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Research article

Power transmission in Afghanistan: Challenges, opportunities and proposals

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Abstract: The power transmission system of Afghanistan is witnessing a significant shortage in terms of capacity, reliability, flexibility, and energy security. The goal of this paper was to identify and examine the associated issues, challenges, and opportunities for domestic transmission grid and power imports in the country. On these bases, proposals and recommendations were provided that can help the Afghan energy sector strategically enhance its transmission capacity and make the country's existing massive renewable energy potential exploitation feasible. The focus was on the expansion of high-voltage direct current transmission technology. The findings of the paper revealed that the utilization of high-voltage direct current, hybrid high-voltage alternating current, and high-voltage direct current transmission technologies can facilitate bulk power transmission and trade between south and central Asia, as well as regional energy sustainability, development, and security.

Keywords: Afghan power transmission system; HVAC/HVDC; challenges; opportunities

Abbreviations: HVDC: high voltage direct current; HVAC: high voltage alternative current; MW: megawatt; GW: gigawatt; CASA: Central Asia South Asia; TAP: Turkmenistan, Afghanistan, and Pakistan; APTS: Afghan power transmission system; CRF: capital recovery factor; DABS: Da

Afghanistan Breshna Sherkat; UN: United Nations; kWh: kilowatt-hours; MEW: Ministry of Energy and Water; NEPS: North East Power System; SEPS: South East Power System; TUTAP: Turkmenistan, Uzbekistan, Tajikistan, Afghanistan, Pakistan; CAPEX: capital expense; USD: US dollar; ADB: Asian Development Bank; EIAD: Energy Infrastructure Attack Database; US: United State; IPP: independent power producer; EIA: environmental impact assessment; EMP: environmental management plan; RoW: right of way; ECO: Economic Cooperation Organization; SCO: Shanghai Cooperation Organization; SAARC: South Asian Association for Regional Cooperation; BRI: Belt and Road Initiative; CASAREM: Central Asia—South Asia Regional Electricity Market; TAPI: Turkmenistan, Afghanistan Pakistan, India; WB: World Bank; SWOT: strengths, weaknesses, opportunities, threats; R&D: research and development

1. Introduction

Access to affordable energy is the key element for poverty reduction, enhancing a country's living standard, and fostering socioeconomic and sustainable development [1]. Afghanistan is a landlocked and mountainous country where only 30% of the population has access to electric power. Rural areas constitute around 77% of the total population, with only 10% having access to electricity [2]. The current domestic electricity generation is insufficient due to the age of the generation stations and their limited capacity. Besides, the majority (77.4%) of available power is imported from other countries but is still insufficient, unreliable, and techno-economically infeasible [3].

On the other hand, Afghanistan has immense grid-scale potential for renewable energy throughout the country. The total renewable energy potential is estimated to be 318 GW, of which the majority is dominated by solar and wind power and exists in the southern and western parts of the nation [3]. Compared to Iran with a total of around 100 GW and Morocco with around 103 GW (25 GW solar, 25 GW wind, and around 3 GW including hydropower, biomass, and geothermal energy), this is an immense potential [4,5]. The development of these sources could fulfill existing domestic energy needs and greatly contribute to the growing energy demand [6]. To do this, grid infrastructure expansion with high investments is required to maintain efficient and robust electric power generation and transmission [7] because the majority of the leading renewable energy potential of the country is in rural areas and far from the main load demand centers [8].

Including power import links, Afghanistan has a limited power transmission infrastructure with frequent outages, technical losses, financial constraints, security concerns, etc., which have hindered the development and reliability of the power transmission system. The previous government's focus from 2001 to 2021 was only on power imports and less attention was paid to domestic transmission lines. The network is still being developed and expanded. Although the power imports from Tajikistan, Uzbekistan, Turkmenistan, and Iran covered most of the power demand, there is still a huge untapped load and these unreliable and insecure projects have not been guaranteed as long-term projects. These countries only export the surplus power to Afghanistan. These imports depend on the season, for instance; as the power generation in Tajikistan is hydropower, it delivers electricity only during the summer season. In addition, some important projects in Afghanistan, for instance, Central Asia South Asia (CASA)-1000 and Turkmenistan, Afghanistan, and Pakistan (TAP), are only for transit purposes and contribute a small portion of power as transit fees [3].

The transmission system in Afghanistan needs a constant balance between power generation, load demand, and wheeling capacity. Besides, to achieve sustainable development goals for Afghanistan and regional security, a unified, reliable, robust, flexible transmission network with a vast capacity is required. This will pave the way for domestic renewable energy utilization and regional power integration. Besides, it will eliminate the congestion and synchronization problem, which is currently the main technical challenge of the Afghan power transmission system (APTS). To date, there has been no research to focus on these issues and provide the factors that influence the current and future functioning of the power transmission network in Afghanistan.

This paper identifies and assesses the various existing challenges in APTS and power imports that act as main constraints on the current and future development of transmission sufficiency. Besides, to overcome these challenges, the country's available opportunities, i.e., huge renewable energy potential availability and massive power transit potential through this territory with its benefits, are identified, and proposals, i.e., HVDC transmission technology, hybrid HVAC/HVDC, and upgrading the current transmission system, have been provided. Moreover, based on the challenges and opportunities, recommendations have been provided to help the government, especially the power sector, modify current and decide on future national and regional transmission projects. It can also help the policymakers and decision-makers better analyze preferences and present policy recommendations to enable a flexible, reliable, and robust power transmission system.

The rest of the paper is structured as follows: Section 2 presents the power demand of the country. Section 3 explains the current power generation and potential of the country. Section 4 describes the transmission network structure of the country. Section 5 discusses the major challenges in detail that hinder the development of APTS. In Section 6, we explain the transmission opportunities. The proposals are described in Section 7. Lastly, in Section 8, the authors provide recommendations, followed by a conclusion in Section 9.

2. Power demand

Electrical power demand is the main indicator for identifying the techno-economic electrification and transmission system. Afghanistan's power demand is influenced by various factors such as population size, economic development, industrial activities, and seasonal variations. Based on United Nations (UN) projections, the population of Afghanistan was 32.927 million in 2015 and reached 42.431 million people (2.86% growth of the annual whole population) in 2023, ranking as the 36th most populated country in the world [3,9]. Additionally, based on UN data and assuming 2.86% growth per year, Afghanistan's population is indicated to reach 64.68 million by the year 2050 [9]. The load demand of the country was generally forecasted by the power sector master plan in 2012. The peak load demand was 600 MW in 2012, is currently around 1500 MW, and is forecast to reach 3502 MW in 2032 [3,10,11]. Figure 1 shows the total peak load development projection until 2032 for Afghanistan. The development of net electricity demand in Afghanistan from 2011 to 2032 is depicted in Figure 2 [3,12]. As can be seen, the net demand, which was 2800 GWh in 2012, would reach around 15,909 GWh in 2032, i.e., 9.8% average growth per year. Historically, Afghanistan has faced challenges in meeting its electricity demand due to limited transmission infrastructure and insufficient generation capacity. Many parts of the country experience frequent power outages and rely on power imports and domestic generation, including diesel generators.

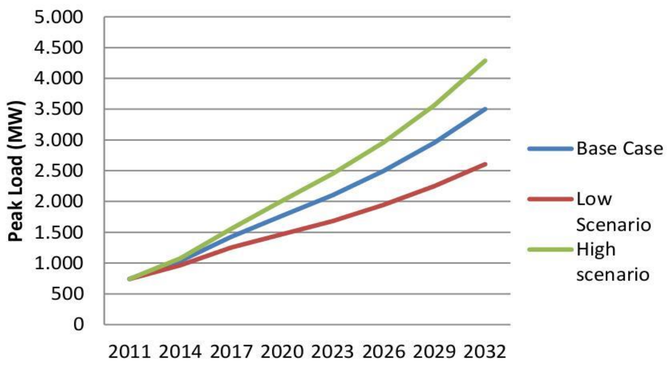

Figure 1. Peak load development in Afghanistan [10].

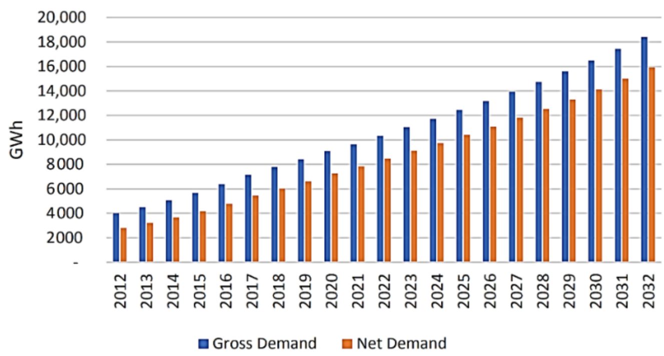

Figure 2. Afghanistan's total projected electricity demand [3,12].

3. Current generation and potential

The current power generation system in Afghanistan is techno-economically insufficient. It is worth noting that electricity access in Afghanistan is unevenly distributed, with urban areas having better access compared to rural regions. Many households in rural areas rely on alternative sources of energy, such as diesel generators, solar panels, or traditional fuels like wood and coal.

