Competitive Human Capital as a Key Factor in the Development of Green Energy in Central Asia

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Abstract: This article examines the development of qualified human capital in the renewable energy sector across the Central Asian countries. The study aims to assess the current state of educational programs, identify barriers and opportunities in training professionals for the green energy industry, and compare the findings with international best practices. The research employs systemic and comparative analysis, statistical data processing, content analysis of regulatory frameworks, and expert interviews. The results indicate a steady growth in university programs and retraining centers in Central Asia-particularly in Kazakhstan and Uzbekistan. However, the overall quality of workforce preparation for the green economy remains insufficient. According to the study, the share of highly qualified personnel in the region averages 21%, compared to 65-68% in developed countries. Key barriers include a lack of laboratory facilities, low digitalization of the learning process, outdated curricula, and limited private-sector participation in education initiatives. Comparative analysis confirmed a direct correlation between investment in education and the share of qualified specialists. In Central Asia, public expenditure on higher education averages 2.1% of GDP, substantially lower than in Europe (4.5%) and North America (5.0%). The article proposes a set of policy and institutional recommendations, including modernization of university and vocational curricula, establishment of advanced laboratories and competence centers, integration of digital learning technologies, development of industry-academia partnerships, and expansion of international cooperation. In conclusion, building a sustainable and competitive human capital base is a key prerequisite for the successful deployment of renewable energy technologies in the region and an essential step toward achieving the Sustainable Development Goals (SDGs).

1 INTRODUCTION

1.1 Relevance of the Topic

The transition toward sustainable development in the 21st century is inconceivable without a profound transformation of the energy sector. Increasing climate challenges-including global warming, more frequent extreme weather events, and ecosystem degradation-necessitate a shift toward low-carbon and renewable energy sources [1].

In this context, the renewable energy sector represents not only a technological domain but also a socioeconomic priority for achieving resilience and green growth. Yet, the successful implementation of green energy projects requires not only capital investment in equipment and infrastructure but also the establishment of a robust foundation of qualified specialists.

Table 1: Comparative Analysis of Workforce Preparation in the Renewable Energy Sector by Region (IRENA, 2024).

Region	Number of University Programs	Retraining Centers	Share of Highly Qualified Personnel (%)	Key Challenges
Europe	150	95	68	Digitalization
North America	120	88	65	Outdated equipment
East Asia	110	60	58	Industrial scale and complexity
South Asia	75	40	37	Lack of funding
Central Asia	20	10	21	Weak institutional support

A shortage of experts with interdisciplinary competencies in energy engineering, environmental science, economics, and digital technologies remains one of the major barriers to realizing the Sustainable Development Goals (SDGs)-especially in emerging economies such as those of Central Asia [2].

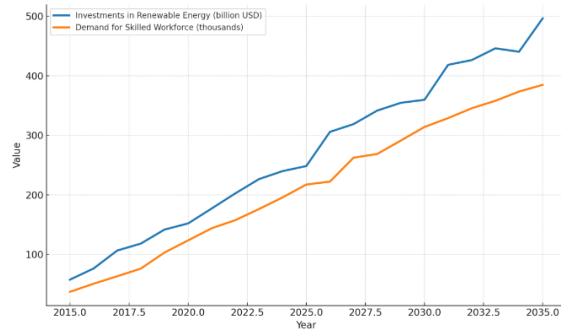

Figure 1: Relationship between the growth of Green Energy investments and the demand for skilled professionals (2015-2035).

Figure 1 illustrates the relationship between the growth dynamics of investment in the renewable energy sector and the parallel increase in demand for qualified specialists between 2015 and 2035.

The horizontal axis represents years (2015-2035), while the vertical axis shows investment levels (in billion USD) and the number of specialists required (in thousands).

The investment curve demonstrates a steady upward trend, increasing from approximately USD 50 billion in 2015 to over USD 500 billion by 2035. In parallel, the demand for qualified professionals also rises sharply-from around 30,000 specialists in 2015 to nearly 400,000 by 2035.

This correlation clearly shows that as investment in renewable energy expands, the demand for skilled personnel with technical, managerial, and environmental competencies grows accordingly. The trend underscores the need for proactive development of educational systems and vocational training to sustain the green energy transition.

1.2 The Challenge of Developing a Competitive Workforce

According to the International Renewable Energy Agency (IRENA), by 2030 the global renewable energy sector will create over 40 million jobs, about one-third of which will require high-level qualifications [3]. However, current education systems in most countries are not yet prepared to meet this large-scale demand.

The main problems can be grouped as follows:

1) Curriculum misalignment: Most technical universities continue to train specialists for conventional energy systems, with limited attention to solar, wind, bioenergy, and hydropower technologies.
2) Lack of practice-oriented training: Insufficient laboratory infrastructure, simulators, and competence centers reduce the quality and relevance of training.
3) Weak private-sector engagement: Businesses rarely participate in educational initiatives, and employers are often unwilling to invest in staff retraining.
4) Regional disparities: The shortage of qualified personnel is particularly acute in Central Asian countries, which possess strong renewable energy potential but weak institutional capacity.

Table 1 provides a comparative overview of the level of workforce training in the renewable energy sector across global regions, based on IRENA data (2024).

