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Optimal Grid Flexibility Assessment for Integration of Variable Renewable-Based Electricity Generation

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Abstract: This study delves into power system flexibility, with a keen focus on the integration of variable renewable electricity generation into power grids. Two scenarios were analyzed. The base scenario revealed an aging grid, insufficient generation capacity, frequent outages, and little renewable energy generation (1.9%), along with a significant (71.23%) loss of load. In contrast, the investment scenario presented solutions including raising VRE capacity to 44%, adding 1000 MW capacity transmission lines, installing 200 MW capacity grid-scale battery storage, and technological enhancements. These interventions effectively eliminated loss of load, reinforcing energy resilience. Investments in CCGPP and grid-scale batteries proved instrumental in mitigating the variability of renewable energy. Improved transmission promised efficient power exchange and regional collaboration. The elimination of annualized energy spills and the removal of ramping constraints marked significant strides in enhancing power system flexibility. This research underscores the pivotal role of grid flexibility in accommodating VRE sources. By implementing the proposed optimal solutions, Afghanistan can lead the way toward a cleaner, more resilient, and more interconnected energy future. These findings offer a replicable framework for addressing similar challenges in integrating renewable energy sources globally and supporting the transition to sustainable and reliable energy.

Keywords: grid flexibility; grid modernization; renewable energy integration; energy transition; flexibility options; energy storage; power system; variable renewable energy; optimization

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1. Introduction

The global energy outlook is undergoing a monumental shift, driven by the pressing imperatives of mitigating climate change and fostering sustainable development [1]. As societies recognize the urgent need to decarbonize their energy sectors, the transition from fossil fuels to renewable energy sources has taken center stage. This pivotal transition not only holds the promise of reducing greenhouse gas (GHG) emissions but also offers the opportunity to reshape energy systems in ways that are cleaner, more resilient, and more conducive to long-term economic growth [2].

Variable renewable energy (VRE) sources such as solar and wind offer a compelling alternative to conventional fossil fuels [3]. Their inherent abundance, environmental friendliness, and potential for decentralized energy production have positioned them as the cornerstones of the global energy transition [4]. Simultaneously, with technological advancements and falling costs, VRE has emerged as a critical pillar for a sustainable energy future [5,6].

Among the various forms of renewable energy, solar and wind power stand out due to their availability, scalability, and potential for widespread implementation [7]. However, the intermittent and variable nature of solar and wind resources introduces unique challenges to power systems [8]. Unlike conventional power plants, which can provide consistent power output, solar panels and wind turbines generate electricity based on weather conditions [9,10]. This intermittency can lead to fluctuations in electricity supply, posing challenges to grid stability and reliability [11].

Integrating variable renewable-based electricity generation requires a paradigm shift in power system operation and management [12]. This is where the concept of power system flexibility comes into play [13]. Flexibility refers to a power system's ability to quickly adapt to changes in electricity supply and demand. A flexible power system can seamlessly accommodate fluctuations in renewable generation, manage energy imbalances, and maintain grid stability [14]. This dynamic capability is essential for ensuring a smooth transition to a future dominated by variable renewables [15].

To integrate VRE sources effectively, power systems must adopt a suite of flexibility options [16], including advanced energy storage systems, demand response mechanisms, grid upgrades, smart distribution networks, and enhanced forecasting techniques [17]. By leveraging these tools, power systems can absorb excess energy during periods of high generation and release stored energy when renewable generation is low, effectively bridging the gaps in supply and demand [18].

Though extensive research has been devoted both to the assessment of VRE integration into the grid and to power system flexibility, a noticeable research gap exists in concurrently analyzing both aspects [4]. Although prior studies have delved into isolated facets of power system flexibility, a lack of comprehensive research addressing all components of the power system, including generation, transmission, distribution, and energy storage, is evident [13]. This research gap underscores the necessity for a comprehensive inquiry into power system flexibility in the context of VRE integration, with the overarching objective of pinpointing optimal flexibility solutions for maintaining power system stability and resilience [2].

The principal aim of this study is to scrutinize the impact of VRE integration on power system flexibility, with a particular focus on optimizing flexibility across all facets of the power system. Furthermore, it seeks to assess power system flexibility within an island-type power system characterized by three nodes, which heavily depends on imported power and fossil fuels [13].

This research paper aims to address these critical issues within the context of Afghanistan's power system [19]. Focusing on the integration of solar and wind energy, we assess the optimal grid flexibility options that can enable Afghanistan to tap into its renewable energy potential while maintaining a stable and reliable electricity supply [20]. By simulating different scenarios using the IRENA FLEXTool, Version 2.0 (April 2020) simulation tool, we uncover insights into the challenges, opportunities, and strategies for achieving a sustainable and resilient energy transition [21].

Our study centers on Afghanistan's power systems and their transition towards a renewable-based future [22]. By analyzing two scenarios—a representation of the current state (base scenario) and an optimized flexibility solution (investment scenario)—we contribute not only to the knowledge of VRE integration in Afghanistan but also offer lessons and methodologies that can be applied in similar contexts worldwide [23]. The findings of this research hold implications for policymakers, energy planners, and researchers working toward sustainable energy futures in both developing and developed nations [24,25].

In the ensuing sections, we delve into Afghanistan's renewable energy potential, explore the country's electricity demand profile, analyze the challenges posed by VRE, and introduce the IRENA FLEXTool, Version 2.0 (April 2020) as a powerful simulation instrument [26]. We then present the results of our simulations under both scenarios, conduct a comprehensive comparative analysis, and conclude with recommendations for policymakers and stakeholders [27].

In essence, this research paper seeks to illuminate the path toward a cleaner, more resilient, and self-reliant energy future by underscoring the vital role of power system flexibility in embracing the variability of renewable energy sources [28,29]. Through a rigorous examination of Afghanistan's energy landscape, we aspire to contribute to the ongoing global efforts toward a sustainable energy transition, one characterized by innovation, adaptability, and a commitment to a more sustainable planet [30].

Motivation and Contribution

Various approaches have been employed to address the challenges related to power system flexibility and the integration of Variable Renewable Energy (VRE). However, a common issue arises when these methods are not analyzed in conjunction with one another. In such cases, the results obtained for individual power system components may not be suitable or optimized for the entire power system [31].

This study brings a novel perspective by conducting a comprehensive assessment of flexibility across all segments of the power system while simultaneously evaluating the integration of VRE. It introduces innovative models and algorithms, conducts a thorough analysis of power system flexibility using real-world data, and utilizes a robust assessment tool that takes a holistic view of power system flexibility. This holistic approach encompasses a wide array of factors, including technical, regulatory, and market-related elements. Such a comprehensive viewpoint is imperative in today's ever-evolving energy landscape [32].

This approach goes beyond conventional modeling tools, offering extensive policy support and actionable recommendations. The study plays a pivotal role in bridging the gap between analysis and practical solutions, empowering decision-makers to make well-informed choices in the dynamic field of energy management [33].

2. Renewable Energy Potential in Afghanistan

Afghanistan's energy sector has traditionally relied mainly on imported power, hydropower, and thermal power to meet its electricity demand. However, the country possesses significant untapped renewable energy potential. As of 2022, Afghanistan's renewable energy capacity was 319,500 MW, primarily comprising 222,000 MW capacity solar and 67,000 MW capacity wind energy installations [34]. Solar capacity is distributed all over Afghanistan, and wind capacity is distributed across the western region (Herat province), the northeast region (Kunduz, Takhar, and Badakhshan provinces), the north region (Balkh and Samangan provinces), and the central region (Kabul, Parwan, and Panjshir provinces), reflecting the geographical diversity of renewable resources [35].

Afghanistan's geographical location places it within the solar belt, granting it significant solar irradiance throughout the year. The vast desert, mountainous landscapes, and high altitudes offer ideal conditions for solar energy capture. The annual solar radiation averages around 1361 kWh/m^2, providing ample potential for solar energy installations across the nation [36].

The rugged terrain of Afghanistan, coupled with its varying elevations and climatic conditions, creates diverse wind patterns ideal for wind energy exploitation. Desert regions, mountain passes, and open plains experience varying wind speeds that can be harnessed for electricity generation. Preliminary studies estimate the country's wind power potential at 67,000 MW, presenting a substantial opportunity for renewable energy growth. See Figures 1 and 2 for Afghanistan's solar and wind resource potential maps, respectively [36,37].

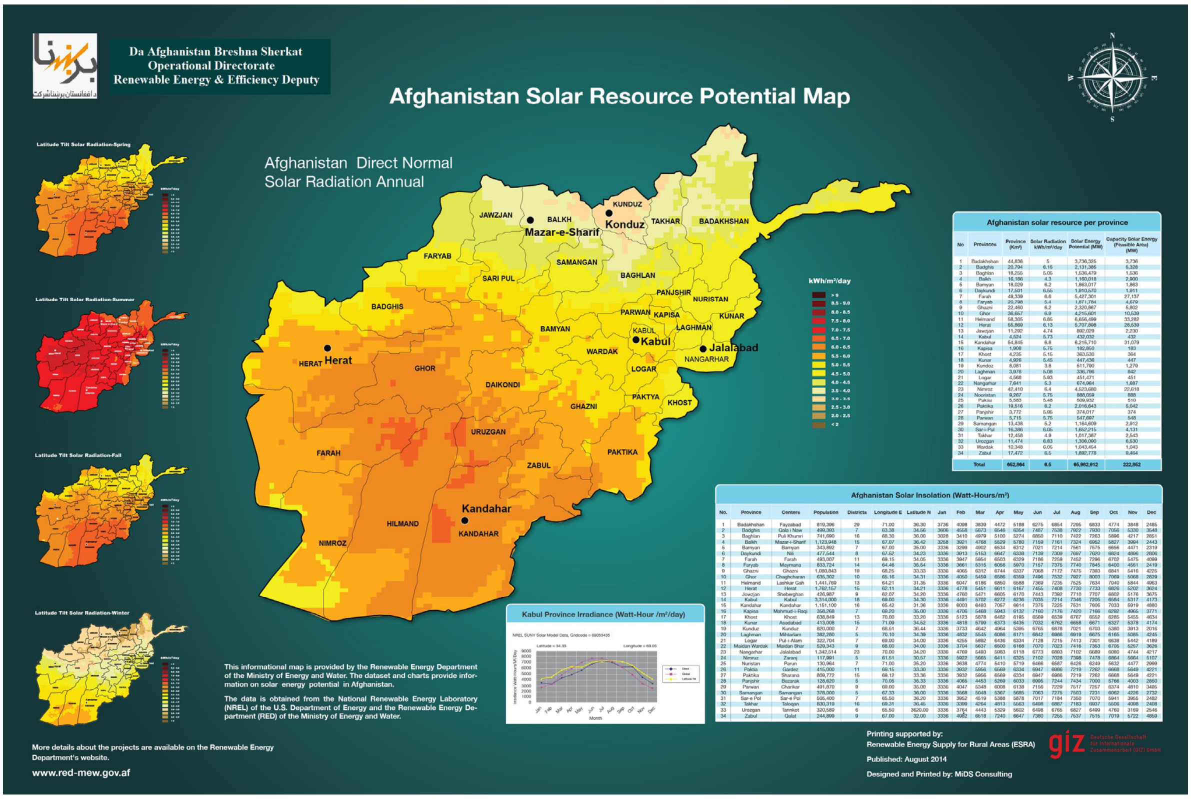

Figure 1. Afghanistan's solar resource potential map.

