manage costs through competitive bidding and sound procurement, even under challenging implementation conditions.

From this analysis, it is noted that the conventional unit cost indicator, expressed in US\$ per kilometer, does not adequately capture the complexity of transmission projects or the interdependency between CAPEX, OPEX, discount rate, and energy transported. This report therefore introduces the Levelized Cost of Transmission (LCOT), an indicator that allows decision-makers to perform cost-benefit analyses for transmission projects.

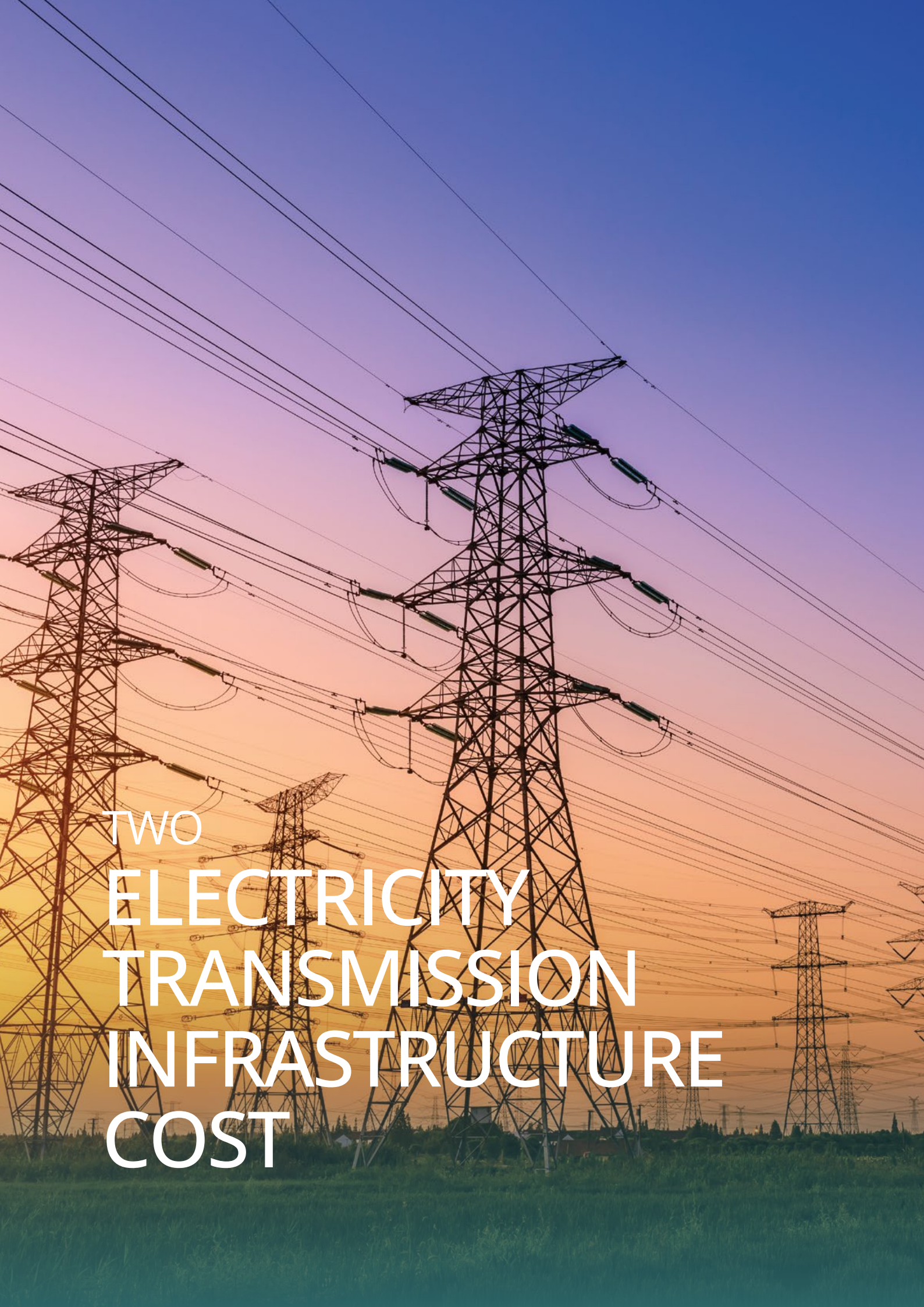
The LCOT is a metric of cost efficiency, which provides a standardized cost-per-unit measure considering a complete picture of the investment within its regulatory environment. Transitioning from US\$ per km to US\$ per kWh aims to address the paradigm of transmission cost investments, which require large upfront capital costs, carry a small portion of cost to the electricity service, while bringing large benefits to the management of power systems in support of the energy transition. While the LCOT may not capture all aspects of system operation—such as peak load requirements or occasional congestion, the framework provides a benchmark for governments, transmission system operators (TSOs), and World Bank Group task teams when assessing transmission investment efficiency and guiding planning and investment decisions.

The report then applied the LCOT methodology to the sampled data to demonstrate how it can be used as a practical benchmark for transmission investments. In situations where official or regulated wheeling tariffs are missing, unreliable, or inconsistent, the LCOT methodology could offer a reference framework to facilitate dialogue with TSOs on potential wheeling charges for cross-border transmission networks.

The LCOT framework also offers reference values as a benchmark across World Bank Group's projects. This benchmark helps to detect deviations and provide confidence in new investments.

Beyond its analytical value, the LCOT methodology allows for investigating technical choices that optimize investments—such as the use of advanced conductors, compact designs, or modular construction—to be evaluated alongside financial strategies and O&M practices. By integrating the World Bank Group's expertise in cost reduction strategies with the LCOT framework, stakeholders can develop optimization strategies for future investments, ensuring efficient resource allocation and enhanced project viability.

The adoption of the LCOT framework in World Bank Group operations, however, relies on the availability of reliable and timely data on transmission cost that underpins the framework. This report and the accompanying database represent initial efforts toward a systematic monitoring of transmission cost within the World Bank Group. Maintaining an updated cost database for transmission assets can support informed decision-making and contribute to the global policy dialogue on achieving net-zero scenarios and the expansion of renewable energy sources. Such data-driven approaches are crucial for developing effective strategies to meet the increasing demand for sustainable energy solutions.



TWO
ELECTRICITY
TRANSMISSION
INFRASTRUCTURE
COST

2.1 STATE OF KNOWLEDGE: LITERATURE REVIEW

Transmission infrastructure cost data is relatively widely available in developed economies while significantly more limited in emerging markets. Existing analyses are helpful for identifying baselines for benchmarking transmission infrastructure costs and bringing valuable insights. Yet they present limited data samples that cannot be generalized to a broader level.

Some studies provide benchmark data on transmission infrastructure costs. Table 2.1 below summarizes available data from the literature: NCEP (2004); Wiser and Bolinger (2010); RETI (2010); Pletka (2014); Saadi *et al.* (2018); ACER (2023), introduced hereafter:

- NCEP (2004) is one of the few early reports that looked into transmission costs. It provides cost data based on a 10-year transmission assessment done by the American Transmission Company, using data collected from 1993 to 2003. The sample size is not detailed, and the report briefly discusses the cost impacting factors, including the terrain, the equipment, etc. It also mentions that higher transmission voltages (500 kV and 765 kV) were becoming more common in the United States.
- Wiser and Bollinger (2010) address the debate on fair allocation of additional transmission costs to wind power projects in the United States. The study intends to increase transparency on the transmission costs associated with wind power development. It proposes methodologies to estimate corresponding incremental transmission costs. As a secondary objective, their contribution sought to improve the understanding of the range of transmission costs and to identify cost drivers. The authors reviewed 40 transmission studies completed over the period 2001-2008. They also recognize methodological challenges, including a lack of data homogeneity.
- The Renewable Energy Transmission Initiative (RETI) focused on developing an expanded power grid for the state of California (US) to facilitate the integration of large shares of variable renewable energy generation. Its study (RETI 2010) highlights the methodological challenges to collect transmission cost data from transmission owners, due to different cost structures and variations in the cost of capital. Cost estimates for the study were recalculated based on a standardized methodology. The study lists 104 projects of 500 kV lines scheduled to be operational between 2013 and 2020.
- Pletka (2014) developed a transmission line cost model in 2014, encompassing base capital costs and adjustment factors ranging from conductor types, tower designs, voltage classes, and other parameters. While the study itself does not include a detailed discussion of the methodology, the engineering firm Black & Veatch may have relied on internal data to compute the factors.

- Saadi *et al.* (2018) examines the costs for different energy transfer methods (including gas pipelines, hydrogen pipelines, electricity transmission, etc.). It provides a summary of transmission cost at different voltages but does not explicitly specify the specific sources of data.
- ACER (2023) presents Unit Investment Cost indicators, to assist the European Network System Operators (ENTSO) in carrying out a cost-benefit analysis for the European Ten-Year Network Development Plan. For overhead lines, the study collected data for 99 investments performed across Europe during 2012-2022. The collected data is unevenly distributed into six subcategories based on voltage ranging from 110 to 400 kV. The study does not disaggregate cost items but concludes on the major impact of the voltage level on investment cost of the transmission line project.

From these studies, transmission cost estimates display considerable variation (Figure 2.1). In the example of the 345 kV double circuit category (Table 2.1), United States sources range from (in US\$ million per km) 0.997 (Wiser and Bolinger 2010), to 1.192 (Pletka 2014), 1.335 (NCEP 2003), and a maximum of 1.952 (Saadi 2018). The data illustrates that unit costs tend to increase with higher line voltage as well as circuit numbers.

In this representation, time variations and location influence are not captured. The large value spreads illustrate the variability of unit cost values available through the literature, due to limited data samples and the project specifics' influence on cost components.

FIGURE 2.1 Transmission Line Unit Cost Range from Assessed Studies

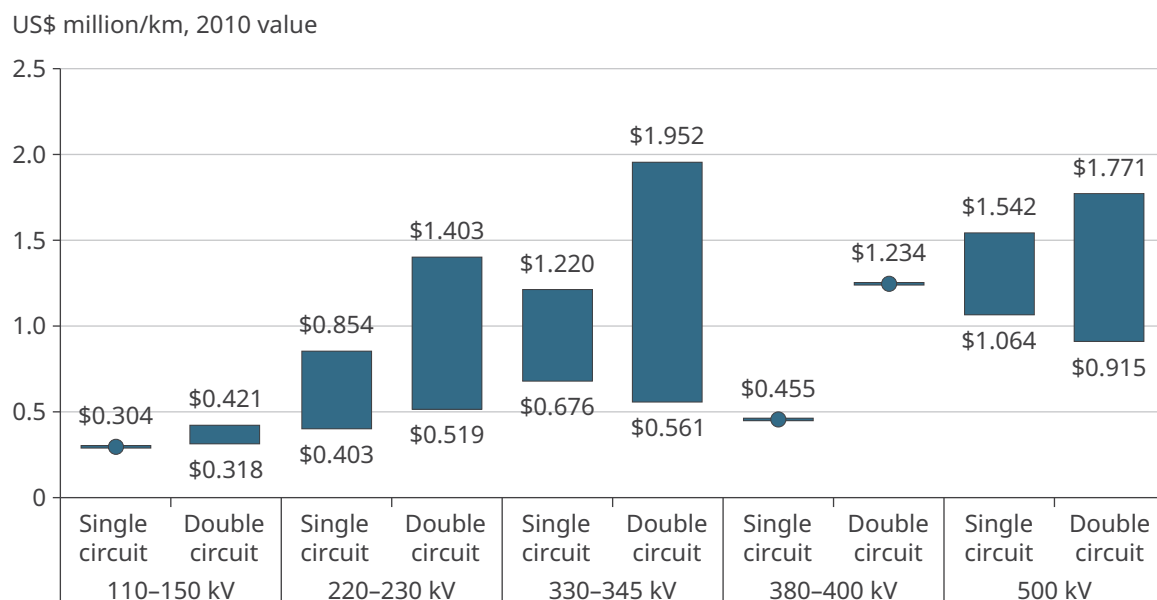


TABLE 2.1 Compiled Transmission Line Unit Cost from Studies

US\$ million/km, 2010 value

Author Region Sample Time Range	ACER Europe 2012-2022		Saadi, <i>et al.</i> US 2018		Pletka <i>et al.</i> US (baseline) 2014		RETI US (California) 2010		Wiser, R., and M. Bolinger US 2001-2008		US-NCEP US 2003	
Asset Range	Study-Specific Range	Unit Cost	Study-Specific Range	Unit Cost	Study-Specific Range	Unit Cost	Study-Specific Range	Unit Cost	Study-Specific Range	Unit Cost	Study-Specific Range	Unit Cost
110 - 150 kV Single Circuit											New 138 kV single	0.304
110 - 150 kV Double Circuit	110 - 150 kV 2 circuits	0.318									New 138 kV double	0.421
220 - 230 kV Single Circuit	220 - 225 kV 1 circuit	0.403	230 kV single	0.854	230 kV single	0.532						
220 - 230 kV Double Circuit	220 - 225 kV 2 circuits	0.519	230 kV double	1.403	230 kV double	0.852			230 kV (double circuit)	1.209		
330 - 345 kV Single Circuit			345 kV single	1.220	345 kV single	0.745			345 kV (single circuit)	0.634	New 345 kV single	0.714
330 - 345 kV Double Circuit	330 kV 2 circuits	0.561	345 kV double	1.952	345 kV double	1.192			345 kV (double circuit)	0.997	New 345 kV double	1.335
380 - 400 kV Single Circuit	380 - 400 kV 1 circuit	0.455										
380 - 400 kV Double Circuit	380 - 400 kV 2 circuits	1.234	400 kV double	4.413								
500 kV Single Circuit			500 kV single	1.159	500 kV single	1.064	500 kV single	1.542	500 kV (single circuit)	1.118		
500 kV Double Circuit			500 kV double	0.915	500 kV double	1.703			500 kV (double circuit)	1.662		
Other					500 kV (VDC B)-POLE	0.852			765 kV (no description)	1.572		
					600 kV (VDC B)-POLE	0.894						

2.2 COST BREAKDOWNS

Another major theme in the literature relates to the breakdown of transmission infrastructure costs under capital costs¹ and operation and maintenance (O&M) costs.²

Capital Costs

In the literature, capital costs are disaggregated by cost categories, including material costs, e.g., towers, supports, foundations, conductors, overhead ground wires (OHGW) or optical ground wires (OPGW), insulators, and line hardware; installation costs of erecting transmission towers, hauling conductor reels, and installing and securing conductors to transmission structures; and land costs of easements, rights-of-way (ROW), land acquisition and clearance, regulatory and permitting fees, as well as other incidental expenditures mandated by state regulations.

One major challenge for monitoring their evolution over time seems to be the lack of standard cost categories. Literature shows disparities in the definitions of such categories, which can lead to significant differences in their evaluation. As a result, the outcomes are hardly comparable, although materials and labor costs appear to be consistently higher compared to other costs.

For example, Table 2.2 illustrates cost breakdowns for major publications. The share of various cost components varies widely, with materials representing the largest share in each study, ranging from 25% (Brinkerhoff 2012) to 59% (DeSantis 2021) of total costs. However, the cost category in other studies may also include labor (Fichtner 2016) or foundations (Brinkerhoff 2012), which makes comparisons and trends uncertain. Due to the overlaps in materials and labor categories, the share of labor costs is difficult to ascertain, with values ranging from a low 11% (DeSantis 2021) to 41% (Saadi *et al.* 2018). This example shows a shortcoming in the current literature, lacking standardized cost components necessary for comparisons, trend analysis, and projections.

