IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received 17 May 2023, accepted 1 June 2023, date of publication 6 June 2023, date of current version 12 June 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3283431

TOPICAL REVIEW

Recent Advances and Future Perspectives of HVDC Development in Pakistan: A Scientometric Analysis Based Comprehensive Review

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This work was supported by the National Natural Science Foundation of China under Grant 52150410399.

ABSTRACT Power generation in the global power sector has recently seen a paradigm shift from centralized bulk generation to distributed generation. In this regard, there are two transmission technologies available: high-voltage alternating current (HVAC) and high-voltage direct current (HVDC). The technical and economic benefits of HVDC transmission technology have enabled many countries to implement it widely for long-distance bulk power transmission, particularly between remote locations and densely populated areas. HVDC technology, however, is still relatively new in Pakistan. Despite this, HVDC technology holds great promise in Pakistan, specifically in utilizing and integrating distributed renewable energy sources with the national grid, as well as enabling cross-border energy trade. This study aims to provide a first-ever scientometric analysis of the HVDC technology field, highlighting key research themes and trends. A correlation is established between HVDC research and its adoption in Pakistan by extracting articles from the Scopus database and analyzing them with the VOS viewer, a modern data analysis tool. The scientometric analysis indicates a minimal contribution from Pakistani authors in the field of HVDC technology as compared to authors of the neighboring nations, highlighting a significant gap in knowledge transfer and technology adoption. Moreover, an overview of HVDC technology is provided, along with a comparison between HVAC and HVDC technologies. Last but not least, Pakistan's existing and proposed HVDC projects, prospects, and challenges associated with HVDC adoption are discussed.

INDEX TERMS HVDC, bulk power transmission, renewable energy, scientometric analysis.

I. INTRODUCTION

As an emerging economy, electricity requirements for Pakistan's domestic and industrial sectors have increased drastically. Several studies have shown a direct correlation between gross domestic product (GDP) growth and electricity demand in developing countries like Pakistan [1]. Various new power plants based on fossil fuels and renewable energy resources have been recently established to increase Pakistan's electricity generation capacity, while some are under construction [1]. Most of these power projects are located in Southern Pakistan [2] and are enlisted in Table 1 [3], [4]. Furthermore, several independent power plants (IPPs) based projects are also under construction.

By 2030, several thousand megawatts of power will be added to the national power grid to meet the country's ever-increasing socioeconomic requirements [5]. However, Pakistan's electricity transmission infrastructure is already weak and overloaded, thus incapable of handling this anticipated increase in electrical demand [6].

With the ever-increasing electricity demand, the transmission system has already proved to be a bottleneck in the

The associate editor coordinating the review of this manuscript and approving it for publication was Chandan Kumar.

TABLE 1. Newly installed/under construction power plants across Pakistan.

Technology	Project	Location	Capacity (MW)	Completion Year
Wind	Hydro China Dawood	Gharo	100	2017
	UEP Wind Farm	Jhimpr	50	2017
	Sachal Wind Farm	Jhimpr	50	2017
	Three Gorges Wind Power Project (1 & II)	Jhimpr	100	2018
	Cacho Wind Power Project	Jhimpr	50	TBA
Solar	Quaid-e-Azam Solar Park	Bahawalpur	400	2016
	Helios Power	Sukkur	50	2022
	HND Energy	Sukkur	50	2022
	Zhenfa Pakistan New Energy Company	Layyah	100	2022
Hydel	Suki Kinari Hydropower Project	Mansehra	870	2022
	Karot Hydropower Project	AJK	720	2022
	Kohala Hydropower Project	Muzaffarabad	1124	2025
	Azad Pattan Hydropower Project	AJK	700	2027
	Dasu hydel power Project	Dasu	4320	2025
	Diamer Bhasha dam	Kohistan	4800	2028
Coal	Sahiwal Coal Power Plant	Qadarabad	1320	2017
	Port Qasim Coal Power Plant	Port Qasim	1320	2018
	China Hub Coal Power Project	Hub	1320	2019
	Engro Thar Coal Power Project	Thar	660	2019
	HUBCO Thar Coal Power Project	Thar	330	TBA
	Thal Nova Thar Coal Power Project	Thar	330	TBA
	Gawadar Coal Power Project	Gawadar	300	TBA

*TBA: to be announced

country's power system. The existing power generation units and the majority of the renewable energy resources, such as wind, solar and hydro, are located in the extreme north and south of the country. In contrast, the majority of the big load centers are situated in the center.

Under this scenario, low-loss, efficient, cost-effective bulk energy transfer technology is required to fulfill the transmission system requirement of the country. HVDC transmission technology is the best suited for this purpose.

To the best of the authors' knowledge, this is the first scientometric analysis of the HVDC technology field, providing a unique perspective on the collaboration and impact of research in this area based on a country's number of publications and international collaboration. Through our innovative approach to scientometric analysis, we identified key research themes and trends in the HVDC technology field, offering new insights into this rapidly evolving area of research.

In addition, this review aims to compare HVDC and HVAC transmission technologies comprehensively. Also, different types of converter technologies utilized in HVDC transmission are discussed. Lastly, a comprehensive overview of present and proposed HVDC projects in Pakistan is presented, that if completed, will significantly boost the transmission capabilities of the country.

The remainder of the paper is structured into several distinct sections for a comprehensive analysis of HVDC technology in Pakistan. Section II presents a meticulous scientometric assessment of the research landscape in the field, providing valuable insights and trends to identify areas for further exploration. Following this, Section III offers a detailed technical comparison between HVDC and HVAC transmission technologies, while Section IV provides a comprehensive overview of HVDC transmission technology itself. Subsequently, Section V delves into the present scenario of Pakistan's power sector, setting the context for the subsequent sections. Section VI focuses specifically on the development of HVDC transmission systems within Pakistan, highlighting key aspects and progress made. Building upon this, Section VII explores the future prospects of HVDC technology in Pakistan, while Section VIII discusses the pertinent challenges associated with its adoption. Finally, Section IX

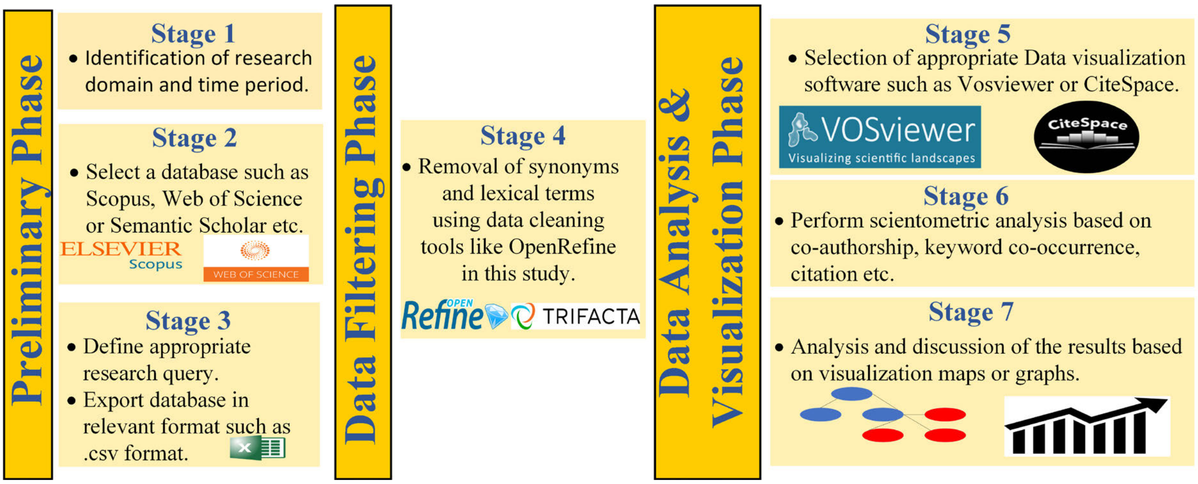

FIGURE 1. Procedure adopted for scientometric analysis.

concludes the paper by summarizing the key findings and offering valuable recommendations for further research and implementation.

This well-organized structure provides a comprehensive assessment of HVDC technology in Pakistan, including research trends, technical intricacies, existing scenarios, future potential, barriers, and practical insights.

II. SCIENTOMETRIC ASSESSMENT

In this article, a brief scientometric analysis has been conducted to give a general assessment of HVDC transmission technology in power systems applications. According to the author's knowledge, no bibliometric study has been done on the HVDC technology research field. Therefore, this is the first-time a thorough scientometric study was undertaken due to the vast amount of technical literature published and the difficulty of physically reviewing all of the literature regarding the HVDC transmission technology. The purpose of scientometric assessment is to use colored graph theory to quantitatively depict scientific knowledge based on the literature database of the particular field [7]. This study used the VOS viewer tool to conduct a descriptive statistical-based scientometric assessment for HVDC transmission [8]. VOS viewer is a software program based on machine learning that provides statistics for functions, visualization, and scientometric research networks [9].

The scientometric analysis depicted in Figure 1 is carried out using the following seven-step procedure that is an amalgamation of methodologies suggested by the authors in [10] and [11]: (i) Identify the domain and period for the literature, (ii) Choose a specific database, such as Scopus chosen in this study, which has a sizable and reputable corpus of scientific literature, (iii) specify a proper keyword search, and export in comma separated value (CSV) format, (iv) Refine the obtained data using data cleaning tools like Open Refine for removal of any repetitions, (v) Select appropriate scientometric analysis tool such as VOS viewer, (vi) perform analysis and visualization of scientometric networks for authors, journals, and keywords, (vii) interpret the results through visualization maps and graphs.