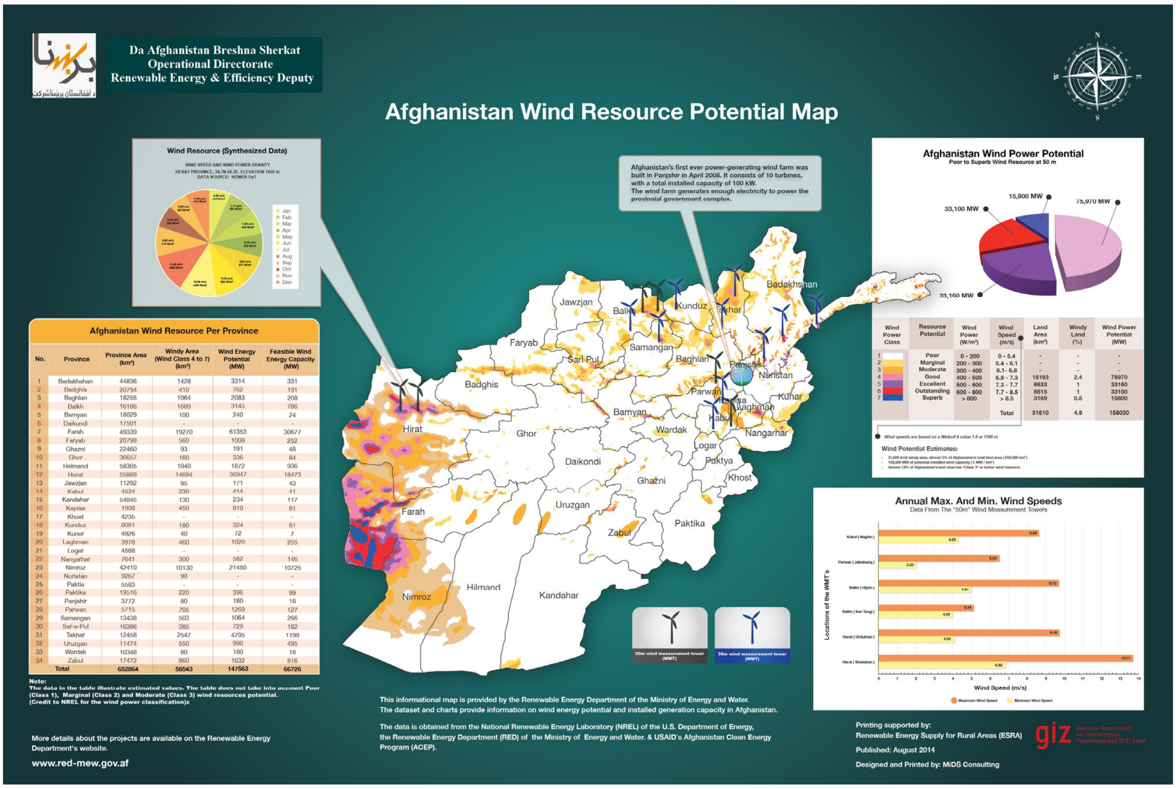

Figure 2. Afghanistan's wind resource potential map.

3. Afghanistan's Power System Overview

The power sector in Afghanistan is characterized by extremely low levels of access to electricity, particularly in rural areas. In urban areas, where access to grid supply is relatively higher, power availability is extremely unreliable, with rampant low-voltage problems [38]. Household energy access in the country is only about 35%, with 90% for urban and 10% for rural populations. Afghanistan has three separate power systems: the Northeast Power System (NEPS), the Southeast Power System (SEPS), and the West Power System (WPS) [39].

The NEPS spans the central, north, and east provinces and features a mix of urban and rural areas. It relies predominantly on thermal power plants (TPP), hydropower, diesel generator set (DG Set), and PV. The power network in this region is interconnected with Uzbekistan, Tajikistan, and Turkmenistan, facilitating cross-border electricity exchanges. In 2022, the NEPS possessed 484 MW of installed capacity, received an import of 465 MW of power, and encountered a demand for 3254 MW [19].

The SEPS, encompassing provinces such as Kandahar, Helmand, Uruzgan, and Zabul, represents a crucial hub for agriculture, mining, and industry. This region relies on a combination of hydroelectric, DG Set, and PV. The Kajaki hydro reservoir power plant with 151 MW of generation capacity along the Helmand River contributes significantly to the power supply of the SEPS; DG Set with 28 MW capacity and PV with 40 MW of generating capacity contribute accordingly. The SEPS has no cross-border electricity connection with neighboring countries. In 2022, the SEPS possessed 220 MW of installed capacity and encountered a demand for 578 MW [40].

The WPS region includes provinces such as Herat, Farah, Badghis, Nimroz, and Ghor and is strategically positioned for potential renewable energy development. This region has significant wind and solar energy potential. The power grid in this area is characterized by a mix of hydroelectricity, DG Set, and a small share of PV. The SEPS is interconnected with Iran for power imports, and in 2022, the WPS possessed 52 MW of installed capacity, received an import of 142 MW of power, and encountered a demand for 471 MW [26].

The demand for electricity in Afghanistan has experienced consistent growth over the past two decades. Several factors contribute to this surge in electricity consumption, including but not limited to urbanization, population growth, and economic development. Figure 3 illustrates the potential demand projection for an average MW. The demand profile in Afghanistan is diverse, reflecting the needs of various sectors such as residential, commercial, and industrial. Understanding the demand dynamics and distribution across these sectors is essential for effective energy planning and grid management, and provides a foundation for the subsequent analyses of grid flexibility and renewable energy integration [27].

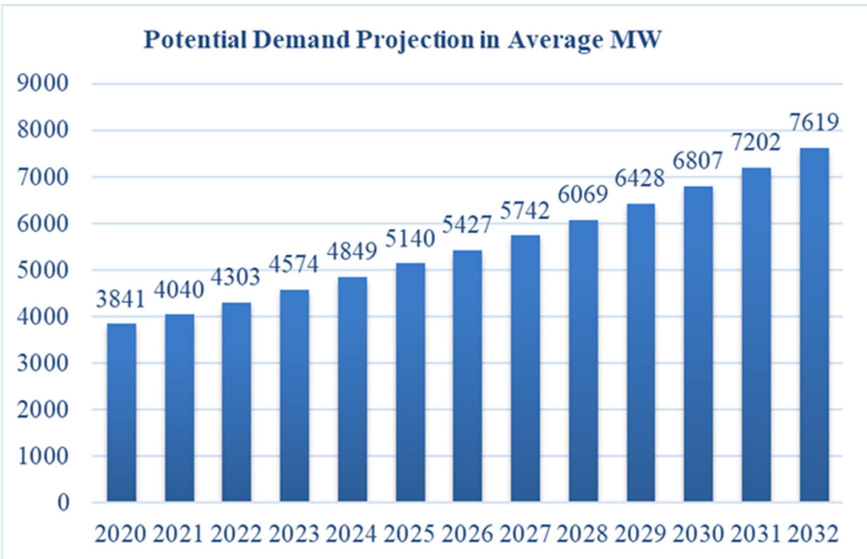

Figure 3. Potential demand projection in average MW.

4. Materials and Methods

To collect the actual and real-time data for the simulation and analysis, a comprehensive data collection procedure was implemented. Actual and real-time data from the grid-connected PV solar power plant, independent power producers (IPPs), Afghanistan Energy Information Center (AEIC), Ministry of Energy and Water, National Environmental Protection Agency (NEPA), academia, utility grid (DABS), companies, and hydro and thermal power plant monitoring systems were collected. For greater precision and more robust results, interviews were conducted with a diverse range of experts. Different procedures were implemented for the data collection, including but not limited to structured interviews, official channels (letters), questionnaires, content analysis, archival research, secondary data analysis, telephone surveys, diaries and journals, and historical analysis. Since there are only a few entities involved in the power sector and there is only one power provider company, all of them were contacted for data collection. Out of every 8 experts, 3 were selected for interviews [9]. It is worth mentioning that 25% of the companies participated in the data collection process. See Figure 4.

After completing the data collection process, the crucial stages of data verification and analysis were initiated. Ensuring the accuracy and validity of the collected data was of paramount importance [41]. To facilitate comprehensive analysis and modeling, we meticulously inputted the data into the IRENA FLEXTool. This software tool (Version 2.0 (April 2020)) is widely recognized for its effectiveness in assessing power system flexibility, making it an ideal choice for our research. The utilization of the IRENA FLEXTool allows us to leverage its robust analytical capabilities to gain deeper insights into power system flexibility assessment, contributing to the overall rigor and reliability of our study [13].

FLEXTool, developed by the International Renewable Energy Agency (IRENA), is a comprehensive simulation tool designed to analyze and assess the flexibility options of power systems [42]. It facilitates the evaluation of various scenarios and strategies for integrating VRE sources, ensuring the stability and reliability of electricity grids [43] (Appendix A).

The flexibility assessment methodology of FLEXTool encompasses a holistic approach, considering factors such as renewable energy generation profiles, demand patterns, transmission capacities, energy storage systems, and grid stability constraints [6]. By simulating different scenarios, the tool provides insights into the ways in which different flexibility measures impact the overall performance of the power system [44,45].