1 The capital cost refers to the fixed, one-time expenses, for example acquiring land, constructing, and procuring equipment necessary to produce goods or the provision of services. In other words, it is the total cost needed to bring a project to a commercially operable status.

2 The O&M cost is associated with maintaining and operating transmission infrastructure systems and equipment.

TABLE 2.2 Compiled Transmission Line Cost Breakdown from Studies

Author Region Publish Time	DeSantis (HVDC 500 kV) US 2021		Saadi. <i>et al.</i> US 2018			Fichtner World 2016		Brinkerhoff UK 2012			
Breakdown	Category	Percentage	Category	Subcategory	Percentage	Category	Percentage	Category	Subcategory	Percentage	
Cost Components	Materials	59%	Materials	Structures	60%	Labor and other materials (like concrete for foundations)	43%	Materials	Foundations total	2%	25% (add up)
				Conductors	30%						
				Other	10%						
	Labor	11%	Labor		41%	Steel material	23%		Tower materials:	10%	
	ROW	4%	ROW		10%	Aluminum material	24%		Conductors + OPGW materials:	8%	
	Misc. costs	N/A	Engineering		5%	Other manufactured equipment	10%		Insulators + fittings materials	4%	
	Substation costs	26%	Siting		3%	<i>Base cost formula:</i> $BC_{py} = BC_{ref} * (a * GIR + b * SPR + c * APR + d * MUV)$		Labor	Erection of towers + stringing	28%	
								Other	Engineering & safety	15%	
									Project launch + mgmt.	9%	
									Build contingency	9%	
							Access roads total		15%		

Note: The data from the Saadi. *et al.* (2018) study is based on the information sheet from the American Electric Power (AEP), a United States utility company. This table does not duplicate the two datasets. The subcategory percentage of the Saadi study refers to the specific share (i.e., within the material category, structures take up 60%, conductors 30%, and other 10%). The percentages of the subcategory mentioned in the Brinkerhoff study measure the share in terms of the total expenditure. The subcategories for materials add up to 25%.

Operation and Maintenance Costs

Due to their long-term nature, O&M costs play a critical role in the total lifetime cost of transmission infrastructures and are an important consideration in investment decisions.

Yet, O&M costs are scarcely documented. Previous studies have pointed out the difficulty of obtaining consistent figures. Some reports estimate average annual United States transmission O&M costs from 5 to 10% of a project's original capital cost (Larsen 2016). Future O&M cost projections are also uncertain, as rising climate-related risks may increase maintenance requirements and operational expenses.

Improving estimates of O&M costs should ensure that infrastructure projects can be compared in a consistent framework, for example between newly constructed lines versus older infrastructures. This aspect is critical, for example, in Africa, which hosts several vintage grids. For instance, in Niger, 96% of grid infrastructures is more than 30 years old; in Zimbabwe, 85%; in Zambia, 80%; and in the Democratic Republic of Congo, 61% (Rosnes 2012). Where O&M costs are underestimated, utilities with poor capacity and limited financial resources may see their grid infrastructure rapidly deteriorating due to inadequate maintenance and inefficient operation.

2.3 TYPICAL COST DRIVERS AND THEIR VARIABILITY

In the context of transmission line cost estimation, cost drivers refer to the key variables or factors that directly influence the total cost of constructing and operating the infrastructure. In summary, a cost driver is any underlying variable or activity that causes cost variation. A good understanding of the underlying cost drivers is therefore important for supporting investment decisions, since cost estimates may vary significantly depending on technical and execution factors.

The definition of cost drivers has been approached through various studies. Gorman (2019) indicates costs vary across projects, locations, and decision factors. These variations can be attributed to regional factors, the time of the study, the level of data considered, as well as reporting and classifications. Similarly, Pletka (2014) has devised a formula comprising a base cost with additional factors³. This report also accounts for inflationary changes and offers specific insights tailored to projects executed between 2012 and 2014. In its report, MISO (2022) presents specific factors into the cost calculation, with detailed information on land acquisition expenses.

³ A cost model for an electrical transmission line was developed by the Black & Veatch Corporation for use by the Western Electric Coordinating Council (Pletka, 2014). This cost model details calculations for transmission line capital costs, right-of-way costs, and allowance for funds used during construction (AFUDC) costs. The cost model itself allows for the selection of various conductor types, tower designs, voltage classes, and other parameters.

Although there is no one-size-fits-all approach, the need to adjust cost estimates based on local conditions learned from past experiences is also noted by Fichtner (2016). Its findings rely on data comparison from existing overhead line projects sourced from Fichtner, utilities in developing countries, and the World Bank Group. This study delivered a cost estimation tool for high-voltage overhead alternating current (AC) transmission lines above 66 kV. The tool was built on a sample of 68 projects, of which 78% are based in Africa. The report identifies and proposes a formula with four primary cost categories: base cost plus three types of developed costs, i.e., line configuration, line location (geographic features), and project location (country), each with a few sub-categories. The report states that the cost comparisons of many projects would not provide usable estimates without accounting for project specifics.

Based on Fichtner (2016), Pletka (2014) and MISO (2022), the section below intends to build a consolidated review of the cost driver categories and specifics encountered in the literature. Following the above-described framework from Fichtner (2016), cost drivers would be clustered under four categories: Base Cost; Line configuration; Line location; Project location.

Base Cost

- **Circuit capacity and quantity:** Higher circuit capacity typically results in higher costs per km (Brinckerhoff 2012), while the Fichtner (2016) notes that a single circuit line will be about 33% cheaper than a similar double circuit line due to the reduced quantity of conductors and insulators and lighter structures.
- **HVAC vs. HVDC:** De Santis (2021) notes that the cost parity between HVAC and HVDC lines occurs at approximately 483 km on a cost per km per MW basis. Below this threshold, HVAC lines are more cost-effective as they do not require HVDC transformer substations. However, for distances exceeding 483 km, HVDC lines would be an economical choice due to lower power losses.
- **Line length:** In general, costs per kilometer tend to decrease with longer lengths. From a base cost determined for a 25-50 km line, a 50% premium could apply to a shorter line (less than 5 km) and a 10% discount could apply for lines over 100 km.

Line Configuration

- **Line support:** The primary requirements for line support are cost-effectiveness, low maintenance, and durability, with materials ranging from wood, concrete, steel, to aluminum. Cost variations can be significant, for example, compared to vertical steel lattice, a concrete portal can decrease costs by 20%, while a steel monopole could incur a premium of 45%.

- **Conductors:** Conductors usually require 20 to 30% of the total material cost of a transmission line construction. The choice of conductor depends on factors such as the specific application, environmental conditions, and required capacity. The cost can vary from 4 to 8% depending on the conductor category. The choice of conductor significantly impacts transmission design by enabling longer spans, higher current capacity, and potentially fewer towers, especially with High-Temperature Low-Sag (HTLS) conductors such as Aluminum Conductor Steel Reinforced / Trapezoidal Wire (ACSR/TW) or Aluminum Conductor Composite Core (ACCC)⁴.
- **Land costs:** Direct land costs encompass right-of-way (ROW) and acquisition expenses, constituting significant components of construction outlays. These costs vary depending on regulatory, economic, and environmental factors. Land costs vary with altitude (+12% over 2,500 m); access (+10% for difficult access); terrain configuration (+15% in mountainous areas and up to 78% in high slopes); and land cover, with large premiums for forested, suburban and urban areas.

Line Location

- **Physical constraints** will significantly influence the line costs. The “straightness” of a line can impact its costs by 14%; foundations on soft soil can involve a premium of 7%, foundations can represent up to 18% of project costs and piled foundations can generate a 35% premium, while environmental conditions will condition insulation. In polluted environments, i.e., sand, dust, industrial pollution, the required specific insulation creepage will be higher.

Additional line location parameters which can influence costs are Terrain configuration; Altitude; Access; Large crossings; Vegetation type (clearing). These elements can typically be analyzed using geographic information systems combined with earth observation data.

Project Location

This cost driver category would relate to the economic and political context of the project. Typical dimensions are listed below:

- **Permitting:** Resettlement, regulatory, and permitting costs fluctuate based on government regulations and valuations. Project resettlement plans and environmental assessments reveal that many cost estimates are in local currencies. The permitting process can be time-consuming, add complexity to routing, and impact the ability to service rural or hard-to-reach areas (Martinez 2020). Permitting can also be the source of delays in project implementation.

⁴ While more expensive, HTLS can significantly increase transmission capacity. A study of these cost-benefit effects is however not within the scope of this report.

- **Cost of financing:** The cost of financing may significantly impact infrastructure investments related to building, maintaining, and upgrading the necessary equipment and infrastructure for electricity transmission and distribution. These factors vary greatly across countries. In developing countries, such costs tend to be high, often attributed to political risks, operational inefficiencies, expensive power generation, and low creditworthiness of utilities (World Bank 2017). These factors collectively contribute to an increased perception of risk and heightened financing expenditures.
- **Difficulty of Doing Business:** Assesses how regulatory frameworks, administrative procedures, and compliance burdens affect firms when starting and operating businesses. Covers areas like licensing, paying taxes, contract enforcement, and trade procedures⁵.
- **Logistics and Infrastructure Performance⁶:** Evaluates the efficiency of supply chains through indicators on customs, infrastructure, shipment quality, tracking, and timeliness. Helps measure how well a country enables the movement of goods domestically and across borders.
- **Governance, Stability, and Corruption⁷:** Measures the quality of institutions through six dimensions: political stability, government effectiveness, regulatory quality, rule of law, and control of corruption. Used to assess risks linked to safety, governance, and bureaucratic efficiency.

5 <https://www.worldbank.org/en/businessready>

6 <https://lpi.worldbank.org>

7 <https://www.worldbank.org/en/publication/worldwide-governance-indicators>

THREE
DATA COLLECTION
AND ANALYSIS

The previous chapter documents the current knowledge gap and limitations in availability of global standardized reference transmission cost data. To address this issue, a comprehensive assessment of the complete World Bank Group project repository was conducted and a structured database to store and analyze transmission cost data in a standardized manner was designed. In this chapter, the availability of transmission cost data from World Bank Group financed projects is documented and analyzed to demonstrate the database's potential in extracting cost components and revealing trends.

3.1 DATA COLLECTION

The World Bank Group's online project repository contains detailed information regarding each investment financed by the World Bank Group in past decades. Data mining was performed from the online repository to extract comparable information allowing analysis. The data points are stored in an Excel-based database ("the Database").

The database was collected from a total of 469 World Bank Group records tagged under the category of "energy transmission and distribution" during the period 2000-2024. From this category, a sub-section containing components related to the construction or rehabilitation of transmission lines/substations was collected. To obtain valid data suitable for this report, projects were filtered for containing the word "transmission" in the title, under the assumption that they are the most relevant ones. The first round of filtering identified 45 projects. To enlarge the sample size, 30 more projects were examined and added manually, based on their relatedness to transmission construction from keyword searches, including "interconnect," "electricity trade," "import/export," "expand," "grid," "power/electricity system." During the process, 201 projects were filtered out as they did not have information that could contribute to the database and study. The total number of projects included in the database and analysis is 74, which is deemed representative of the World Bank Group-executed projects.

The data analysis of the full sample (Table 3.1) reveals geographic differences in project distribution: Western & Central Africa hosts the highest share—120 out of 469 projects (25.6%)—followed by Eastern & Southern Africa, which accounts for 98 projects (20.9%). East Asia & Pacific (62 projects, 13.2%), Europe & Central Asia (59 projects, 12.6%), and South Asia (58 projects, 12.4%) each holds smaller shares. Latin America & Caribbean (39 projects, 8.3%) and Middle East & North Africa (31 projects, 6.6%) are less represented.

TABLE 3.1 Number of Projects Screened per Region

Region	Count	Share
East Asia and Pacific	62	13.2%
Eastern and Southern Africa	98	20.9%
Europe and Central Asia	59	12.6%
Latin America and Caribbean	39	8.3%
Middle East and North Africa	31	6.6%
South Asia	58	12.4%
Western and Central Africa	120	25.6%
Other	2	0.4%
Total	469	100%

3.2 DATABASE STRUCTURE

The sample of 74 projects was analyzed in detail. Disaggregate data was extracted from the project documentation package: Project Appraisal Document, Project Restructuring Paper, Implementation Completion and Results Report, Additional Financing Paper, project Environmental Assessment, and Resettlement Plan.

The available information was organized into the Database, which then formed the basis for further analyses. Table 3.2 provides a description of the Database structure, divided into project “Basic,” “Technical,” and “Cost” information. The cost information is further broken down into capital, O&M, community development, resettlement, or the applied discount rates in a consistent and comparable format. The technical and basic information enables qualitative analysis, based on technical elements (e.g., voltage, elevation) or contextual elements (geographical, project type, or financial dimensions).

The granularity of information available in the documentation does not fully align with all cost drivers discussed in the previous section. Table 3.2 documents essential project-level data—such as identifiers, timeline, financing, technical specs, and social cost component—while the Database structure (Table 3.2) references the deeper technical, geographic, and institutional cost drivers impacting transmission line development.

TABLE 3.2 Transmission Costs Database Structure

Project Basic Information	Technical Information	Cost Information
• Project ID/Name • Start/closing date • Region • Country • Location • Project type (construction or upgrade) • Project description • Restructuring/closing information • Project type (new construction vs. upgrade) • Routing (Existing vs new) • Implementation Delays (Y/N)	• Ownership • Route length • Voltage • Elevation • Number of transmission towers • Number of substations • Conductor type • Conductor Materials • Estimated transmission loss	• Total project cost, WB Financing, and Cost by component • Capital cost for transmission component • Discount rate applied • Operation & Maintenance (O&M) rate • Community development cost • Resettlement cost

3.3 DESCRIPTION OF THE DATA POINTS

Table 3.3 displays the number and proportion of projects analyzed through the database. These projects were selected based on the detailed cost information provided by the project documents.

Consistent with the full data sample, the subset of 74 selected projects presents substantial regional disparities. Eastern & Southern Africa accounts for the largest share with 21 projects (28.4%), followed by Western & Central Africa with 16 projects (21.6%), Europe & Central Asia also with 16 projects (21.6%), South Asia with 11 projects (14.9%), and East Asia & Pacific with 7 projects (9.5%). Middle East & North Africa is comparatively underrepresented, with just 2 projects (2.7%), and Latin America & the Caribbean even more so, at 1 project (1.4%).

TABLE 3.3 Data Sample's Geographic Distribution

Region	Count	Share
East Asia and Pacific	7	9.5%
Eastern and Southern Africa	21	28.4%
Europe and Central Asia	16	21.6%
Latin America and Caribbean	1	1.4%
Middle East and North Africa	2	2.7%
South Asia	11	14.9%
Western and Central Africa	16	21.6%
Total	74	100%

Disparities in the scale of projects can be noted as well. The 220 to 230 kV range is the most frequent category: out of 24 projects in this capacity bracket, 13 are in Western Africa. In contrast, larger interconnection initiatives requiring 400 kV and above are more prevalent in the Eastern and Southern Africa region, consistent with the reinforcement of the East Africa and Southern Africa Power Pools. Beyond Sub-Saharan Africa, Europe and Central Asia as well as South Asia are also well represented in the sample, featuring a diverse spectrum of projects spanning from 220 kV up to 500 kV.