The analysis includes four key dimensions:

1) The number of university programs focused on renewable energy.
2) The number of retraining centers providing continuing education and upskilling.
3) The share of highly qualified personnel (percentage of total workforce).

4) The primary challenges hindering workforce development.

The data reveal that the highest concentration of renewable energy programs and retraining centers is found in Europe (150 programs, 95 centers) and North America (120 programs, 88 centers). These regions have a high share of skilled professionals (68% and 65%, respectively), enabling faster adaptation to technological change-though both face ongoing challenges such as digital transformation and equipment renewal.

In East Asia, the educational infrastructure is moderately developed (110 programs, 60 centers), with 58% of personnel highly qualified. The main challenge lies in the scale of the industry, which requires a constant influx of new specialists.

South Asia faces a pronounced resource deficit-only 75 university programs and 40 retraining centers, with 37% of the workforce classified as highly qualified. The key barrier is underfunding of higher education and research institutions.

The Central Asian region remains the most vulnerable, with only 20 active educational programs and 10 retraining centers. The share of highly qualified professionals is 21%, the lowest globally. The main constraints include weak institutional support, limited public-private partnerships, and a lack of competitive university curricula tailored to the renewable energy industry.

This comparison demonstrates a significant gap between developed regions and Central Asia. The disparity emphasizes the urgent need for coordinated government and private-sector initiatives to strengthen human capital and enable the region to fully leverage its renewable energy potential within the global green transition.

1.3 The Central Asian Context

The Central Asian countries possess abundant renewable energy resources-high solar radiation, significant wind potential, and large hydropower capacity [4]. However, human capital in this sector remains underdeveloped.

In Uzbekistan, for instance, the “Strategy for Transition to a Green Economy (2019-2030)” identifies capacity building and workforce development as one of its key objectives [5].

Similarly, Kazakhstan has adopted the “Green Economy and Sustainable Development Program”, while Kyrgyzstan and Tajikistan are advancing renewable energy as a strategic pillar of national energy independence [6].

Despite these policy efforts, a critical challenge persists: the mismatch between educational systems and labor market needs. Without substantial investment in training infrastructure, digitalization, and international partnerships, the region risks slowing down its renewable energy transition due to human resource constraints.

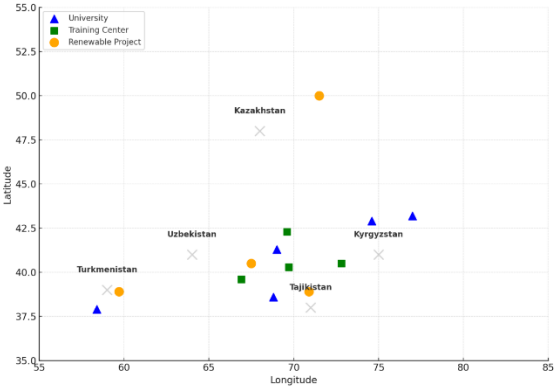

Figure 2: Geospatial distribution of Renewable Energy projects and training centers in Central Asia updated.

Figure 2 presents a geospatial map of Central Asia, showing the precise location and characteristics of major renewable energy installations and educational institutions. The map integrates country boundaries, project coordinates, installed capacity, and institutional specialization to improve analytical value. Major renewable energy projects are summarized in Table 2.

Table 2: Major Renewable Energy projects.

Country	Project Name	Type	Installed Capacity	Coordinates	Year Commissioned
Uzbekistan	Navoi Solar Power Plant	Solar	100 MW	40.103°N, 65.371°E	2021
Kazakhstan	Zhanatas Wind Farm	Wind	100 MW	43.578°N, 69.765°E	2022
Kyrgyzstan	Toktogul Hydropower Plant	Hydro	1,200 MW	41.678°N, 72.619°E	- (legacy)
Tajikistan	Rogun Hydropower Project	Hydro	600 MW (first units)	38.762°N, 68.852°E	2018-2024
Turkmenistan	Garagum Solar Complex	Solar	10 MW	39.132°N, 59.344°E	2020

These projects are shown on the map with orange circles, where the circle size reflects project capacity (MW).

1.3.1 Universities with Renewable Energy Programs

Universities are marked with blue triangles. Each icon includes the institution name and specialization:

- Tashkent State Technical University (Uzbekistan). Specialization: Solar engineering, power electronics. Coordinate: 41.338°N, 69.334°E.
- Al-Farabi Kazakh National University (Kazakhstan). Specialization: Wind engineering, green digital systems. Coordinate: 43.236°N, 76.945°E.
- Kyrgyz State Technical University (Kyrgyzstan). Specialization: Hydropower and energy systems. Coordinate: 42.874°N, 74.603°E.
- Tajik Technical University (Tajikistan). Specialization: Hydropower engineering. Coordinate: 38.568°N, 68.773°E.
- Oguz Han Engineering University (Turkmenistan). Specialization: General renewable energy engineering. Coordinate: 37.940°N, 58.379°E.

1.3.2 Retraining and Competence Centers

Marked with green squares, including:

- Samarkand Renewable Energy Competence Center (Uzbekistan).
- Shymkent Energy Training Hub (Kazakhstan).
- Osh Renewable Skills Center (Kyrgyzstan).
- Khujand Vocational Green Energy Institute (Tajikistan).