To conduct accurate simulations, FLEXTool relies on precise input data and assumptions [5]. The collected input data include, but are not limited to, the following categories: geographical region of interest, time horizon, policy and regulatory, economic, hourly annual demand and import in MWh, losses, capacity margin (MW) per node and for the whole power grid, maximum share of non-synchronous generation (solar, wind and battery storage), interconnection with other countries, transmission capacity between power systems (MW), existing capacity by fuel/technology (MW), details of capacity by fuel (efficiency, O&M, cost), generation by fuel/technology (MWh), hydro reservoir capacity (MWh), hourly time series data including electricity demand, hydro inflow, capacity factor, electricity import and reserves hourly time series, load profiles to depict electricity demand fluctuations, and information about existing grid infrastructure and technological capabilities [42]. Ensuring the accuracy of these inputs is paramount for generating reliable results. See Figure 4 for the detailed and comprehensive data collection and simulation process [46,47]. Meanwhile, the following assumptions were made for a successful run of the simulation and accurate results:

- A maximum of 80% share of non-synchronous generation.
- A maximum of 1% of hourly demand as reserves in each node.
- A maximum of 1% hourly demand of all nodes as power system reserve.
- The absence of a capacity margin allocation for each node and the entire power system due to the shortage of generation.
- The absence of an inertia limit due to higher demand than supply.
- 50 min reserves availability time.

- At least 20% of the generation is from non-renewable sources.
- An allocation of 1% of PV generation as dynamic reserves.

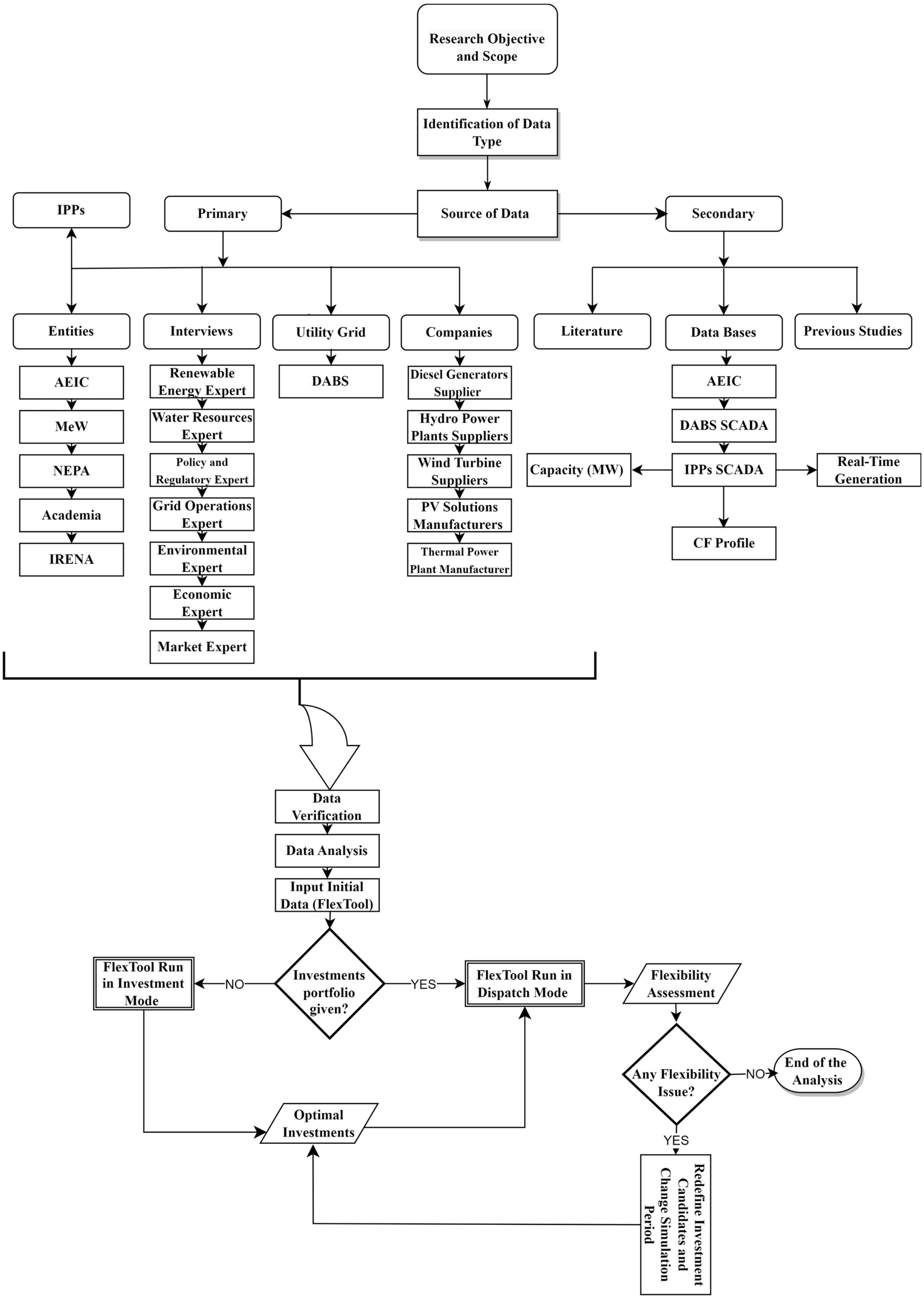

Figure 4. Detailed and comprehensive data collection and simulation process.

FLEXTool incorporates advanced models for renewable energy generation, allowing users to simulate the behavior of solar and wind power plants under different conditions [48]. These models consider variables such as irradiance, wind speed, and temperature to estimate the electricity output of renewable installations, thus enabling a detailed analysis of their impact on the power system [49].

The utilization of FLEXTool offers several advantages for power system planners and researchers. It enables the identification of optimal flexibility solutions to address the challenges posed by VRE integration [50]. Moreover, the tool assists with understanding the economic, technical, and environmental implications of different scenarios, guiding decision-makers in making informed choices [51].

FLEXTool has emerged as an asset in the quest for effective renewable energy integration [52]. Through its sophisticated simulation capabilities, it empowers stakeholders to explore a spectrum of possibilities, from demand-side management to energy storage implementation, thus charting a course toward resilient, low-carbon power systems. In the subsequent sections, we apply the tool to assess two scenarios: the current state of Afghanistan's power system (the base or dispatch scenario) and an optimized flexibility solution (the investment scenario) [53].

5. Results and Analysis

5.1. Base Scenario: Current State of the Power System

To comprehensively assess the current state of Afghanistan's power systems, meticulous data analysis and modeling processes were undertaken. Leveraging historical data, various facets of the power infrastructure were examined, including:

Historical Load Profiles: Analyzed demand patterns in the NEPS, SEPS, and WPS Power Systems. This analysis provided insights into peak demand periods, seasonal variations, and regional disparities in consumption.

Generation Mix: By the end of 2022, the potential demand of Afghanistan was 4303.09 MW and the total installed capacity of the power grid was 755.4 MW, including 240 MW of TPP, 51 MW of DG Set, a 43.3 MW PV power plant, and a 421 MW hydro power plant. See Table 1 for the NEPS, SEPS, and WPS power systems' 2022 generation mix.

Table 1. NEPS, SEPS, and WPS 2022 generation mix.

Type of Power Plant	Installed Capacity (MW)	Location
Hydro Reservoir	100	NEPS
Hydro Run-of-River	127.4	NEPS
TPP	240	NEPS
DG Set	15.25	NEPS
PV	1.27	NEPS
Hydro Reservoir	151.4	SEPS
Hydro Run-of-River	0.32	SEPS
DG Set	28	SEPS
PV	40	SEPS
Hydro Reservoir	42	WPS
DG Set	7.7	WPS
PV	2	WPS

In 2022, the imported power from neighboring countries (Uzbekistan, Tajikistan, Iran, and Turkmenistan) was about 606 MW and contributed to meet 14% of the annual demand (4303.9). Hydropower makes up the highest proportion of the total installed capacity of the power system, and TPP, DG Set, and PV contribute accordingly. Table 2 illustrates different generation units' proportion of the installed capacity and the demand as a percentage.

Table 2. Proportion of different generation units to the installed capacity and demand.

Generation Unit	Quantity (MW)	% of Total Installed Capacity	% of Demand
Hydro Power	421	55.7	9.8
TPP	240	31.8	5.6
DG Set	51	6.8	1.2
PV	43.3	5.7	1

Grid Infrastructure: Afghanistan's power system mainly suffers from aging infrastructure, limited grid coverage, insufficient generation capacity, voltage fluctuations, frequent power cuts, a lack of grid resilience, inadequate cross-border connections, fuel supply challenges, limited renewable energy integration, a lack of advanced metering infrastructure (AMI), a lack of interconnection between the three power systems for energy transfer, a lack of the required capacity margin, a lack of battery storage systems, a lack of upward reserves, high dependence on imported power, limited grid automation, and an inertia limit.

Flexibility Issues Identification

The simulation analysis revealed several key flexibility issues within Afghanistan's power system when integrating VRE sources.

These findings provide valuable insights into the challenges and opportunities associated with the transition towards a more sustainable and reliable energy mix.

One of the key metrics assessed in our study is the VRE share, which is expressed as a percentage of the annual electricity demand. In Afghanistan, this share is determined to be 1.9%. This figure represents the portion of electricity generated from VRE sources, primarily solar, relative to the total electricity demand in the country. It indicates that VRE sources currently contribute a modest 1.9% of the total electricity.

A critical aspect of the analysis is the assessment of loss of load within the power system. Loss of load signifies the percentage of annual electricity demand that cannot be met due to supply limitations or other constraints within a system. In Afghanistan, the loss of load is alarmingly high, amounting to 71.23% of the annual demand. This means that a substantial portion of the electricity demand remains unfulfilled due to various factors such as transmission constraints, inadequate infrastructure, and supply fluctuations and inadequacy.

The maximum net loss of load, quantified in megawatts (MW), is another crucial parameter evaluated in this study. The maximum net loss of load is found to be 2605 MW. This value represents the peak demand that cannot be met during periods of high electricity consumption. It reflects the severity of supply–demand imbalances and the need for grid enhancements and better management strategies to ensure a reliable power supply. The loss of load and supplied power is illustrated in Figure 5.