Only 30% of the total population (70–75% in the capital and 15% in rural areas) has access to electricity [13]. The country's power consumption has been relatively low compared to many other nations. Of the estimated 7.5 billion kilowatt-hours (kWh) of electricity consumed in Afghanistan in 2019, 77.4% was from power imports: 35.3% from Uzbekistan, 12.3% from Turkmenistan, 30.7% from Tajikistan, and 21.7% from Iran. The remaining 22.4% is produced by national power stations. It is worth mentioning that most of the national stations are now out of their useful life cycles. Out of a total of 623 MW of domestic installed capacity, thermal generation constitutes 312.5 MW (50%), hydropower 255.5 MW (41%), and renewable energy, particularly photovoltaic and wind power, constitutes 75.0 MW (9%) [2,3,14]. In 2020, with the installation of two projects with 15 MW each in Kandahar, solar PV generates about 46 MW, contributing 5% of the total installed capacity. The 10 MW in Kandahar and the 1.05 MW in Bamiyan are the two other major solar power plants in the country.

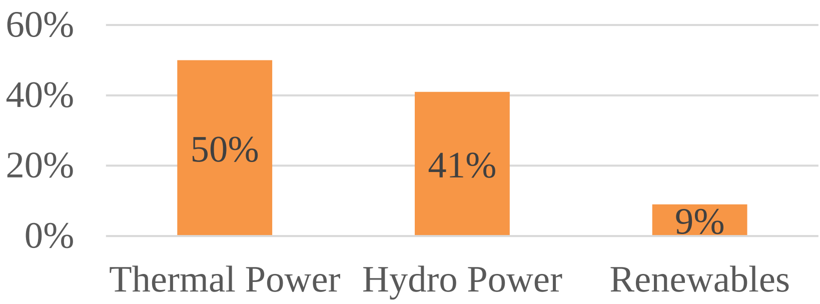

Figure 3. National installed capacity.

On the other hand, Afghanistan possesses huge renewable energy potential. According to MEW, the total electricity generation potential of these resources is 318 GW. Solar power with 222 GW, wind power with 66 GW, and hydropower with 23 GW, respectively, constitute the leading parts [2,15]. The biomass and geothermal power generation potential dispersed throughout the nation is 4000 MW and 3000–3500 MW, respectively [13]. The power sector master plan of the country has assigned 95% (5000–6000 MW) of the total generation to be generated by renewable energy by 2032 [16]. As two major resources of the country, the global horizontal irradiance map is shown in Figure 4, and the annual mean wind speed map is depicted in Figure 5 [17]. As can be confirmed from the figures, the major parts of these resources are in the southwestern and southern provinces, i.e., Herat, Farah, Kandahar, and Nimroz.

As eco-friendly sources, solar power (with 300 sunny days annually, 9.0 kWh/m^2/day in the summer, and 6.5 kWh/m^2/day average irradiation) and wind power (with 120 windy days annually, 5 MW/km^2 density, and over 8.5 m/s wind speed in the south and southeastern provinces) seem eminent and promising choices for Afghanistan. Deployment of the mentioned sources can intersect the present and future demands of the country and also facilitate various leading opportunities. For instance, power exports and trading with neighbors can create employment opportunities. More importantly, it can liberate the country from its current unreliable, uneconomic, and insecure energy imports. The total and practical potential of solar and wind power per province of Afghanistan is available in [2]. Assuming that only 2% of the total land is deployed with 300 sunny days and 12 hours per day, and considering 6.5 kWh/m^2/day density, the practical potential of solar energy will be 23.575 GW, which is almost 6.7 times greater than the demand of the country in 2032.

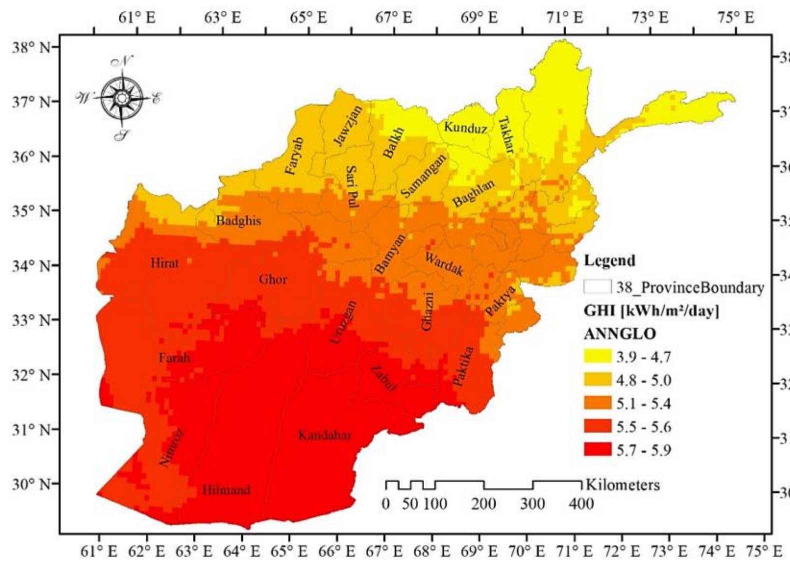

Figure 4. GHI (global horizontal irradiance) map [3,17].

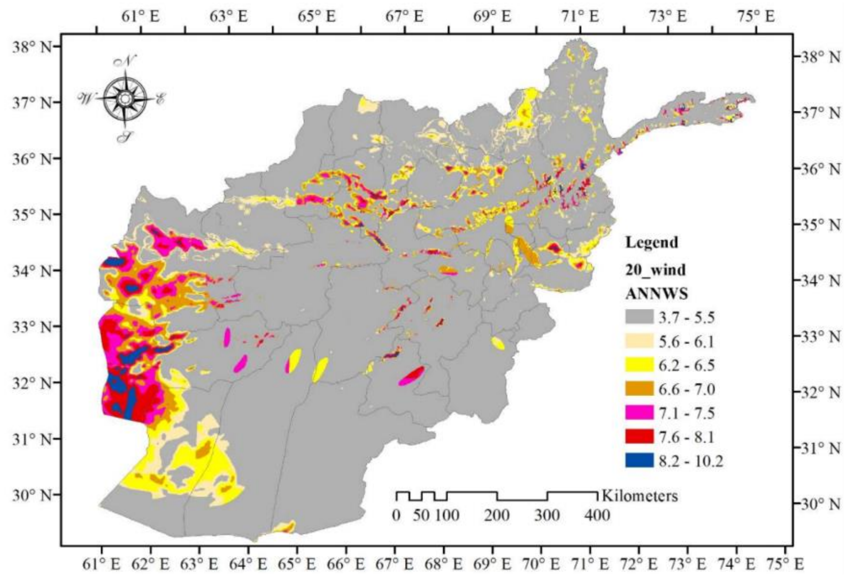

Figure 5. Yearly mean wind speed (m/sec) map at 50 m above the ground level [3,17].

4. Transmission network structure

Afghanistan has a limited power transmission infrastructure, and the network is still being developed and expanded. The transmission system is affected by history and natural topography and consists of distinct and isolated power systems and grids.

After a delay of 17 years (from 1988 to 2005) due to the war, the extension of the 220 kV transmission line for importing power from Tajikistan to Kabul (the capital of the country) was completed in 2005. This line first feeds the Arghandi substation in Kabul and, from this substation, the 110 kV transmission lines are connected to the north and northwest substations of Kabul City. With the connection of this line from Pul-e-Khumri to Kabul, the northern part was connected to the central part of the country. The eastern part of the country is connected to the northern part by connecting Nangarhar province to the Naghlu power plant using a 110 kV transmission line.

The overall power system is separated into four regions linking various sources to the grid: 1) North East Power System (NEPS), which connects several networks, mainly Kabul, Jalalabad, and Mazar-e-Sharif with Uzbekistan and Tajikistan at 220 kV, 110 kV, and 35 kV voltages; 2) The South East Power System (SEPS) links Kandahar province to Kajaki power station at 110 kV; 3) Herat province, which is connected with Turkmenistan and Iran at 132 kV and 110 kV voltages; and 4) Turkmenistan, which links Faryab, Jawzjan, Sar-e-Pul Andkhoy district, as well as Herat at 110 kV. The NEPS is supplied by imported power from Tajikistan and Uzbekistan, and domestic hydro and diesel generation.

Herat is isolated from the national transmission network and still needs 150 MW more power to cover its current demand, though it is connected to both Iran and Turkmenistan and imports 150 MW of power from these countries [18]. Nimroz is also isolated from other provinces and supplied by Iran at 20 kV. It is worth mentioning that all of the above-mentioned transmission networks are HVAC. The overall map of the current and planned transmission grid, along with the location of domestic power plants in the country and imports, is shown in Figure 6 [19]. The blue line shows the planned and unfunded parts of the grid, which means that there is still no grid in the western part of the country.

With the unification and socioeconomic development purposes, and due to the existence of the main import power in the north, it was essential to unify the overall grid. Though the expansion has been interrupted several times, efforts are ongoing to interconnect the distinct regional power systems, i.e., NEPS and SEPS. This is highlighted with the red line in Figure 6. Besides, it is expected that this will facilitate renewable energy integration in the south and west, as 80% of the country's potential of wind and solar is in these regions. It is also planned to link the Arghandi substation to the southeastern network of the country via a 220 kV line. This new grid, which connects all of the northern provinces, the center, some eastern provinces, and the southeastern network of the country and is connected to Tajikistan, Uzbekistan, and Turkmenistan, is called the North East Power System (NEPS). The one-line diagram of the NEPS is depicted in Figure 7 [20].