The collected dataset contains a total of 15 interconnection projects across countries (Table 3.4). Five of them are in Eastern and Southern Africa, two in South Asia, and eight in Western and Central Africa. Interconnection projects contribute to the mutualization of infrastructures and the organization of regional electricity markets as power pools.⁸

⁸ For more information on power pools, please refer to: <https://blogs.worldbank.org/en/trade/power-pools-how-cross-border-trade-electricity-can-help-meet-development-goals#:~:text=A%20recent%20working%20paper%20published%20by%20the%20World,lessons%20for%20the%20promotion%20of%20future%20trade%20arrangements>.

TABLE 3.4 Interconnection Projects Identifiers, Localization, and Specifics

Project ID	Region	Country	Voltage (kV)
P084404	Eastern and Southern Africa	Mozambique; Malawi	220 kV - 230 kV
P163752	Eastern and Southern Africa	Tanzania, Zambia	400 kV
P126579	Eastern and Southern Africa	Ethiopia; Kenya	500 kV
P069258	Eastern and Southern Africa	DRC, Zambia	220 kV - 230 kV
P173763	Eastern and Southern Africa	Djibouti; Ethiopia	220 kV - 230 kV
P167898	South Asia	Pakistan (mainly), Kyrgyz Republic, Tajikistan, Afghanistan	500 kV
P145054	South Asia	Kyrgyz Republic, Tajikistan, Pakistan, Afghanistan	500 kV
P162933	Western and Central Africa	Togo/Benin	330 kV
P168185	Western and Central Africa	Cameroon, Chad	220 kV - 230 kV
P146830	Western and Central Africa	Guinea, The Gambia, Guinea Bissau, Senegal	220 kV - 230 kV
P094919	Western and Central Africa	Ghana, Burkina Faso	220 kV - 230 kV
P166042	Western and Central Africa	Guinea, Mali	220 kV - 230 kV
P075994	Western and Central Africa	Ghana, Benin	330 kV
P113266	Western and Central Africa	Côte d'Ivoire, Liberia, Sierra Leone, and Guinea	220 kV - 230 kV
P094917	Western and Central Africa	Ghana, Benin	330 kV

3.4 KEY FINDINGS AND TRENDS IN WORLD BANK GROUP DATA ANALYSIS

Capital Costs

Chapter 1 presented a review of transmission line unit costs, highlighting both the limited number of studies, data sources, and particularly the lack of data from developing countries. This report therefore sets out to examine if transmission cost data collected from World Bank Group financed projects can complement to fill current data gaps and add knowledge to the existing literature.

The following section compares the average values of the 74 sampled World Bank Group projects with the literature values. The results are presented in Table 3.5 and Figure 3.1.

In the data analysis, project costs are compared after normalization as unit cost values. This indicator has the advantage of allowing comparison of investment costs independent of the line length. Table 3.5 therefore presents the unit cost values (in US\$ million/km) according to voltage levels and circuit numbers side by side for the World Bank Group and the literature benchmark data respectively. All values were adjusted to 2010 US\$ values using the World Bank Group commodity price index.⁹

For each category, Table 3.5 displays the average unit cost (US\$ million/km), the lowest and highest values and the data sample size for each category ('sample count'). Sample counts vary from a single project (e.g., 110-161 kV single circuit) to 19 individual projects (220-230 kV double circuit). It is generally believed that larger samples, covering a variety of configurations, tend to provide more confident estimates of the cost average, whereas small samples carry a larger error margin.

⁹ The values are adjusted based on the Manufactures Unit Value (MUV) index, from the World Bank Pink Sheet, which measures inflation in traded manufactured goods (e.g., steel, transformers) but does not capture monetary-value inflation, which reflects labor, domestic construction, and overall purchasing power changes. Commodity prices track goods price changes, while monetary-value inflation tracks broader economic price level changes.

TABLE 3.5 Transmission Line Unit Cost

US\$ million/km, 2010 value

Asset Range	World Bank Data					Literature Benchmark Data			Average Unit Cost Ratio (World Bank vs Benchmark)
	Average Unit Cost	Unit Cost Lower	Unit Cost Upper	Data Sample Count	Difference	Average Unit Cost	Unit Cost Lower	Unit Cost Upper	
110 - 161 kV Single Circuit	0.131	0.131	0.131	1	0.001	0.304	0.304	0.304	2.33
110 - 161 kV Double Circuit	0.110	0.061	0.196	11	0.135	0.369	0.318	0.421	3.35
220 - 230 kV Single Circuit	0.216	0.147	0.278	8	0.131	0.596	0.403	0.854	2.76
220 - 230 kV Double Circuit	0.326	0.147	0.568	19	0.422	0.996	0.519	1.403	3.06
330 - 345 kV Single Circuit	0.504	0.475	0.534	2	0.059	0.828	0.676	1.220	1.64
330 - 345 kV Double Circuit	0.336	0.251	0.363	7	0.111	1.208	0.561	1.952	3.59
380 - 400 kV Single Circuit	0.292	0.287	0.296	2	0.009	0.455	0.455	0.455	1.56
380 - 400 kV Double Circuit	0.351	0.271	0.522	12	0.251	1.234	1.234	1.234	3.52
500 kV Single Circuit	0.281	0.281	0.281	1	0.000	1.221	1.064	1.542	4.35
500 kV Double Circuit	0.646	0.365	0.979	5	0.615	1.427	0.915	1.771	2.21
765 kV Double Circuit	2.865	2.865	2.865	1	0.000				

World Bank Group cost data appears to be lower than the global literature average, by a factor of 1.56 to 4.35 (Table 3.5). Several factors could explain this large variability:

- The primary reason for discrepancies can likely be attributed to differences in cost definitions across studies. In the collected studies, limited information is provided about how cost categories are defined and how data is collected. The projects may therefore not include the same cost elements.
- A second factor may relate to costs related to labor, regulatory and environmental compliance, land acquisition cost, as well as other compensations, which may result in differences.

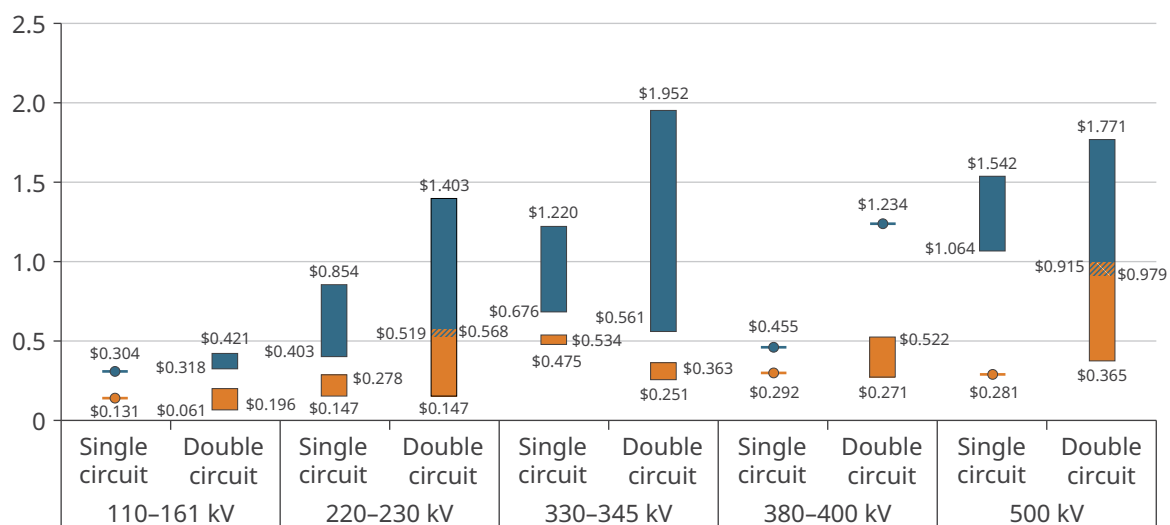
- Procurement could be a contributing factor as well, as stated in many project completion results reports.
- Further, the data time range is different. For example, ACER (2023) is based on 2012-2022 data, Wiser and Bollinger (2010) considers data from 2001-2008. This might create discrepancies, which may not entirely be covered by compensating for commodity price variations. The commodity price index may not necessarily reflect the inflation index / monetary value change over the years.

Figure 3.1 presents Table 3.5 data as a graph, with literature-based data in blue and World Bank Group data in orange. Both datasets show a similar trend with an increased unit cost with increased system scale (higher voltage, larger number of circuits).

As described previously, the average values computed from World Bank Group data are systematically lower than reference values from the United States and Europe. For both samples, the spread between min and max values demonstrates similar ratios of two to three. This finding indicates that averages alone are insufficient for rough estimates, and investment assessments should use cost ranges reflecting lower and upper bounds.

FIGURE 3.1 Transmission Line Unit Cost Range Comparison

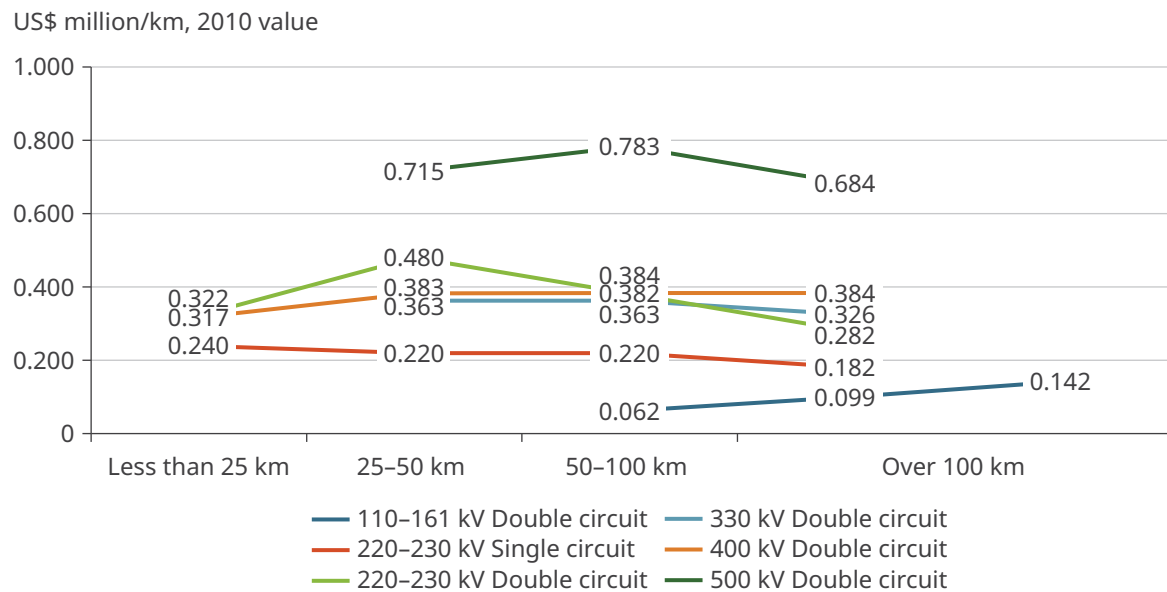
US\$ million/km, 2010 value



Note: This graph shows the comparison between data collected from World Bank Group-executed projects (in orange) and data from literature review (in blue). In general, the World Bank Group data is much lower than data from other sources.

For the World Bank Group projects, the unit cost indicator was further disaggregated by line length (Figure 3.2). The outcome does not provide conclusive evidence of cost reductions due to economies of scale with increased line distance. There is, however, a pattern of cost increasing with the voltage levels, potentially related to the cost of raw materials (copper, steel) increasing with the voltage level.

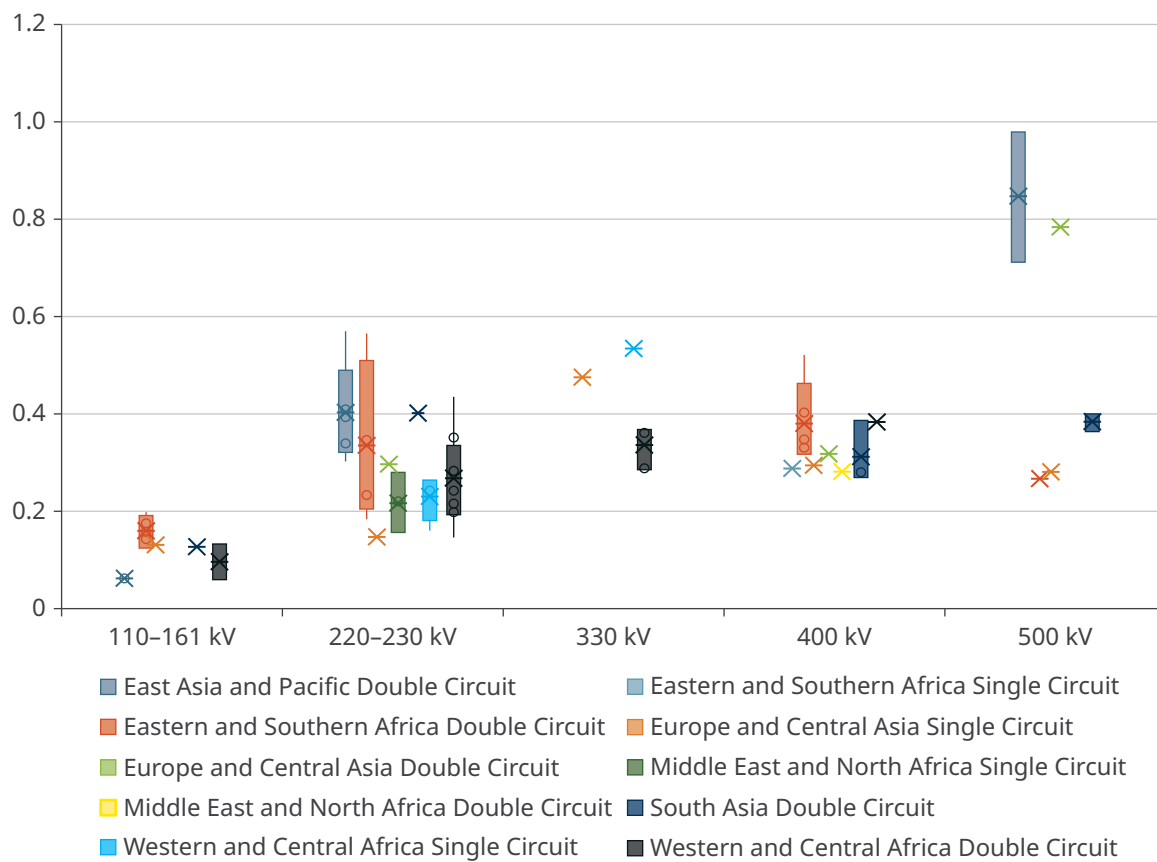
FIGURE 3.2 Unit Cost Comparison by Length



At a disaggregated level, the cost per km exhibits a notable degree of variation across regions (Figure 3.3). This variance is particularly evident in the 220-230 kV voltage range, where data is most available. Based on collected data, the unit cost under each voltage level tends to be higher for the Asian and African regions. Specifically, the Eastern and Southern Africa region demonstrates higher unit costs than the world average, while Western and Central Africa demonstrate lower values.