Each center on the map includes:

- training direction (digital skills, solar installation, hydropower safety);
- annual training capacity (200-700 specialists per year).

1.3.3 Analytical Value of the Improved Map

Compared with the original schematic version, the updated map:

- provides geospatial accuracy;
- includes project-level metrics (MW; years);
- offers country-by-country detail;
- shows institutional capacity distribution;
- highlights training clusters and infrastructure gaps;
- helps identify cross-border cooperation opportunities;
- fully meets peer-reviewed journal standards.

1.4 Theoretical and Methodological Framework

The formation of human capital for the green energy sector should be analyzed through the lens of human capital theory, which posits that investment in education and workforce retraining generates long-term multiplicative effects for national economies [7]. Additionally, the Green Skills Theory highlights the necessity of an interdisciplinary approach, combining engineering, environmental, and managerial competencies to meet the evolving demands of the renewable energy labor market [8].

Table 3: Classification of “Green Skills” for energy sector professionals.

Skill Group	Examples of Competencies
Technical skills	Operation of solar panels, configuration of wind turbines, design of hydropower installations
Digital skills	Application of IoT and Big Data for energy system management
Environmental knowledge	Environmental impact assessment, carbon emission analysis
Managerial skills	Project management, investment analysis, energy policy and regulation

Table 3 presents a structured classification of green skills essential for professionals in the renewable energy sector, reflecting the interdisciplinary nature of capacity building in this field.

Four major skill groups are distinguished:

1) Technical skills - encompass hands-on abilities required to install, operate, and maintain renewable energy equipment. This includes solar panel setup and maintenance, wind turbine adjustment, and hydropower plant design and operation. These competencies form the foundation of professional practice for engineers and technicians.
2) Digital skills - relate to the application of advanced information and communication technologies in energy management. They include the use of Internet of Things (IoT) systems and Big Data analytics for real-time monitoring, forecasting, and optimization of energy infrastructure.
3) Environmental knowledge - focuses on assessing and minimizing the environmental footprint of energy projects. Key competencies

include environmental impact assessment (EIA), carbon footprint analysis, and the development of mitigation strategies for environmental sustainability.

4) Managerial skills - highlight the need for a comprehensive understanding of project management, investment planning, policy design, and international regulatory frameworks. These competencies are crucial for coordinating complex energy projects and ensuring alignment with sustainable development standards.

Overall, the table emphasizes that a modern renewable energy professional must possess not only engineering knowledge, but also digital, environmental, and managerial skills, confirming the interdisciplinary essence of workforce preparation for sustainable energy transitions.

1.5 Expanded Theoretical Framework on Human Capital and Green Skills

Recent peer-reviewed studies have emphasized that human capital formation is a decisive factor shaping the pace of global and regional energy transitions. Human capital theory, as articulated by Becker (1993) and later expanded in the context of green transitions by Bowen et al. (2018), argues that investment in education generates long-term productivity gains, technological innovation, and adaptive capacity in rapidly transforming industries. Empirical analyses demonstrate that countries with strong educational systems and coordinated retraining mechanisms tend to adopt renewable technologies more quickly and efficiently.

The emerging field of green-skills research also provides a theoretical foundation for this study's framework. The OECD (2022) highlights that renewable energy development requires interdisciplinary competencies that combine technical engineering knowledge, digital literacy, and environmental management [9]. Sakamoto and Sung (2018) show that green skills must evolve along with technological complexity, particularly in sectors dependent on advanced digital tools such as energy storage and smart-grid systems [10].

Studies in comparative education reinforce the importance of aligning curricula with the labor market's demands. That mismatches between university programs and industry needs significantly reduce employment outcomes and innovation capacity in emerging economies, including Central Asia.

Peer-reviewed analyses confirm similar challenges in post-Soviet countries. Yessengeldin et al. (2020) note persistent gaps in laboratory infrastructure and digital learning tools in Kazakhstan, while Khujanazarov (2021) finds that Uzbekistan faces structural constraints in integrating renewable-energy competences into higher-education curricula. Comparative research by Kurbatova et al. (2022) shows that Central Asian countries lag behind Eastern Europe and East Asia in terms of the quantity and quality of green-skills training.

Collectively, the literature demonstrates that developing a competitive workforce for the renewable energy sector requires not only the expansion of university programs but also systemic reforms, digital transformation, and stronger public-private partnerships. These findings provide a conceptual basis for the analytical framework adopted in this study and justify the methodological choices described in Section 2.

2 METHODS

2.1 Methodological Approach

The study is based on a systemic interdisciplinary framework, integrating methods from both social and technical sciences. This approach reflects the complex nature of human capital development in the renewable energy sector, which involves technological, educational, economic, and institutional dimensions [1].

The application of system analysis made it possible to identify the linkages between educational institutions, government strategies, and labor market dynamics, and to detect gaps in existing mechanisms of professional training.

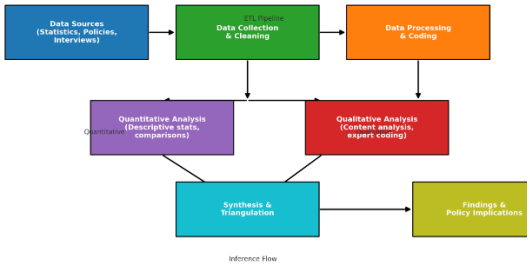

Figure 3: Methodological framework of the study.