On the other hand, a few efforts are available in the field of HVDC transmission systems. The CASA-1000 HVDC transmission link is the project that transmits 1300 MW of summer surplus power from Kirgizstan and Tajikistan through Afghanistan to Pakistan. There is a bidirectional converter station in Kabul, Afghanistan, to allow the country to draw up 300 MW as a transit fee [21,22]. The yellow line in both Figures 6 and 7 shows this transmission line. Notwithstanding the expected remarkable benefits, for instance, reliable cross-border power delivery, private sector involvement, and job creation, CASA-1000 will only generate income from power transit purposes for Afghanistan [23]. Likewise, one of the important and large-scale projects is the Turkmenistan, Afghanistan, and Pakistan (TAP) project, which will transfer 4000 MW of power from Turkmenistan to Afghanistan (1500 MW) and Pakistan [24]. This project is shown with the indigo color in Figure 6. In addition, one of the main projects is the TUTAP transmission link, which enables power exports from Turkmenistan, Uzbekistan, Tajikistan, and Afghanistan to Pakistan. Pul-e-Khumri in Afghanistan will serve as a transit hub where a 500 MW HVDC back-to-back converter station will be installed to synchronize the Turkmen and Afghan power systems [25]. All of these projects propose considerable benefits to Afghanistan, particularly synchronization and high-power delivery for distant regions. Nevertheless, they will not contribute to the incremental energy demand of the nation.

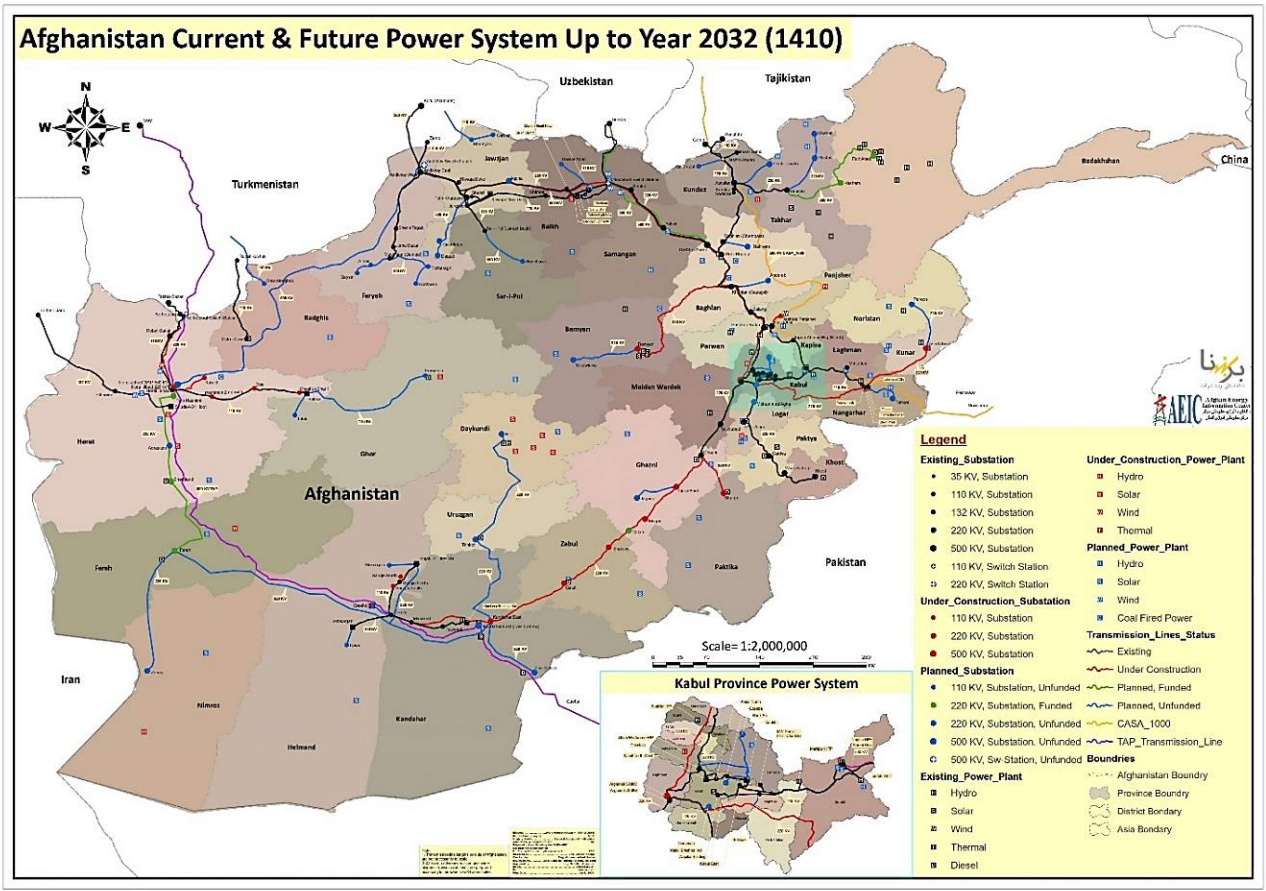

Figure 6. The current and planned transmission grid of Afghanistan [19].

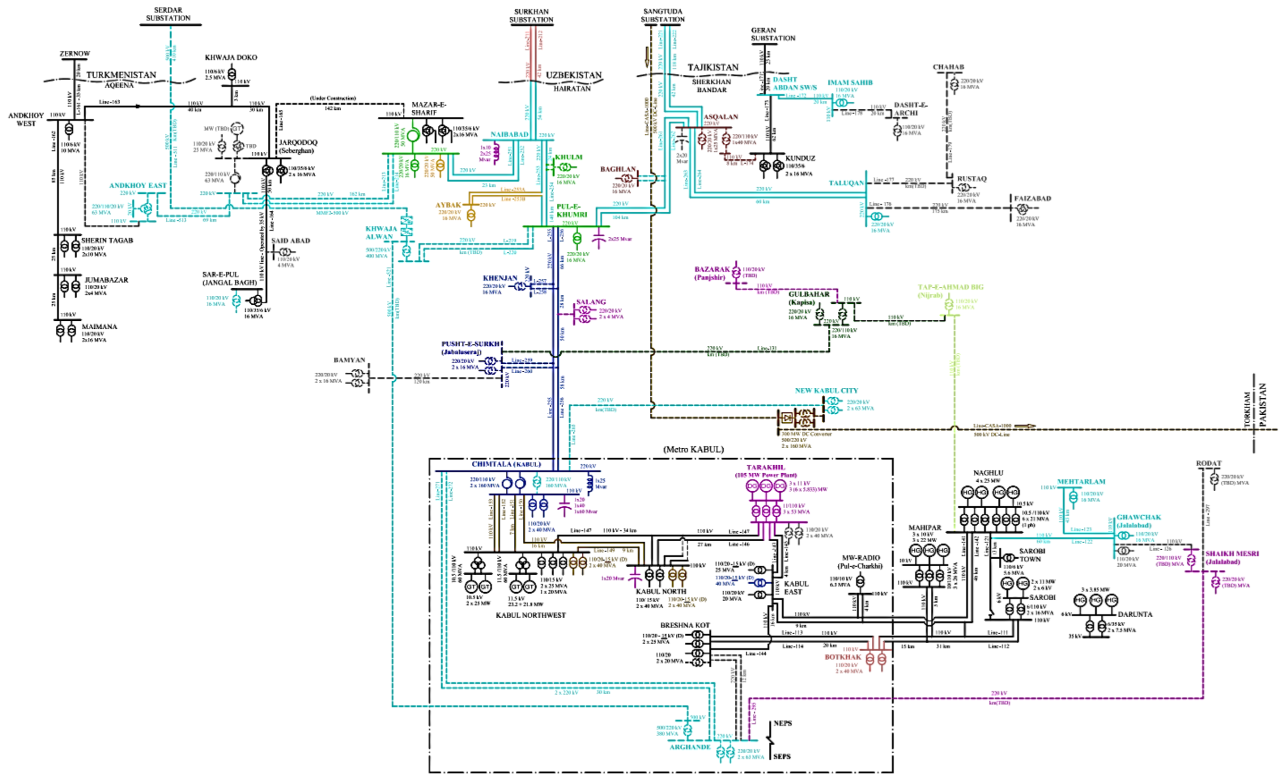

Figure 7. The single-line diagram of NEPS [20].

5. Challenges

The history of APTS can be traced back to the early 20th century, when the country began developing its electricity infrastructure. Following the Soviet invasion in 1979, Afghanistan plunged into a period of civil war and political instability. The conflict severely disrupted the power transmission system, leading to damage and destruction of infrastructure, including power stations, transmission links, and substations. The lack of maintenance and investment during this period resulted in a significant deterioration of the power transmission network.

After the establishment of the new government in 2001, Afghanistan embarked on a process of reconstruction and rehabilitation. International aid and assistance played a crucial role in rebuilding the power transmission infrastructure. Efforts were made to repair and upgrade damaged transmission lines, substations, and power plants to restore electricity supply across the country. Despite progress in power transmission infrastructure development, APTS continues to face significant challenges in maintaining a reliable and robust electricity grid. The major challenges of APTS are identified and summarized below:

5.1. Lack of strategic planning in transmission

There is no strategic and centralized planning among the generation, transmission, and distribution sectors. Hence, there is a remarkable gap between the existing and future demand, generation, and transmission capacity of the country. This can be attributed to the fact that instead of the national transmission grid of Afghanistan, the focus of policymakers was given to power imports.

Besides, the planning between inter-state and intra-state transmission systems is not centralized and synchronized. The inexistence of centralized transmission planning reduces transparency in terms of capacity enhancement and new transmission lines. Therefore, the existing transmission lines are not adequate to transmit the future increasing power generation capacities and fulfill the demand.

5.2. Lack of funds or financial constraints

Financial constraints and inadequate investment can be considered one of the main challenges to the increase in transmission capacity that delay the development of transmission plans. Even though the exact amount of investment is unknown, it is obvious that considerable investment is required in the transmission sector to utilize the internal energy resources and meet the targeted electricity demand of the country.