In this regard, the following search query for data extraction was searched in the paper's title, abstract, as well as keywords: TITLE-ABS-KEY ("high voltage direct current") AND PUBYEAR > 2012 AND PUBYEAR < 2023 AND (LIMIT-TO (DOC-TYPE, "ar") OR LIMIT-TO (DOC-TYPE, "cp")) AND (LIMIT-TO (SUBJAREA, "ENGI") OR LIMIT-TO (SUBJAREA, "ENER") OR LIMIT-TO (SUBJAREA, "COMP") OR LIMIT-TO (SUBJAREA, "MATH") OR LIMIT-TO (SUBJAREA, "MATE") OR LIMIT-TO (SUBJAREA, "PHYS") OR LIMIT-TO (SUBJAREA, "ENVI") OR LIMIT-TO (SUBJAREA, "DECI") OR LIMIT-TO (SUBJAREA, "CHEM") OR LIMIT-TO (SUBJAREA, "CENG")).

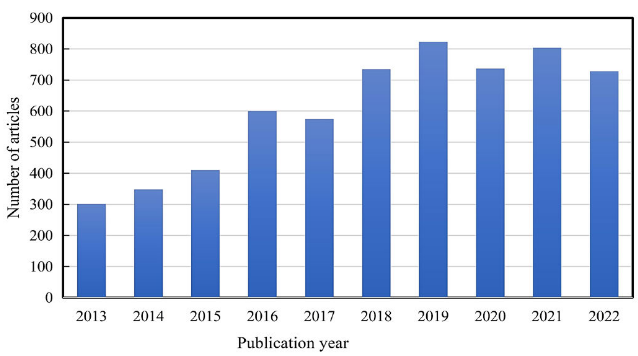

FIGURE 2. Yearly publication trend in the period 2013-2022.

As a response, networks of bibliometric data that reflect the interaction between the concurrence of keywords, nations, and scientific journals were visualized and grouped. These networks are presented and analyzed in the subsections that follow. In particular, the results of the scientometric analysis conducted as part of the current work are a significant

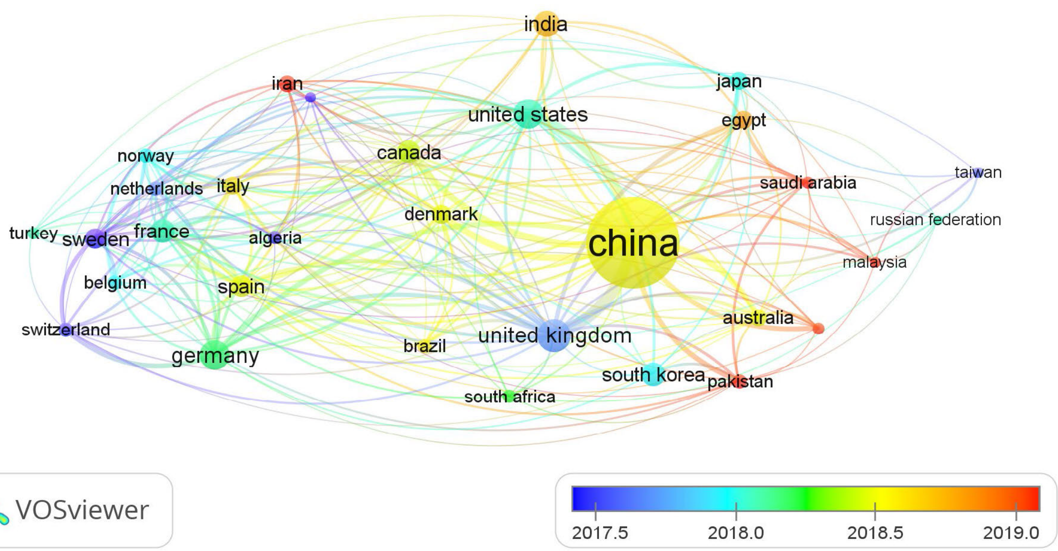

FIGURE 3. Scientometric network visualization map based on countries.

contribution to the effort to formulate a data-driven approach for determining the research trends and difficulties related to HVDC transmission globally, particularly in Pakistan.

A. YEARLY PUBLICATION TREND

The abovementioned search matched 6,128 publications after being checked against the Scopus database. Figure 2 illustrates the development and status of the HVDC domain using the annual pattern of scientific production (i.e., the number of research publications) between 2013 and 2022. The information provided demonstrates that many research studies were carried out over the period under consideration. The number of publications has significantly risen from 2013 until reaching its highest value of 823 publications in 2019. This steady increase mainly contributed to academics and researchers worldwide concentrating on using HVDC technology for renewable energy applications, providing energy services, and mitigating climate change. However, after 2019, the number of publications was approximately halted, ranging from 737 to 804, which reflects that the HVDC field is a challenging domain that requires consistent research and development.

B. COUNTRY-SPECIFIC PUBLICATION DISTRIBUTION

VOS viewer has been used to create a statistically-driven representation of any country's co-authorship networks based on each country's number of publications and the strength of its collaborative effort, also referred to as link strength. Examining international collaboration through this evaluation enables one to recognize a country's significant contributions to advancing HVDC technology. The map of co-authorship based on countries is illustrated in Figure 3. To refine the results, a threshold of 25 articles per country is set so that a total of 31 out of 135 countries meet the criteria. Also, the data is used to classify and tabulate the top 25 countries concerning the number of publications in Table 2.

TABLE 2. List of top 25 countries based on the number of publications in HVDC technology domain.

Sr. No.	Country	Publications	Citations
1	China	3610	36836
2	United Kingdom	380	6694
3	Germany	311	2842
4	United States	298	7001
5	India	237	1583
6	South Korea	184	1853
7	France	182	1818
8	Canada	161	2216
9	Spain	142	2062
10	Sweden	137	2534
11	Denmark	113	1955
12	Japan	103	608
13	Egypt	100	1144
14	Italy	96	604
15	Australia	87	1176
16	Iran	79	631
17	Belgium	65	1768
18	Switzerland	64	756
19	Netherland	59	768
20	Norway	57	1306
21	Brazil	56	464
22	Pakistan	56	525
23	South Africa	55	461
24	Algeria	48	256
25	Singapore	46	763

It is evident from Figure 3 that China is leading in the field of HVDC technology in terms of a total of 3,610 publications and 36,836 citations. In contrast, Pakistan comes in 22nd place in publications, thus lacking significant collaboration with the three major countries, China, the United Kingdom, and

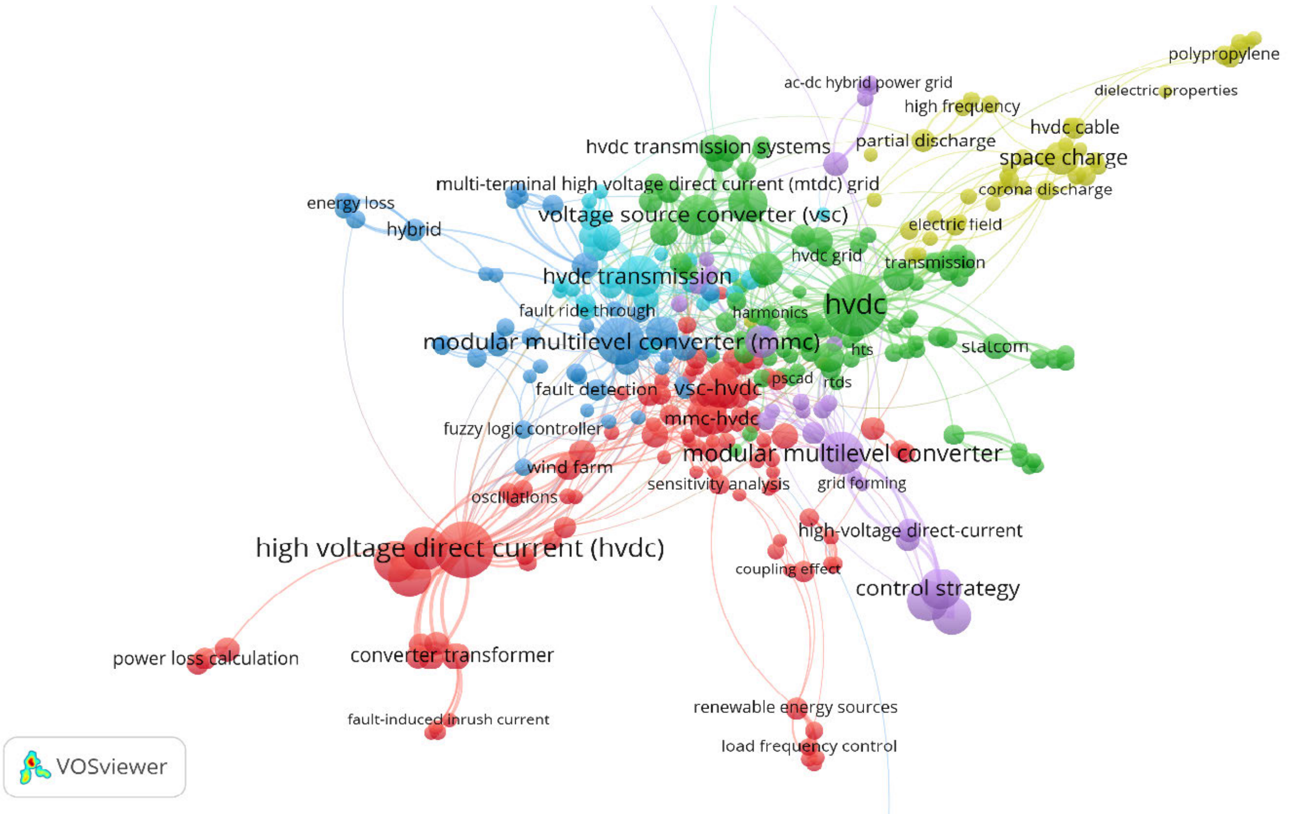

FIGURE 4. Concurrence analysis of author keywords.