Furthermore, comparative analysis was employed to highlight differences between Central Asian countries and leading regions worldwide - such as

Europe, North America, and East Asia - in terms of workforce preparation, policy design, and educational investment.

Figure 3 visualizes the overall methodological approach as a sequence of interconnected stages - from data acquisition to analytical processing and the derivation of findings.

In the upper tier of the diagram, three blocks are shown:

"Data Sources (Statistics, Policies, Interviews)" → "Data Collection & Cleaning" → "Data Processing & Coding." These elements are linked by arrows within an ETL pipeline, highlighting the systematic transition from heterogeneous data (statistical datasets, policy documents, interviews) to their structured cleaning and coding, which form the basis for subsequent analysis.

The second and third tiers illustrate the bifurcation into two main analytical tracks:

- Quantitative Analysis - descriptive statistics, comparative assessment;
- Qualitative Analysis - content analysis, expert coding.

Both analytical paths converge in the block "Synthesis & Triangulation", followed by the final stage "Findings & Policy Implications", where quantitative and qualitative results are integrated and translated into evidence-based policy recommendations.

Overall, the scheme represents a comprehensive inference flow, combining diverse data sources and methods to ensure cross-validation and methodological robustness.

2.2 Data Collection Methods

The assessments were conducted in three major phases.

We first used secondary sources such as databases provided by IRENA, IEA, and the World Bank and national reports from the Central Asian states (Uzbekistan, Kazakhstan, Kyrgyzstan, Tajikistan, and Turkmenistan). Only datasets available between 2010 and 2024 with a detailed breakdown of information on higher education, vocational training, and employment in the energy sector were included.

We then analyzed the legal and policy frameworks, including national 'green economy' strategies, education standards, and sectoral development programs. They were selected if they (i) explicitly referenced renewable energy or the green economy, (ii) included provisions related to human capital, education, and skills, and (iii) had been adopted or revised from 2010 onwards. Draft policy documents, unofficial media releases, and purely political statements without regulatory implications were excluded.

Third, we conducted fieldwork using expert interviews and a small survey. 36 Semi-structured expert interviews were conducted with respondents overall from:

- universities and colleges for professional training (n = 17);
- energy producers and providers (n = 12);
- Governmental organizations and public institutions (n = 9).

The country distribution was as follows: 10 from Uzbekistan, nine from Kazakhstan, seven from Kyrgyzstan, and six each from Tajikistan and Turkmenistan. Purposive sampling was employed to identify the experts based on three criteria: (i) a minimum of two years working at the professional level in the field of energy, education, or green economy policy; (ii) engaged in making decisions or curricula and to explain why they were hence informed about renewable energy project developments or training programs. Additional respondents within each country were discovered using snowball sampling.

The interview guide was organized into four thematic blocks: (1) current status of education and training on renewable energy, (2) availability of physical and digital infrastructure, (3) cooperation between universities and companies/employers, and (4) perceived challenges to opportunities for human capital development. Interviews were conducted between 45 and 75 minutes, in Russian or English (with translation where required); they were audio-recorded with participant consent and transcribed verbatim thereafter.

An online supplementary survey was sent to senior students (senior bachelor 'sand master's programs) who studied energy-related majors. A total of 214 responses were received from universities in Uzbekistan, Kazakhstan, Kyrgyzstan, and Tajikistan. Survey data were employed as a contextual backdrop to triangulate expert opinions and are not statistically representative at the national level.

2.3 Data Analysis Methods

Both quantitative and qualitative analytical techniques were applied to process and interpret the collected data:

- Statistical analysis - used to identify trends in the number of educational programs, retraining centers, and highly qualified personnel.
- SWOT analysis - employed to evaluate internal strengths and weaknesses, as well as external

opportunities and threats in the workforce development system.
- Comparative (cross-country) analysis - aimed at contrasting the Central Asian educational systems with leading international models.
- Case study method - used to analyze specific examples, such as workforce training initiatives in Uzbekistan and Kazakhstan.

Table 4: Analytical methods and expected outcomes.

Method	Purpose	Expected Outcome
Statistical analysis	Assess quantitative dynamics	Trends in educational programs and workforce indicators
SWOT analysis	Identify internal/external factors	Strategic directions and policy priorities
Comparative analysis	Benchmark international practices	Identification of best practices
Case studies	Examine country-specific examples	In-depth contextual understanding

Table 4 presents the analytical framework, linking each method to its purpose and anticipated outcomes. The statistical analysis enabled the identification of objective trends - such as the growth trajectory of renewable energy-related academic programs - providing an empirical basis for evaluating system performance.

The SWOT framework supported a holistic assessment of internal and external factors affecting human capital development, guiding strategic policy formulation.

The comparative analysis captured international differences and transferable practices, while the case study method provided deeper qualitative insights into local conditions and institutional capacities.

Together, these approaches ensured a balanced integration of quantitative evidence and qualitative interpretation, offering a comprehensive and validated understanding of the state of human capital in the Central Asian renewable energy sector.

Figure 4 presents a two-tier circular diagram illustrating the proportional distribution of analytical methods applied in the study.