The current planned transmission lines in the country are estimated at 2841 km with 110 kV, 2667 km with 220 kV, and 1393 km with 500 kV operating voltages. In addition, according to the master plan of Afghanistan, the total capital expense (CAPEX) on the transmission networks of Afghanistan is projected to be USD 1056 million [13]. Regarding the allotment of CAPEX to the expansion phases within the planning horizon, about USD 317 million was estimated to be required in Stage A up to 2015 and about USD 430 million in Stage B between 2015 and 2020. In addition, the total investment in major projects, i.e., the Turkmenistan-Afghanistan interconnector, Hindukush crossing, NEPS-to-SEPS link (an interconnector to Herat and Pakistan), and CASA-1000, is estimated at USD 2599.8 million. But in addition to political instability, the financial constraints and funding support cessation delayed the transmission plans and electrification of most rural and urban areas of the country. The 500 kV power transmission line between Turkmenistan and Afghanistan is one of these stalled projects funded by ADB; 90% has been completed in 2021, and the remaining 10% will require only about 6 months to complete if funding resumes [26].

5.3. Limited transmission capacity and infrastructure

Afghanistan has a limited power transmission capacity and infrastructure, and the network is still being developed and expanded. To have more energy capacity and security, the transmission network needs to be extended. Although 1,176,030 households were connected to the power grid in 2015, which was enhanced by 11% in the last few years, and the transmission lines increased from 2261 km to 6907 km, Afghanistan's power generation is not used at its total capacity [13]. On the other hand, the capacity of NEPS-to-SEPS was 150 MW in 2012 and is currently 300 MW [10]. Therefore, bulk transport of energy is not possible. In addition, the exploitation of renewable energy resources (85% of demand covering target by 2032) and the cooperation of other planned large projects in the country, such as the Bamiyan thermal power plant (in two phases: from 2027–2028 with 400 MW and from 2029–2032 with 1200 MW), and their transmission to the main load centers further limit the transmission capacity. Moreover, the non-standardization of the network restricts its ability to stay secure and develop.

5.4. Lack of a single transmission grid (synchronous power grid)

Afghanistan needs a unified national power grid. Generally, there are four isolated grids supplied as passive islands from Uzbekistan, Turkmenistan, Tajikistan, and Iran, as shown in Figure 8 [27].

However, the grid lacks flexibility and reliability due to asynchronous operations. Hence, the connection of network-to-network is difficult, and therefore a converter station is required to align the frequency and load dispatch [28]. Asynchronous grids also prevent efficient energy connections and trade. This also impedes efficient load dispatch and therefore causes blackouts due to dependency on power imports and the absence of reserves. In addition, AC links complicate the utilization of the grid and reduce its reliability and stability during a fault. When a fault occurs, the increased current also affects the healthy parts of the system [29]. Therefore, the existing asynchronous and isolated networks need to be updated to form a unified national grid.

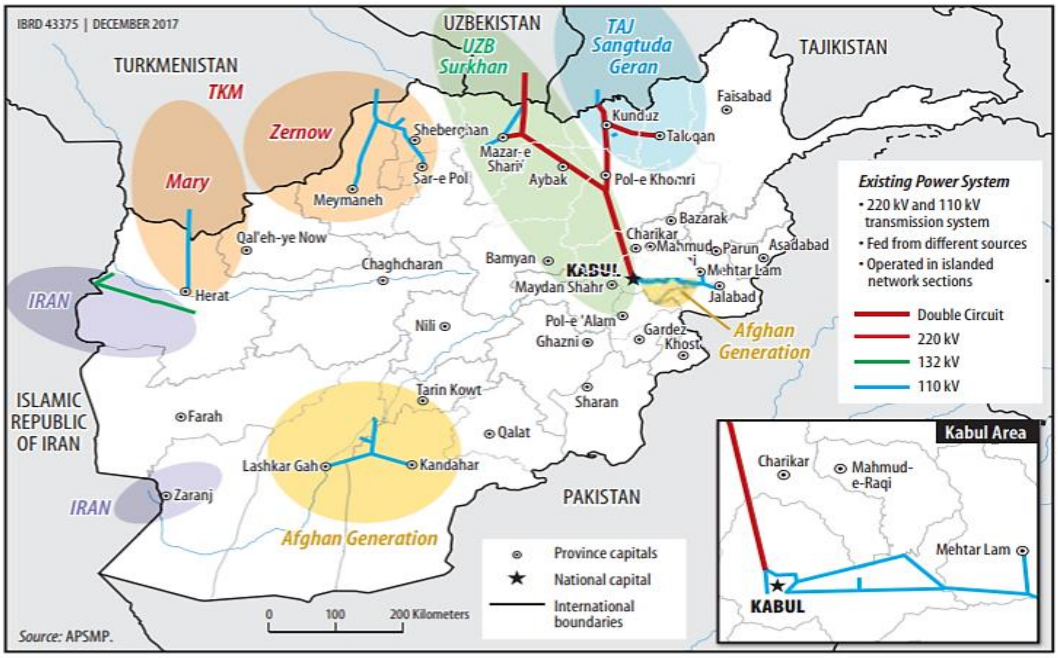

Figure 8. Current Afghan power grids [27].

5.5. *High energy loss and low energy efficiency*

As the transmission network in Afghanistan is HVAC, the losses in the line are higher due to the existence of the skin effect and both the resistance and reactance of the line. The loss level of transmission and distribution networks was estimated to be about 24%, down from 54% in 2008. If the acceptable level of technical and commercial losses, i.e., 10%, is assumed, the 13.5% balance is calculated to be USD 71.2 million per year [30]. In order to achieve the financial sustainability of the energy sector and supply sufficient power, minimizing these losses is crucial. Although DABS attempts to manage and decrease them through its metering and annual maintenance plans, there is still insufficient planning and strategy to efficiently mitigate this huge loss.

5.6. *Political instability*

Political stability is one of the main factors in the Afghan power system. Particularly, the stalling of foreign aid in 2021 gave rise to considerable uncertainties. The long-term war in the country and political instability throughout the region further complicated relationships between Afghanistan and international donors, and threatened power imports as well. In addition, it caused the under-constructed projects to be delayed and made it a challenge to be fully committed to building new transmission lines and power plants.

5.7. Security concerns

Insecurity has been a considerable obstacle to the development of transmission projects in Afghanistan. The presence of armed conflicts and insurgencies makes it challenging to attract foreign investments and secure project sites. Additionally, the risk of theft and damage to energy infrastructure has been a concern. On the other hand, one of the major causes of frequent power outages has been insecurity and vulnerability to assaults on transmission lines and towers. Due to this, fixing destroyed lines and towers often takes several days or weeks and sometimes further delays in war areas. Based on the Energy Infrastructure Attack Database (EIAD), power infrastructures, especially transmission lines and towers, witnessed 500 attacks in 2011, and the country was listed 4th as the highest focus of attacks on electricity infrastructure [31]. In October 2021, an explosion hit a transmission line transmitting imported energy, leaving Kabul in darkness. Similarly, in June 2021, about 25 power towers were demolished or damaged by explosions. Therefore, reliable transmission lines are needed, and their security should be guaranteed to expand the grid, develop internal energy resources, and access imported power within Afghanistan.

5.8. Economic challenges

As a major part of electricity is supplied by imports from neighboring countries, there is no singularity in imported power rates. The price of imported power in Turkmenistan and Uzbekistan is respectively 2.0 cents per kWh and 8.5 cents per kWh [12,32]. Besides, imported power is expensive for Afghanistan. Afghanistan is paying around USD 280 million per year for power imports [3]. Currently, the takeover of the country by the Taliban, the international community's reluctance to recognize the Taliban's government, and the freezing of almost USD 9.5 billion in assets belonging to the Central Bank of Afghanistan by the U.S. have created further economic uncertainties [33]. In October 2021, unpaid bills stood at USD 62 million. The government had demanded USD 90 million from the United Nations to pay the tariffs. Besides, the current government is unable to restart most of the ongoing transmission projects due to severe economic challenges.

5.9. Inadequate import power purchase agreements

The government of Afghanistan should make considerable front-end investments in power transmission infrastructure and transit arrangements, sometimes without support from legally enforced strategic power purchases and formal transit indentures. In addition, these indentures are in USD but sold in Afghani to customers. The exchange rate of USD to Afghani mostly forces the power utility to increase the cost of energy to pay off the power import bill. This results in substantial inconvenience to customers [28].

5.10. Provision and participation of private players

The Afghan power sector is a monopoly where the participation of private players is absent. The wholly government-owned vertically integrated utility DABS controls all of the energy infrastructure, i.e., generation, transmission, and distribution. The Ministry of Energy and Water (MEW) is responsible for planning, policy, and strategy development for the energy sector. The inexistence of private investment and private-public partnerships mostly affects the quality and cost of the projects [34]. High system outages ought to make the government of Afghanistan consider further diversification of its supply sources of power imports as well as developing indigenous power generation options to encourage competition. In Afghanistan, a lack of private participation inhibits the development of a robust domestic electricity generation and transmission infrastructure. However, the first gas-based IPP plant, which was recently launched, is expected to lead to increased investments. However, the power sector's efforts are insufficient, both in the public and private sectors, to develop transmission networks to pave the way for the deployment of other non-renewable and renewable energy sources.