The maximum loss of loads over the course of one year in the NEPS, SEPS, and WPS are 20.7 TWh, 3.7 TWh, and 2.5 TWh, respectively (see Figure 6). A high loss of load indicates a potential lack of flexibility in the power system to handle variations in generation and demand. The relatively low VRE share coupled with the high loss of load indicates the Afghanistan power system's flexibility challenges in integrating VRE and balancing demand and supply.

The simulation declared the total annualized energy spill from reservoirs to be 0.8 TWh/year, and this energy spill was observed at the NEPS and WPS power systems. It quantifies the amount of energy lost due to spills from reservoirs over the course of one year. The energy spill from reservoirs signifies inflexibility in hydroelectric power generation, where excess water resources are not effectively harnessed and utilized. The energy spill from reservoirs signifies an inflexibility in the hydroelectric power generation process, where excess water resources are not effectively harnessed and utilized. This phenomenon occurs when hydroelectric power plants are unable to capture and convert all available water flow into electricity, resulting in the wastage of valuable energy resources.

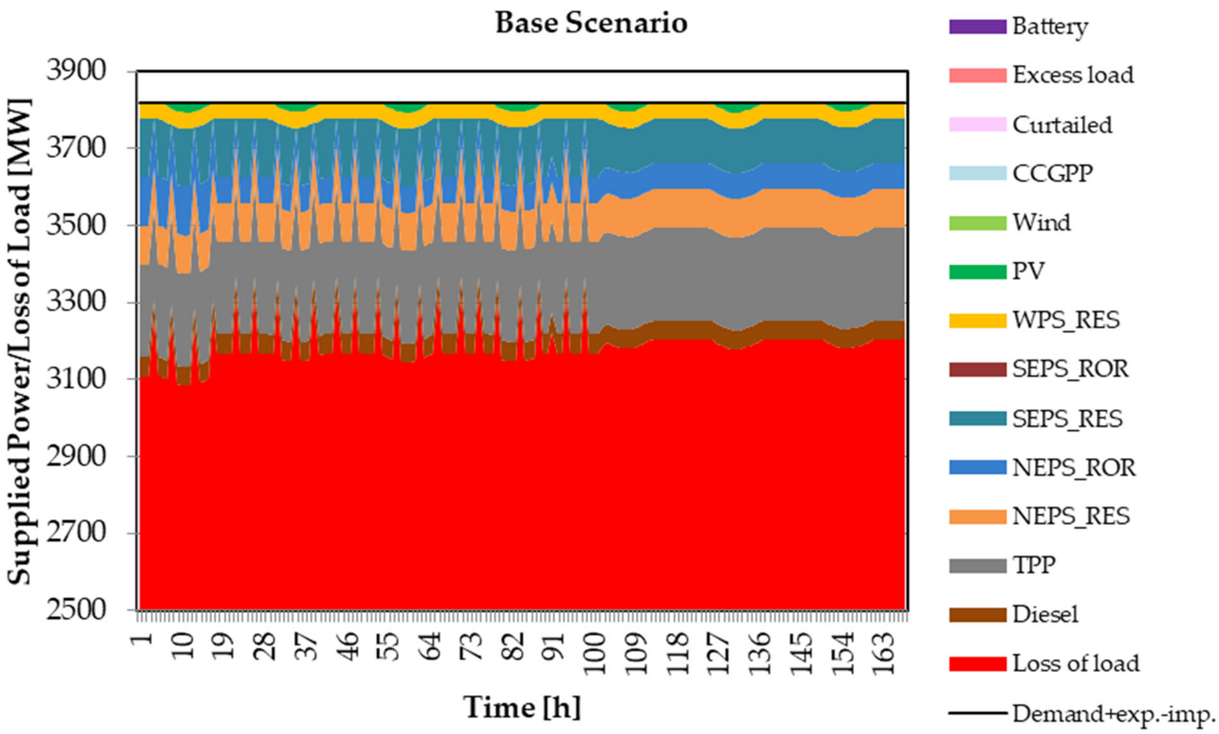

Figure 5. Loss of load and supplied power.

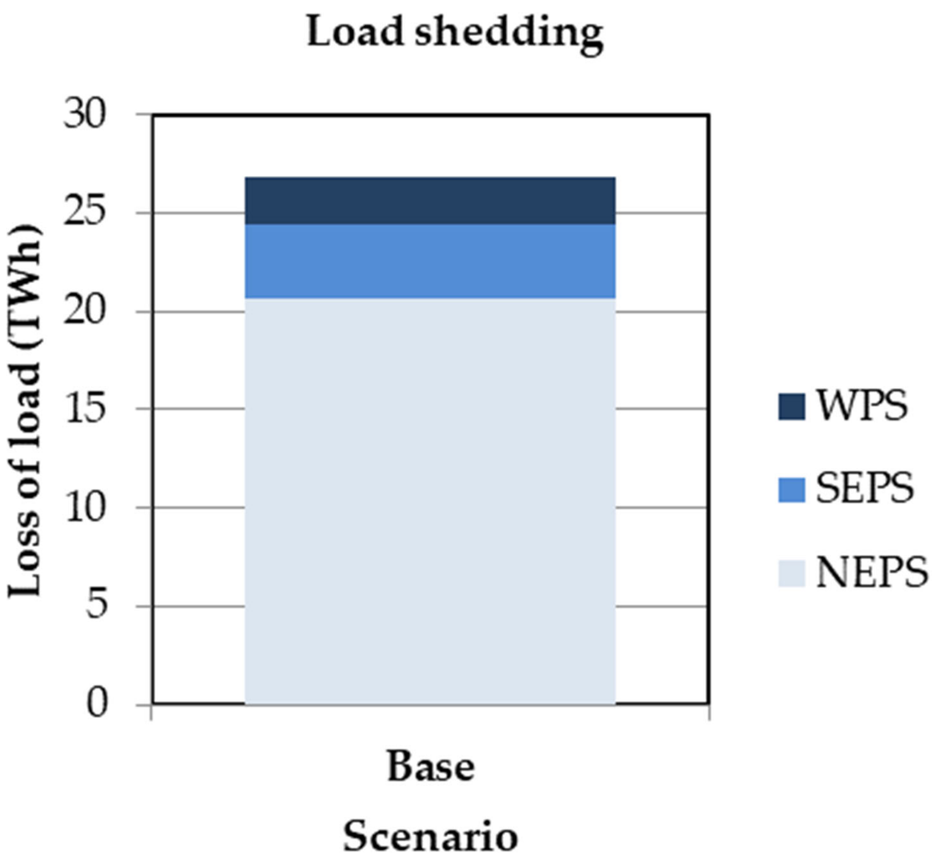

Figure 6. Loss of load in the NEPS, SEPS, and WPS.

Several factors contributing to energy spill include, but are not limited to, variability in water supply, capacity constraints, grid integration challenges, and environmental challenges.

Spills from hydro reservoir storage in the NEPS and WPS power systems are illustrated in Figure 7.

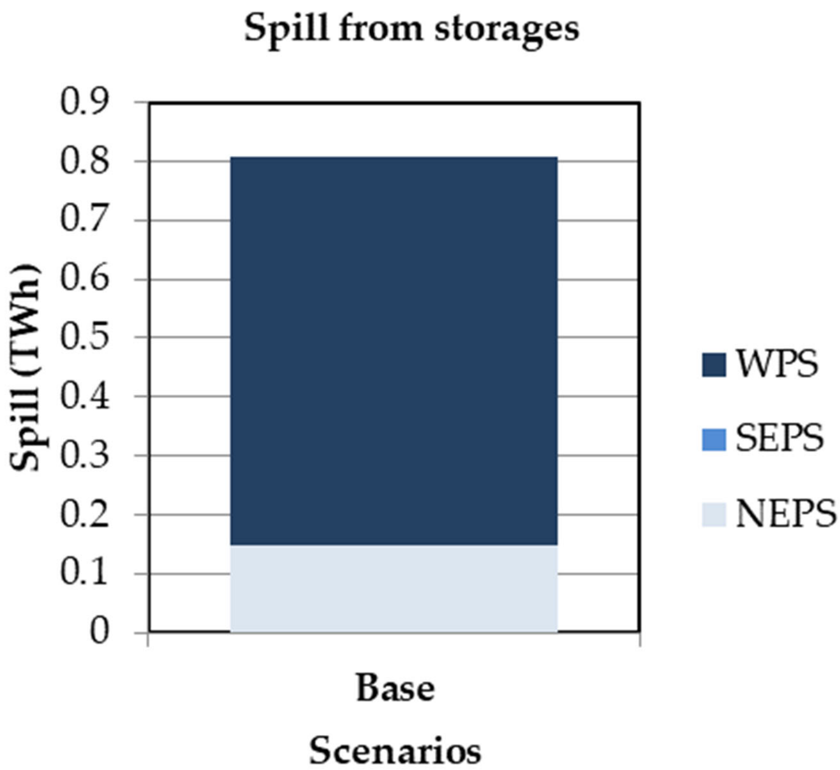

Figure 7. Spill from hydro reservoir storages in NEPS and WPS power systems.

The simulation results provide an overview of the utilization rate of different generation units. The utilization rate indicates the proportion of available generation unit capacity that was effectively harnessed for electricity generation. A high utilization rate of TPP and DG Set suggests a lack of flexibility in the system. On the other hand, a higher utilization rate of VRE and hydropower indicates better flexibility in optimizing PV generation to meet electricity demand and accommodate VRE intermittently. Table 3 illustrates the utilization rate of generation units.

Table 3. Utilization rate of generation units.

Generation Unit	Utilization Rate (%)
TPP	100
DG Set	97.8
Hydro Reservoir	88.3
Hydro Run-of-River	59
PV	17

The simulation revealed that due to limitations on the supply side, the Afghanistan power system experienced ramp-up and ramp-down constraints in its ability to rapidly increase or decrease power generation to meet sudden spikes in demand and overgeneration in supply to accommodate fluctuations in VRE output. Afghanistan's power system requires certain capabilities, including a minimum upward ramping and upward VRE capacity of 1 to 153 MW over a one-to-four-hour period and net load ramps ranging from −18 to 60 MW. The power system should also have downward ramping capabilities of −432 to −584 MW and downward ramping of VRE between −500 and −735 MW during high VRE renewable generation occasions (see Figure 8).