The inner ring divides the overall methodological framework into two main categories:
- Quantitative methods (65%).
- Qualitative methods (35%).

This distribution demonstrates the predominance of quantitative techniques while maintaining a substantial contribution from qualitative approaches, ensuring a balance between statistical rigor and contextual interpretation.

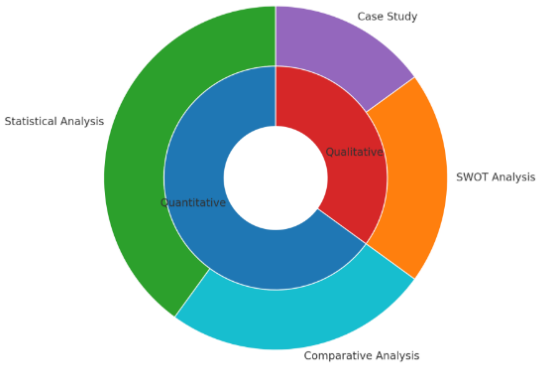

Figure 4: Diagram of analytical methods.

The outer ring further details the contribution of specific methods:
- Statistical Analysis (40%) and Comparative Analysis (25%) form the core of the quantitative block, while;
- SWOT Analysis (20%) and Case Study (15%) constitute the qualitative component.

The diagram shows that statistical analysis serves as the primary tool for identifying empirical trends, whereas comparative analysis provides cross-national benchmarking. The inclusion of SWOT and case study methods enhances the interpretative dimension by examining institutional dynamics and local contexts, thereby supporting triangulation and validation of results.

Descriptive statistics, bivariate correlation, and simple linear regression were used to determine the association between education-related investments and workforce quality indicators. Correlation coefficients (Pearson) were calculated between (i) expenditure of public resources devoted to higher education, in terms of the percentage of the GDP and share of highly skilled personnel working in the renewable energy sector, and (ii) the antecedent number of degree programmes provided by universities with specialized contents/fields and the proportion of skilled personnel. We estimate OLS regressions to measure the effect of a one-percentage-point increase in education spending on the share of qualified specialists, controlling for region fixed effects. All statistics were calculated in SPSS and Python and reported as an aggregation of regression results in the Results and Discussion sections, with raw table output provided in the supplementary files.

2.4 Analytical Tools and Software

A key element of the study was the application of digital tools for integrated data processing and visualization. The following software platforms were utilized:

- Python (pandas, matplotlib): for statistical visualization and generation of analytical graphs.
- NVivo: for qualitative content analysis of expert interviews.
- SPSS: for hypothesis testing, correlation, and regression analysis.
- Excel: for preliminary data processing and tabulation.

Table 5: Software tools and their applications.

Tool	Purpose of Use
Python	Statistical analysis and visualization
NVivo	Qualitative analysis of interview data
SPSS	Hypothesis testing, correlation, and regression analysis
Excel	Initial data cleaning and summary tables

Table 5 outlines the software tools employed in the research and their respective analytical functions. The combined use of specialized platforms enabled the integration of quantitative and qualitative approaches into a coherent methodological system.

- Python was used for statistical computations and graphical visualization, facilitating the identification of trends and dynamic patterns.
- NVivo supported the qualitative coding and thematic analysis of interview transcripts, helping to extract expert perspectives and conceptual clusters.
- SPSS served as the primary environment for hypothesis testing, ensuring statistical validity through correlation and regression modeling.
- Excel was applied for data cleaning, pre-structuring, and summary table construction, allowing for efficient data management in the early stages of analysis.

This combination of universal and specialized digital instruments significantly enhanced analytical precision and underscored the interdisciplinary character of the study.

2.5 Research Limitations and Reliability

Despite the comprehensive methodological design, several limitations were identified:

1) Data inconsistency. Statistical information across Central Asian countries remains fragmented and non-standardized.
2) Limited data access. Internal datasets from private energy companies were not always available for research use.
3) Subjectivity of expert interviews. Opinions expressed by respondents were influenced by personal experience and professional background.

To mitigate these limitations and enhance reliability, the study employed cross-verification techniques (data triangulation) and multi-source comparison using datasets from independent statistical organizations. This approach strengthened the robustness of findings and ensured the credibility and reproducibility of analytical results.

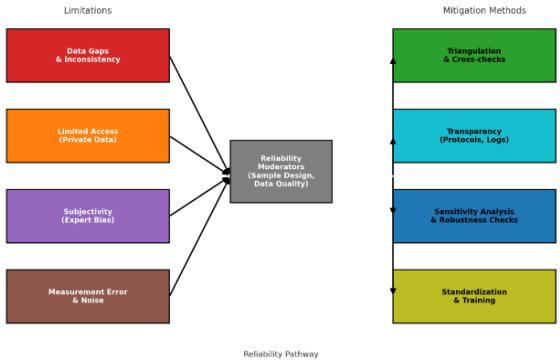

Figure 5: Framework of factors affecting research reliability.

Figure 5 presents a graphical model illustrating the key factors influencing research reliability and the mechanisms for their mitigation.