FIGURE 3.3 Unit Capital Cost Per Region and Voltage

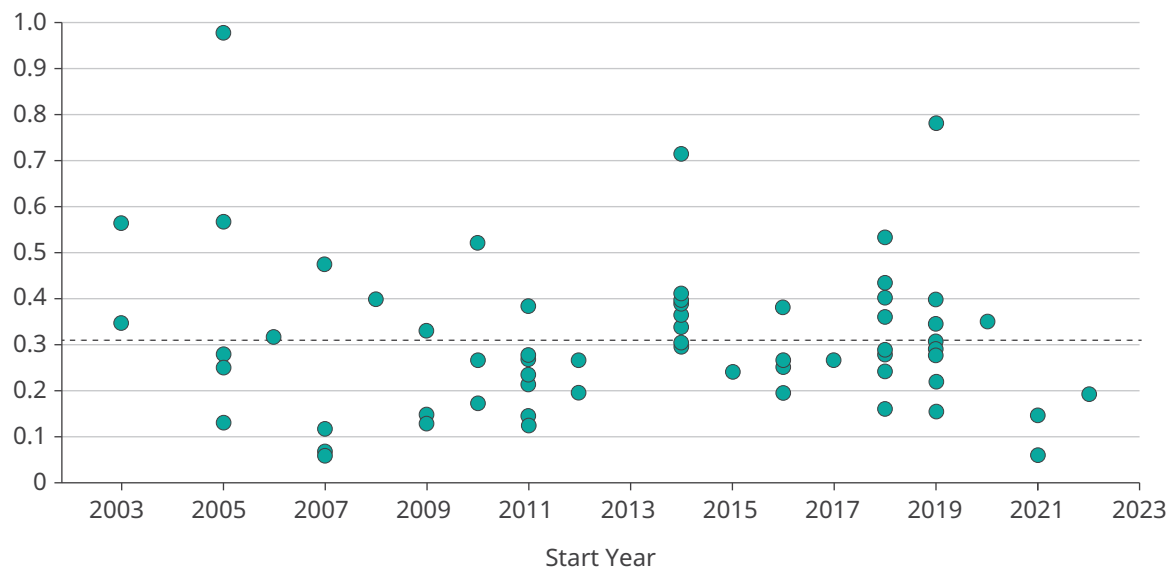
US\$ million/km, 2010 value



Timewise, Figure 3.4 indicates a slight downward cost trend from 2000 to 2020 (in US\$ 2010 value). The average cost decreased from around US\$ 0.38 million per km to close to US\$ 0.30 million per km. The dataset is, however, limited, regions are unevenly represented (as described in Section 3.3), and the trend line is at the p-value of 0.35, which does not indicate a firm correlation between the unit capital cost and start time.

FIGURE 3.4 Unit Capital Cost Change Over Time

US\$ million/km, 2010 value



Further, while the time analysis (Figure 3.4) may suggest a slight downward trend in general, the data has not distinguished among factors such as voltage, regional distribution, and sample size. Aiming to capture some of these nuances, Figure 3.5 reveals regional differences while focusing on the 220-230 kV category, where most data points are collected (Table 3.6). In this category, projects are primarily located in Western and Central Africa (yellow in Figure 3.5), with most projects achieved post-2010, a few data points on period 2000-2010.

The type of transmission project is also an influencing factor. Where data is available, the comparison shows that the interconnection projects across countries tend to have a higher unit capital cost than projects in individual states. The difference may derive from additional efforts in interstate coordination, different standard adjustment, or regulatory requirements.

FIGURE 3.5 Unit Capital Cost Time Repartition for the 220-230 kV Category by Region

US\$ million/km, 2010 value

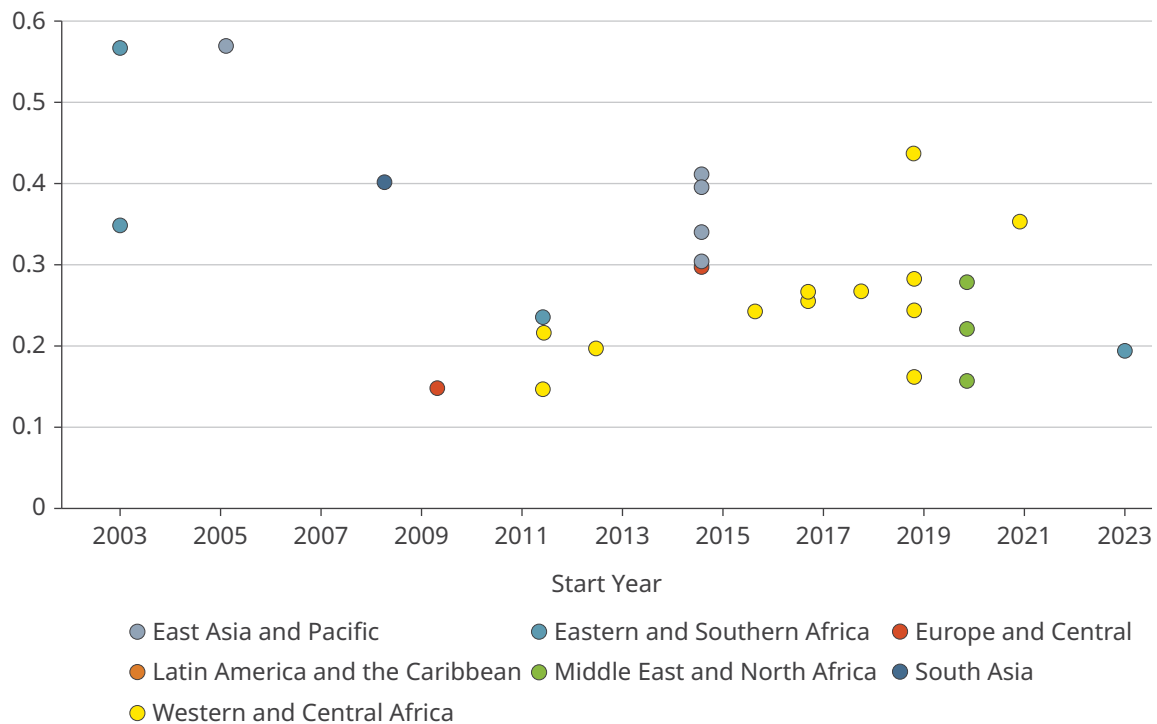


TABLE 3.6 Transmission Unit Cost Comparison to Interconnection Projects

US\$ million/km, 2010 value

Voltage	Region	Unit Cost per km (million) (constant: 2010)	Average Discount Rate	Average O&M Rate	Number of Data Points
220 - 230 kV	Eastern and Southern Africa	\$0.34	10.40%	2.25%	4
220 - 230 kV	Individual	\$0.29	11.33%	2.25%	2
	Interconnection	\$0.38	9.00%	2.25%	2
	Western and Central Africa	\$0.26	8.46%	2.86%	12
	Individual	\$0.23	7.71%	3.17%	6
	Interconnection	\$0.28	9.33%	2.50%	6
330 kV	Western and Central Africa	\$0.36	6.89%	1.00%	8
	Individual	\$0.35	6.00%	1.00%	6
	Interconnection	\$0.39	8.67%	1.00%	2
400 kV	Eastern and Southern Africa	\$0.37	9.50%	2.00%	6
	Individual	\$0.36	9.43%	2.00%	5
	Interconnection	\$0.40	10.00%	2.00%	1

Comparison between individual projects (within a country) and interconnection projects (across countries) suggests slightly higher unit cost for the latter type. Regional differences are notable: Eastern and Southern Africa show higher unit costs, while Western and Central Africa are lower for interconnection projects. The 220 to 230 kV category is the most represented in the sample, reflecting both data availability and regional project concentration. Differences between World Bank Group and literature data may reflect variations in project scope, procurement practices, regulatory environments, and the period covered. These results highlight the importance of considering cost ranges, regional context, and project characteristics when estimating transmission line investments and point to areas for further investigation.

Overall, this section shows that analyzing transmission line cost data is useful for identifying broad patterns across voltage classes, regions, and project types, but the current dataset remains limited for final conclusions. Small sample sizes, uneven regional coverage, and inconsistent cost definitions mean that unit costs provide only an order of magnitude, and the influence of individual cost drivers cannot be reliably isolated. Apparent trends, such as regional differences or systematically lower costs in World Bank Group projects, are indicative. These initial findings highlight the need to expand and harmonize datasets so that future analyses can draw on a more robust empirical basis.

Operation and Maintenance (O&M) Costs

The data sample features 41 projects with exploitable O&M cost data, expressed as a percentage of the total capital costs in Table 3.7. While the O&M rates consistently remain in the 2 to 3% range, individual data points demonstrate variations across time with slight upward trend (Figure 3.6). Analysis does not suggest correlation between the rate percentage and time.

The O&M rate in the observed dataset (Table 3.7), is much lower than the rate of 5 to 10% estimated for United States projects (Larsen 2016). However, internal discussions with clients, transmission practitioners mentioned that utilities with poor capacity may require special assistance to operate the O&M services, which may increase the rate to 5 to 7%.

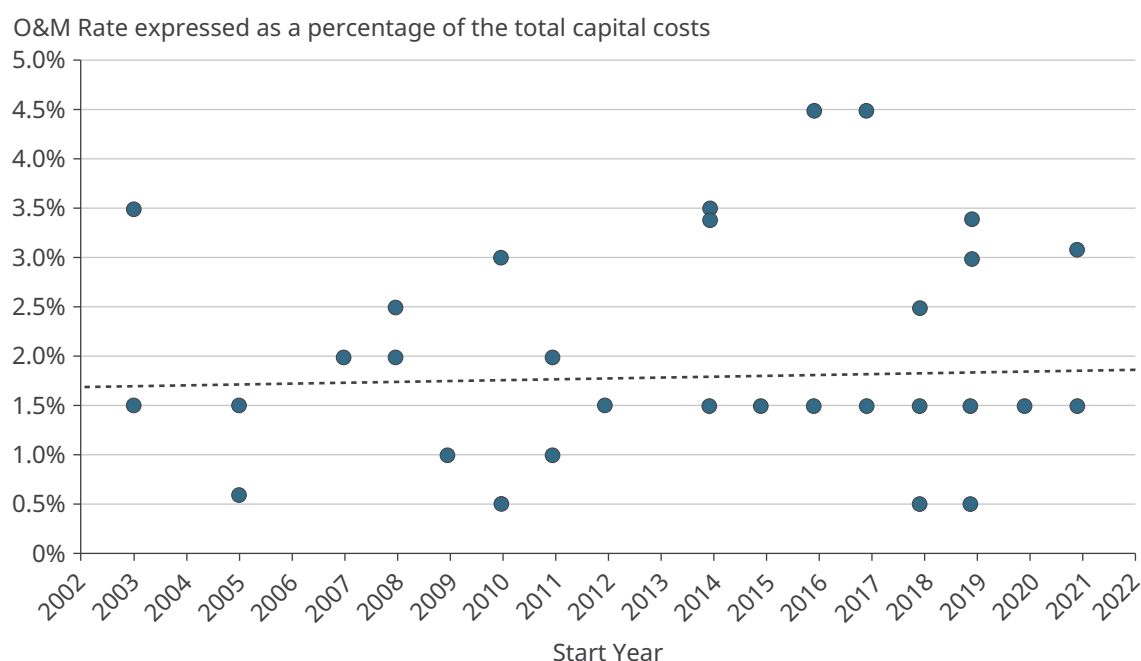
Large variations in O&M rates, presented in Figure 3.6, are difficult to interpret in the absence of consistent descriptions across projects. For example, Central Asia-South Asia Electricity Transmission and Trade (Project P145054) has multiple O&M rates for different components: 2% for HVAC design, supply and installation (DS&I) and local grid reinforcement; 3.9% for HVDC DS&I (World Bank Group 2014). The Côte d'Ivoire, Liberia, Sierra Leone, and Guinea Regional Interconnector (Project P113266) mentions that the O&M rate is 1% for transmission lines, 3% for substations, and 10% for the SCADA system (World Bank Group 2017).

Discrepancies are also noted for other cost elements such as the resettlement action plans, environmental management plans, and community development activities, which vary significantly per specific project conditions. Some transmission lines are constructed across inhabited lands, where no resettlement work is concerned, while others involve intensive compensation for crops and livestock for the local community. Data reporting for the three cost categories is not always consistent, as some environmental costs are included in the resettlement action plan, and vice versa, creating challenges for holistic comparison across regions.

TABLE 3.7 O&M Rate Change Per Region and Voltage, Averaged Over Period 2003–2021

Region	Voltage (kV)				
	110kV - 161kV	220kV - 230kV	330kV	400kV	500kV
East Asia and Pacific	2.50%	2.29%			2.00%
Eastern and Southern Africa	2.20%	2.25%		2.00%	2.00%
Europe and Central Asia	2.00%	1.75%			1.23%
Middle East and North Africa		2.00%		2.00%	
South Asia	1.50%	3.17%		1.50%	3.90%
Western and Central Africa		2.86%	1.00%	5.00%	
Total Average	2.23%	2.55%	1.00%	2.25%	2.34%

FIGURE 3.6 O&M Rate Change Over Time



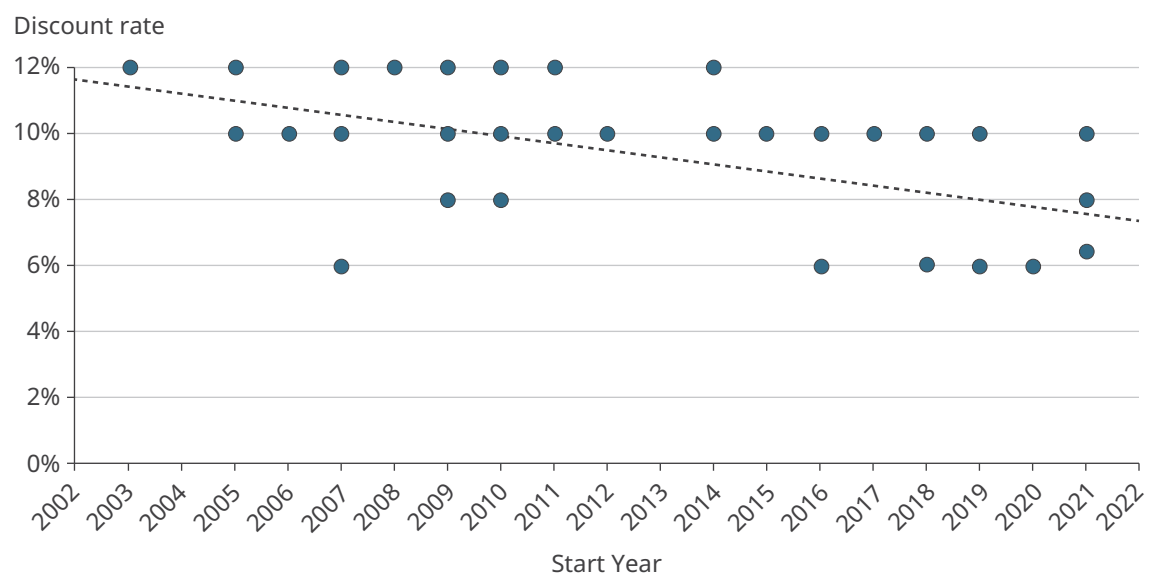
Discount Rate

Discount rates are commonly expected to provide an indication of perceived risk, opportunity, or attractiveness. Trends in discount rates can provide indications of an evolving perception of the investment environment. Specifically, discount rates reflect assessments of sovereign and currency risk, weighted average cost of capital (WACC), regulatory and policy stability, counterparty creditworthiness, and offtake risk. They determine how future cash flows are translated into present value, directly influencing project valuations, financing feasibility, and ultimately investment decisions. The data sample features 48 projects with exploitable discount rate indication. Discount rates remain in the 6 to 12% envelope (Figure 3.7) over the period 2003 to 2021 across the various regions (Table 3.8).