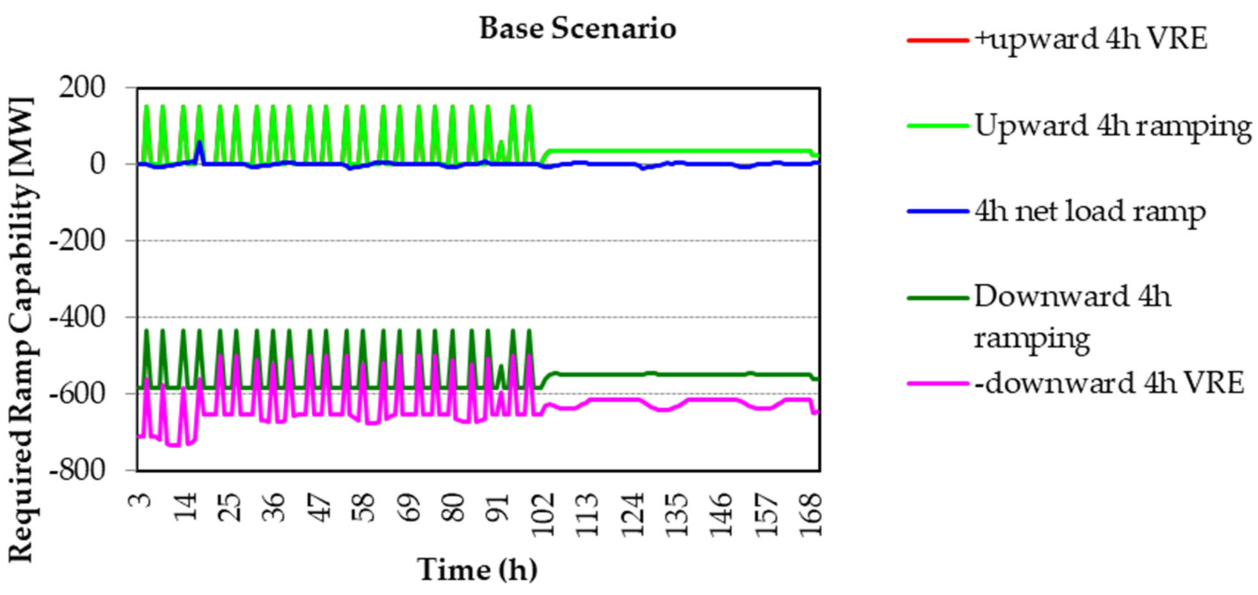

Figure 8. One to four hours required ramping capability.

Finally, since there is no interconnection between the NEPS, SEPS, and WPS power systems, there is no capacity rightward (transmission capacity for power transfer from the NEPS to the SEPS) and capacity leftward (transmission capacity for power transfer from the WPS to the SEPS), which indicates the lack of flexibility in the Afghanistan power system. This is because without interconnection, surplus VRE generation generated in a specific region cannot be transferred to a different region with high demand.

In the context of Afghanistan, capacity rightward implies the capability to transmit electricity from the NEPS to the SEPS, while capacity leftward signifies the capacity to transfer electricity from the WPS to the SEPS. These transmission capacities are vital for balancing the supply–demand dynamics across various regions. The absence of interconnection infrastructure signifies a fundamental lack of flexibility within the Afghanistan power system. This lack of connectivity restricts the movement of electricity between regions, preventing surplus VRE generation in one specific area from being efficiently transferred to regions with high electricity demand.

Without interconnection, several implications arise. Firstly, there is uneven energy distribution, as surplus electricity from sources such as solar and wind cannot be efficiently redistributed to areas with high demand, causing shortages in some places and wasting potential in others. Grid stability is also compromised, with energy supply and demand imbalances straining the grid, causing instability, voltage fluctuations, and blackouts. Moreover, Afghanistan's untapped renewable energy potential, particularly in remote regions, goes unused due to the absence of interconnection, representing a significant missed opportunity to harness clean energy sources effectively. These challenges highlight the critical need for interconnection to ensure equitable energy distribution and grid stability while unlocking Afghanistan's renewable energy potential.

5.2. Investment Scenario: Optimal Flexibility Option

Building upon the insights gained in the base scenario, the investment scenario focuses on a detailed assessment of the optimal flexibility needs within Afghanistan's power systems. In the investment scenario, a wide range of flexibility options have been evaluated to address the identified needs, each meticulously analyzed to improve the flexibility, sustainability, and reliability of the national electricity grid. The optimal solutions include: increasing the capacity of VRE sources such as solar and wind to harness abundant clean energy; extending and upgrading the transmission network between the NEPS, SEPS, and WPS; the deployment of large-scale energy storage systems to store excess energy during periods of high generation and release it during peak demand hour; enhancing the grid's ability to ramp power generation up or down quickly to respond to sudden fluctuations in supply or demand; developing and implementing a flexible grid code that accommodates the variability of renewable energy sources and encourages grid-friendly practices; technological improvements; the modernization and retrofitting of hydropower plants and the grid; and the use of smart meters and advanced metering infrastructure (AMI).

The cornerstone of the investment scenario is the identification of an optimal generation mix, strategically designed to meet electricity demand while ensuring a balanced supply–demand equilibrium. This mix comprises a diverse array of energy sources and technologies.

The optimal generation mix includes investment in solar, wind, hydropower (reservoir and pumped hydro), combined cycle gas power plants (CCGPP) with fast ramp-up capability, and grid-scale battery storage with a minimum capacity of 4 h. These are the identified generation mixes required to balance supply and meet demand. Figure 9 visually represents the optimal generation mix. This mix not only satisfies the nation's electricity needs but also empowers Afghanistan to transition towards a more sustainable and flexible energy landscape. The synergy of these elements puts the country on the path towards a resilient and adaptive power system capable of meeting current and future challenges while reducing its environmental footprint.

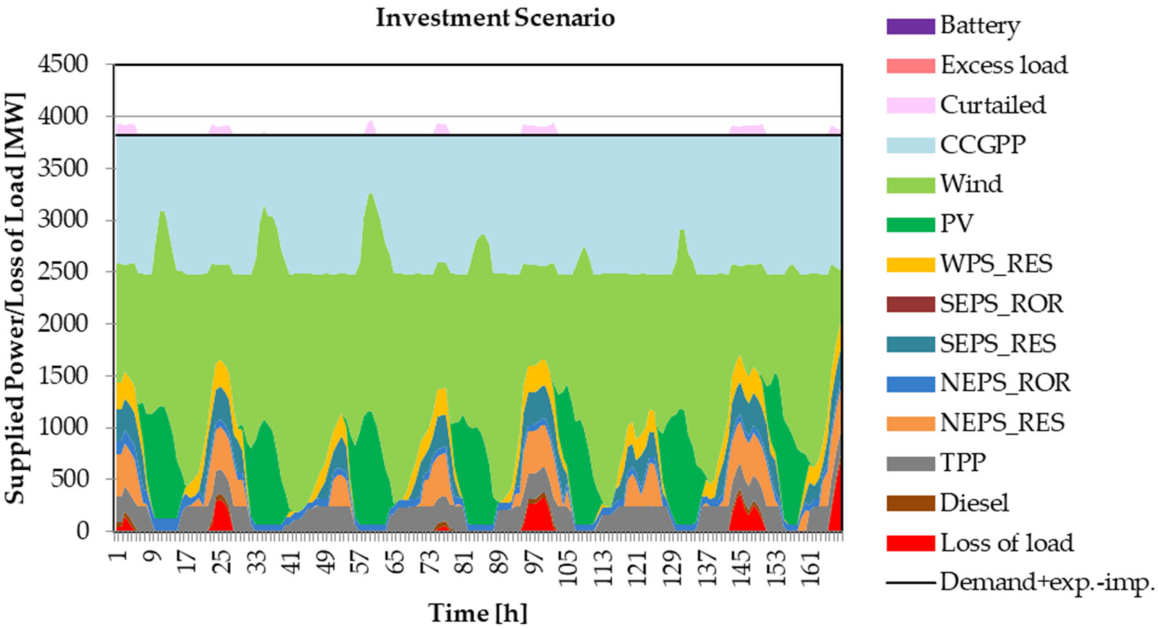

Figure 9. Identified optimal generation mix.

The invested capacity, utilization rate, and actual generation mix capacity of individual generating units is illustrated in Table 4.

Table 4. Invested capacity, utilization rate, and actual generation of units.

Type of Power Plant	Invested Capacity (MW)	Utilization Rate (%)	Actual Generation Capacity (MW)
Hydro Reservoir	975	36	351
Hydro Run-of-River	127.4	59.6	76
TPP	240	67	161
DG Set	51	0	0
PV	1831	17	312
Wind	6000	26.2	1570
CCGPP	1339	91.71	1228

The flexible CCGPP is meant to complement the variable nature of renewable energy sources to bolster the country's energy resilience and enhance grid flexibility. When solar and wind power generation is abundant, the gas power plant can reduce its output, conserving fuel and aligning with the principles of sustainability. On the other hand, during periods of peak electricity demand or when renewable energy generation is limited, the gas turbines can rapidly ramp up to full capacity, providing additional power to promptly meet the grid's requirements.

Following the implementation of the flexible options, a remarkable transformation has occurred. Notably, the most striking outcome is the complete elimination of load loss. This milestone underscores the significant positive impact that well-conceived flexibility measures can have on the reliability and efficiency of the grid. The elimination of loss of load, particularly in the NEPS, is a noteworthy accomplishment. The negligible loss of load and curtailment observed in the NEPS can be attributed to two key factors: high electricity demand and the variable nature of solar and wind resources (see Figure 10). The presence of high demand in the NEPS underscores the need for a resilient and adaptable grid infrastructure. As demand surges, particularly during peak hours, a responsive grid is essential to ensure that electricity supply continuously matches the dynamic demand patterns. The flexible options implemented in the investment scenario have enabled the power system to meet this challenge effectively.