Germany. Pakistan's research collaboration in the domain, as mentioned earlier, with significant countries is insufficient, even when compared to its neighbors like India and Iran, which ranks in the 5th and 16th positions in the number of research publications.

C. ARTICLE KEYWORD ANALYSIS

To track and investigate trends in any particular research domain, keyword analysis in research articles is extremely intriguing [12], [13], [14]. As a result of the above search query, a total of 12,758 keywords between 2013 and 2022 were obtained. However, the quantity was too large to be divided into manageable research clusters. To make data more meaningful, removing any keywords conveying the same meaning and having similar spellings and pronunciation was necessary.

Open Refine, an open-source tool, was utilized for grouping and combining text with high similarity using algorithms such as Metaphone3 in this study. Lastly, the obtained keywords from Open Refine were further analyzed and modified manually to incorporate redundant keywords such as voltage source converter and VSC. After the data mentioned above filtering, 8,547 cases were finally selected.

After a series of trials in VOS viewer, the author's keywords concurrence was analyzed after selecting the minimum number of occurrences and cluster size to ten and thirty, respectively. As a result, 339 out of 8,547 keywords met the threshold, and six clusters formed. This ensured research continuity and narrowed the research focus. Table 3 shows the top 25 keywords in the field of HVDC technology whereas Figure 4 depicts the linkage of the topics investigated using the acquired maps of keyword concurrence analysis in the period under consideration.

In Figure 4, each node represents a keyword associated with the HVDC domain in the obtained keyword concurrence network. Each term's node size is directly proportionate to a keyword's occurrence, with relatively more prominent nodes representing a gradually increasing repetition of the keyword. The link among the nodes depicts the relationship between the investigated keywords. Also, the closer two or more terms appear the smaller the distance between them. The more similar two or more terms are, the closer they seem. Furthermore, the thickness of a respective line indicates that these keywords emerged together in numerous papers in the acquired publication data.

According to Figure 4, the most outstanding cited term by article authors (i.e., the larger-sized nodes) is 'high voltage direct current (HVDC),' with 1,737 occurrences and the maximum overall link strength with other terms of 4,347, indicating it as a hot spot in the research domain. Even though these clusters are deeply connected and have overlapping themes, six different strands are distinguishable.

Cluster 1 (red) was the greatest and constituted the most items (106) and was primarily concerned with the application

TABLE 3. List of the 25 most used keywords in HVDC technology domain.

Keyword	Concurrences	Total link strength
high voltage direct current (HVDC)	1737	4347
voltage source converter (vsc)	899	2653
Modular multilevel converter (mmc)	958	1413
Wind turbine generator	410	1206
dc fault	260	1073
HVDC transmission	337	912
multi-terminal dc grids (MTDC)	279	911
control strategy	299	724
probabilistic reliability	225	675
dc protection	155	640
dc circuit breaker	96	384
commutation failure	197	355
converter valve equipment	162	324
drop control	66	300
load commutation switch	123	277
converter transformer	65	268
power conversion	78	264
off-shore windfarm	113	194
dc grid	61	171
volage control	56	169
frequency control	46	157
coordinated operation and control	19	152
steady-state analysis	22	156
power system control	20	151
fault location	46	106

of the core keyword, i.e., high voltage direct current (HVDC) technology in the context of renewable energy generation, power system expansion planning, and reliability. This cluster included keywords like probabilistic reliability, expansion planning, HVDC grids, multi-terminal dc grids (MTDC), and offshore wind farms. Cluster 2 (green) contains 88 items that are focused on voltage source converter (VSC) based multi-terminal grids and their associated control and protection, as evidenced by the keywords: voltage source converter, multi-terminal high voltage direct current grids (MTDC), power flow control, dc circuit breakers, secondary control, and droop control. Cluster 3 (violet), with 53 items, is primarily concerned with the study of modular multi-level converter (MMC) technology in HVDC systems and consists of keywords like sub-module failures, converter fault tolerance system, reliability, fault detection, fault ride through an insulated gate bipolar transistor (IGBT) which are vital research topics in this type of systems. Cluster 4 (yellow), with 42 items, is concerned with the study of insulation coordination of HVDC transmission cables as evidenced by keywords such as HVDC cable, cross-linked polyethylene (xlpe), space charge, and corona discharge. Cluster 5 (purple) includes 33 keywords associated with MMC control. Lastly, cluster 6 (blue) deals with keywords linked to HVDC transmission, such as transformers, dc bias, HVDC line protection, fault location, etc.

III. TECHNICAL COMPARISON OF HVDC AND HVAC TRANSMISSION TECHNOLOGIES

The primary goal of developing a transmission system is to reduce power losses and provide power at the lowest possible

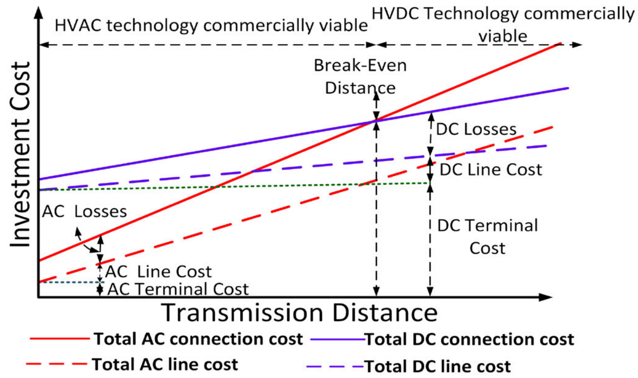

FIGURE 5. HVAC and HVDC technology cost comparison as a function of transmission distance.

TABLE 4. A comprehensive comparison between HVAC and HVDC technologies.

Characteristics	HVAC	HVDC
Active and reactive power control	complex (required external components like FACT devices)	Easy (inherent VAR control in VSC-HVDC)
Grid interconnection requirement	Only synchronized grid interconnection is possible	Asynchronized grid inter-connection is possible
Bulk power transmission capacity	No	Yes
Reliability	Low	High
Skin effect	Yes	No
Space requirement	More	Less
Right of way	May exceed three times that of similar rated HVDC system	Narrow
Charging current phenomena	Present	Absent

cost. In Pakistan, the conventional and non-conventional energy generation centers are typically far from the load centers, typically located in the extreme south or north of the country. Also, under China Pakistan Economic Corridor (CPEC), most new energy projects are located in the south and southeast of the country, where an adequate electrical transmission network is absent [15].

Pakistan's existing long transmission system comprises HVAC technology, which causes significant transmission losses [15]. Compared to HVAC, utilizing HVDC transmission over large distances gives various techno-economic advantages, like; the absence of transmission line capacitance (charging current) effects, costs associated with HVDC transmission losses are substantially lower than HVAC [16]. Also, the absence of line charging capacitances in HVDC transmission lines only leads to resistive line losses, thus eliminating the need for expensive external AC reactive power compensators [17], [18]. Compared to HVAC transmission, HVDC transmission requires fewer cables/conductors and uses the full transmission capacity of the lines up to their rated thermal limits.

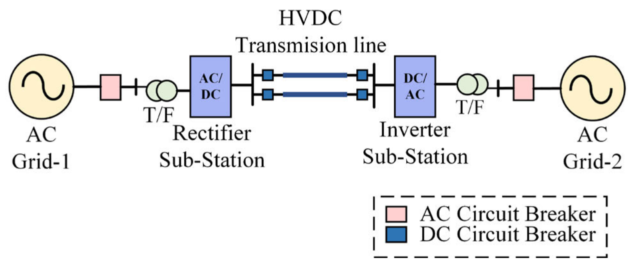

FIGURE 6. **Schematic diagram of HVDC transmission system.**

This minimizes the necessary cross-sectional area for DC cables and, as a result, the transmission cost [19], [20], [21]. Furthermore, the minimum horizontal land space clearance, also known as Right-of-Way (ROW), for HVDC transmission is significantly less than for HVAC transmission for overhead and underground bulk power transmission alternatives [22]. Lastly, some technical and non-technical issues regarding HVAC technology are; corona losses, skin effect, proximity effect, high visual pollution, and electromagnetic interference, which are mitigated by employing HVDC systems [23].

The main expense of an HVDC system is related to the converter station, which includes the converter valves, smoothing reactors, and transformers. These costly rectifiers and inverter stations for AC/DC and DC/AC conversion that are not required in the HVAC applications significantly increase the terminal cost of HVDC systems, as shown in Figure 5.

Nonetheless, the reduced HVDC transmission line costs and losses are heavily weighted in favor of HVDC technology. As a result, a breakeven distance for both HVAC and HVDC technology is established, after which HVDC transmission becomes commercially viable, as illustrated in Figure 5 [21], [24]. Due to material cost differences, the breakeven distance varies between overhead transmission lines (400-700 km) and under-ground/submarine cables (25-50 km) [25]. Although initial costs associated with HVAC technology are lower, as the transmission distance increases, it becomes costlier than HVDC transmission due to reactive power compensation and increased line losses.

Thus, HVDC transmission technology is best suited because of its techno-economic superiority over HVAC transmission technology [17]. A comprehensive comparison between HVAC and HVDC technologies is given in Table 4 [24], [26], [27].