5.11. Delay in project execution due to land ownership

Installation of transmission lines commonly requires permanent land possession for pylons and substation areas. The impacts start with land surveying and the stringing of conductors, which harms agricultural land and crops. Besides the social impacts, such as health and safety, the environmental impact assessment (EIA) and environmental management plan (EMP) evaluations are important. Moreover, the most serious effect of transmission line installation is the dislocation of people from the whole line route. All obstacles need to be lifted from the line route, which is called the right of way (RoW), and relocated to the appropriate location. The RoW corridor estimates are based on the tower base area, the land underneath the conductors, and the transmission voltage level. According to the master plan of Afghanistan, the RoW corridor for a 500 kV and 220 kV single circuit is respectively set to 60 m and 40 m. Also, it is mentioned that the center strip of 25 m and 15 m in dense forest must be fully cleared to enable the conductor stringing [10]. The land acquisition further delays the project execution time and sometimes requires revising the overall project plan, which increases costs accordingly.

5.12. Integration of renewable energy into the grid

The Renewable Energy Roadmap, developed by the Afghan government in collaboration with international partners, outlines the long-term vision for renewable energy development. The roadmap sets a capacity target of about 5000 MW to be generated from renewable energy by 2032, with a specific focus on solar, wind, and hydroelectric projects [35]. The country faces several challenges in terms of renewable energy integration into the energy mix. Afghanistan's existing energy infrastructure is underdeveloped and lacks the necessary transmission and distribution grids to support utility-scale renewable energy projects. In addition, renewable energy sources are intermittent, depending on weather conditions. Afghanistan needs to address the issue and invest in energy storage technologies, such as batteries, to ensure a stable and reliable power supply. Addressing these challenges requires a multi-faceted approach involving government initiatives, international support, capacity building, and investment in renewable energy and transmission infrastructure.

5.13. Lack of technical expertise

The lack of technical expertise in the transmission sector is a significant challenge in Afghanistan. The country needs trained professionals in the planning, design, installation, operation, and management of transmission systems. The management and operational capacity of the energy sectors of the country are sorely lacking because of a shortage of technically skilled and professional people [36]. The shortage of technical professionals increases dependency on external consultants and hampers the progress of transmission projects. Here are some specific impacts of this issue:

Inadequate Planning and Design: The absence of sufficient technical expertise can result in poor planning and design of power transmission systems. This can lead to suboptimal routing of transmission lines, improper selection of equipment, and inadequate capacity planning. Therefore, the transmission system may suffer from inefficiencies, congestion, and an inability to meet the growing electricity demand.

Substandard Construction and Maintenance: The lack of technical expertise can contribute to substandard construction and maintenance practices. Insufficient knowledge and skills among personnel involved in these activities can lead to improper equipment installation, inadequate grounding, and insufficient maintenance procedures. This can result in increased transmission losses, frequent breakdowns, and compromised system reliability.

Inefficient Operation and Grid Management: Technical expertise is essential for the efficient operation and management of the transmission grid. Without skilled professionals, the ability to monitor and control power flows, balance supply and demand, and ensure grid stability is compromised. The lack of technical expertise can hinder the optimization of transmission operations, response to contingencies, and efficient grid integration of renewable energy.

Limited Problem Diagnosis and Troubleshooting: A deficit of technical expertise can make it challenging to diagnose and resolve issues in power transmission systems. Without skilled personnel, identifying the root causes of transmission problems, such as voltage drops, line faults, or equipment failures, becomes difficult. This can result in prolonged outages, increased downtime, and delayed restoration of power supplies.

Lack of Innovation and Technology Adoption: The absence of technical expertise hampers innovation and the adoption of advanced technologies in power transmission. Without a skilled workforce, there may be limited capacity to explore and implement cutting-edge technologies, such as smart grid solutions, advanced monitoring systems, or digital control mechanisms. This can impede the modernization and optimization of power transmission infrastructure.

5.14. Frequent outages

Blackouts occur due to vandalization, i.e., the destruction of towers by insurgents and unknown people in different parts of high-voltage transmission line routes in the country. Besides, high-voltage transmission lines fall due to harsh weather, such as in the winter season with heavy snowing or snowstorms in the Salang Pass route and other northern parts of the country. On the other hand, since the Taliban occupied Afghanistan in August of 2021, power outages have continued. The regular demolition of electricity pylons in the northern provinces of the country and power outages cause the unavailability and unreliability of electricity and result in loss of revenue and other serious problems for power delivery. The restoration of damaged towers and/or lines sometimes takes several days or weeks. Besides, in January 2023, Uzbekistan, as a main exporter to Afghanistan, reduced the export of electricity, which caused frequent outages and disruptions of the power supply in several provinces. The residents of Kabul, the capital of the country, had access to electricity for only 7 or 8 hours per day. The technical problems of transmission lines during harsh winters and the non-payment of bills for imported power create major problems. Load-shedding is the only way in Kabul, both in winter and summer, due to a shortage of power.

5.15. Aged infrastructures

Most of the hydropower generation stations are out of date and need severe rehabilitation or replacement. Besides, due to years of conflict and neglect, Afghanistan's transmission infrastructure requires extensive rehabilitation and maintenance. Existing transmission lines and substations need to be repaired, upgraded, and properly maintained to ensure reliable and efficient power transmission. Rehabilitation projects can involve equipment replacement, refurbishment, and the implementation of modern technologies.

5.16. Corruption

Corruption has a detrimental impact on the power transmission system in Afghanistan. Below are some of the ways corruption can affect the power transmission sector:

Misallocation of Funds: Corruption can lead to the misallocation or diversion of funds intended for the development and maintenance of the power transmission system. This can result in inadequate investments in infrastructure, leading to system inefficiencies, frequent outages, and compromised reliability.

Substandard Infrastructure: Corruption may involve the use of substandard materials or construction practices in power transmission projects. When contractors or officials engage in corrupt practices, they may cut corners to maximize their profits, compromising the quality and durability of transmission infrastructure. This can lead to frequent breakdowns, increased maintenance costs, and reduced system performance.

Delays and Cost Overruns: Corruption can result in project delays and cost overruns. Bribes and kickbacks can influence contract awards, leading to the selection of less qualified or inexperienced contractors. As a result, projects may face delays in completion or require additional funds, which ultimately hamper the expansion and improvement of the power transmission system.

Lack of Transparency and Accountability: Corruption thrives in an environment of limited transparency and accountability. When there are weak governance structures and inadequate anti-corruption measures, it becomes easier for corrupt practices to occur within the power transmission sector.

Inefficient Operations and Maintenance: Corruption can lead to ineffective management of power transmission assets. When corrupt practices influence the appointment of personnel responsible for operations and maintenance, it can result in a lack of technical expertise, inadequate training, and insufficient maintenance practices. This can lead to operational inefficiencies, increased losses, and reduced system performance.

Impacts on Investment and Development: Corruption in the power transmission sector can deter domestic and foreign investments. Investors are less likely to commit funds to projects in an environment where corruption is prevalent, as it increases project risks and undermines confidence in the sector. This can impede the development and expansion of the power transmission infrastructure, hindering the country's overall energy sector growth.

6. Opportunities

Afghanistan has significant opportunities for power generation and transmission development that can significantly contribute to improving the country's electricity infrastructure and expanding access to reliable electricity. Including limited access to electricity and outdated power stations and infrastructure, the country's power sector has faced various challenges, which have been discussed in Section 5. However, below are the potential areas for growth and key opportunities available in the country:

6.1. Vast renewable energy potential

As explained in Section 3, Afghanistan is a rich country of renewable energy resources, particularly solar, wind, and hydroelectric power. The country experiences abundant sunshine throughout the year, making solar power an attractive option. Additionally, Afghanistan's mountainous terrain offers great potential for small to medium-sized hydroelectric projects. Wind power can also be harnessed in certain regions, such as the western and northern provinces. Therefore, this high potential of renewable energy could not only suppress the current and future power demand of the country but also make Afghanistan an electric power hub in the region.

6.2. Strategic location of Afghanistan for regional energy integration

Afghanistan can explore opportunities for regional energy integration, particularly with its neighboring countries. Cooperation in energy trading and cross-border transmission infrastructure can enable energy trading, diversify energy sources, enhance regional energy security, promote economic development, and provide access to vast energy resources and the surplus power of the countries [37]. As shown in Figure 9, Afghanistan has a unique strategic location and therefore has the opportunity to act as a land bridge and the most economical and unparalleled terrestrial energy corridor between major regional projects such as the Economic Cooperation Organization (ECO), Shanghai Cooperation Organization (SCO), South Asian Association for Regional Cooperation (SAARC), China's Belt and Road Initiative (BRI), Central Asia-South Asia Regional Electricity Market (CASAREM), and Turkmenistan, Afghanistan, Pakistan, India (TAPI) gas pipeline, etc. [38,39]. Compared to the current routes, this land bridge could save billions of dollars annually in power trade between Asia and Europe [40]. The benefits tree of regional interconnection expansion is summarized and shown in Figure 10.

Figure 9. Regional location of Afghanistan between CASA countries [38].