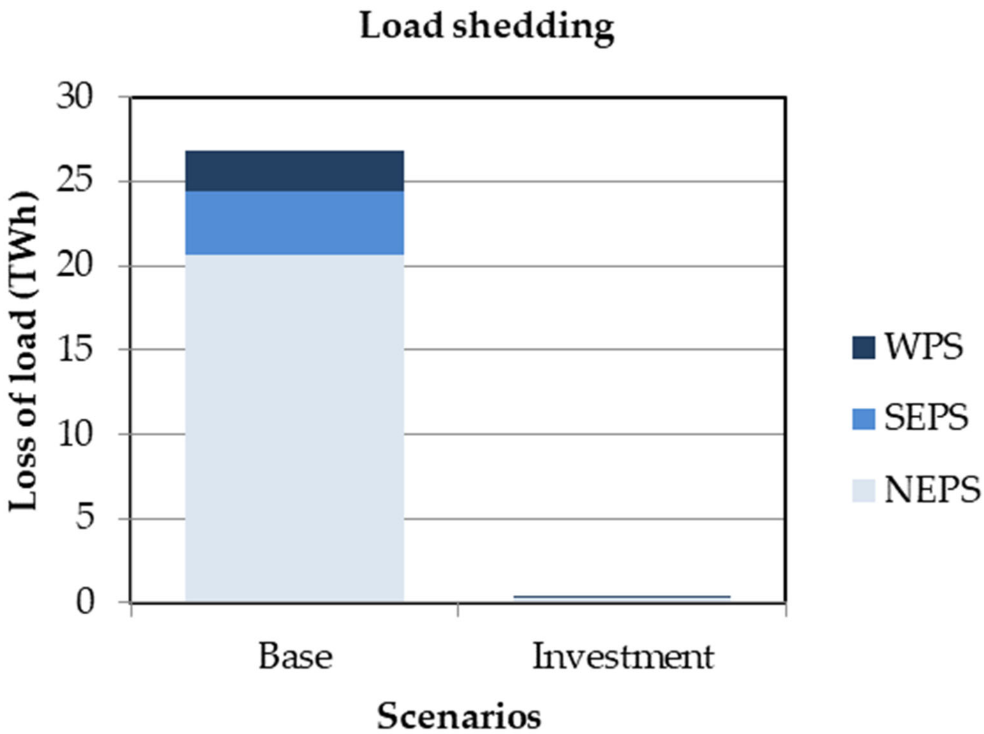

Figure 10. Loss of load at the NEPS, SEPS, and WPS.

The option to expand 1000 MW of transmission between the NEPS, SEPS, and WPS allows for efficient power exchange and better load balancing. The improved grid interconnection will facilitate the transfer of surplus electricity from regions with high renewable generation to areas experiencing higher demand, enabling the optimal utilization of renewable energy resources, thereby reducing the need for curtailment and avoiding loss of load.

Furthermore, the investment plan includes cross-border transmission interconnections with neighboring countries, including Uzbekistan, Tajikistan, Iran, and Turkmenistan. These interconnections will enhance regional energy cooperation by enabling power exchanges and access to diverse energy resources. By leveraging cross-border transmission, Afghanistan can import electricity during periods of domestic shortfall and export excess renewable energy to neighboring countries when it is available. This not only enhances energy security but also fosters regional collaboration in the development and integration of renewable energy sources.

The 200 MW of grid-scale battery storage will significantly enhance the flexibility of Afghanistan's power system, promoting a seamless transition towards a sustainable, low-carbon, and reliable energy future. The integration of energy storage systems will enable the efficient management of VRE fluctuations, reducing reliance on conventional fossil fuel-based generation and paving the way for a cleaner and more resilient energy system. Additionally, the expanded and interconnected grid will improve the reliability of electricity supply, support the integration of variable renewable sources, and unlock the full potential of renewable energy resources across the country and the region.

The results reveal that after implementing the optimal flexible options, there is no annualized energy spill from reservoirs. Figure 11 shows the spillage in the base and investment scenarios. The elimination of energy spill is a significant achievement, realized through a combination of strategic measures. These measures encompass infrastructure upgrades, improved grid integration, advanced forecasting, and a balanced approach to environmental considerations. The investment in the expansion and modernization of reservoirs and the associated infrastructure plays a pivotal role in increasing the capacity to store excess water, effectively reducing spillage. Enhanced grid integration, characterized by the improved coordination between hydroelectric facilities and grid operators, enables the grid to absorb surplus electricity during peak water flow periods, minimizing energy spillage. Additionally, the implementation of advanced forecasting techniques for water availability empowers power plants to anticipate and manage surplus water more efficiently, further mitigating energy losses. Striking a balance between environmental preservation and energy generation, strategies have been developed to allow controlled releases from reservoirs while minimizing the wasteful loss of energy. These combined efforts not only eliminate energy spill but also enhance the sustainability and reliability of the power system, marking a significant milestone in the nation's energy transition journey.

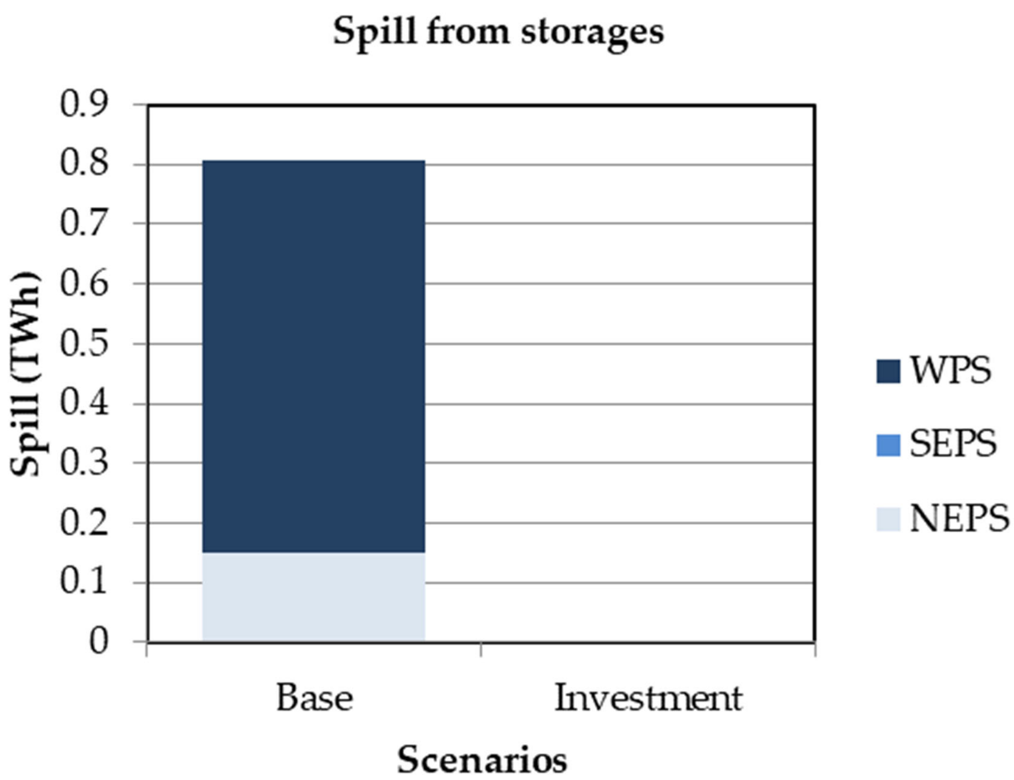

Figure 11. Spill from storage in the base and investment scenarios.

The simulation showed a complete elimination of the Afghanistan power system's ramping constraints because there were no longer any limits on the supply side after investments in generation mix, transmission capacity expansions, and energy storage. The power system no longer experiences ramp-up and ramp-down constraints, and the required ramping capabilities are provided. Figure 12 illustrates the ramping capabilities.

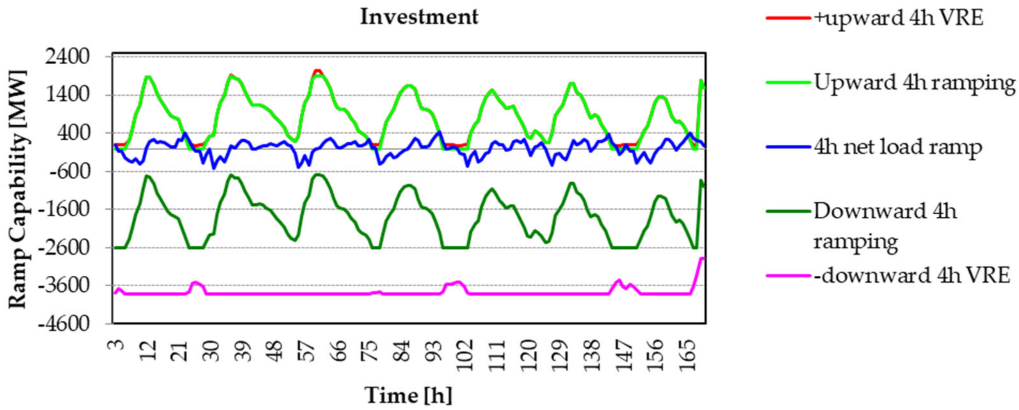

Figure 12. Ramping capability.

5.3. Discussion on Implications

The findings of this study hold significant policy implications for Afghanistan's energy sector. As the nation seeks to diversify its energy sources and reduce its reliance on fossil fuels and imported power, the assessment of grid flexibility for integrating Variable Renewable-Based Electricity generation becomes pivotal. The results of the study can inform the formulation of policies aimed at accelerating the deployment of renewable energy technologies. Specifically, policymakers in Afghanistan can use the insights gained from the optimized flexibility solution to design targeted policies and incentives. This may include the development of feed-in tariffs or power purchase agreements that encourage private investment in VRE projects, as well as regulations that promote the adoption of grid-friendly technologies such as energy storage systems. Moreover, the identification of optimal flexibility measures can guide the allocation of resources for grid upgrades and reinforcement, ensuring the stability and reliability of the electricity grid.

From a technical perspective, the study highlights critical challenges and solutions for integrating VRE sources into Afghanistan's power system. The identification of technical limitations such as data accuracy and model constraints underscores the need for improved data collection and modeling efforts. Investments in high-quality meteorological data and improved modeling tools can enhance the accuracy of renewable energy generation forecasts, aiding grid operators in managing fluctuations more effectively. Additionally, the study suggests that enhancing the technological capabilities of the power system is essential. This includes the development of grid infrastructure that can accommodate higher levels of VRE, as well as the integration of advanced grid management and control systems. Technical experts and engineers can use these findings to guide the design and implementation of grid upgrades that optimize VRE integration while maintaining grid stability.