IV. OVERVIEW OF HVDC TRANSMISSION TECHNOLOGY

In the late 1940s, with the advent of solid-state power electronic components, HVDC systems technology gained significant attention from researchers. HVDC systems are generally used for two primary reasons: (i) Bulk energy transfer over long distances and (ii) interconnecting asynchronous AC grids. DC transmission provides lower losses

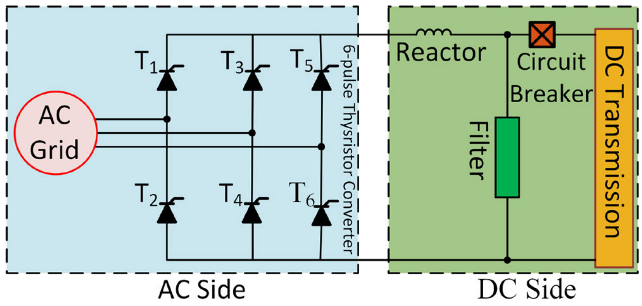

FIGURE 7. **LCC-based HVDC transmission topology.**

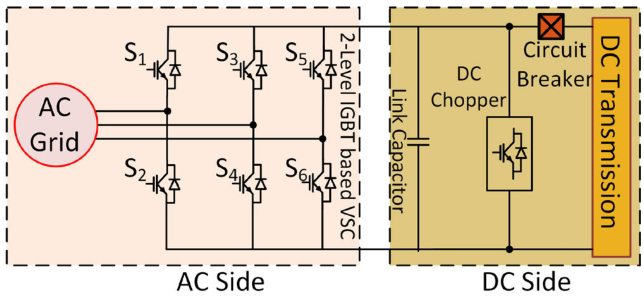

FIGURE 8. **VSC-based HVDC transmission topology.**

than AC transmission of a similar power rating for long-distance transmission.

An HVDC system's primary operating principle is to convert AC into DC at the transmitting/rectifier station and back to AC at the receiving/inverter station [28]. As a bidirectional device, the HVDC converter can operate under rectification and inversion modes, thus simplifying the system. Like an AC transmission system substation, an HVDC converter station has essential terminal devices, such as switchgear, converters, transformers, and other auxiliary equipment, to permit AC-to-DC and DC-to-AC conversion [24], [29]. The schematic diagram of a basic HVDC system is shown in Figure 6.

A. CONVERTER STATION

High-voltage AC is converted to DC at a converting station, and DC is then converted back to AC. There are two main types of converters used in HVDC systems [24], [30], [31], [32], [33], [34], [35], namely Line Commutated Converters (LCCs) and Voltage Source Converters (VSCs), as illustrated by Figure 7 and 8 respectively. These two technologies are developed to take advantage of developments in power electronic devices, primarily thyristors, and IGBTs. LCC-HVDC converters incorporating thyristor valves were prevalent in the 1970s [14]. However, in the 1980s, with the advent of IGBT technology, the HVDC industry was revolutionized, and HVDC transmission technologies became more reliable and mature. A window emerged to develop and implement VSC-HVDC transmission networks using IGBTs instead of thyristor valves [15]. By 1997, ABB commissioned a 3 MW, 10 kV Hallsjon VSC-HVDC pilot project in Sweden [36].

TABLE 5. VSC-HVDC projects installed worldwide.

Project	Country	Rated capacity (MW)	Rated DC link voltage (kV)	Transmission distance (km)	Operational year
Gotland	Sweden	54	±80	70	1999
Eagle Pass B2B intertie	U.S.A – Mexico	36	±15.9	0 (inter-tie)	2000
cross Sound Cable	U.S.A	330	±150	40	2002
Estlink	Estonia – Finland	350	±150	105	2006
Valhall off-shore	Norway	78	±150	292	2009
Trans Bay Cable	U.S.A	400	±200	88	2010
Caprivi Link	Namibia	300	±350	951	2010
Shanghai Nanhui	China	18	±30	8.6	2011
Nan'ao	China	200	±160	40.7	2013
Inelfe	France	1,000	±320	65	2013
Skagerrak 4	Norway	700	±500	244	2014
Zhoushan	China	1,000	±200	140.1	2014
Xiamen	China	1,000	±320	10.7	2015
DolWin1	Germany	800	±320	165	2015
Luxi	China	3,000	±500	0 (inter-tie)	2016
Yu'e	China	5,000	±420	0 (inter-tie)	2019
Zhangbei	China	9,000	±500	666	2020
Wudongde	China	10,200	±800	1,489	2020
Syd-vastlanken	Sweden-Norway	1,400	±300	570	2021
Baihetan	China	1,6000	±800	2,172	2022

The project's successful operation highlighted VSC-HVDC's ability to integrate renewable and non-renewable energy sources into the grid and allow remote load interconnection.

The switching frequency of LCC-HVDC technology is low; the power losses are lower than VSC-HVDC, which has a high switching frequency due to PWM used to control the gate signal [37]. Because the thyristor is just a turn–on device, power flow in LCC-HVDC is managed by regulating the firing and extinction time of gate control signals before commutation to the subsequent valve, making it more susceptible to commutation failure [30], [38]. The power flow in the LCC system is unidirectional, as changing the power flow direction is problematic because it would necessitate a polarity change [39]. In LCC-HVDC, reactive power (Q) is consumed on both the inverter and rectifier stations, which must be supplied from the AC side via filters and additional capacitors. The LCC-HVDC system consumes 60% of the transmitted power as reactive power. So, shunt capacitors must be added to the AC bus to sustain the reactive power [40], [41]. However, the LCC-HVDC substation has less than 1% losses at the rated current, out of which the converter station transformer accounts for 50% of the losses [30]. VSC-HVDC transmission systems have become popular for long-distance bulk power transmission due to their numerous techno-economic benefits, undoubtedly outweighing some limitations. In contrast to LCC technology, VSC-HVDC systems provide high dynamic performance, the ability to black-start, and multi-terminal interconnection capability. Also, independent active and reactive power control is achievable, thus eliminating the need for any external harmonic filter [19], [42]. A VSC station adds 1.6 % to total losses, with converter valves accounting for 70% of the total losses [43], [44]. However, in VSC converter stations, anti-parallel diodes to IGBTs operate as an unregulated rectifier in the event of a DC failure. Due to the system's low impedance, there is a high rate of DC fault current. DC capacitors also discharge and help the fault current [45], [46]. VSC-HVDC technology can be switched on and off at any time, regardless of the AC voltage, and can generate voltages even after a black start [37]. Also, this technology offers great flexibility, making it more useful in urban power networks [47]. Several VSC-HVDC projects have been completed or are in the planning stages worldwide, as summarized in Table 5 [29].

Some VSC-HVDC limitations are associated with the IGBT capacity rating and higher losses compared to the LCC system of a similar rating. And high dielectric stress on equipment insulation is expected to be addressed with further improvement in IGBT semiconductor technology [24], [48]. According to a recent analysis by BNEF (Bloomberg New Energy Finance), VSC-HVDC technology might account for 65% of new projects by the end of this decade [24]. A comparison of various dissimilarities between LCC-HVDC and VSC-HVDC technologies is summarized in Table 6 [24], [38].

B. HARMONIC FILTERS AND REACTIVE POWER COMPENSATION DEVICES

Depending on the converter topology, several filters may be required for an HVDC system. The AC filter is connected to the AC side of the converter transformer, while the DC filter is connected to the DC side. AC filters prevent harmonics and high-frequency components from entering the system. In contrast, DC filters avoid the inference of harmonic voltages in transmission lines where currents overlap and cause noise, thus preventing overheating of adjacent components [49].

High harmonic distortions in the system voltage are caused by switching thyristors, which may impact surrounding installations. Thus, additional filters are required to reduce the harmonics in LCC-HVDC. The DC smoothing reactor flattens the DC and creates the DC filter.

In contrast to LCC-HVDC technology, VSC-HVDC technology does not produce lower order harmonics. Therefore, only the high-frequency PWM signals must be filtered in PWM-based converters. Also, because a VSC system does not require reactive power adjustment, the AC harmonic filters have a lower rating than LCC-HVDC. Low-pass filters (LC filters) are commonly employed to dampen high-order harmonic components. Lastly, DC filters are used in parallel with the DC capacitor to prevent harmonics from being fed into the DC grid in the VSC-HVDC systems [50].

TABLE 6. Dissimilarities between LCC and VSC HVDC technologies.

Characteristics	LCC-HVDC	VSC-HVDC
Switching Components	Thyristor	IGBT
Switching frequency range	50-60 kHz	1-2 kHz
Operational power rating	± (400 – 1100) kV, 6400 MW	± (220 – 500) kV, 400-800 MW
Converter loss	Low	High (approximately 1 % of rated power)
Harmonic distortion	High	Low
Inherent reactive power control	No	Yes
Power flow	Unidirectional	Bidirectional
Reliability and maturity	High	Low
Black-start capability	Absent	present
Power reversal mechanism	Voltage polarity	current direction
DC rector requirement	Large	Small
DC fault current handling	Low, controllable	High, uncontrollable
Multi-terminal grid interconnection capability	Restricted	High

C. TRANSFORMER

It is a static device used to change the voltage level at the AC side of the HVDC system. HVDC converter transformers may have different design requirements than AC power transformers [24]. In an HVDC installation, transformers are not usually required. However, they are always employed in HVDC systems for various reasons, such as enabling the DC system voltage to be optimized independently of the AC transmission system. The converters are additionally isolated from the associated AC networks by trans-formers. To reduce losses, tap-changers can be employed. The coils of the transformer act as a smoothing reactor, limiting the flow of current into valves during short circuits.

D. HVDC SWITCHGEAR

The primary function of switchgear is to ensure safe switching operations and assist the system in operating normally even after being subjected to fault conditions [23].

V. PRESENT SCENARIO OF PAKISTAN'S POWER SECTOR

Electric power demand is essential in determining the most cost-effective transmission methods. The expected population increase and other demand-related factors determine future electricity generation demand. As per UN population data, Pakistan's population climbed from 183.3 million in 2011 to 225.2 million in 2021. This is approximately a 2.28% rise in the total population each year.

Therefore, according to UN estimates and assuming an annual growth rate of 2.28%, the country's population is expected to reach around 263 million in 2030 [51].