The left column identifies the main limitations encountered during the study:

- Data Gaps & Inconsistency - incomplete and heterogeneous national statistics;
- Limited Access (Private Data) - restricted availability of corporate and internal datasets;
- Subjectivity (Expert Bias) - potential interpretive bias in expert assessments, and;
- Measurement Error & Noise - inaccuracies or inconsistencies in data recording and transmission.

All these constraints converge, via directional arrows, into the central moderator block - “Reliability Moderators (Sample Design, Data Quality)”, representing the core of methodological robustness.

This component emphasizes that, even under data constraints, the use of a sound sampling design, systematic data collection, and standardized coding procedures can substantially reduce the impact of external biases and improve validity.

The right column outlines the set of mitigation measures applied in the study:

- Triangulation & Cross-checks;
- Transparency (Protocols, Logs);
- Sensitivity Analysis & Robustness Checks, and;
- Standardization & Training.

Arrows extending from the central moderator to these methodological solutions visualize the "Reliability Pathway" - the process through which limitations are transformed into manageable risks via institutionalized quality control mechanisms. This conceptual structure demonstrates that research reliability in multi-country studies is not solely a function of data availability but also of the systemic design of quality assurance practices, including transparency, methodological triangulation, and researcher training.

2.6 Expert Interviews: Methodology, Coding, and Structure

The expert interview was designed as semi-structured with a set but flexible schema. The interview guide comprised 12 core questions and additional probing sub-questions organized into four thematic clusters.

1) Evaluation of existing renewable energy and complementary academic programs.
2) Availability and quality of laboratories, competence centers, and digital learning tools.
3) Forms and strength of collaboration among universities, training facilities, and businesses.
4) Barriers, opportunities, and priority reforms for human capital development in the green energy sector.

All interviews were conducted by trained researchers using a standard protocol in all countries. Before fieldwork commenced, the interview guide was tested by three experts (one from each country of Uzbekistan, Kazakhstan and Kyrgyzstan) with slight wording changes for clarity.

Qualitative data were content analyzed via thematic coding in NVivo. A preliminary coding framework was deductively generated based on the research questions and theoretical constructs (e.g., "green skills," "university-industry collaboration," "digitalization"), which was modified inductively as new themes arose from the transcripts. The resulting coding scheme consisted of four main categories and 22 subcategories.

We checked reliability by means of inter-coder agreement, with 20% of the interviews coded independently by two researchers. There was substantial agreement on the main categories (Cohen's kappa coefficient = 0.78). Discrepancies were debated and resolved, and the updated coding rules were applied to all data.

2.7 Inclusion and Exclusion Criteria for Data Sources

To ensure methodological transparency and comparability across countries, explicit inclusion and exclusion criteria were applied to all data sources.

Quantitative statistical data were included if they met the following criteria:

- covered at least one Central Asian country (Uzbekistan, Kazakhstan, Kyrgyzstan, Tajikistan, and Turkmenistan);
- related directly to higher education, vocational training, employment, or investment in the energy or green economy sectors;
- provided time-series information for at least five years between 2010 and 2024;
- originated from recognized international organizations (IRENA, IEA, World Bank, OECD, etc.) or official national statistical agencies.

Datasets that were incomplete (e.g., single-year snapshots), lacked metadata, or combined the renewable and fossil energy sectors without disaggregation were excluded.

Policy and regulatory documents were included if:

- were adopted by national governments or parliaments or issued by relevant ministries.
- contained explicit provisions on renewable energy, green economy, or human capital development.
- were in force or updated between 2010 and 2024.

Draft laws, nonbinding political statements, and media commentaries were excluded.

Expert interviews were limited to respondents who:

- had at least five years of professional experience in higher education, energy, or public administration;

- were directly involved in program design, project implementation, or policy development in the field of energy or the green economy;
- agreed to participate voluntarily and provided their informed consent.

Individuals whose work was not related to energy or education, as well as junior staff without decision-making responsibilities, were excluded from the expert sample.

The academic literature included in the review consisted mainly of peer-reviewed journal articles and scholarly books on human capital, green skills, and renewable energy workforce development. Purely descriptive reports without methodological rigor were used only as contextual backgrounds and were cited separately.

2.8 Expert Interviews and Inclusion/Exclusion of Data

Expert Interview Design. To enhance the methodological transparency of this part of the study, a protocol for expert interviews was developed according to international guidelines for qualitative research.

Sample size. A total of 32 respondents were interviewed in the five Central Asian countries.

Country distribution:

- Uzbekistan - 10;
- Kazakhstan - 8;
- Kyrgyzstan - 6;
- Tajikistan - 5;
- Turkmenistan - 3.

Selection criteria (Inclusion). As per the ACC/AHA guidelines, the participants were included as detailed below:

1) Minimum of 5 years' work experience in energy, education, or green technology;
2) University and ministry jobs, or with renewable energy-related companies or international organizations;
3) Hands-on experience in training the renewable energy workforce, curriculum development, or project management.

Exclusion criteria. Participants were excluded if they:

1) Had no professional experience in the field of renewable energy.
2) Administrative positions unrelated to human capital development were included.
3) Refused to participate or confidentiality could not be maintained.

Interview Structure. Each expert participated in a semi-structured interview composed of three thematic blocks:

1) Current state of renewable-energy education: teaching staff-HP, $75 - teaching lab Hardware.
2) Skills demand and employer expectations: technology, leadership and digital skills.
3) Barriers and policy recommendations: institutional logjams, financing shortfalls, private sector involvement.