The economic implications of the study are significant, as they shed light on the cost-effectiveness of various flexibility measures and the potential economic benefits of VRE integration. Decision-makers can use this information to evaluate the return on investment for renewable energy projects and flexibility solutions. The economic analysis can help identify the most cost-effective strategies for achieving grid flexibility. For instance, the study may reveal that investments in energy storage systems or demand-side management are economically viable and could yield substantial benefits in terms of grid stability and reduced reliance on costly conventional generation sources.

This study serves as a valuable resource for stakeholders in Afghanistan's energy sector, including policymakers, technical experts, and investors. The implications of this research extend beyond Afghanistan and are relevant to regions around the world striving to integrate renewable energy sources into their grids. By leveraging the insights provided in this study, Afghanistan can make significant strides toward building a resilient, low-carbon power system that contributes to a sustainable energy future. However, it is essential to acknowledge the ongoing evolution of the energy landscape and to adapt policies and strategies accordingly, ensuring that the nation continues to progress toward its energy goals.

5.4. Limitations

One of the primary limitations of this study is related to data collection. While efforts were made to collect actual and real-time data from various sources, including grid-connected PV solar power plants, independent power producers, government agencies, and monitoring systems, there may still be limitations in terms of data availability, accuracy, and completeness. Some data gaps or inconsistencies could affect the precision of the analysis and simulation results. Additionally, the study's reliance on historical data might not fully capture future changes in energy generation and demand patterns. While the study discusses policy implications to some extent, it does not delve deeply into the complexities of policy implementation and the potential barriers that policymakers might face. Implementing new policies and regulatory frameworks to support VRE integration can be challenging and may require a more extensive analysis of the political, legal, and institutional aspects. This study acknowledges that it contacted all relevant entities involved in the power sector for data collection but notes that only 25% of the companies participated. This limited participation could have implications for the comprehensiveness and representativeness of the data collected.

5.5. Future Direction

Future research can prioritize the enhancement of data collection methods and data quality; explore and integrate advanced modeling techniques, including machine learning and artificial intelligence; conduct comprehensive sensitivity analyses; delve deeper into the development and implementation of energy policies that facilitate VRE integration; monitor and analyze emerging technologies related to renewable energy generation, energy storage, and grid management; build partnerships between government agencies, energy providers, academic institutions, and international organizations; and explore strategies to enhance the resilience of Afghanistan's energy infrastructure to extreme weather events and other disruptions.

6. Conclusions

This research paper undertook a comprehensive assessment of power system flexibility, with a particular focus on assessing grid flexibility options for the integration of variable renewable-based electricity generation. Two distinct scenarios were rigorously evaluated to understand the current state of the power system and to propose optimal flexibility solutions.

The base scenario provided a detailed snapshot of Afghanistan's power infrastructure, revealing significant challenges and limitations. These challenges included an aging grid infrastructure, inadequate generation capacity, frequent power cuts, and limited renewable energy integration. The analysis showed a low percentage (1.9%) of electricity generated from VRE sources in relation to total demand, coupled with a 71.23% loss of load, highlighting the system's inflexibility in handling variations in generation and demand.

In contrast, the investment scenario presented a roadmap for addressing these challenges. This scenario showed that Afghanistan could have a resilient and sustainable energy future by carefully evaluating different flexibility options. These include increasing the actual VRE generation capacity to 44%, adding 1000 MW capacity transmission between the NEPS, SEPS, and WPS, putting 200 MW capacity grid-scale battery storage in place, making technological improvements, and more. Notably, the implementation of these optimal flexibility options eliminated the loss of load and curtailment while enhancing the country's energy resilience.

Key investments such as flexible CCGPP and grid-scale battery storage were shown to mitigate the variability of renewable energy sources, thereby ensuring a stable and reliable power supply. The expansion of transmission connections both within Afghanistan and with neighboring countries offered the promise of efficient power exchange, load balancing, and regional energy cooperation.

Furthermore, the eradication of annualized energy spill from reservoirs and the elimination of ramping constraints signified a substantial improvement in the power system's flexibility. With the right mix of investments, Afghanistan's power system could be transformed into a more adaptable and sustainable energy ecosystem.

In conclusion, the findings of this research underscore the critical importance of investing in grid flexibility to accommodate the growing share of VRE sources. By implementing the optimal flexibility options outlined in the investment scenario, Afghanistan can pave the way for a cleaner, more reliable, and regionally interconnected energy future, positioning itself as a key player in the transition to sustainable energy in the region. These findings offer valuable insights not only for Afghanistan but also for other regions worldwide grappling with the integration of VRE sources into their power systems, offering a replicable framework for enhancing grid flexibility, reducing energy losses, and fostering regional energy cooperation. As the global transition to cleaner energy accelerates, the insights presented here provide a timely roadmap for optimizing power infrastructure and ensuring reliable and sustainable energy supplies for the future.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

This appendix contains an in-depth exploration of the powerful, actual and sophisticated model that has been meticulously analyzed and simulated using IRENA FLEXTool in the context of our study. Our model is designed to provide a profound understanding of the existing and future power systems in Afghanistan, with a special focus on NEPS, SEPS, and WPS Power Systems. This model represents a culmination of extensive research and methodical development, ensuring its robustness and effectiveness.

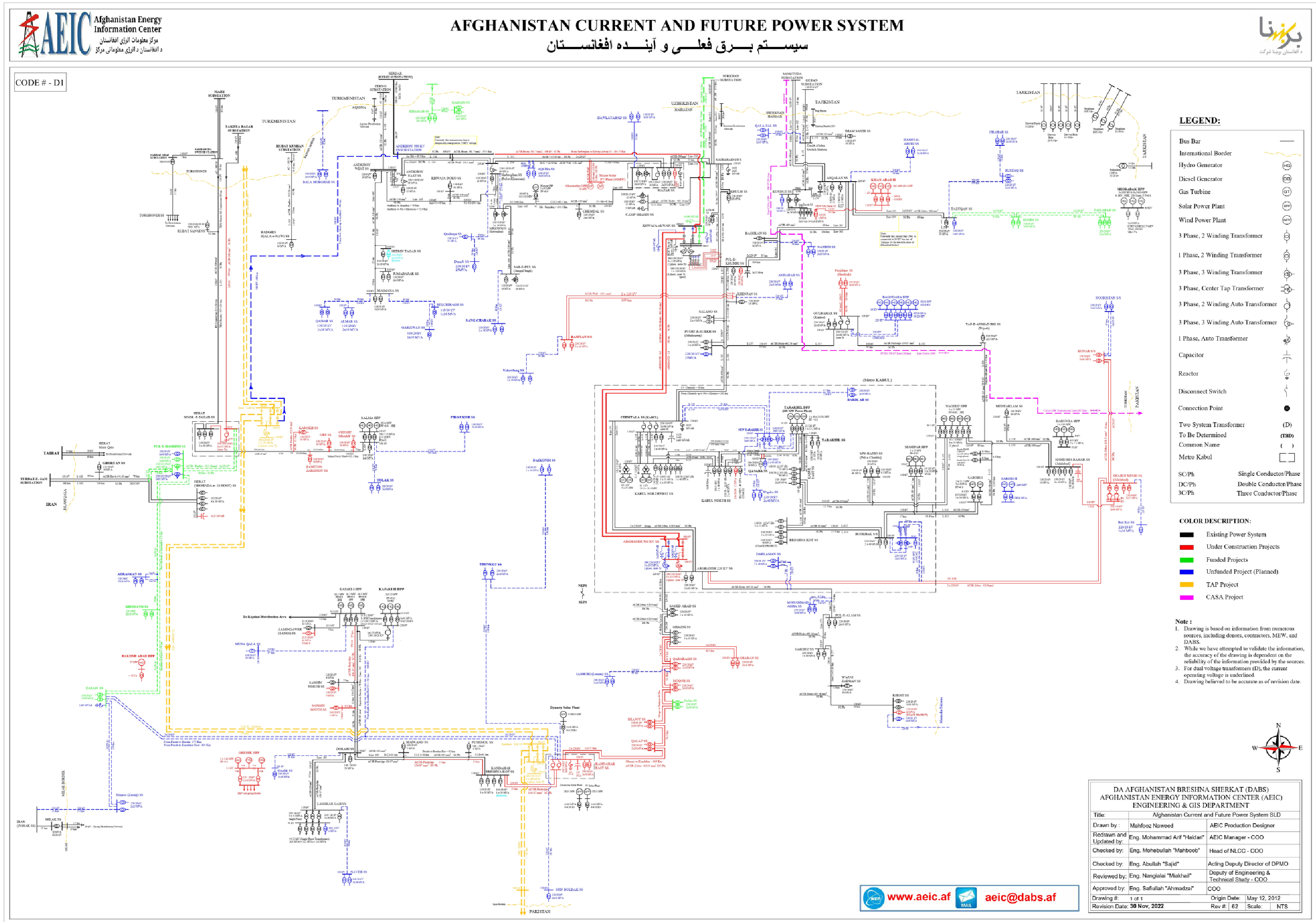

Figure A1. NEPS, SEPS and WPS existing and future power system plan.