Likewise, Pakistan's demand for electricity is soaring. The total generation and demand data from both the national transmission and dispatch center (NTDC) and Karachi Electric (KE), as stated in the 'State of the Industry Report' by the National Electric Power Regulatory Authority (NEPRA), is summarized in Table 7. It is seen that the country is facing a power deficit issue [4].

Pakistan's electricity consumption is systematically anticipated as part of the Indicative Generation Capacity Expansion Plan (IGCEP) 2021-30 [52]. Furthermore, a study conducted by Abbasi SA et al. has proposed that Pakistan's electricity demand is expected to rise from 122 TWh in 2020 to 1,552 TWh in 2050, showing an average 8% annual growth [53], as illustrated in Figure 9.

TABLE 7. Total generation capacity and peak hour demand data of Pakistan.

Year	Generation capacity (MW.)	Peak hour demand (MW.)
2017	21,940	28,387
2018	26,774	30,268
2019	27,761	29,157
2020	30,982	29,856
2021	31,243	31,857

At present, Pakistan's sources of power generation include thermal (coal, furnace oil, RLNG), hydel, nuclear, and renewable (wind, biogas, and solar) energy. Thermal power plants are responsible for generating bulk power in the country;

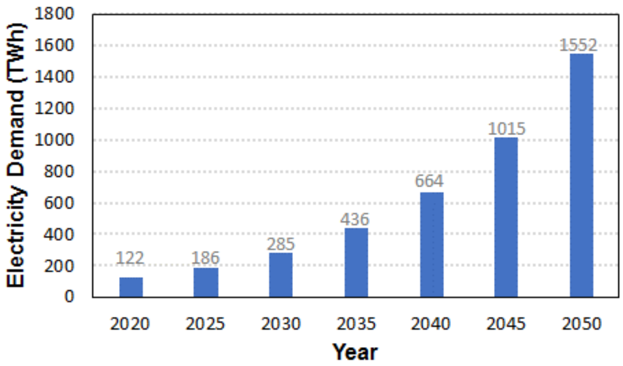

FIGURE 9. Expected electricity demand of Pakistan.

nevertheless, the pollutants from these power stations pollute the environment severely.

Accordingly, countries worldwide are shifting to green energy, employing wind and solar power. Pakistan has significant potential for hydel generation. Still, the requirement for vast land areas, relocation expense of affected people, extremely high initial investment, and various environmental and social constraints have hampered the construction of hydel power facilities in the past [54]. As of 2021, Pakistan has a total installed generation capacity of 39,772 MW, including renewable and non-renewable energy resources. The contribution of various renewable energy resources in the entire energy mix of Pakistan is 9,915 MW of hydropower, 1,248 MW of wind, 530 MW of solar, 369 MW of bagasse, and 2612 MW of nuclear. While in the case of non-renewable resources, 24,607 MW is thermal, and 491 MW is contributed by Small Power Producers (SPPs) and Captive Power Producers (CPPs). The total energy mix of Pakistan in 2021 is depicted in Figure 10 [4]. It can be concluded that Pakistan heavily depends on thermal fuels such as coal and oil, much of which is imported, for power generation. Pakistan's economy is struggling and debt-ridden; therefore, importing fuel for power generation will further increase the burden on the country's national reserves.

NTDC and KE are the two entities responsible for power transmission in Pakistan. At present electrical transmission network of Pakistan is degraded and overloaded [55]. As of 2020, the transmission network capacity of Pakistan was stalled at 22,000 MW [56]. By the end of 2021, Pakistan, under the umbrella of the China-Pakistan Economic Corridor (CPEC), completed the installation of its first-ever 4000 MW, ± 600 kV HVDC link from Matiari to Lahore. Although, this project contributed to increasing the transmission capability of the country to roughly 26,000 MW. However, around 5,000 MW of electricity generation still cannot be transmitted due to the congestion in the transmission system, as observed in Table 7. Ultimately, this unused, excess generation capacity contributes to huge circular debt in Pakistan's energy sector. In addition, there is a significant mismatch between electricity generation and demand. To meet the new demand, substantial investments in power generation and transmission are needed.

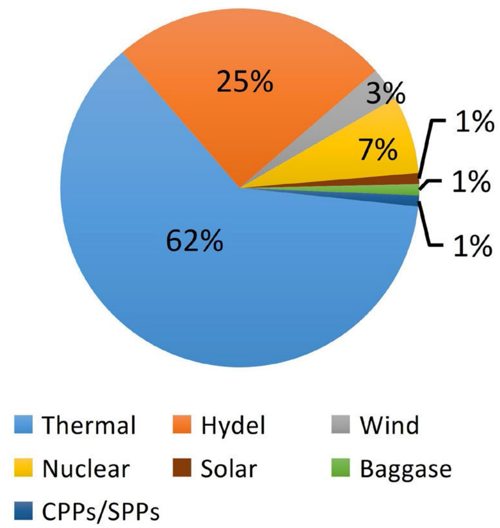

FIGURE 10. Energy mix by source in Pakistan.

Although several new conventional and non-conventional power plants are planned to be connected to the national grid by the end of 2022, all these power plants are located far from major load centers. The present literature well establishes that a traditional HVAC transmission system is unfeasible for long-distance bulk energy transfer, especially if the transmission distance is more significant than 644 km [23]. Accordingly, the HVDC transmission system is more techno-economically feasible, especially for integrating remotely located conventional and non-conventional energy resources and cross-border electricity trade.

VI. DEVELOPMENT OF HVDC TRANSMISSION SYSTEM IN PAKISTAN

To meet Pakistan's ever-increasing demand for electricity, the development of HVDC transmission lines with technical, economic, and environmental benefits should be accelerated. This will enable the utilization of the various available energy resources and connect the several regions of the country which previously had not been electrified.

The HVDC project can take advantage of the coal potential available in Thar (the country's southeast) and connect it to the densely populated load centers in the east. Similarly, Pakistan's northern regions have abundant hydroelectric potential far from the load center. Furthermore, the country's southeast region (for example, Thatta in Sindh province) has much wind energy potential. On the contrary, the eastern region of the country (Punjab) and the southern region (Karachi), unquestionably Pakistan's economic center, have a lot of load demand. As a result, long-distance power transmission lines that are both economical and efficient are becoming increasingly important in connecting different regions of the country. Furthermore, the government of Pakistan intends to import electricity from neighboring countries, and HVDC

TABLE 8. Analysis of wind electric potential in Pakistan.

Resource Potential	Wind power class	Wind Speed (m/s)	Wind Power Density (W/m^2)	Area coverage (km^2)	% Area	Expected total wind electric output (GW)
Poor	1	0.0-5.4	0-200	357,775	40.8	1,788.88
Marginal	2	5.4-6.2	200-300	82,874	9.4	414.37
Fair	3	6.2-6.9	300-400	123,951	14.1	619.76
Good	4	6.9-7.4	400-500	18,106	2.1	90.53
Excellent	5	7.4-7.8	500-600	5,218	0.6	26.10
Outstanding	6	7.8-8.6	600-800	2,495	0.3	12.48
Superb	7	>8.6	>800	543	0.1	2.72

Note: The total capacity installed is calculated based on the assumption that 5 MW of capacity can be installed per km^2 of land.

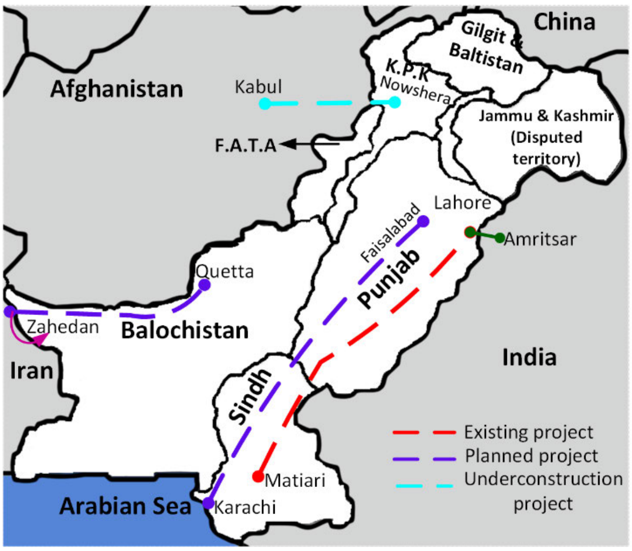

FIGURE 11. Outline of HVDC projects in Pakistan.

transmission can be used efficiently for this purpose. A comprehensive overview of various HVDC projects completed or under the planning phase is presented in the subsequent section and illustrated in Figure 11.

A. MATIARI-LAHORE TRANSMISSION LINE PROJECT

The country's first HVDC project under CPEC started its commercial operation on 1st September 2021 [57]. The Matiari-Lahore HVDC transmission line aims to evacuate electric power from coal-based power plants located at Thar, Port Qasim, and Hub in the Southern region to the load centers in Punjab province. A 185 km long 500 kV AC transmission line from the Port Qasim power plant and a 200 km long 500 kV AC transmission line from the HUBCO power plant feed power to the Matiari converter station. Also, another set of 275 km and 250 km AC transmission lines from SSRL Thar Block 1 and Engro Thar coal power plants are connected to the Matiari converter station, respectively [3].

This project implements a bipolar operation with a transmission capacity of 4,000 MW at $\pm$ 600 kV across an 886 km line length from Matiari (Sindh) to Lahore (Punjab). More than 60% of the transmission line route is in desert areas to avoid issues like settlement and conflicts over the right-of-way. A grounding station consisting of a 40 km long electrode line is situated at each converter station. Furthermore, LCC-HVDC technology is utilized for the two substations at each end of the line. Also, each HVDC substation is connected to the national grid via 500 kV HVAC lines.

This project is solely invested in, constructed, and operated by State Grid Company of China (SGCC) under the BOOT (build-own-operate-transfer) concept for 25 years. After this period, the project will be handed over to NTDC. The estimated cost of this project is around 1658.34 million USD.