TABLE 3.8 Discount Rates Per Region and Voltage, Averaged Over Period 2003–2021

Region	Voltage (kV)				
	110 kV - 161 kV	220 kV - 230 kV	330 kV	400 kV	500 kV
East Asia and Pacific	10.00%	10.29%			10.00%
Eastern and Southern Africa	8.88%	10.40%		9.50%	10.00%
Europe and Central Asia	12.00%	10.00%	10.00%	8.00%	9.50%
Latin America and Caribbean		8.00%			
Middle East and North Africa		10.00%		10.00%	
South Asia	10.00%	12.00%		12.00%	10.00%
Western and Central Africa	10.00%	8.46%	6.89%	6.00%	
Total Average	9.72%	9.65%	7.45%	9.38%	9.82%

FIGURE 3.7 Discount Rate Change Over Time, For All Regions



Note: The discount rate data tends to concentrate significantly around 6-12%, with a majority at 10%. Therefore, one dot may represent multiple data points. The total sample is 48.

Appraised vs. Completed Project Costs

Most of the collected data reflects cost estimates at project appraisal stage, which can vary from actual project expenditures at project closure. Generally, projects centered on new construction are more susceptible to deviations to cost estimates, while those with actual costs close to appraisal estimates typically involve transmission rehabilitation or upgrade components.

According to the collected data of 40 projects with available Implementation Completion and Results Reports (ICRs), 45% ended up costing less than initially appraised ("Below" category in Figure 3.8, which presents overall project total costs for transmission line investments). For these projects, actual costs ranged from 47 to 90% of the initial estimates.

Significant differences are noted for transmission lines operating at 400 kV and 500 kV (Figure 3.9, which presents the line unit cost analysis). The ICRs attribute these savings to competitive bidding, effective procurement and administration, and decreased steel prices. Conversely, the projects that exceeded their appraisal cost estimates did so due to increased prices for transmission equipment, rerouting requirements, and changes in financial procedures.

FIGURE 3.8 Project Actual-to-Appraisal Cost Percentage

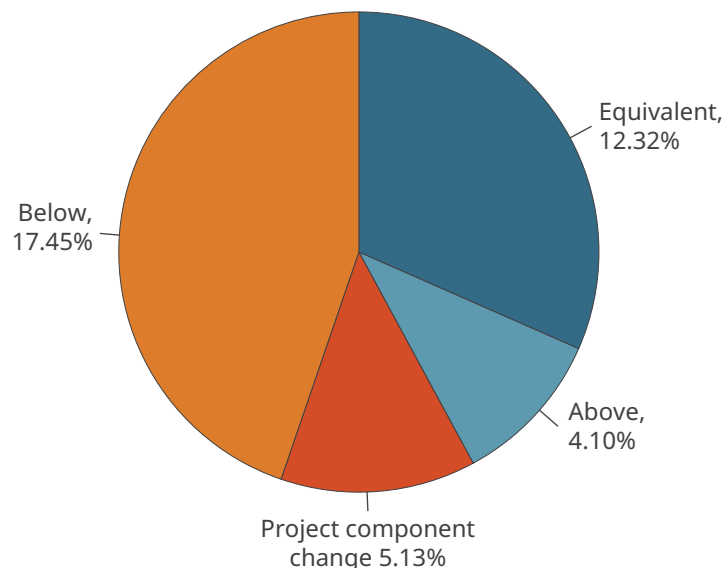
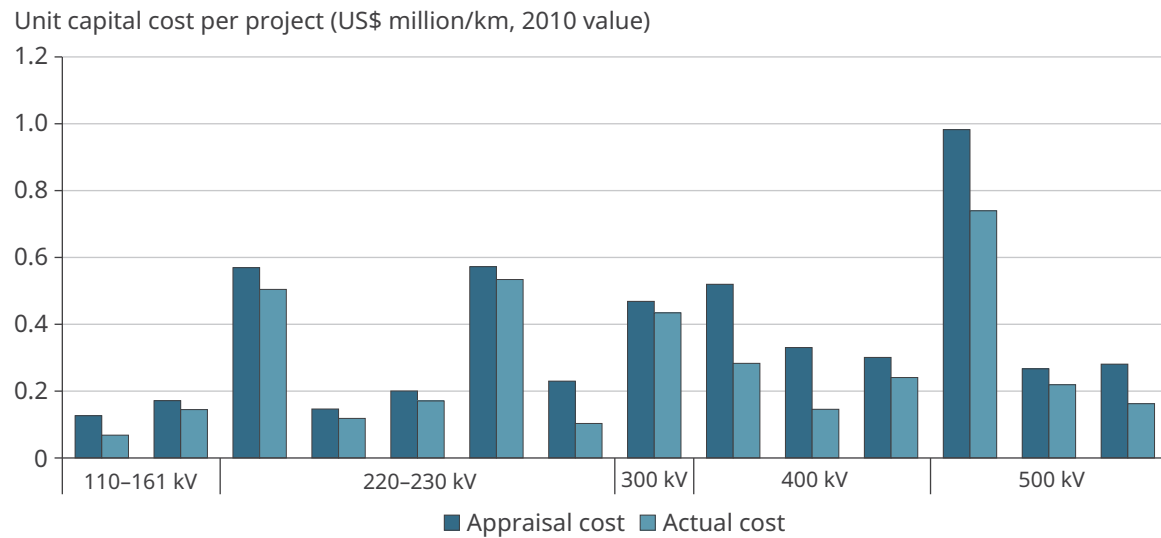


FIGURE 3.9 Appraisal Costs vs. Actual Costs



Commodity Prices as Cost Drivers

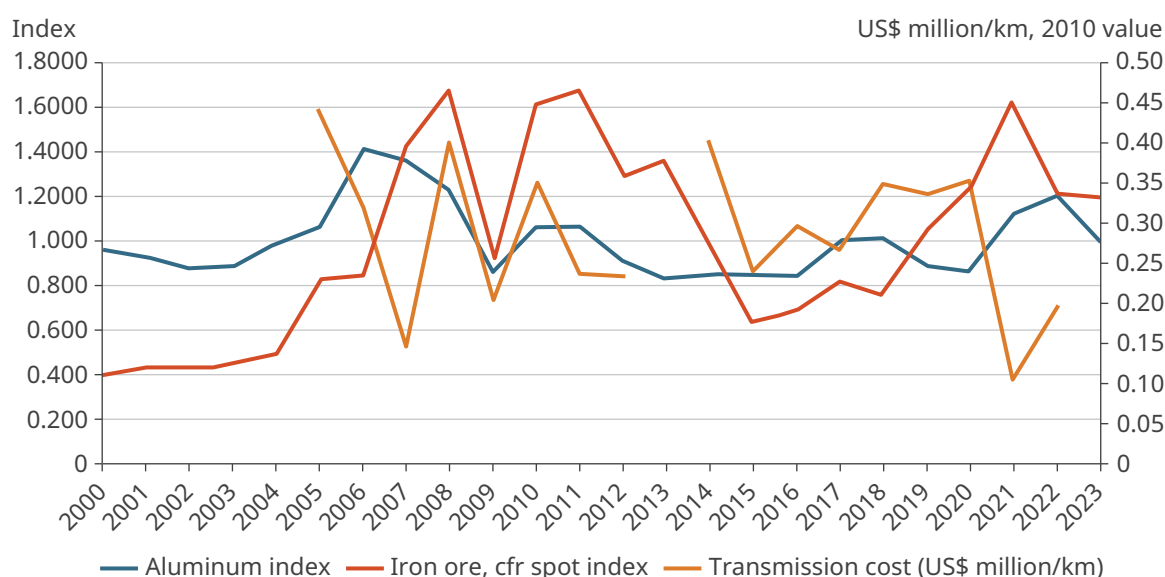
Transmission infrastructure costs are influenced by multiple drivers, among which fluctuations in key commodity prices play a significant role. Changes in particular in aluminum and steel input prices can affect overall project expenditure and contribute to deviations from initial cost expectations. Figure 3.10 illustrates the unit cost of transmission construction variations with the price trends of aluminum and iron ore. The literature indicates that material costs, specifically steel and aluminum, are major components in transmission construction, and can account for up to 30 to 40% of the total expenditure (Table 2.2). Steel is primarily used for the towers and support structures, while aluminum is predominantly utilized for conductors.

According to World Bank commodity price data, aluminum prices have shown a slight decline from 2000 to 2023, whereas iron ore prices, a key input for steel, have been trending upward. These price fluctuations result from a range of factors, including shifts in supply and demand, financial conditions, and global events such as the COVID-19 pandemic. The chart captures significant price increases due to production and supply chain disruptions while simultaneously reducing transmission construction activities.

The variability of raw material supplies has an influence on the final costs of completed infrastructure projects, which may deviate from initial estimates. However, the transmission costs presented in Figure 3.10 do not appear to fully correlate with the

aluminum or iron ore variations. One explanatory factor is the limited data availability and insufficient global representation from the sample. The dataset for 2020-2023 includes only four data points, in contrast to 12 in 2018 and ten in 2019. Future data collection exercises may be able to supplement the analysis.

FIGURE 3.10 Cost Comparison with Prices of Relevant Commodities

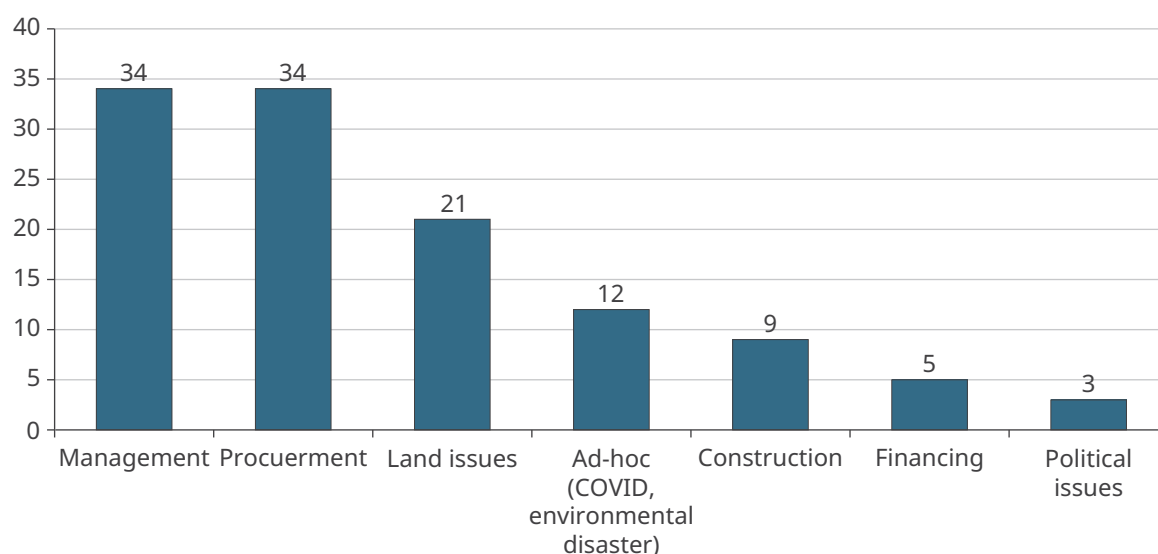


Implementation Delays

Some transmission projects in the database have experienced implementation delays. During implementation, 51 out of the 74 projects (69%) have encountered delays that result in a project extension. Changes in the implementation timeline of a project can lead to deviations between the original appraisal costs and the actual final cost, for example due to the cost variations in raw materials.

The two major reported factors relate to management (including document signing/ approval, communication and coordination with government counterparts, commissioning issues, etc.) and procurement. Further, land issues, predominately related to resettlement plans and land valuation, have also impacted project implementation, as is illustrated in Figure 3.11. It should be noted that a single project may fall into multiple delay categories.

FIGURE 3.11 Causes of Implementation Delays (multiple causes for some projects)



3.5 PRELIMINARY CONCLUSIONS

The analysis of World Bank Group project data against literature benchmarks shows that, while both datasets follow the same trend of higher costs with increased voltage and circuit numbers, World Bank Group projects consistently report lower unit costs—by a factor of 1.56 to 4.35. Both sources display a high variability, with min-to-max ratios of two to three, which underlines the limited reliability of averages and the importance of using cost ranges instead of single values for investment estimates.

Several factors explain these differences, including variations in project scope definitions, regulatory environments, procurement practices, and the different time periods covered. Regional disparities are also prominent: Eastern and Southern Africa tend to have higher costs, while Western and Central Africa are lower, contributing to a slight downward global trend over time.

O&M costs across 41 projects are generally reported in the 2 to 3% range of capital costs, substantially lower than the 5 to 10% observed in the literature. The data does not show consistent trends by region or period. Overall, while a 2 to 3% baseline is common, O&M estimates remain context-dependent, and averages should be treated with caution when used for planning or comparison.

The analysis of 48 projects with available discount rate data shows values consistently clustered between 6 to 12% from 2003 to 2021, with the majority concentrating around 10%. These rates may reflect the financing conditions of World Bank Group projects, where concessional funding plays a role, and their interpretation would require a more detailed breakdown of financial components than available in the dataset.

Delays in project implementation are common, with 69% of projects extended beyond their planned closing dates, mostly due to management and procurement bottlenecks, as well as land and resettlement challenges, all of which can exacerbate cost deviations over the project lifecycle. With extended implementation timelines, costs may be vulnerable to commodity price fluctuations, particularly for steel and aluminum, recognized as major cost drivers.

However, costs are controlled. Data from 40 Implementation Completion and Results Reports indicate that nearly half of the projects ended below their initial appraisals—sometimes by as much as 50%—with savings possibly linked to competitive bidding, effective procurement, and falling steel prices. The few projects that exceeded estimates were driven by higher equipment prices, rerouting, or procedural changes.

3.6 DATA COLLECTION FRAMEWORK & LIMITATIONS

The Transmission Cost Database is built on data mining of the World Bank Group's online Project & Operations repository. The data sampling was performed manually, and can be subject to limitations:

- There is a high degree of variation regarding the availability of granular disaggregate information across projects, for both the technical and cost categories. For example, around 30% of the sampled projects have not reported an O&M rate, whereas even more projects lack specific figures for their capital cost. It was also difficult to identify specific costs regarding resettlements and environmental mitigations. While these numbers can be found in resettlement plans or environmental assessments, not all the information is available online. Furthermore, technical information, especially the number of towers, elevation, and conductor type/materials, have been difficult to identify for some projects, as the Project Appraisal Documents are different from the related feasibility studies, which are more likely to contain technical details. The lack of complete data does impose limitations on database coverage.
- This database contains a large amount of both qualitative and quantitative data. In Project Appraisal Documents, most data points are incorporated into project descriptions. It is also normal that one project component includes data for multiple variables that relate to each other. Separating individual data points therefore requires some assumptions and judgments, which may introduce biases to the analysis.
- While existing cost frameworks suggest variations by terrain type, land structures, vegetation, etc., such information remains fragmented, and the availability varies significantly across projects, making it challenging to collect and analyze.