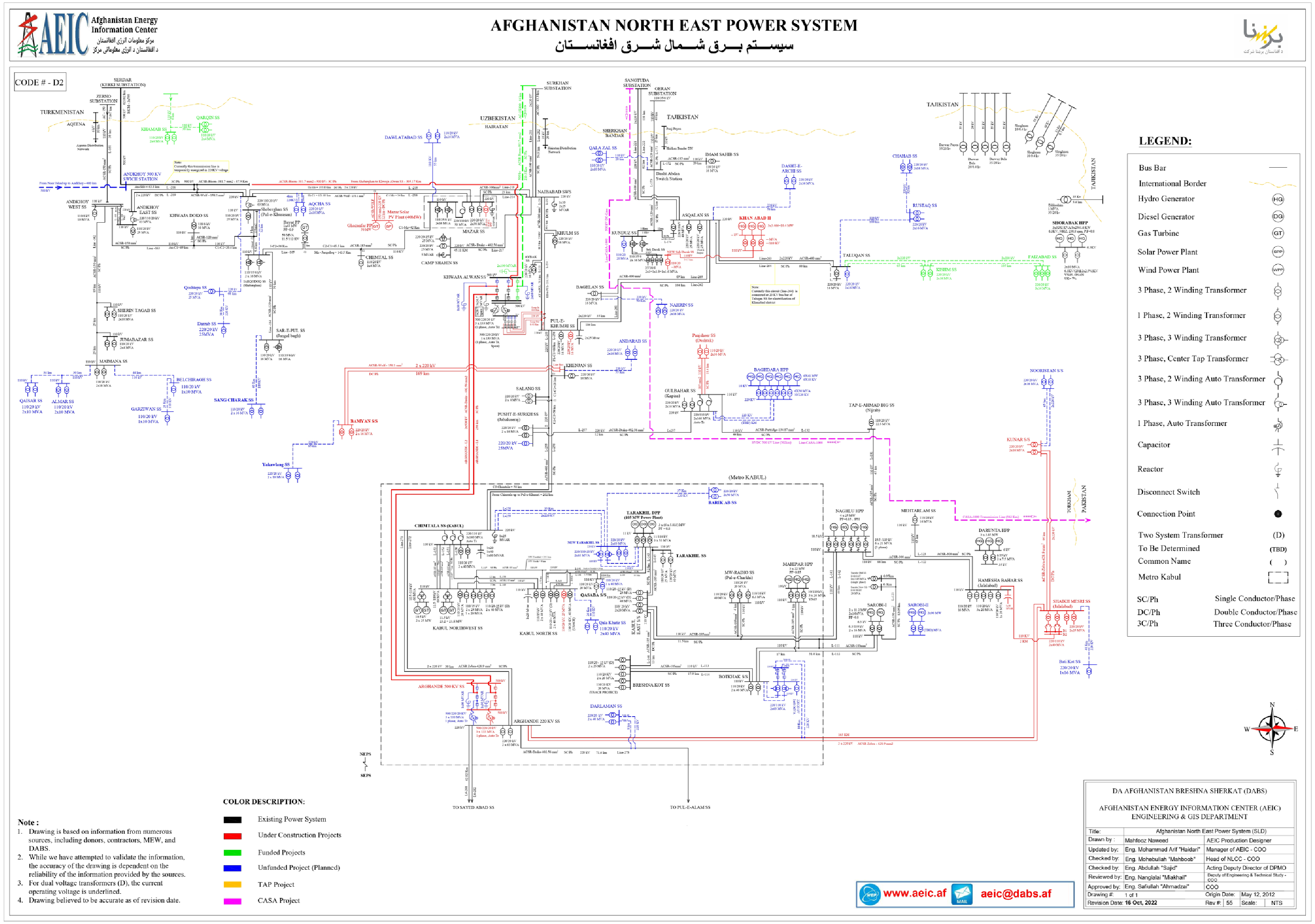

Figure A2. NEPS existing and future power system plan.

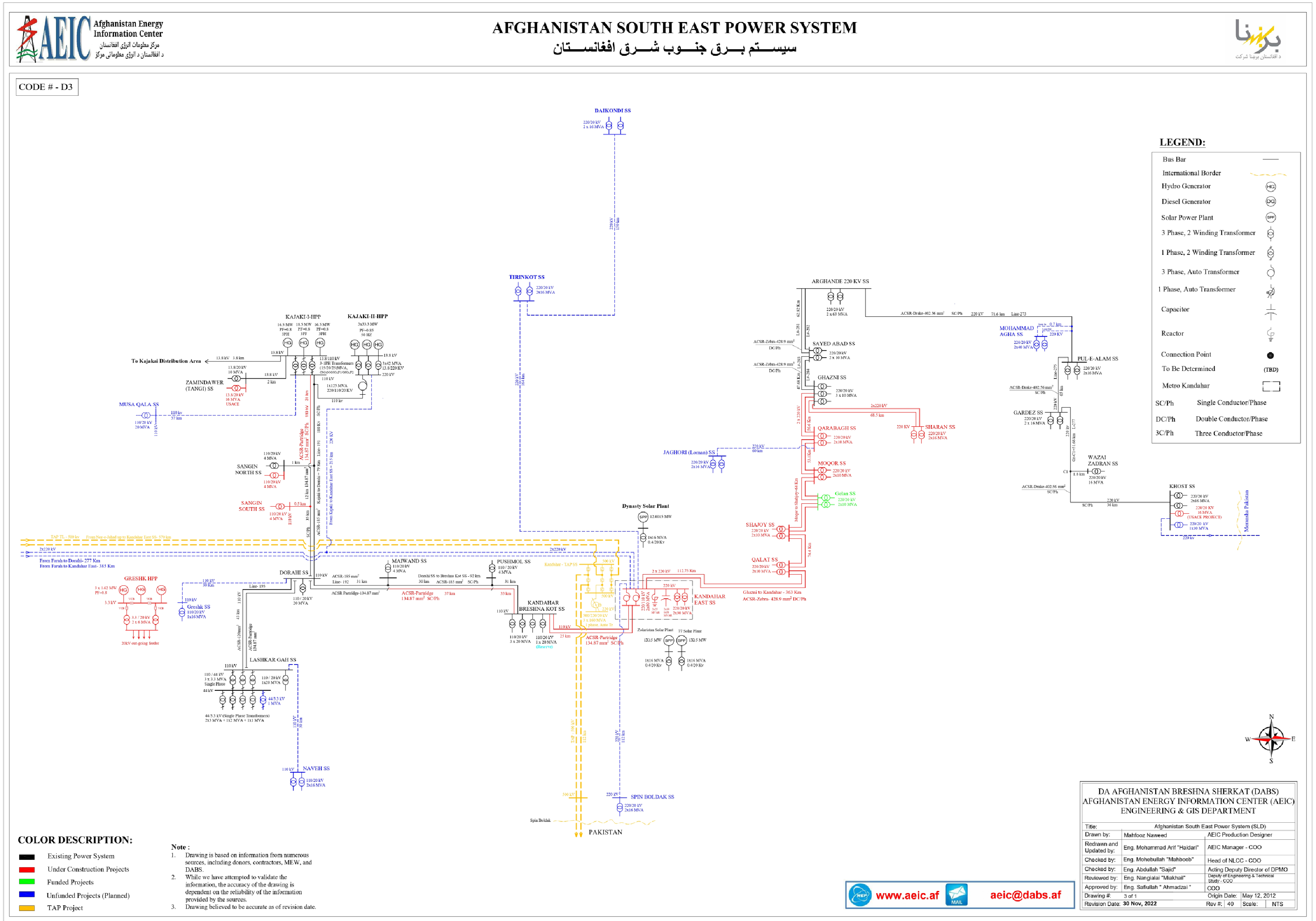

Figure A3. SEPS existing and future power system plan.

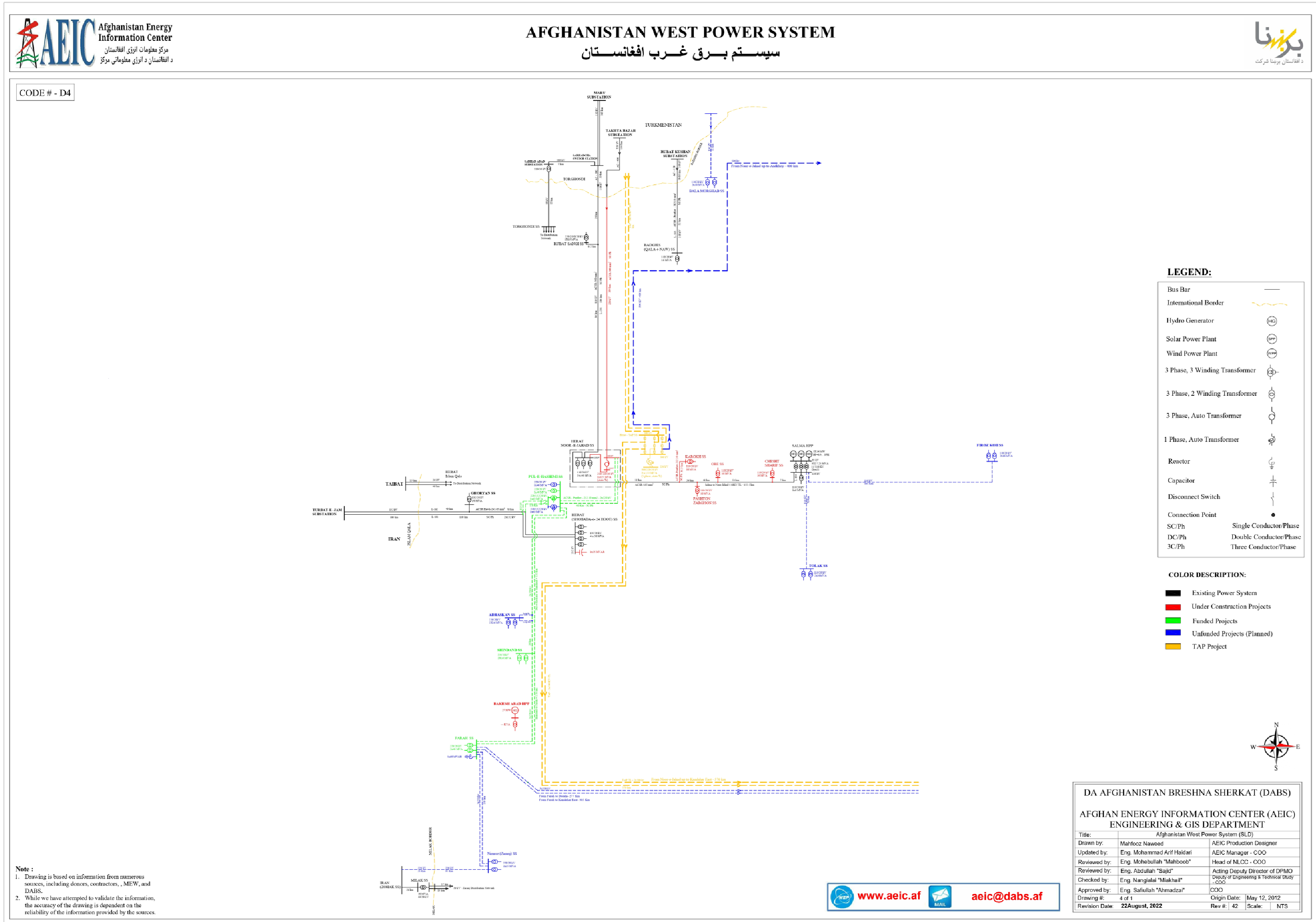

Figure A4. WPS existing and future power system plan.

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