B. PORT QASIM-FAISALABAD TRANSMISSION LINE PROJECT

In recent years, Faisalabad, Pakistan's textile capital, has faced numerous power outages, which forced many textile units to close. An HVDC project is similar to the Matiari-Lahore HVDC transmission line was proposed under CPEC in 2015 to meet Faisalabad's energy needs [58]. The proposed project involved the construction of a $\pm$660 kV 1,150 km long HVDC transmission line in evacuating 4000 MW of power from port Qasim to Faisalabad. The first study was conducted in 2016, using load flow data from the Matiari-Lahore and Port Qasim-Faisalabad HVDC transmission lines [59]. However, the work on this project is halted until another study is carried out to reassess the need for this project [60].

C. CASA-1000

The Central Asian states are among the world's richest energy-capacity countries. Kyrgyzstan and Tajikistan are two Central Asian countries possessing some of the world's most plentiful hydropower resources [61]. During the summer season, both countries generally have hydro energy surpluses that, if not utilized, would have been spilled and wasted. In the last decade, Pakistan and Afghanistan have been considered resource-rich countries to ensure energy supplies due to limited energy resources and poor infrastructure.

Under this circumstance, Tajikistan, Kyrgyzstan, Afghanistan, and Pakistan agreed in 2006 to create a 1400 km long high voltage DC cross-border energy transmission grid project known as Central Asia South Asia-1000 (CASA-1000). The project plans to export 1300 MW of power from Kyrgyzstan and Tajikistan to Afghanistan (300 MW) and Pakistan (1000 MW) [62]. This 1.2 Billion USD project, funded by various international agencies, was meant to be completed in 2018. However, due to various economic and political constraints, the project is anticipated to be completed in 2024 [63].

The CASA-1000 project design includes constructing a 477 km long 500 kV HVAC link from Datka, Kyrgyzstan, to Khujand, Tajikistan. From there, a new 150 km long, 500 kV AC transmission line will be constructed to evacuate the power to Tajikistan's Sangtuda HVDC converter station. A three-terminal ±500 kV, 750 km long bipolar HVDC link will connect the HVDC converter station in Nowshera, Pakistan, to the Sangtuda HVDC converter station via a converter station in Kabul, Afghanistan. The combined capacity of Sangtuda, Kabul, and Nowshera HVDC converter stations is 1300 MW, 300 MW, and 1000 MW, respectively.

D. CROSS BORDER ELECTRICITY IMPORT FROM IRAN AND INDIA USING HVDC TECHNOLOGY

The diversified electrical power supply is of utmost importance for advancing economic development. In this regard, the GoP, in the past, has planned to import electricity from its neighboring, Iran, and India. However, these projects have halted in recent years due to various geopolitical conflicts.

According to a supply-demand balance analysis, Iran will have a significant excess of power to export in the coming years, primarily during the winter [64]. Pakistan intends to import from Iran, mainly to supply it to remote areas of Baluchistan, where extension of the local transmission network is unfeasible [4]. In this regard, Pakistan signed a memorandum of understanding (MoU) with Iran in 2012 to import 1000 MW of power from Zahedan (Iran) to Quetta (Pakistan) [65]. A ± 500 kV bipolar HVDC transmission line with converter stations at each end will be constructed between these cities. The distance of the transmission line will be 678 km, of which 93 km will be built in Iran, and 585 km will be in Pakistan. In addition, a dedicated 1300 MW gas power plant will be constructed at Zahedan to supply electricity to Pakistan through the proposed HVDC line. However, despite Iran's willingness, the US sanctions on Iran are the leading cause for Pakistan's hesitation to pursue the Tavanir-Quetta HVDC project [66].

Pakistan's 500 kV transmission network generally stretches from Jamshoro in the south to Tarbela in the north. These lines run pretty close to India's neighboring border. Dina-Nath (Lahore, Pakistan) and Patti (Amritsar, India) can act as potential substations for cross-border electricity imports with India [64], [67]. According to the Asian development bank, it is feasible to import 500 MW utilizing a 400 kV HVDC transmission line between Lahore (Pakistan) and Amritsar (India) [68].

VII. FUTURE PROSPECTS OF HVDC TECHNOLOGY IN PAKISTAN

The use of High Voltage Direct Current (HVDC) technology holds great promise for Pakistan's power sector. As the electricity demand continues to grow and the need for efficient power transmission increases, HVDC has the potential to improve the reliability and stability of the country's power grid. It also opens up opportunities for energy trade and regional cooperation, enabling Pakistan to import and export electricity to neighboring countries. With Pakistan's increasing investment in renewable energy sources like wind and solar, HVDC technology can aid in the integration of these intermittent sources into the grid. Consequently, the adoption of HVDC technology is likely to have a significant impact on the future of Pakistan's power sector.

In the following subsection, various factors that may contribute to the adoption of HVDC technology in Pakistan are briefly examined.

A. INTEGRATION OF RENEWABLE ENERGY RESOURCES WITH THE NATIONAL-GRID UTILIZING HVDC TRANSMISSION TECHNOLOGY

The Pakistani government has pledged to deploy green technology such as wind and solar energy to meet a large amount of the country's electricity needs. According to the Alternative Energy Development Board (AEDB) and the Pakistan Meteorological Department (PMD), coastal Sindh and Baluchistan, as well as some northern regions, have great wind energy potential. Wind energy building, deployment, and operation are feasible in the districts of Thatta, Karachi, Jamshoro, and Badin in Sindh province, as well as Gwadar and Makran Coastlines in Balochistan province [69].

According to one research, Pakistan has immense capacity to produce 3200 GW of clean energy, including 340 GW of wind, 2900 GW of solar, 50 GW of hydropower, 3.1 GW of micro hydro, 1.8 GW of bagasse energy conversion, and 0.5 GW of trash [70], [71]. Therefore, the prospects of wind and solar energy in various parts of Pakistan must be carefully studied for electricity generation and interconnection with the national grid system via HVDC transmission technology in the future.

According to the National Renewable Energy Laboratory (NREL), Pakistan has a total wind energy potential of around 346 GW [72]. Table 8 summarizes NREL's estimation of Pakistan's wind electric potential at 50 m height for wind power classes 1 to 7 [73] whereas Figure 12 illustrates wind speed at a heigh of 50 m [74]. According to data in Table 8, with an installed capacity of 5 MW per km^2, approximately 3% of the land can produce nearly 132 GW of wind electric output power.

Wind energy generation could be weighed up to 40% of Sindh and Baluchistan's coastlines, excluding low-wind and metropolitan areas [71]. Wind energy's theoretical output potential has been estimated to be 123 GW, assuming a density factor of 5.40 MW/km^2. Wind power generation along

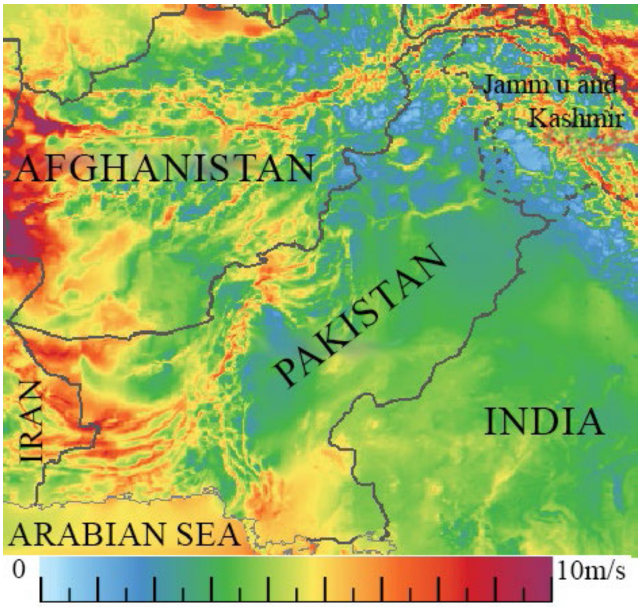

FIGURE 12. Wind speed map of Pakistan at 50 m height.

Pakistan's coastlines is predicted to be 212 TWh per year or 2.15 times the country's total conventional power output. NREL has identified several suitable wind energy production locations along the coastlines of Sindh and Balochistan [75]. According to Figure 12 and analysis of data from 47 wind observation sites along Sindh and Balochistan's coastlines, a wind corridor stretching from Hyderabad to Keti Bandar and Quetta to Gwadar was discovered to have significant potential for electricity production [69], [75].

Wind energy projects in the Jhimpir, Gharo, and Keti Bandar corridors would help to alleviate energy shortages and the $12 billion in yearly oil imports [76]. The GOP has currently secured only 1.245 GW of wind power from this corridor, which has the potential to supply steady power from June to September when the southwest monsoon moves through Pakistan. While in comparison, Pakistan's neighbor India has constructed numerous wind farms along this wind corridor across the border, which extends into Rajasthan state. With a capacity of 18.7 GW, Rajasthan is one of India's leading states for harnessing wind energy to create power. Wind turbine manufacturers Suzlon and Enercon have commissioned 4.3 GW of wind power capacity from 15 independent projects in Rajasthan, accounting for roughly 68% of the total capacity.

Furthermore, due to its long coastline along the Arabian Sea (1,046 km), Pakistan has significant opportunities for offshore wind energy development. According to research published in the Journal of Renewable and Sustainable Energy, Pakistan's offshore wind energy potential is larger than 50 GW, which is much greater than the country's current installed electrical capacity of around 37 GW [77]. In another study it was found that the coastal areas of Sindh and Balochistan provinces have excellent prospects for offshore wind energy development, with average wind speeds ranging from 7.5 to 8.5 m/s, making them appropriate for offshore wind turbines [69].