- The sample size is relatively limited regarding its ability to yield a robust analysis that can identify patterns and trends.
- The cross-region comparison has not been checked against country/region-specific criteria, including labor productivity, permitting and regulations, and purchasing power parity (PPP), which may influence the ultimate cost estimation.
- Data collection relied primarily on manual extraction and review of project documents. As AI-assisted tools for structured cost analysis continue to evolve, future updates of the database could potentially benefit from more automated and advanced analytical methods.

Overall, a consistent monitoring of cost data would benefit from a more systematic data collection framework across the World Bank Group, based on a standardized canvas, and centralized through a transmission costs database.

FOUR
ESTIMATING THE
LEVELIZED COST OF
TRANSMISSION

Investment decisions related to transmission investments are complex with a diverse range of variables, including load growth, generation capacity changes, energy market dynamics, and price variation. To make efficient investment decisions, it is important to secure projects that have a positive benefit-cost ratio. This approach ensures that investment is directed toward projects that maximize net social benefits.

However, the notion of “benefit” can vary with the overall development objectives, for example, to advance decarbonization of the power system; to facilitate energy markets; to increase power system flexibility and security to manage fluctuations in demand and supply or increase system resilience. Depending on such high-level objectives, different technical scenarios can be developed, such as, increasing the capacity of existing transmission infrastructure, establishing alternate routes for power transmission, linking separate power grids, rehabilitating transmission lines to minimize transmission losses, or upgrading transmission lines to increase capacity. A Cost-Benefit Analysis (CBA) is an effective tool for monetizing these benefits over the full lifetime of the asset. It provides a robust methodology for project justification, stakeholder alignment, and regulatory submission. For example, ENTSO-E utilizes CBA as its standard methodology for regional transmission planning, which enhances its institutional credibility with both regulators and investors.

As not all information is available at the start of the project, and project preparation progresses, the need for more detailed and comprehensive data increases. Since transmission benefits are multi-dimensional and context-specific, early-stage analysis may focus on the cost component of transmission infrastructure before integrating it into a broader CBA.

In this context, the report presents Levelized Cost of Transmission (LCOT) as a tool to support broader CBA studies (Gorman 2019). The LCOT framework represents the total discounted cost of building and operating a transmission line over per unit of electricity transported (Equation 4.1). When comparing different investments, the LCOT has therefore the advantage of providing a standardized cost-per-unit measure that reflects the technical and financial characteristics of the investment. Applying LCOT across conductor and route variants can support the identification of the most efficient solution, which can then be incorporated into the broader CBA, helping to reduce the risk of over- or under-costing.

The LCOT formula (Equation 4.1) takes into account the CAPEX and O&M costs, which vary with the technical solution (e.g., technology, voltage level); the discount rate, which varies with the level of risk, the equity / debt ratio and sources of financing; the lifetime of the asset, which varies with the selection of materials; the line capacity and its utilization factor, which depends on the regulatory and market conditions.

EQUATION 4.1 Levelized Cost of Transmission (LCOT) Calculation

$$LCOT = \left[\frac{(CAPEX + O\&M) * r}{[1 - (1 + r)^{-n}]} \right] \div [K * UF * 8760] \quad (\text{Eq. 1})$$

CAPEX = Capital cost of transmission investment
 O&M = Operational and Maintenance (O&M) costs
 r = Discount rate
 $(1 + r)^{-n}$ = The discount factor for year n, with r being the discount rate
 n = Transmission asset lifetime (in years)

$K \cdot UF \cdot 8760$ is an estimate of the average energy transported over a typical year, where:

K = Incremental capacity (in MW) that the transmission line delivers to the grid, constrained by generation capacity and line capacity (depending on the voltage range)
 UF = Utilization factor, the fraction of maximum possible energy transmitted over time, reflecting generation availability and operational constraints¹⁰

In the following, the LCOT methodology is demonstrated **for three situations** of interest for the World Bank Group's operations:

- Where official or regulated wheeling tariffs are missing, unreliable, or inconsistent, the LCOT offers a potential reference framework to facilitate dialogue with transmission system operators on wheeling charges for transmission networks.¹¹
- When evaluating a transmission project, the LCOT could offer consistent reference values based on a benchmark across World Bank Group projects. Such a benchmark can help detect deviations and provide confidence in new investments.
- When designing a transmission project, various factors can be adjusted. The LCOT framework provides a consistent basis for comparing these measures, capturing their combined effects on capital, operational, and energy costs over the project's lifetime.

The LCOT provides a useful benchmark for comparing transmission investments while representing a simplified view of reality. It is based on assumptions about line capacity, utilization, technical design, and asset lifetime, which can vary in practice. In mature electricity markets, where transmission is often designed for peak capacity and reliability rather than average energy throughput, costs per unit may not fully reflect the broader value of the assets. Financial and regulatory factors, as well as changes in generation or demand, can also influence actual costs. In addition, LCOT focuses on the cost per unit of electricity transported and may not capture wider system benefits such as improved reliability, reduced losses, or enhanced integration of variable renewables. It is therefore best considered as an indicative guide rather than a precise measure of project value.

10 UF is largely driven by the availability and dispatch of generation using the line. Operational constraints (e.g., congestion management, outages, reliability requirements), seasonal variance, and asset lifespan may also affect utilization but are typically secondary in simplified analytical scenarios. Information on generation capacity can be found here, <https://www.energy.gov/ne/articles/what-generation-capacity>. The LCOT calculations include assumptions intended to approximate utilization patterns associated with different energy sources.

11 LCOT is a cost metric that reflects the levelized cost of transmitting electricity. It is different from a regulated wheeling tariff but may serve as a reference point for discussions with TSOs and regulators.

4.1 WHEELING CHARGES IN UNCERTAIN ENVIRONMENTS: LCOT AS A REFERENCE

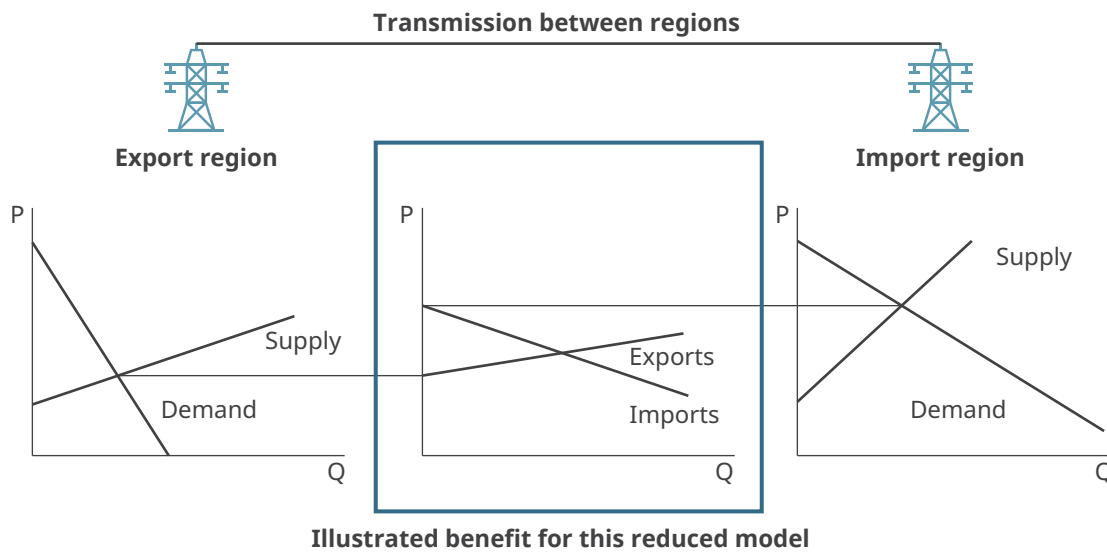
A Simplified Model to Assess the Economic Benefit of a Transmission Project

Transmission infrastructure projects can provide multiple types of benefits, depending on development priorities. These may include enhanced system integration, increased competition, securing energy supply, achievement of climate goals, and integration of renewable energy (ESMAP 2024). Assessing these benefits is complex, as identifying beneficiaries and determining their impacts involves multiple dimensions and context-specific considerations. Economic assessment is therefore one facet of this broader landscape.

The economic evaluation of a proposed transmission project can be highly sensitive to specific input assumptions. To simplify the analysis, the following example focuses on the economic conditions for long-distance, high-voltage transmission lines connecting two points, aimed at transporting power from one location (the electricity export region) to another (the import region). Transmission investments are made to increase the electricity transferred from generators to the load.

The scenario below illustrates a decision process to connect two transmission regions, with the expectation of reducing electricity costs for end consumers (Figure 4.1). The low-cost, or exporting, region generates a net electricity surplus, whereas the high-cost, or importing, region experiences unmet demand, creating an opportunity for cost-efficient electricity transfer. The export potential is determined by the excess supply, defined as the difference between generation and local demand at a given price level. The import demand in the high-cost region corresponds to the local unmet electricity needs. The transmission infrastructure enables electricity transfers from the low-cost (exporting) region to the high-cost (importing) region. The expected outcome is a reduction in electricity prices in the importing region, while the exporting region benefits from selling its surplus at a price above its local marginal cost, thereby capturing part of the price differential.

FIGURE 4.1 Transmission Export Scenario (simplified model)



Source: Hogan (2018).

Transmission line investments are justified when the value of the delivered power outweighs the investment cost, such that the distant generation cost plus levelized transmission cost is less than the local generation cost. This is determined by the equation:

Equation 4.2 Transmission Cost Competitiveness Condition

$$\text{GCD} + \text{LCOT} < \text{GCL} \quad (\text{Eq. 2})$$

Where:

GCD = Distant generation cost

LCOT = Levelized cost of transmission

GCL = Local generation cost

Application of LCOT in Case Study

The next section presents a case study to demonstrate how the LCOT framework can be utilized. It is acknowledged however that the wheeling or transmission tariffs are set within regulatory and market contexts and may diverge from LCOT values due to policy decisions, cross-subsidization among customer classes, or market-based congestion pricing mechanisms that deviate from pure cost-of-service.

The case study explores the Cameroon-Chad Power Interconnection Project (World Bank ID: P168185), which aims to trade electricity between the two countries. The project's transmission capital cost is US\$ 275 million for a line spanning 805 km. Once in operation, the interconnection will export 876 GWh of electricity to Chad every year from 2030.

Case Study: Cameroon-Chad Power Interconnection Project (World Bank Group 2020)

As of 2020, Chad's unit cost of electricity generation is approximately US\$ 0.24 per kWh, and the cost of service can reach US\$ 0.43 per kWh when distribution and transmission costs are considered. This high end-user retail tariff limits electricity access and constrains economic development. In contrast, Cameroon's average electricity tariff was at US\$ 0.13 per kWh. The country's abundant hydropower potential reduces generation costs and enables it to become a regional exporter of electricity.

The project is established on the basis that the Chadian government will lower the average domestic power generation cost to US\$ 0.19 per kWh by converting up to 80% of diesel plants to heavy fuel oil (HFO). With lower generation costs, the benefits from the interconnector can be shared by both countries if the export price lies between US\$ 0.13 per kWh and US\$ 0.19 per kWh, excluding wheeling charges.

Table 4.1 (World Bank Group 2020) presents a sensitivity analysis of the project's financial net present value (FNPV) and the financial rate of return (FIRR) according to the PPA export price. In this example, the financial analysis of the project under the base case export price scenario at US\$ 0.15 per kWh indicates an FNPV of US\$ 280 million and an FIRR of 5.1% (Table 4.1).

TABLE 4.1 Sensitivity of Project Financial Returns to Export Price

PPA Export Price US\$/kWh	Wheeling Charge US\$/kWh	FNPV US\$ million	FIRR %
0.13	0.02	86	2.9
0.15	0.02	280	5.1
0.17	0.02	474	7.0

Source: World Bank Group 2020.

In Table 4.1, the wheeling charges are fixed and set at US\$ 0.02 per kWh. Using the LCOT method, an additional sensitivity analysis is performed (Table 4.2). The LCOT varies with the line's utilization factor, within a range of US\$ 0.006 to US\$ 0.020 per kWh, comparable to the wheeling charge estimated in Table 4.1. The sensitivity analysis supports the wheeling charge value estimated by World Bank (2020) and the hypothesis that Chad can indeed benefit from the project.

TABLE 4.2 Sensitivity Analysis of the Levelized Cost of Transmission as a Proxy for Wheeling Charges

PROJECT SPECIFIC INFORMATION	Length	517 km	
	Cost/km	US\$ 0.35 million (2010 value)	
	Discount Rate	6.00%	
	O&M Rate	2.00%	
	Voltage Range	220/230 kV	
	Project Lifetime	35 years (assumed)	
ASSUMPTIONS AND RESULTS	Transmission Capacity (MW)	Utilization Factor	Levelized Cost (US\$ per kWh)
	300	0.25	0.020
		0.5	0.010
		0.8	0.006

4.2 BENCHMARKING TRANSMISSION COSTS: INSIGHTS FROM 74 WORLD BANK GROUP PROJECTS

The LCOT methodology has been applied to 74 World Bank Group projects. In Chapter 3, cost data were compared using the traditional US\$ per km index, but this approach did not reveal clear trends across regions or technologies. By contrast, LCOT normalizes transmission costs on a per-unit basis, integrating investment, operation, and losses over the project's lifetime. This allows projects of different scale, context, and voltage levels to be compared on a consistent basis. For the World Bank Group, this perspective is valuable as it supports more transparent benchmarking, highlights cost drivers, and strengthens the analytical foundation for investment decisions and policy dialogue.

Table 4.3 presents LCOT simulations for 74 World Bank Group projects where cost information was sufficiently detailed to run the analysis, for two discount rates (6% and 10%) and for three utilization factors (0.25, 0.5 and 0.8). The scenarios combine hypotheses on key variables presented below. Capital costs were extracted from the World Bank Group's documents. This table is a helpful illustration of the influence of discount rate, line length, and utilization factor on the LCOT. At the same time, Table 4.3 also compares unit cost (US\$ per km) and the LCOT (US\$ per kWh) side by side to demonstrate how the two metrics diverge.

- Presented side by side, the unit cost does not capture utilization factors, nor discount rate (financial efficiency and risk analysis). In that perspective, the LCOT presents a more precise picture of the investment.
- The utilization factor has the largest impact, tripling the LCOT when it varies from 0.25 to 0.8. This illustrates the need to evaluate precisely the energy transfers before deciding on the line's voltage levels and puts emphasis on the need to conduct reliable power flow simulations at system level to support the decision.
- Higher voltage ranges tend to result in lower LCOT. Higher voltage ranges are associated with higher equipment costs (and CAPEX), which may increase the unit cost. However, the higher the voltage, the more electricity units can be delivered, therefore reducing the LCOT.
- Higher discount rates tend to lead to higher LCOT. The impact of a change in discount rate is however variable, and tends to reduce with higher transported electricity volumes, either due to higher capacity or utilization factor.