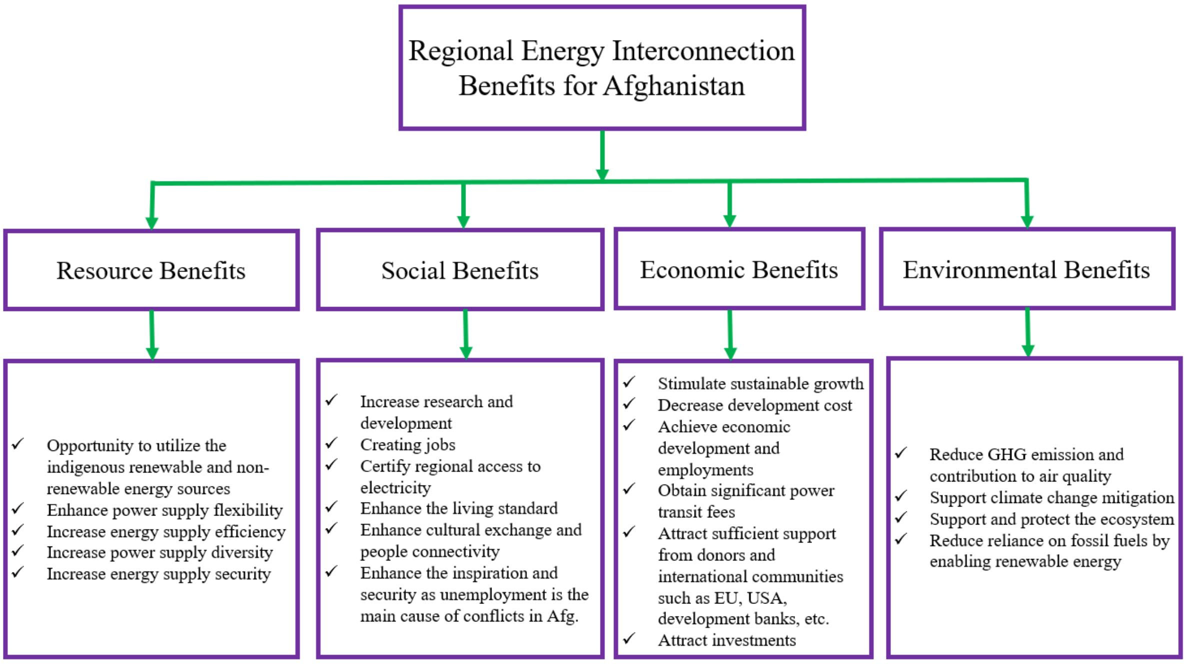

Figure 10. The regional interconnection benefits of Afghanistan.

7. Proposal scenarios

Scenario 1: Advancing the existing transmission networks

1) Current infrastructure expansion

There have been limited efforts to improve Afghanistan's power infrastructure, including initiatives supported by international organizations such as the World Bank (WB) and the Asian Development Bank (ADB). These efforts have focused on expanding access to electricity, rehabilitating existing infrastructure, and promoting small-scale renewable energy sources. Afghanistan requires a substantial expansion of its transmission grid to connect power generation sources to demand centers across the country. This involves the construction of new high-voltage transmission lines, substations, and associated infrastructure. Priority should be given to strategically linking existing and future power generation projects to load centers, industrial zones, and population centers. Therefore, the planned 110 kV, 220 kV, and 500 kV transmission projects (until 2032) shown in Figure 7 are required to be implemented. On the other hand, the completion of this plan cannot guarantee fulfilling the future demand of the country due to the fixed and limited capacity and inflexibility of transmission lines. In addition, Afghanistan will not possess a unified and synchronized grid throughout the country. The integration of large-scale renewable energy would still be a challenge due to its intermittent nature. Moreover, the country will lose the power transit opportunity through its transmission capacity-limited network.

2) Development of meshed transmission networks

As the current structure of the transmission network is radial, it would be advantageous if more loops were added to the transmission grid, in order to form a meshed network. A meshed power network, also known as a looped or magistral network, is a configuration where power transmission and distribution lines form interconnected loops or rings. In this network, multiple paths are available for power to flow, allowing for alternative routes in case of a fault or outage. The loops provide redundancy, ensuring a more reliable power supply to consumers. The looped structure of magistral networks improves system reliability by providing alternate paths for power flow. If a fault occurs, power can be rerouted through other paths, minimizing the impact on consumers. Besides, the interconnections allow for better voltage regulation and control, reducing voltage drops and ensuring consistent voltage levels across the network. Additionally, magistral networks offer more flexibility for expansion and load growth as new loops or interconnections can be added to accommodate increased demand.

On the other hand, the utilization of meshed networks has some challenges, such as higher infrastructure costs and more complex design, operation, and maintenance required for interconnections and coordination. In addition, it can be more challenging to identify and isolate the fault section during any fault occurrence.

Although Afghanistan will have a national ring transmission grid if the existing four isolated grids and planned generations and transmission networks shown in Figures 6 and 8 are to be completed by 2032, there are significant parts of the nation that this grid will not reach [41]. Therefore, in this case, meshed transmission networks, or micro-grids and distributed generation would be feasible options for these areas [42]. However, the choice of configuration depends on factors such as the size of the network, reliability requirements, cost considerations, and the expected future growth of the power system.

3) Development of a single unified transmission grid

The development of a single unified transmission network in Afghanistan can pave the way for connecting various locations and isolated and local networks by solving the synchronization problem. Besides, this will enable the effective integration of domestic renewable and conventional power sources. The single transmission grid should be a super grid, such as 500 kV or at least 220 kV, to increase the power transmission capacity and minimize transmission losses. A unified transmission grid enables a more robust and stable power system. It allows for effective load balancing and facilitates the integration of diverse energy sources. This can help mitigate power outages, reduce voltage fluctuations, and enhance grid reliability, ensuring a consistent and reliable power supply across the country. Additionally, a unified transmission grid can enable power exchange and cooperation with neighboring countries. Afghanistan can benefit from importing or exporting electricity based on demand and availability, enhancing energy security and regional collaboration. Besides, consolidating the transmission infrastructure into a single grid allows for better planning, optimization, and cost savings. It reduces the need for duplicate infrastructure and improves resource allocation. By avoiding the construction of multiple transmission systems, the country can save on capital investments, maintenance costs, and operational expenses, promoting economic efficiency.

Nonetheless, the development of a single and unified transmission grid in Afghanistan would require careful planning and significant investments in infrastructure, including the construction and upgrading of transmission lines, substations, and other associated facilities. It would also necessitate coordination and cooperation among various stakeholders, including government agencies, power utilities, and international donors. In addition, due to the limited transmission capacity, higher losses, and difficult controllability, the regional interconnection and integration of the country's massive renewable energy in the future seem to be challenging. Nonetheless, the potential benefits make it an attractive option for Afghanistan's energy sector.

Scenario 2: HVDC transmission technology

Due to its superior characteristics, HVDC transmission has attracted a lot of attention worldwide [43]. These characteristics include high power transfer capability, easy and efficient power flow control, the non-existence of synchronization challenges, and high reliability and stability, as explained in detail in [44–46]. For the utilization of grid-scale renewable energy available in rural areas and far from load centers, massive power exchange, and improving the quality of the grid, HVDC seems to be a feasible and preferable technology for Afghanistan.

Several studies have been done on the importance and effectiveness of HVDC transmission technology compared to HVAC transmission [46–48], proving its technical and economic applicability and feasibility for renewable energy integration and large-power transmission over long distances. In [3], the author performed a techno-economic analysis of an HVDC link for renewable energy integration and transmission in Afghanistan that transmits large-scale renewable energy (solar and wind) from Herat to Kabul. The study covered the technical and corona loss calculations and the discounted cash flow (DCF) method for net present cost (NPC) estimation for both HVDC and HVAC transmission technologies. The research findings of the author clarify the techno-economic feasibility of HVDC technology over HVAC. Except for CASA-1000, which is only an energy transit project that transits electricity to Pakistan, there is no domestic and independent HVDC transmission link in Afghanistan. Afghanistan has significant potential for the development of HVDC transmission technology. Some of the key opportunities for HVDC transmission in Afghanistan include:

Abundant Renewable Energy Potential: Afghanistan has a large potential for renewable energy, especially solar and wind energy. HVDC transmission can help unlock and utilize this potential by enabling the efficient transmission of energy from remote areas to population centers.

Energy Security: Afghanistan has historically been heavily dependent on insecure imported energy from neighboring countries, as discussed in Section 4. Developing a domestic HVDC transmission network can help improve energy security and reduce dependence on imports.

Economic Development: Developing a domestic HVDC transmission network can help stimulate economic development by creating new job opportunities, attracting investment, and improving energy access for households, industries, and businesses.

Achieving a Synchronized Grid: Utilization of the HVDC transmission grid can enable synchronization, i.e., connecting various AC networks with different voltage levels and frequencies.

Regional Energy Trade: Afghanistan is strategically located between energy-rich countries in Central Asia and energy-hungry markets in South Asia. Developing an HVDC transmission network could enable Afghanistan to play a key role in facilitating energy trade between these regions.

Climate Change Mitigation: The utilization of renewable energy sources and HVDC transmission can help relieve the impacts of climate change by reducing greenhouse gas emissions and promoting sustainable development.

To realize the HVDC transmission grid in Afghanistan, a strengths, weaknesses, opportunities, and threats (SWOT) model analysis has been performed, as shown in Figure 11. The SWOT analysis is a comprehensive overview of internal and external factors that can assist the country's power sector in decision-making based on present strengths, weaknesses, opportunities, and threats in the market.