Apart from immense wind energy potential, Pakistan has ample solar energy resources. However, despite the abundance of sunlight, Pakistan's solar energy potential remains virtually untapped, as evident from Pakistan's source-wise energy mix, Figure 10. In contrast, Figure 13 illustrates that the country receives 5 to 7 kWh/m^2 of solar radiation per day on average, making it a perfect option for solar energy harvesting [78], [79]. Recently, several studies have reported that Pakistan's solar energy potential is projected to be over 2.9 million GWh per year [80], [81]. This demonstrates solar energy's huge potential to contribute to the country's electricity generation if proper attention is given to this sector by the GoP.

Typically, solar power plant site is feasible where: (i) high-intensity horizontal radiations in the range 5.2 to 6.4 kW h/m^2 per day are available [82], [83]. (ii) proposed site is a waste land or barren with minimum slope of no more than 5% [84]. Figure 14, shows the potential sites for photovoltaic plants. The Thar Desert in Sindh province, where solar irradiation is strong, and the Cholistan Desert in Punjab are also ideal places for solar photovoltaic (PV) power plants [85]. Balochistan and Sindh's coastline areas are also excellent for solar energy projects. Apart from PV technology, Pakistan is an ideal candidate for concentrated solar power (CSP) technology. In this regard, the feasibility and practicality of CSP plants in the Thar Desert region as well as waste lands of Baluchistan were recently studied and highlighted [84], [86], [87].

The abundance of solar and wind energy resources gives Pakistan a unique opportunity to meet its rising energy demands and overcome the country's prevailing energy crisis. Therefore, to resolve the country's energy deficiency, it is necessary to fully utilize Pakistan's solar and wind energy potential, through an efficient and resilient transmission system. The existing, aging transmission system presents considerable hurdles in handling the increasing development of renewable energy output. As a result, the construction of new HVDC transmission lines is critical to facilitating power transfer from energy-rich regions to demand centers.

Furthermore, Gwadar, a hotspot in CPEC, is a strategically significant deep-sea port in Balochistan and possesses enormous potential for wind-generated electricity transmission to Sindh province. The region's significant wind resources can be efficiently exploited and incorporated into the national energy grid by creating a HVDC transmission line from Gwadar to Sindh.

In the aforementioned perspective, a proposed 623 km long HVDC transmission line from Gwadar, Baluchistan to Karachi, Sindh intends to link the solar-rich southwest part of Pakistan with the densely populated cities of exterior Sindh and even southern Punjab. This transmission line would make

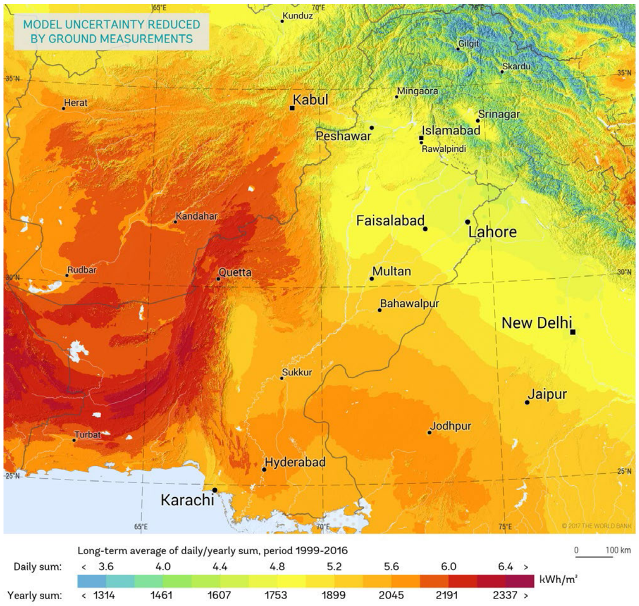

FIGURE 13. Global horizontal irradiation (GHI) map of Pakistan.

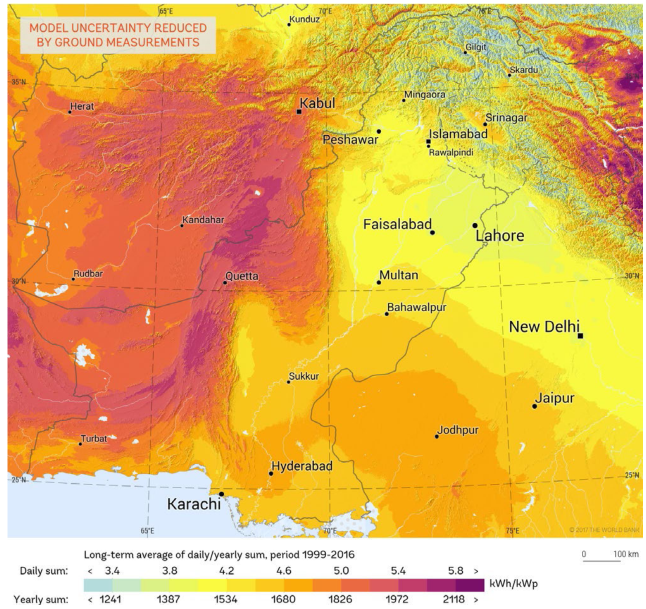

FIGURE 14. The photovoltaic power potential of Pakistan.

it easier to transfer solar energy generated in Balochistan to fulfill the provinces' expanding electrical demand. Similarly, another proposed 778 km long HVDC connection from Quetta, Baluchistan to Gujranwala, via sub-stations at Multan and Faisalabad, Punjab. Figure 15 depicts the proposed transmission lines from the potential renewable energy generation sites to load centers. The proposed HVDC transmission lines would allow wind energy to be sent from wind-rich Balochistan to energy-intensive industries of northern Punjab. Upon practical realization, Pakistan can optimally utilize its solar and wind energy potential and provide a dependable and sustainable electricity supply by integrating these regions via HVDC transmission.

Lastly, the construction of new HVDC transmission lines linking Gwadar and Quetta to highly populus load centers in Sindh and Punjab, respectively, would unlock the full potential of Pakistan's solar and wind energy resources. These transmission routes would provide efficient power transfer, make renewable energy integration into the national grid easier, and contribute to Pakistan's transition to a clean and sustainable energy future.

B. RETROFITTING OF EXISTING HVAC TRANSMISSION LINES TO HVDC TRANSMISSION TECHNOLOGY

Converting existing HVAC transmission lines to HVDC lines has the potential to greatly improve power transfer capabilities [88]. This strategy has advantages such as better transmission efficiency, improved grid stability, and the incorporation of renewable energy sources. Converting to HVDC can reduce costs and expedite development timetables by leveraging existing infrastructure, such as towers and rights-of-way [89]. However, this conversion process presents obstacles that necessitate thorough planning and engineering considerations to maintain compatibility and reliability. Upgrades to converter stations, control systems, and protective measures in existing infrastructure may be required. Despite these obstacles, HVDC transmission presents a promising alternative for meeting rising energy demands while facilitating the optimal use of renewable energy resources [89], [90].

The main advantage of this strategy is that additional transmission rights-of-way may be difficult to get because the cost of occupying the land may be several times the other associated expenditures. Furthermore, regulatory difficulties, vested interests in transmission, and public environmental and aesthetic concerns are some of the major obstacles to overcome when installing a new transmission line [88].

Various schemes have been proposed in the literature for the conversion of existing HVAC lines to HVDC [91], [92], [93], [94]. Figure 16 shows a potential scheme for retrofitting existing HVAC transmission lines to HVDC lines. Figure 16 (a) depicts the initial conversion strategy. A three-phase HVAC transmission line system is converted into a symmetric monopole HVDC system, with two phases of alternating current lines serving as positive pole and negative pole DC lines, respectively, and the third phase, illustrated as a dotted line, serving as a spare line. The second design, shown in Fig. 16 (b), converts a three-phase HVAC line into a bipolar direct current system, with two phases of the alternating current lines functioning as a positive pole and negative pole dc line, while the third phase serving as a metallic return.

The Cahora Bassa transmission project in Southern Africa is an example of HVAC to HVDC conversion. The current HVAC transmission line was upgraded to a 533 kV HVDC system that spans roughly 1,450 km.

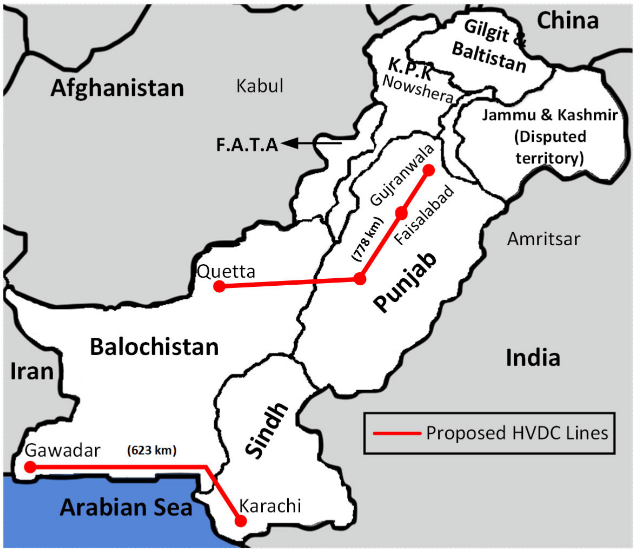

FIGURE 15. The proposed route for future HVDC transmission lines.