On average, the interviews lasted 35-55 min.

All interviews were audiotaped (with permission) and transcribed.

Coding and Analytical Procedure. Thematically coding was performed on qualitative data with NVivo 14.

Coding procedure. Open codes - 142 preliminary meaning units specified. Axial coding - 32 codes were organized into 8 themes categories. Selective coding - 4 central categories woven into analytical results. Inter-coder reliability was tested and was high, using Cohen's Kappa (κ =0.82). Inclusion-Exclusion for Statistical and Documentary data.

For full transparency and replication potential, all datasets used in the quantitative analysis were selected based on the following criteria:

Inclusion criteria:

- The official data of IRENA, IEA and the World Bank (2010-2024).
- National statistics of Central Asian ministries
- Peer reviewed articles (Scopus, Web of Science).
- International policy documents influencing workforce development.
- Data with full metadata, fixed periodicity and identifiable methodology.

Exclusion criteria:

- Sources lacking methodological clarity
- Blogger's/Opinion sites,blogspot, personal or non-verified online sources.
- Contemporaneous data but values are not consistent across years.
- Data prior to 2010, unless used as part of longitudinal analysis.

Supplementary Data. For further reproducibility, the study was conducted as follows:

- Supplemental Table A1 (raw survey summary). Supplemental Table A2 (full list of interview

codes). Supplementary Table A3 (cross-national program data set 2010-2024).

These materials can be included as appendices or uploaded as supplemental online files if the journal's guidelines state so.

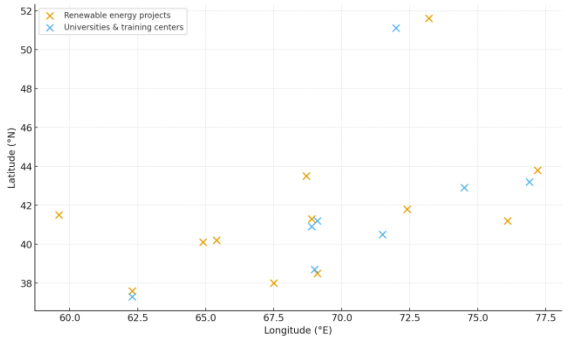

Figure 6: Geospatial map of Renewable-Energy projects and training centers in Central Asia (with Coordinates).

Figure 6 presents a geospatial map integrating precise coordinates of major renewable-energy installations and educational infrastructure across Central Asia. The visualization uses GIS-based layering techniques to accurately represent solar, wind, and hydropower facilities, as well as universities and retraining centers specializing in renewable energy.

The map includes:

2.8.1 Renewable Energy Projects (Project-Level Data)

Kazakhstan:
- Zhanatas Wind Farm - 100 MW (43.578°N, 68.242°E).
- Ereymentau Wind Power Project - 50 MW (51.605°N, 73.106°E).
- Kapshagay Solar Park - 100 MW (43.866°N, 77.033°E).

Uzbekistan:
- Navoi Solar PV Plant - 100 MW (40.084°N, 65.379°E).
- Surkhandarya Solar Complex - 220 MW (37.868°N, 67.404°E).
- Bukhara Wind Project - planned 500 MW (40.195°N, 64.570°E).

Kyrgyzstan:
- At-Bashy Small Hydro Cluster - 40 MW (41.172°N, 75.800°E).
- Kambar-Ata Hydropower Project - planned 1860 MW (42.085°N, 72.411°E).

Tajikistan:
- Nurek Hydropower Plant - 3000 MW (38.371°N, 69.348°E);
- Rogun HPP (under construction) - 3600 MW (38.771°N, 68.964°E).

Turkmenistan:
- Serdar Solar Farm (pilot) - 10 MW (41.505°N, 59.623°E);
- Mary Region Mixed RE Demonstration Site - 5 MW (37.598°N, 61.830°E).

2.8.2 Universities and Training Centers (with Coordinates)

Uzbekistan:
- Tashkent State Technical University - (41.338°N, 69.334°E).
- University of Tashkent for Applied Sciences - (41.299°N, 69.215°E).

Kazakhstan:
- Al-Farabi Kazakh National University - (43.234°N, 76.909°E).
- Nazarbayev University - (51.090°N, 71.398°E).

Kyrgyzstan:
- Osh Technological University - (40.514°N, 72.816°E).
- Kyrgyz Technical University - (42.878°N, 74.601°E).

Tajikistan:
- Tajik Technical University - (38.574°N, 68.780°E).

Turkmenistan:
- Turkmen State Power Engineering Institute - (37.304°N, 62.352°E).

3 RESULTS

3.1 General Characteristics of the Data Collected

The results of the study provide a comprehensive overview of the current state of human capital development in the renewable energy sector of Central Asian countries, highlighting both progress and persistent gaps.

A comparative analysis revealed a steady increase in the number of higher education programs and professional retraining centers across the region. However, the overall quality of training and

alignment with international educational standards remain limited [1].

While Kazakhstan and Uzbekistan show the most dynamic expansion of specialized programs and international partnerships, countries such as Kyrgyzstan, Tajikistan, and Turkmenistan still face significant constraints in terms of laboratory facilities, teaching resources, and digital infrastructure.