One of the scenarios is charted in Figure 4.2, for 500 km lines with a 10% discount rate. The value spread can be significant due to the diversity of projects, time and data limitations, with a fourfold spread between low and high LCOT estimates for a given voltage category and region. Figure 4.2 displays a higher consistency between regions for each voltage group, compared to traditional cost comparisons based on US\$ per km values. The graph also logically translates the fact that higher voltage levels translate into lower LCOT values.

Based on the current database of transmission projects, the method proved reliable for project intercomparison, and the LCOT methodology enabled the construction of a benchmark consistent across regions. Some outliers can be identified, and further investigations could be conducted to review these.

This analysis underscores the importance of data comparability in centralized databases, in particular for infrastructure projects where costs vary widely with scale and complexity. Larger projects often exhibit higher costs per kilometer, potentially diminishing their perceived value. The LCOT methodology offers a standardized approach to assess a project's value by encompassing capital expenditures (CAPEX), operational expenditures (OPEX), and the total energy transported over the project's lifespan. This evaluation facilitates more accurate comparisons across diverse projects, enabling stakeholders to make informed investment decisions.

FIGURE 4.2 LCOT Calculated for World Bank Group Projects

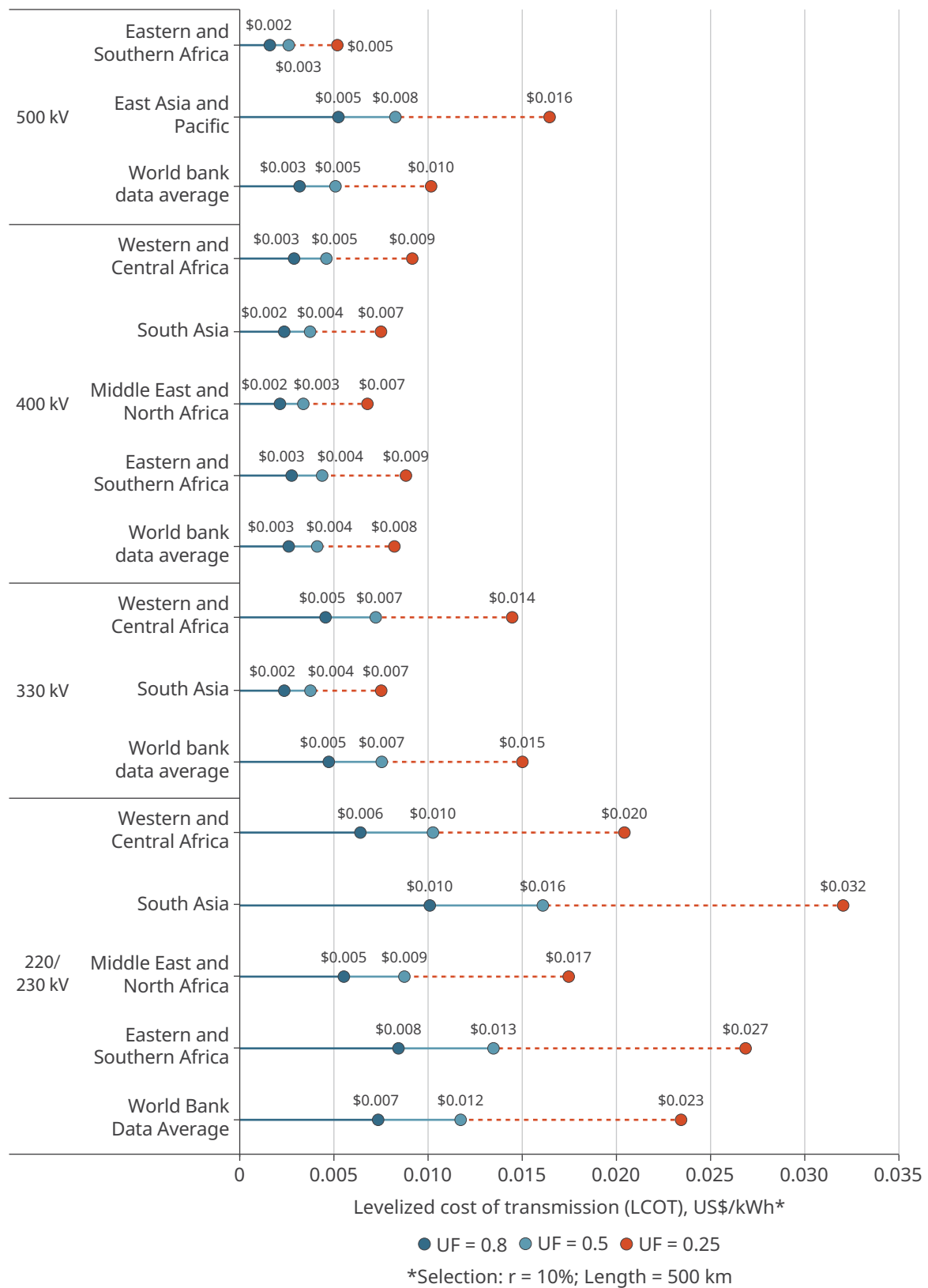


TABLE 4.3 Simulations of LCOT Values for 74 World Bank Group Transmission Projects

Assumptions				Capital Cost			LCOT			
Voltage Range (kV)	Transmission Capacity (MW)	Utilization Factor (UF)	MWh Transferred	UIC (US\$ million/km)	250 km (US\$ million)	500 km (US\$ million)	r: 6% 250km (US\$/kWh)	r: 10% 250km (US\$/kWh)	r: 6% 500km (US\$/kWh)	r: 10% 500km (US\$/kWh)
<i>Region: World Bank Data Average</i>										
220/230	300	0.25	657000	0.293	73	146	0.008	0.012	0.015	0.023
		0.5	1314000				0.004	0.006	0.008	0.012
		0.8	2102400				0.002	0.004	0.005	0.007
330	600	0.25	1314000	0.374	94	187	0.005	0.007	0.010	0.015
		0.5	2628000				0.002	0.004	0.005	0.007
		0.8	4204800				0.002	0.002	0.003	0.005
400	1000	0.25	2190000	0.342	86	171	0.003	0.004	0.005	0.008
		0.5	4380000				0.001	0.002	0.003	0.004
		0.8	7008000				0.001	0.001	0.002	0.003
500	1200	0.25	2628000	0.522	131	261	0.003	0.005	0.007	0.010
		0.5	5256000				0.002	0.003	0.003	0.005
		0.8	8409600				0.001	0.002	0.002	0.003
<i>Region: East Asia and Pacific</i>										
500	1200	0.25	2628000	0.847	212	423	0.005	0.008	0.011	0.016
		0.5	5256000				0.003	0.004	0.005	0.008
		0.8	8409600				0.002	0.003	0.003	0.005
<i>Region: Eastern and Southern Africa</i>										
220/230	300	0.25	657000	0.335	84	167	0.009	0.013	0.017	0.027
		0.5	1314000				0.004	0.007	0.009	0.013
		0.8	2102400				0.003	0.004	0.005	0.008

Assumptions			Capital Cost				LCOT			
Voltage Range (kV)	Transmission Capacity (MW)	Utilization Factor (UF)	MWh Transferred	UIC (US\$ million/km)	250 km (US\$ million)	500 km (US\$ million)	r: 6% 250km (US\$/kWh)	r: 10% 250km (US\$/kWh)	r: 6% 500km (US\$/kWh)	r: 10% 500km (US\$/kWh)
400	1000	0.25	2190000	0.366	92	183	0.003	0.004	0.006	0.009
		0.5	4380000				0.001	0.002	0.003	0.004
		0.8	7008000				0.001	0.001	0.002	0.003
500	1200	0.25	2628000	0.267	67	135	0.002	0.003	0.003	0.005
		0.5	5256000				0.001	0.001	0.002	0.003
		0.8	8409600				0.001	0.001	0.001	0.002
Region: Middle East and North Africa										
220/230	300	0.25	657000	0.218	55	109	0.006	0.009	0.011	0.017
		0.5	1314000				0.003	0.004	0.006	0.009
		0.8	2102400				0.002	0.003	0.004	0.005
400	1000	0.25	2190000	0.282	71	141	0.002	0.003	0.004	0.007
		0.5	4380000				0.001	0.002	0.002	0.003
		0.8	7008000				0.001	0.001	0.001	0.002
Region: South Asia										
220/230	300	0.25	657000	0.400	100	200	0.010	0.016	0.021	0.032
		0.5	1314000				0.005	0.008	0.010	0.016
		0.8	2102400				0.003	0.005	0.007	0.010
330	600	0.25	1314000	0.311	78	156	0.002	0.004	0.005	0.007
		0.5	2628000				0.001	0.002	0.002	0.004
		0.8	4204800				0.001	0.001	0.002	0.002
400	1000	0.25	2190000	0.384	96	192	0.002	0.004	0.005	0.007
		05	4380000				0.001	0.002	0.002	0.004

Assumptions				Capital Cost			LCOT			
Voltage Range (kV)	Transmission Capacity (MW)	Utilization Factor (UF)	MWh Transferred	UIC (US\$ million/km)	250 km (US\$ million)	500 km (US\$ million)	r: 6% 250km (US\$/kWh)	r: 10% 250km (US\$/kWh)	r: 6% 500km (US\$/kWh)	r: 10% 500km (US\$/kWh)
		0.8	7008000				0.001	0.001	0.002	0.002
Region: Western and Central Africa										
220/230	300	0.25	657000	0.255	64	127	0.007	0.010	0.013	0.020
		0.5	1314000				0.003	0.005	0.007	0.010
		0.8	2102400				0.002	0.003	0.004	0.006
330	600	0.25	1314000	0.361	90	180	0.005	0.007	0.009	0.014
		0.5	2628000				0.002	0.004	0.005	0.007
		0.8	4204800				0.001	0.002	0.003	0.005
400	1000	0.25	2190000	0.382	96	191	0.003	0.005	0.006	0.009
		05	4380000				0.001	0.002	0.003	0.005
		0.8	7008000				0.001	0.001	0.002	0.003

Note: The result display is based on available data.

For this simulation, the following assumptions were taken:

- O&M rate 3%
- Project life (n) = 40 years
- Discount rate (r) is calculated and presented under two scenarios: 6% and 10%
- Incremental Transmission Capacity (k) is indicated as below:
- 220/230 kV: 300 MW
- 330 kV: 600 MW
- 400 kV: 1000 MW
- 500 kV: 1200 MW
- Utilization Factor (UF) adopts the following scenarios: 0.25, 0.5, 0.8
- The lines losses (e.g., % per km) are not factored into this formula

4.3 SENSITIVITY ANALYSIS OF LCOT FOR TRANSMISSION INVESTMENT OPTIMIZATION

The delivery of cost-efficient electricity transmission projects depends on a complex mix of technical and operational decisions. Each optimization measure should be assessed as part of a broader system perspective. Some interventions may require higher upfront investment but yield long-term savings through reduced operation and maintenance (O&M) costs, reduced technical losses, improved asset utilization, or improved transfer efficiency. This section illustrates the impact that optimization measures can have on the LCOT.

To assess the impact of each parameter, the analysis uses a base case based on typical or average values for each variable. High and low cases are then introduced, where each parameter is varied by a specific amount to represent different scenarios, as shown in Table 4.4. This approach enables a clear comparison of how key factors influence LCOT and highlights the main drivers.

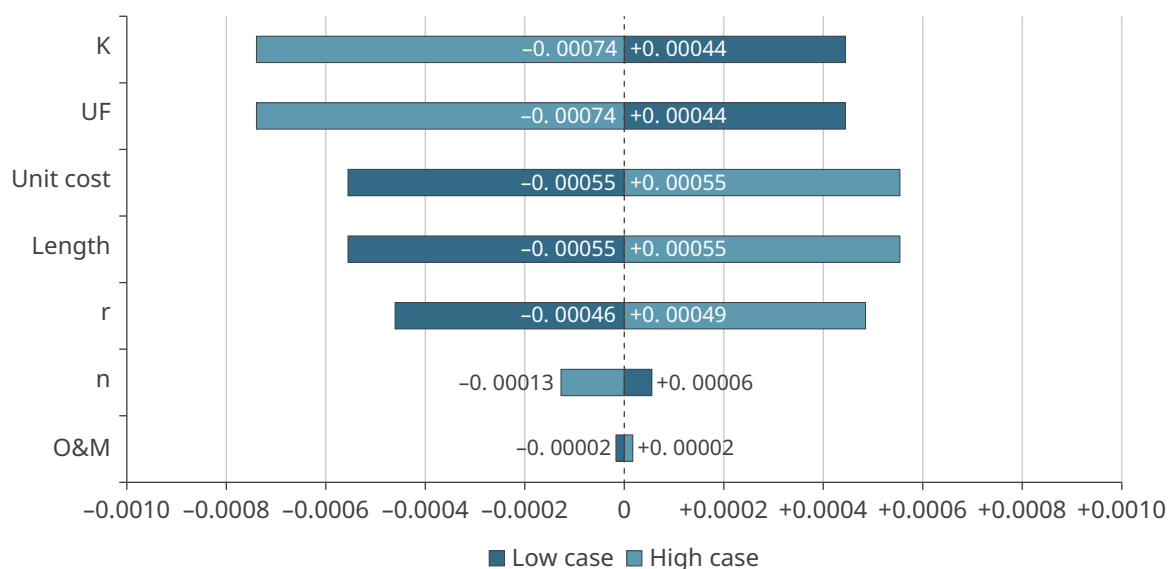
TABLE 4.4 LCOT Sensitivity Setup

Variables	Low		Base	High	
Changes	Value	%	Value	Value	%
Unit Cost (US\$ million/km)	0.225	-25%	0.3	0.375	+25%
Length	225	-25%	300	375	+25%
O&M (%)	2.25%	-25%	3%	3.75%	+25%
r (%)	6%	-25%	8%	10%	+25%
n (year)	30	-25%	40	50	+25%
K (MW)	600	-25%	800	1,000	+25%
UF	0.375	-25%	0.5	0.625	+25%
LCOT (US\$/kwh)			0.002		

As demonstrated in Figure 4.3 the following key insights highlight the most influential parameters affecting LCOT and their respective impacts on the base case:

- The transmission capacity (K) and utilization factor (UF) are the most influential variables, as they relate directly to the transported energy. The two variables exhibit a reverse relationship with LCOT: A 25% reduction in UF increases LCOT by 0.00044 US\$ per kWh (or +20%), while a 25% increase in UF decreases LCOT by 0.00074 US\$ per kWh (or -33%). The sensitivity of the LCOT formula to these parameters highlights the need to optimize the line voltage with regards to the utilization factor.
- Transmission length, Unit Cost, and discount rate (r) represent a second tier of influential variables, each producing meaningful changes in LCOT. Variations in transmission length and Unit Cost, which together calculate the CAPEX, directly transfer into the LCOT consideration, with ± 0.00055 US\$ per kWh ($\pm 25\%$) change for each variable. Adjusting the discount rate by $\pm 25\%$ varies the LCOT by ± 0.00046 - 0.00049 US\$ per kWh (± 21 - 22%).
- Asset lifetime (n) has a relatively limited effect on LCOT compared with other financial parameters. However, the impact is not symmetrical. Designing transmission assets for longer lifetime (+25%) slightly decreases the LCOT by 0.00013 US\$ per kWh (-6%) while shorter lifetime may increase it by 0.00005 US\$ per kWh (+3%).
- O&M costs show the lowest sensitivity, indicating that moderate changes in operating expenses have minimal influence on the overall transmission cost per unit of electricity. However, O&M costs will influence the line performance and availability, which may impact the utilization factor.