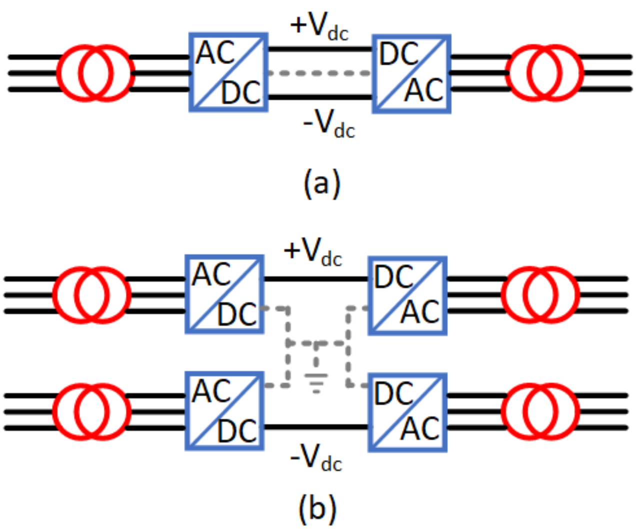

FIGURE 16. The proposed conversion HVAC to HVDC conversion scheme (a) Monopolar topology (b) bipolar topology.

This modification boosted the capacity of power transfer, reduced losses, and improved interconnection between Mozambique and South Africa [95]. Some more examples of conversion of HVDC transmission lines to HVDC include Cross-Skagerrak line in New Zealand, UltraNet in Germany and Angle-DC in Whales [20], [24].

Due to the constraints and overload of the existing transmission network, the need for new HVDC transmission lines is crucial. The rapid growth of renewable energy installations necessitates a strong infrastructure capable of transporting power across vast distances. HVDC transmission lines are especially well-suited for this purpose, as they provide benefits such as decreased transmission losses, improved transmission capacity, and the tendency to link remote energy sources to the main grid. Furthermore, advances in HVDC technology, such as voltage source converters (VSC) and HVDC circuit breakers, have rendered these transmission lines economically and technically viable for large-scale renewable energy integration.

VIII. CHALLENGES ASSOCIATED WITH HVDC TECHNOLOGY IN PAKISTAN

Pakistan, a major developing country, has a wide range of issues, particularly in combating unemployment and improving low-income people's health, education, and socioeconomic status. The electricity sector is crucial for making progress in resolving these issues, but limited investment, unpredictable energy supply, weak governance, and bad fiscal management have vital limitations.

As shown in Figure 9, Pakistan's electricity demand is expected to rise significantly over the coming years. Increasing the power generation capacity and minimizing the transmission line losses are mandatory to overcome this issue. However, the HVAC transmission infrastructure is already congested and outdated [96]. Therefore, it needs time to develop, upgrade and modernize the country's transmission infrastructure to support the future increase in the generation capacity and minimize transmission line losses.

Cost is one of the essential factors in establishing new or upgrading existing power transmission lines. It is found in the literature that when compared to an HVAC system carrying the same amount of energy over the same distance, HVDC is a better alternative for bulk power distribution since the overall cost of the HVDC transmission system is much lower [97]. Apart from price, several other challenges to adopting HVDC technology in Pakistan exist.

A. GRID PROTECTION CHALLENGES

Owing to its low impedance and lack of zero-crossing in DC, the protection of the HVDC transmission line is more challenging than the HVAC transmission line. Therefore, this fact demands that the HVDC protection system's reaction time be only a few milliseconds [98]. Also, the Overload capability of power electronic devices is limited, and traditional relays are not appropriate for HVDC transmission line protection [99]. Lastly, the absence of fast-acting, low-loss HVDC circuit breakers also challenge HVDC grid protection [100].

B. SOCIOECONOMIC CHALLENGES

Although new energy and transmission projects usually boost overall social welfare in the associated regions, public opposition is joint, especially in the industrialized areas. Transmission lines are deemed unsightly and are subject to the not in my backyard (NIMBY) and similar syndromes [23].

Also, financing a new HVDC project is a significant challenge, especially for a developing country like Pakistan. Generally, achieving an accurate economic assessment of a new HVDC project is a difficult task due to variations in project features and global market supply and demand conditions [15], [18]. Considering that Pakistan's economy is already in debt and struggling to repay its previous loans, obtaining additional financing from international agencies like the International Monetary Fund (IMF) and Asian Development Bank (ADB) for HVDC projects could be challenging [101], [102].

C. ENVIRONMENTAL CHALLENGES

The impact of HV transmission on the environment and humans has become a hotly debated topic in recent years. However, no scientific evidence supporting the adverse effects of this technology on human health is yet documented [23]. The majority of the environmental issues of HVDC transmission, such as radio frequency interference, electromagnetic interference, and acoustic noise, originate from a phenomenon known as the corona effect [90], [103].

Also, minimizing visual impact while planning new HVDC transmission routes must be considered, especially if the transmission line passes through a lake, natural parks, sensitive areas, archaeological sites, or agricultural lands [104]. Even if under-ground HVDC transmission cables (oil-filled cables or Gas Insulated) are to be used, there is a risk of potentially harmful or disastrous leaks.

D. GRID STABILITY AND INTEGRATION

When adding HVDC systems into Pakistan's current AC grid infrastructure, grid stability, and integration may present considerable problems. To ensure uninterrupted and dependable operation, the integration of HVDC technology necessitates careful planning, coordination, and prospective improvements to the grid infrastructure [104], [105]. HVDC systems have unique properties and operational demands that must be carefully studied.

Grid code modifications are required to accommodate the technical needs and specifications of HVDC systems to address these problems [2]. These changes ensure that the grid can handle the power flow, control, and protection requirements of HVDC transmission [106]. System analyses, including load flow analysis, transient stability analysis, and fault studies, are critical for determining the influence of HVDC on grid stability, voltage control, and power quality [107]. These studies aid in identifying potential challenges and developing appropriate solutions to ensure grid stability and easy integration.

Furthermore, the deployment of advanced control and protection schemes, such as wide-area monitoring and control systems, can improve grid stability and dependability during HVDC technology integration [108]. These technologies offer real-time grid monitoring, fault detection, and control, ensuring peak performance and reducing the danger of grid instability.

Technical knowledge and collaboration between power system operators, grid regulators, and HVDC technology manufacturers are vital for effectively tackling the challenges linked to grid stability and integration. A thorough understanding of the technical issues, as well as good coordination and cooperation, are required for the successful implementation of HVDC technology in Pakistan's power grid.

E. POLITICAL CHALLENGES

Political influence has a significant role in the current state of Pakistan's electricity industry. IPPs and rental power plants generate electricity at unaffordable high prices, but because of corruption and large commissions, it is impossible to eliminate such political meddling. Unfortunately, investment is not being made in renewable energy resources to discover alternative affordable power sources to address the energy shortfall.

Political uncertainty and regime changes in Pakistan have resulted in an inconsistency in the implementation of HVDC projects. These issues interrupt long-term planning, create an uncertain environment, and impede project progress. Changes in government priorities, laws, and regulations pertaining to the energy sector only exacerbate the situation, resulting in delays, contract renegotiations, and investor uncertainty. To overcome this challenge, a stable and consistent policy framework that transcends political transitions is required, assuring a long-term vision for the energy industry. Involving regulatory agencies and energy specialists in policy formation can also assist in making decisions based on technical feasibility and economic viability rather than short-term political considerations.

F. LIMITED MANUFACTURING CAPACITY

Pakistan's domestic industry lacks the capacity to manufacture HVDC equipment and components domestically. HVDC systems necessitate specialized equipment like converter transformers, thyristor valves, control systems, and other key components.

Importing HVDC equipment can provide many issues. For starters, it may result in increased expenses due to factors such as shipping, import duties, and exchange rate fluctuations. As a result, HVDC projects may become cost-prohibitive and less economically feasible. Furthermore, importing equipment and components may result in lengthier lead times, causing project delays.

Another source of concern is the possibility of supply chain disruptions. Because the country relies largely on imported equipment, it is exposed to interruptions induced by global market circumstances, geopolitical concerns, and trade restrictions. Supply chain interruptions can have a substantial influence on project timeframes and overall grid reliability.

G. LACK OF REGULATORY FRAMEWORK

The development of an adequate regulatory framework is critical for the effective use of HVDC technology in Pakistan. To enable the adoption of HVDC systems, clear norms, standardization, and efficient processes must be developed.

To get things started, precise rules and regulations for HVDC technology are required to ensure that technical specifications, safety norms, and performance requirements are met. Standardization is critical for fostering interoperability and dependability. Second, to avoid unnecessary delays and problems, project approval processes, including permits and environmental clearances, must be expedited. In order to attract investment and provide financial stability, a well-defined regulatory framework should cover tariff structures, pricing systems, and interconnection agreements.

Collaboration between regulatory bodies, government agencies, and industry stakeholders is required to build an efficient regulatory system. This collaboration has the potential to harness international best practices while also ensuring that policies are tailored to the specific demands and aims of Pakistan's electricity sector. Pakistan may encourage private sector investment, foster competition, and make the widespread implementation of HVDC technology by developing a supportive regulatory framework.

IX. CONCLUSION

This study shows the significance of scientometric analysis in delivering new insights into the evolution and impact of research in the field of HVDC technology, providing valuable data for researchers, policymakers, and industry professionals. Our analysis, however, highlights that Pakistan tends to lag in publications and international collaborations in this field, implying the need for increased investment and collaboration to support research in this area and develop HVDC technology indigenously.

Pakistan is currently experiencing an energy crisis due to rising electricity demand, overburdened distribution and transmission infrastructure, aged power plants, and the requirement of expensive imported fuel for power generation. Implementing HVDC technology will undoubtedly be beneficial for overcoming power shortages and ensuring energy security for Pakistan's socioeconomic development. Considering the provided analysis and statistics regarding HVDC transmission, it can be stated that HVDC Transmission is superior to HVAC transmission, despite some of the technical, social, and legal challenges. Existing HVDC projects in the nation are insufficient, and on the other hand, setting up new HVDC projects based on conventional fuels is economically challenging in the present scenario. In this regard, the idea of retrofitting existing HVAC transmission lines to HVDC discussed in this review must be further evaluated. However, long-term cross-border cooperation between countries would result in a more sustainable energy mix and benefit energy source diversity and security.

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