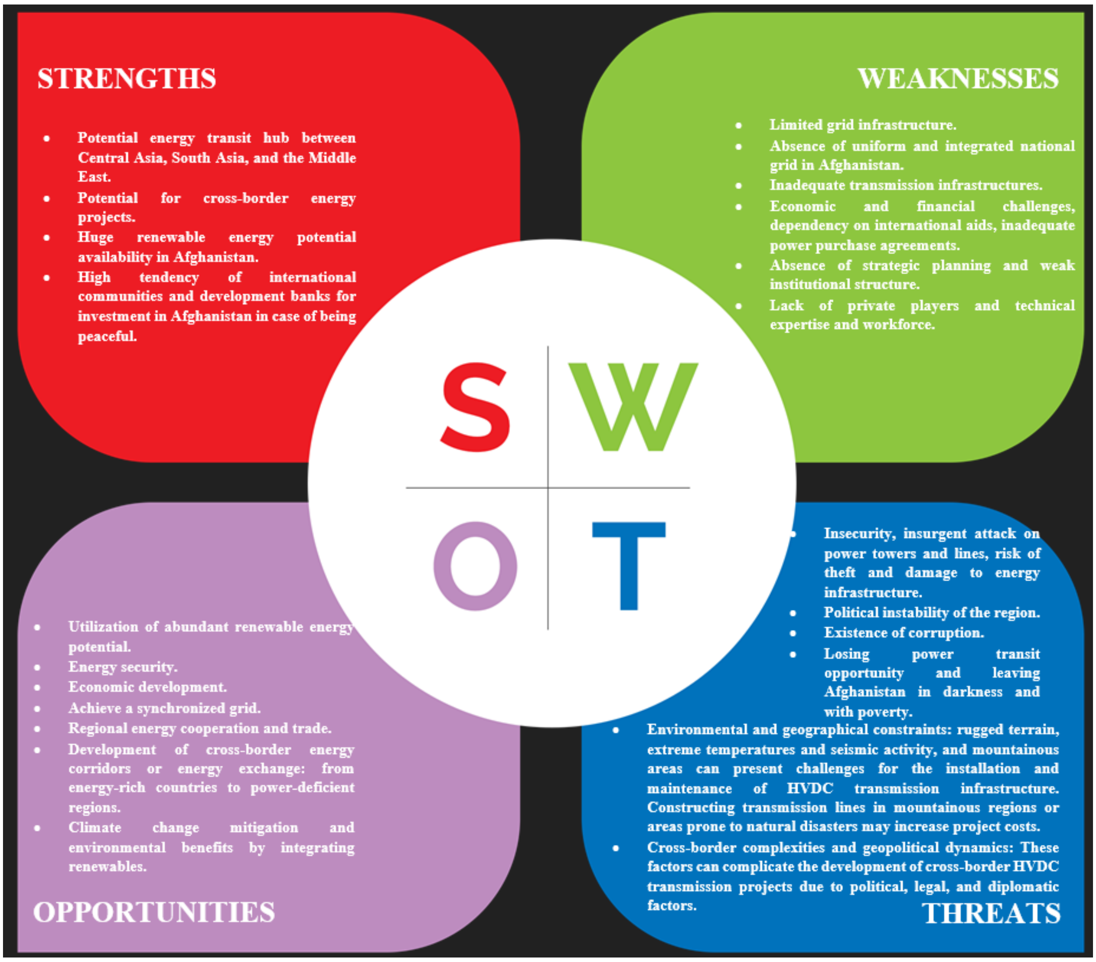

Figure 11. SWOT analysis for HVDC technology utilization in Afghanistan.

Scenario 3: Upgrading current HVAC to HVDC

Upgrading HVAC to HVDC transmission systems can provide several benefits in certain scenarios. Below are some key advantages [49–52]:

Reduced Losses: HVDC transmission has lower losses compared to HVAC systems, especially over long distances. This is because HVDC uses direct current, which experiences fewer losses due to only the resistance in the transmission lines. As a result, more energy can be delivered to end-users, improving overall system efficiency.

Increased Transmission Capacity: HVDC transmission has a higher transmission capacity compared to HVAC systems. HVDC can transmit more power over longer distances without significant voltage drop issues. This makes HVDC suitable for transmitting electricity over intercontinental distances or connecting remote power sources to the main grid.

Enhanced System Stability and Control: HVDC systems offer improved system stability and control. They provide better control over power flow, allowing for efficient balancing of electricity generation and consumption [53]. HVDC also supports the integration of renewable energy sources by enabling the transfer of power from resource-rich regions, such as Afghanistan, to areas with high demand.

Smaller Transmission Infrastructure: HVDC transmission lines require fewer conductors and smaller towers compared to HVAC lines for the same power capacity. HVDC lines can be implemented as underground or submarine cables, which reduces right-of-way requirements and minimizes environmental impact. This makes HVDC a suitable option for areas with limited space or challenging terrain.

Interconnection of Asynchronous Grids: HVDC systems can connect asynchronous AC grids, enabling power exchange between regions operating at different voltages, frequencies, or phases. This interconnection can enhance grid reliability, facilitate cross-border power trading, and improve grid resilience against disturbances.

Power Quality Improvement: HVDC transmission provides superior power quality compared to HVAC systems. They can mitigate issues such as voltage fluctuations, harmonic distortions, and reactive power management, resulting in improved power stability and reliability.

A few studies are in the literature on converting AC to DC power transmission. Reference [52] researched the conversion of double-circuit AC lines into three DC circuits, each having two conductors. The obtained results show a 147% increase in power transmission and a 68% reduction in power loss if HVDC technology is used. It is also mentioned that if underground cables are used, higher transmission power and smaller losses than those of overhead lines can be achieved. Some of the proposals in [54] can be considered as implementation methods. The most suitable is to convert an AC double-circuit line to a bipolar DC line due to simple modifications in the head of the tower to build the two poles of the HVDC line. Each pole concentrates all of the conductors of one AC circuit with no change in conductors or total rated current. Hence, the power transfer increases proportionally to the adopted new DC line-to-ground voltage. If the converted line DC voltage is double the line-to-line AC voltage, the transmitted power will increase by 3.5 (or $2\sqrt{3}$) times [52]. Nonetheless, these conversions involve the design and installation of converter stations both on the power-sending and receiving sides of the line, which can be counted as a disadvantage and the main objective of the process. Therefore, the decision to upgrade a transmission system is dependent on various factors. Here are some key points to consider regarding upgrading HVAC to HVDC in Afghanistan:

Technical Feasibility: Assessing the technical feasibility of upgrading the existing HVAC transmission system to HVDC is crucial. Factors such as the condition of existing infrastructure, converter stations, and compatibility with the power generation sources need to be evaluated.

Cost Considerations: Upgrading the transmission system from HVAC to HVDC involves significant investment, including the installation of converter stations and associated infrastructure. A thorough cost-benefit analysis should be conducted to evaluate the economic viability of such an upgrade, considering factors such as expected energy savings, reduced losses, and long-term operational costs.

Interoperability and Integration: It is essential to ensure that the upgraded HVDC system can interoperate with the existing power generation infrastructure, distribution networks, and other interconnected and import regions. Compatibility issues, synchronization challenges, and grid code modifications should be addressed during the upgrade process.

Environmental Impact: Assessing the environmental impact of the upgrade is crucial. While HVDC systems generally have lower transmission losses, the overall environmental impact should be evaluated, considering factors such as the manufacturing and disposal of HVDC equipment, electromagnetic fields, and any potential effects on local ecosystems. It is worth noting that the decision to upgrade a transmission system is a complex process involving technical, economic, and environmental considerations. Conducting a detailed feasibility study involving relevant experts and stakeholders is crucial to determining the suitability and benefits of upgrading HVAC to HVDC in Afghanistan.

Scenario 4: Hybrid HVAC/HVDC Grid

Hybrid HVAC/HVDC transmission refers to a combination of two power transmission technologies, i.e., HVAC and HVDC, to optimize and improve the efficiency and reliability of power transmission over long distances. HVAC is suitable for short- to medium-distance transmission, as it experiences lower losses compared to HVDC over shorter distances. However, HVAC technology suffers from higher losses due to factors like resistance and reactance over long distances. The hybrid approach typically involves using HVDC for the long-distance transmission segments and converting to HVAC for shorter distances or distribution to local grids. This way, the benefits of HVDC can be harnessed for long-distance transmission, while the advantages of HVAC, such as lower infrastructure costs, can be utilized for shorter distances. Hybrid HVAC/HVDC transmission systems are also often employed in large-scale renewable energy projects, interconnecting grids across regions or countries, such as the CASA-1000 project between Afghanistan, Pakistan, Kirgizstan, and Tajikistan. The major advantages of utilizing hybrid HVAC/HVDC transmission systems are [55–59]:

Efficient Long-Distance Transmission and Integration: By incorporating HVDC segments in the transmission system, renewable energy generated in remote areas can be efficiently transmitted with minimal losses to population centers or areas with high electricity demand. Besides, the hybrid HVAC/HVDC system provides a reliable means to connect renewable energy sources to the grid.

Enhanced Grid Stability and Reliability: In a hybrid HVAC/HVDC transmission system, the HVDC component can provide grid stabilization services, such as reactive power control and voltage regulation. This enhances the overall stability and reliability of the power grid, especially when integrating intermittent renewable energy sources.

Interconnection of Asynchronous Grids: Hybrid HVAC/HVDC systems enable the interconnection of asynchronous power grids and efficient power transfer between these grids. This facilitates the sharing of renewable and non-renewable energy resources between regions or countries and improves overall grid resilience.

Flexibility and Scalability: Hybrid HVAC/HVDC systems offer flexibility and scalability in power transmission. They can be designed and configured based on specific project requirements, enabling the transmission of varying amounts of power over different distances. Also, the hybrid approach allows for the optimization of infrastructure costs, considering the advantages of both HVAC and HVDC technologies. There are several notable examples of hybrid HVAC/HVDC transmission technology. Some of them are:

North Sea Link (NSL): The North Sea Link is a joint project between the United Kingdom and Norway, aiming to connect their power grids through an underwater HVDC cable. The 1.4 GW interconnector utilizes a hybrid transmission system, combining HVAC and HVDC technologies [60]. It stretches approximately 720 kilometers, making it the world's longest subsea interconnector. The project enables the exchange of renewable energy, primarily hydropower from Norway and offshore wind power from the UK.