FIGURE 4.3 Sensitivity of LCOT to Key Input Parameters



The findings underscore that minimizing LCOT relies heavily on maximizing transmission utilization and optimizing system capacity. Decision-makers should focus on strategies that enhance grid utilization and ensure optimal infrastructure sizing to achieve significant cost savings. By prioritizing efficient grid planning and coordinated expansion, transmission costs can be minimized more effectively. Well-planned investments in transmission infrastructure and utilization will lead to the most significant reductions in LCOT and the overall cost of electricity transmission. Grid enhancement technologies such as dynamic line rating, should also be considered to increase grid utilization.

The report summarizes key optimization practices from previous best practices, identifying nine optimization groups that apply to different project development phases. For each group, up to three practice items are illustrated, with their impact on LCOT values presented Table 4.5.

The LCOT framework provides an integrated view of transmission project economics, linking design, construction, operation, and financing decisions to their overall cost impact. It provides a tool for decision-makers in identifying trade-offs between capital investment, operational performance, and other key cost metrics. Additionally, the framework highlights how optimization measures, such as adopting advanced materials, modular construction, or innovative maintenance practices, can reduce long-term costs.



TABLE 4.5 Optimization Groups, Items, Corresponding Project Phases and Impact on LCOT

Group	No.	Item	Project Phases	Illustrative Example
Optimizing Design and Engineering	1.a	Standardization	Transversal to several phases	Utilizing standardized designs for towers, foundations, and components can reduce engineering costs and simplify the procurement process
	1.b	Compact Transmission Lines	Engineering	Using compact designs can reduce the need for wide corridors and minimize land acquisition costs; these designs also decrease the environmental impact, which can reduce costs associated with environmental mitigation
	1.c	Optimized Conductor Selection	Engineering / Procurement	Choosing conductors with higher current-carrying capacity or using advanced materials, like aluminum conductor composite core (ACCC) can reduce the number of conductors required, lowering material costs and simplifying installation
Efficient Construction Practices	2.a	Pre-fabrication	Construction	Pre-fabricating components off-site can reduce on-site labor costs and speed up the construction process, leading to lower overall project costs
	2.b	Use of Drones and Robotics	Construction / O&M	Employing drones for line stringing and inspection, as well as robotics for difficult or hazardous construction tasks, can reduce labor costs and increase safety, minimizing delays and associated costs
	2.c	Modular Construction	Construction	Implementing modular construction techniques, where large sections of the transmission infrastructure are built off-site and then assembled on-site, can reduce construction time and costs
Material and Equipment Efficiency	3.a	Alternative Materials	Engineering / Procurement	Using alternative, cost-effective materials that provide similar performance to traditional materials (e.g., high-strength, low-weight alloys) can reduce costs without compromising safety or reliability (see Box 4.1).
	3.b	Bulk Purchasing	Engineering / Procurement	Procuring materials in bulk or through long-term contracts can lead to significant cost savings due to economies of scale
Reducing Land Acquisition Costs	4.a	Undergrounding in Urban Areas	Development	While underground transmission lines are generally more expensive, in densely populated urban areas, they can reduce land acquisition and right-of-way costs, offsetting some of the additional expenses
	4.b	Corridor Sharing	Development	Utilizing existing infrastructure corridors, such as those for highways or railways, can reduce the need for new land acquisition and associated costs
	4.c	Easements	Development	Working closely with landowners to negotiate favorable easements rather than outright land purchases can reduce upfront costs

Group	No.	Item	Project Phases	Illustrative Example
Maintenance and Operations Optimization	5.a	Condition-Based Maintenance	O&M	Implementing condition-based maintenance strategies, using sensors and monitoring technologies to predict failures before they occur, can reduce unplanned outages and maintenance costs
	5.b	Vegetation Management	O&M	Adopting advanced vegetation management techniques, such as targeted herbicide applications or the use of grazing animals, can reduce the frequency and cost of clearing transmission corridors
Energy Loss Reduction	6.a	High-Temperature Low-Sag (HTLS) Conductors	Engineering / procurement	Installing HTLS conductors can reduce energy losses due to lower resistance
	6.b	Voltage Optimization	Engineering	Optimizing the voltage levels of the transmission system can reduce energy losses and improve overall system efficiency, leading to cost savings
Regulatory and Financial Strategies	7.a	Incentives and Financing	Development	Taking advantage of government incentives, subsidies, or favorable financing terms can reduce the overall cost of the project. Innovative financing mechanisms like public-private partnerships (PPPs) can also help spread the costs over time
	7.b	Streamlining Permitting	Development	Working with regulatory bodies to streamline the permitting process can reduce delays and associated costs, allowing for quicker project completion
Innovation and Technology	8.a	Smart Grids and Digitalization	Engineering	Implementing smart grid technologies and digitalizing transmission operations can optimize the performance and reduce operational costs through better data analysis and automated decision-making
	8.b	Energy Storage Integration	Engineering	Integrating energy storage systems with transmission lines can reduce the need for building new lines by optimizing the usage of existing infrastructure
Outsourcing and Partnerships	9.a	Outsourcing Non-Core Activities	Management	Outsourcing activities such as routine maintenance, vegetation management, or even some aspects of construction to specialized firms can reduce costs by leveraging the expertise and economies of scale of third-party providers
	9.b	Collaborative Development	Management	Partnering with other utilities or private entities for the development and operation of transmission lines can share costs and reduce the financial burden on a single entity. Implementing a combination of these strategies can lead to significant cost reductions for high-voltage transmission line projects, while maintaining safety, reliability, and environmental stewardship



BOX 4.1 Example of Design Optimization: The Case of Guyed Masts

Guyed masts represent a cost-effective alternative for the construction of transmission lines, particularly in remote or difficult-to-access areas. Compared to free-standing towers, they are lighter, require less material, and are therefore easier to transport and assemble. This makes them especially suitable for challenging terrains such as mountains, forests, or wetlands, where conventional towers would be technically complex or prohibitively expensive to install. Despite their lighter structure, guyed masts can achieve significant heights, allowing them to span large distances or natural obstacles efficiently. They are used in countries such as Russia, Canada, the United States, Brazil, India, China, and Australia, where they help reduce construction costs and environmental impacts while maintaining reliability of transmission.

- Guyed masts generally use less material than self-supporting towers because they are supported by cables (guy wires) that distribute the load. This reduces the amount of metal or concrete needed for the main structure of the mast.
- The manufacturing and installation process for guyed masts is often simpler and quicker, which reduces labor costs and construction time. Foundations can also be lighter, reducing site preparation costs.

- Guyed masts can be installed on various types of terrain, including areas where it would be costly to install self-supporting towers. Their flexible design allows them to adapt to complex geological conditions, potentially lowering the expenses related to terrain adjustments.
- The components of guyed masts are generally lighter and more compact, making them easier to transport to remote or difficult-to-access sites, thereby reducing logistics costs.
- Guy wires require regular inspection to ensure proper tension and may be sensitive to weather-related wear and tear. If maintained, guyed masts can however offer a long service life with moderate maintenance costs. Their simple design can also reduce repair costs in case of damage.
- Guyed masts however require a large amount of land around the mast, which may not be feasible in densely populated or urban areas.

Estimating the cost reduction associated with using guyed masts compared to other types of structures, such as self-supporting towers, depends on several factors, including the specific project, location, materials, and labor costs. However, some general guidelines and considerations can help provide a rough estimate:

- Guyed Masts typically use 30 to 50% less steel compared to self-supporting towers. The reduction in material usage can result in 20 to 40% cost savings on materials alone, depending on the market prices of steel and other materials.
- The installation process for guyed masts is generally simpler and quicker. Savings on installation labor and equipment can range from 15 to 30% compared to self-supporting towers. This includes reduced foundation work, as guyed masts often require lighter foundations.
- Given that guyed masts are lighter and have fewer components, transportation costs can be reduced by 10 to 20%, especially for projects in remote or hard-to-access areas.
- While guyed masts require regular inspection and maintenance of the guy wires, the overall maintenance costs can be lower due to the simpler structure. Over the lifespan of the structure, maintenance cost savings could range from 5 to 15%.
- When considering all factors, the total cost reduction for using guyed masts compared to self-supporting towers could be estimated at 25 to 40%. This range can vary based on the specific details of the project, such as height, environmental conditions, and local labor costs.

4.4 CONCLUSIONS ON THE VALUE OF LCOT

The Levelized Cost of Transmission (LCOT) framework provides a more comprehensive and equitable basis for comparing electricity transmission investments than traditional unit cost indicators. By integrating capital expenditures (CAPEX), operational expenditures (OPEX), financing conditions, and the total energy transmitted over a project's lifetime, the LCOT captures the real economic efficiency of transmission infrastructure. It corrects the bias of cost-per-kilometer metrics that tend to penalize larger or higher-voltage systems, enabling decision-makers to focus on value delivered rather than scale alone.

Where official or regulated wheeling tariffs are missing, unreliable, or inconsistent, the LCOT offers a potential reference framework to facilitate dialogue with Transmission System Operators on wheeling charges for networks. The case study for the Cameroon–Chad interconnection demonstrates how the LCOT framework can be utilized values are consistent with wheeling charges hypotheses, validating its relevance as a proxy for initial assessments where regulatory environments are uncertain.

Applied across 74 World Bank Group projects, the LCOT methodology demonstrated its robustness for benchmarking and policy dialogue. The LCOT framework has the potential to offer consistent reference values based on a benchmark across World Bank Group projects. Such a benchmark could help detect deviations and provide confidence in new investments.

Beyond its analytical value, LCOT also supports optimization across the project's life cycle by highlighting the sensitivity of transmission costs to key variables. As discussed earlier, parameters such as transmission capacity, utilization factor, and CAPEX have the most significant impact on LCOT. The LCOT framework allows stakeholders to evaluate technical choices—such as the use of advanced conductors, compact designs, or modular construction—alongside financial strategies and O&M practices. By integrating these insights with the World Bank Group's expertise in cost reduction, stakeholders can develop targeted optimization strategies for future investments, ensuring efficient resource allocation and improved project viability.

A full-page background image showing a high-voltage power line tower. A worker wearing a white hard hat and safety harness is positioned on a horizontal cross-arm of the tower, working on the power lines. The tower's lattice structure is prominent, and multiple power lines stretch across the frame. The sky is overcast and grey. The bottom portion of the image has a teal-colored gradient overlay.

FIVE CLOSING THE DATA GAP FOR COST OF TRANSMISSION

Reliable, affordable, and sustainable electricity systems are critical for achieving energy access, energy security, economic growth, and facilitate the energy transition. As countries accelerate renewable energy deployment, regional energy markets and electrification, transmission infrastructure becomes increasingly critical for ensuring system reliability, integrating variable resources, and reducing overall power system costs. Strengthening grids is therefore not only a technical necessity, but also a strategic pillar of climate and development policy.

This report addresses a persistent gap in the global energy literature and data foundations by providing data on the cost of transmission infrastructure for developing countries. Similarly, existing benchmarks are fragmented and largely centered on advanced economies. The absence of a unified methodological approach further limits comparability and evidence-based decision-making.

At the core of this contribution is the Transmission Cost Database compiled from 74 World Bank Group-financed projects between 2000 and 2024, representing approximately US\$ 21 billion in total investment. This database provides a comprehensive assessment of transmission costs in developing economies to date. By consolidating CAPEX, O&M expenditures, discount rates, implementation timelines, and regional variations within a single analytical framework, the Database introduces structured, comparable evidence into a review often shaped by limited data. The analysis demonstrates that projects can achieve competitive unit costs, manageable O&M levels, and financing terms supported by concessional structures—offering practical insights to inform economic analysis of transmission projects, transmission investment, and power systems planning.

At the same time, analysis of the database must consider important limitations. Conventional indicators such as US\$ per kilometer do not fully reflect financing conditions, utilization rates, implementation risks, or the broader system value of transmission assets. These difficulties are further compounded by manual and inconsistent reporting formats, variations in accounting practices, and differences in currency treatment, underscoring the challenges of conventional analysis and the need for more systematic, standardized, and harmonized data collection.

To move beyond the limitations of conventional metrics, this report introduces the Levelized Cost of Transmission (LCOT) framework. By shifting the perspective from cost per kilometer to cost per kilowatt-hour transported, LCOT integrates CAPEX, OPEX, discount rates, asset lifetimes, and energy flows into a unified indicator. This structure enables a more comprehensive measure of cost efficiency by relating infrastructure investment to the service delivered. It supports comparative benchmarking across projects and structured cost-benefit analysis, while also offering a platform to assess how technical design choices—such as advanced conductors, compact configurations, or modular construction—interact with financing conditions and O&M strategies to influence overall performance.

As an initial step, LCOT remains a complementary and evolving analytical tool. This paper considers a simple scenario of transferring power between two points. It thus reflects one

dimension of transmission efficiency and cost-benefit analysis. As assets are built for different purposes, LCOT may overstate costs over broader benefits such as resilience, price convergence, and energy security.

LCOT may shed lights for conducting robust Cost-Benefit Analysis (CBA) by establishing the cost of the preferred technical option, which is then used in the broader benefit assessment of the CBA. This ensures the most efficient solution is considered, preventing over- or under-costing during project justification.

Looking ahead, this report shows the benefits of transmission cost data. Capturing such data consistently across international financial institutions (IFIs) beyond World Bank Group could potentially further contribute to closing the global data gap. Moreover, broadening the scope of data collection to include additional infrastructure types—such as substations, distribution lines, and even related cost components like materials, labor, and maintenance—could further address existing data gaps. By capturing a wider array of technical and financial information, the report could offer deeper insights into cost drivers, system efficiency, and investment planning, ultimately enhancing the quality and relevance of the data for stakeholders across different regions and sectors. This expansion would support more informed policymaking, investment strategies, and project evaluations, contributing to more sustainable and cost-effective energy systems globally.

Further, establishing standardized reporting templates for transmission projects would significantly enhance comparability and transparency across countries and institutions. Advances in artificial intelligence offer promising opportunities both for automated data extraction and for deeper analytical use of the Database. AI-driven tools could support cost forecasting, anomaly detection, sensitivity analysis, and interactive benchmarking platforms for planners and financiers. Developing intelligent applications built on top of the Database could further strengthen evidence-based decision-making and accelerate investment readiness.

The value of this technical report lies in its effort to bring structure, transparency, and analytical rigor to an underexamined area of the energy transition. By compiling one of the most comprehensive transmission cost datasets focused on developing economies and introducing an innovative framework for cost assessment, this work contributes to more informed planning and financing decisions. Strengthening transmission systems is indispensable for universal electricity access, renewable energy integration, economic growth, and energy system decarbonization. Robust and well-planned grids enable private investment, support regional integration, reduce system costs, and enhance reliability. Ultimately, improving cost transparency and advancing analytical tools for transmission investment are essential steps toward building reliable energy systems worldwide, fostering economic opportunity through electricity access, and a decarbonized grid.

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