Viking Link: The Viking Link is another major interconnector project connecting the power grids of the United Kingdom and Denmark [61]. It involves a 1.4 GW underwater HVDC cable, approximately 760 kilometers in length. The Viking Link project incorporates a hybrid HVAC/HVDC transmission system, allowing for efficient transmission of renewable energy, including wind power, between the two countries.

Western HVDC Link: The Western HVDC Link is a transmission project connecting Scotland and England in the United Kingdom [62]. It combines HVAC and HVDC technologies, utilizing a hybrid transmission system. The project facilitates the transmission of renewable energy generated in Scotland, particularly wind power, to the demand centers in England. The Western HVDC Link has a transmission capacity of 2.2 GW and spans over 420 kilometers [63].

China's Ultra High Voltage Projects: China has been at the forefront of developing large-scale renewable energy projects and has implemented several UHV projects that incorporate hybrid HVAC/HVDC transmission [64–66]. These projects involve transmitting power generated from renewable sources, including wind and solar, from remote regions to population centers.

On the other hand, the implementation of hybrid HVAC/HVDC transmission systems requires complex design, advanced converters, control systems, grid codes and standards, coordination, and compatibility between HVAC and HVDC components to ensure efficient and reliable power transmission. Besides, the conversion of power from AC to DC and vice versa involves semiconductor devices, which introduce some level of energy loss, broadband oscillation, and transient over-voltage [67].

8. Recommendations

Based on the increasing demand of the country, the vast availability of renewable and non-renewable energy resources, insufficient infrastructure and transmission network capacity, and associated current and future challenges, the following recommendations on the transmission networks have been made to improve energy access, security, and sustainable development in the country and with neighboring countries.

8.1. Load demand forecasting

Accurate load demand forecasting is essential for transmission planning. Afghanistan should invest in comprehensive data collection and analysis to accurately project future electricity demand growth. This information will help determine the capacity requirements for the transmission network and guide infrastructure development accordingly.

8.2. Strategic transmission expansion planning

Afghanistan should develop a comprehensive long-term transmission expansion plan that outlines the required infrastructure investments over a specified period. This plan should align with Afghanistan's energy goals and consider factors such as demand growth, renewable energy targets, and regional cooperation opportunities. The plan should be regularly reviewed and updated to reflect changing circumstances and technological advancements. The planning must involve all of the stakeholders from multiple sectors of the economy, including government agencies, regulatory bodies, power utilities, renewable energy developers, and local communities, throughout the process. The plan should foster collaboration and open dialogue to ensure that the planning decisions consider diverse perspectives, address socioeconomic impacts, and promote transparency. Afghanistan should constitute a central organization to function as a coordination catalyst to improve the perception of overall energy requirements and coordinate monitoring and planning with stakeholders. The planning should be optimal in the long term to create competition and stability for domestic and foreign investors and speed up the advancement of the transmission sector. Transmission planning should also focus on the assessment of transmission infrastructure requirements for effectively integrating renewable energy from resource-rich areas into the main grid. In addition, the plan should identify the transmission corridors, considering factors such as geographical constraints, extreme weather events, population centers, renewable energy potential, and interconnection points with neighboring countries to optimize the routing of power flows across the country. This will help determine the most efficient and cost-effective routes for new transmission lines. The network flexibility and modularity approach, such as modular substations, converter stations, and transformers, should also be considered. This allows for incremental expansions and/or replacements if needed, making it easier to adapt to changing demand patterns and the integration of new energy sources.

8.3. Well-coordinated regulatory framework development

Afghanistan should develop a well-coordinated regulatory framework as a key catalyst for the successful implementation of new and improved transmission networks. Such a framework ensures that the networks are efficiently planned, constructed, operated, and maintained while promoting fair competition, investment, and consumer protection. The regulatory framework should establish clear objectives and policy goals for the new transmission networks. This may include enhancing grid reliability, promoting renewable energy integration, improving energy efficiency, and fostering competition among market participants. An independent regulatory authority with appropriate expertise and power is recommended to oversee the transmission networks' development and operation. The authority should have the ability to set and enforce rules, resolve disputes, and ensure compliance with regulatory requirements. It should also encourage stakeholder engagement and public participation to ensure that the interests of consumers, the power sector (generators, transmission companies), and other relevant parties are considered. In addition, the regulatory framework should be flexible and adaptable to accommodate technological advancements, changing market conditions, and evolving policy goals. Moreover, if the new transmission networks involve cross-border connections or regional integration, the regulatory framework should promote international cooperation and harmonization of regulatory approaches.

8.4. Transmission investment encouragement

The development of the entire power system in Afghanistan depends on a robust transmission network. Strengthening regulatory frameworks and providing clear policies and administrative procedures are essential to attract investments and develop transmission projects. To overcome these challenges, a multi-faceted approach involving government initiatives, international supportive agencies, capacity building, and investment in infrastructure is necessary. Besides, the country's power sector master plan has not been updated since 2013. It is recommended to revise the master plan to adequately re-plan the investment to execute a sufficient power transmission system. In addition, the existing transmission grid infrastructure should be assessed to identify areas that require upgrades or replacement. The condition, capacity, and reliability of transmission lines, substations, transformers, and other equipment should be evaluated. This assessment will provide insights into the necessary investments and prioritize areas for improvement. Currently, the international community has stopped assisting Afghanistan and even frozen the development budget of the country. Therefore, the current situation in Afghanistan requires attracting foreign investments, seeking international support and financing from development partners, multilateral institutions, and donor agencies to fund transmission planning studies and infrastructure through negotiations, and facilitating a peaceful and cooperative environment. Moreover, the establishment of an investment insurance agency is recommended to encourage internal and international investors and the private sector to securely invest.

8.5. Capacity-building and institutional strengthening

Afghanistan must focus on capacity-building and institutional strengthening in the power sector. This includes training programs for engineers, technicians, and operators to develop the necessary skills for operating and maintaining the transmission networks effectively. In addition, to address the lack of technical expertise in power transmission, Afghanistan needs to invest in education, training, and capacity-building programs. This includes developing partnerships with technical institutions, establishing collaborations with international organizations, and implementing targeted training initiatives for power sector professionals. Additionally, promoting research and development (R&D) activities can foster innovation and knowledge-sharing within the power transmission field. By prioritizing the development of technical expertise, Afghanistan can improve the efficiency, reliability, and performance of its power transmission systems.

8.6. Technology option

The decision on the technology of the transmission network in Afghanistan is a complex task and therefore requires various national and regional technical, economic, environmental, geographical, and political considerations. It is essential to conduct research and a detailed feasibility and optimization study between the different transmission options and scenarios, i.e., HVAC, HVDC, and hybrid HVAC/HVDC, proposed in Section 7. The study should involve the relevant researchers, experts, technical institutes, stakeholders, and international communities, especially neighboring countries, who would be a part of the projects in various aspects, to determine the suitability and benefits of the chosen option and enhance the transmission capacity and reliability. The study should be done based on real and updated data, considering the population growth of the country, load demand, the technically feasible potential of renewable energy, the power import network with its various detailed technical and economic challenges, and existing and planned generation and transmission networks with their capacities, geographics, and health. Afghanistan has a significant rural population (85%) with no access to electricity [68]. The study should determine the feasibility of expanding the transmission grid with its applicable HVDC/HVAC technology or off-grid and mini-grid solutions to provide electricity to these underserved communities.

8.7. Regional cooperation

Afghanistan should explore opportunities for regional cooperation in power transmission. Collaborating with neighboring countries to establish cross-border transmission interconnections, such as the CASA-1000 project to facilitate the import and export of electricity, would ensure a more reliable and diverse energy supply.

8.8. Resilience and security

Given Afghanistan's geopolitical situation, ensuring the resilience and security of the power transmission network is crucial. Appropriate measures should be taken to protect critical infrastructure from physical and cyber threats. This includes employing advanced monitoring systems, backup power supplies, and investing in cybersecurity measures.

By implementing these recommendations, Afghanistan can ensure the efficient, reliable, and sustainable operation of its power transmission network, facilitating economic development and improving access to electricity for its population.

9. Conclusions

Despite having huge renewable energy potential, Afghanistan is extremely dependent on unreliable and insecure imported power, which puts strain on economic development. Besides, the Afghan transmission grid is very weak due to insufficient technology, capacity, and links to facilitate the utilization of grid-scale renewable energy. In this paper, the associated major issues, challenges, and constraints of transmission networks and power imports are comprehensively described. In addition, opportunities and proposals are highlighted that could overcome these challenges. Finally, recommendations have been provided that can enhance the transmission network capacity, improve the existing weak grid, and pave the way for reliable, stable, and techno-economic integration of renewable and non-renewable energy with high security. The proposals and recommendations can help the country and its power sector make decisions about large-scale transmission projects and long-term power trade with neighboring countries.

In conclusion, considering the transmission network as the backbone of the power sector of the country, which enables various power generation and transmission to the main load centers, improving and upgrading current transmission links, and designing and installing new and robust transmission links with updated and efficient technology, such as HVDC, are veritable tools for the domestic and regional power integration and sustainable development of Afghanistan and the region. The findings of this paper recommend optimal strategic planning and infrastructure investment in the transmission sector of the country, with regional and international support for the country.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Author Contributions

Gul Ahmad Ludin: Conceptualization, Methodology, Formal analysis, Investigation, Writing—original draft. Mohammad Amin Amin: Writing—review and editing. Ahmad Shah Irshad: Writing—review and editing. Soichiro Ueda: Data curation. Zakirhussain Farhad: Writing—review and editing. M. H. Elkholy: Writing—review and editing. Tomonobu Senjyu: Conceptualization, Resources, Supervision, Administration.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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