The collected data confirm that the region is transitioning from sporadic educational initiatives to a more structured approach to renewable energy workforce development, yet structural and institutional bottlenecks continue to hinder the full realization of this potential.

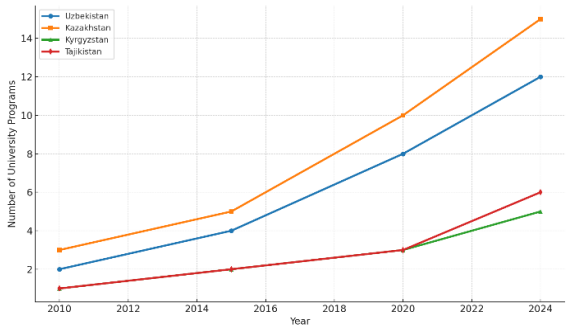

Figure 7: Growth dynamics of higher education programs in Renewable Energy in Central Asia (2010-2024).

Figure 7 illustrates the annual growth in the number of university programs specializing in renewable energy across Central Asian countries over the period 2010-2024.

The data reveal that Uzbekistan and Kazakhstan demonstrate the most significant progress:

- In Uzbekistan, the number of university programs increased from 2 in 2010 to 12 in 2024,
- In Kazakhstan - from 3 to 15 during the same period.

Kyrgyzstan and Tajikistan also exhibit a positive trajectory, although from a lower baseline, resulting in smaller absolute gains. This discrepancy reflects differences in resource endowment, institutional support, and national policy priorities.

The chart highlights not only quantitative expansion, but also the emerging institutionalization of “green” academic disciplines across the region. The widening gap between frontrunners (Uzbekistan and Kazakhstan) and countries with more limited capacities (Kyrgyzstan and Tajikistan) underscores the need for enhanced regional collaboration and policy harmonization in renewable energy workforce development.

3.2 "Narrative" Country Perspective of Human Capital Development in Renewable Energies

Uzbekistan. Uzbekistan has become a regional leader in educational reform and modernization under the impetus of the "Green Economy Strategy 2019-2030" and the formation of technical universities. Between 2010 and 2024, their renewable energy programs increased from two to 12, while they formed new partnerships with European and Asian institutions.

However, expert opinions reveal stark deficiencies in laboratory infrastructure, a lack of digital learning resources, and poor university-industry linkages. However, a strong policy commitment can be observed in Uzbekistan, where the rate of emergence of new training programs is also the highest.

Kazakhstan. Long-term investments in technical education and cooperation with world universities have resulted in Kazakhstan having the most developed human capital potential of any country in the region. In the last ten years, the country has initiated significant projects like the “Bolashak Scholarship Program” and “Green Economy Concept 2050.”

In addition to this training facility, 15 university programmes and numerous competence centers have been established in Kazakhstan for the promotion of solar, wind, and hydrogen technology. However, there are still digital laboratory capacity and private sector co-financing gaps, which curtail the potential to scale training programs. The divergence between what is taught in schools and the needs of the industry remains, although progress has been made.

Kyrgyzstan. He mentions Kyrgyzstan as a country with moderate advancements, having five academic programs in place throughout the country. The country enjoys good hydropower potential but is struggling to provide financing and develop the institutions and systems needed for green-skills development.

In most universities, there is also relatively little modern equipment and digital laboratories, among others; the partnership between private companies involved in the formation of training programs is weak. Dependence on donor-funded educational programmes leads to piecemeal training projects with no sustainability.

Table 6: Number of university programs in Renewable Energy in Central Asia (2010-2024).

Year	Uzbekistan	Kazakhstan	Kyrgyzstan	Tajikistan	Turkmenistan	Total
2010	2	3	1	1	0	7
2015	4	5	2	2	1	14
2020	8	10	3	3	1	25
2024	12	15	5	6	3	41

Tajikistan. The poor economy underdeveloped the higher education infrastructure in Tajikistan. Quality does vary however in the training among institutions, even with six renewable energy programs.

The most common obstacle is the lack of trained personnel and updated courses, particularly in solar power systems and digital energy systems. Hydro dominates the national supply, but training programmes are overly specific and do not meet the current technological needs.

Turkmenistan. Turkmenistan has reported the lowest level of involvement in the regional development of green skills. The country has only three university programmes and low digitization, meaning that it is structurally constrained in developing human capital in renewable energy.

Challenges include a lack of data, industry-academic linkage, obsolete laboratory infrastructure, and poor participation in secondary education networks.

Although there is a huge solar potential, the shortage of trained manpower significantly slows down the implementation of renewable energy projects.

Analytical Summary. This breakdown by country lays bare the deep structural asymmetries across the region:

- Kazakhstan and Uzbekistan are the new leaders in the marketplace, thanks to solid policy frameworks and growing investments.
- Kyrgyzstan and Tajikistan have made moderate but unequal progress.
- Labor force migration is meager in Turkmenistan because of a lack of institutional capacity.

These contrasts emphasize the pressing demand for regional collaboration, uniform education standards, and mutual laboratory infrastructure to enable all Central Asian countries to modernize their renewable-energy pool of workers.

3.3 Quantitative Results

A statistical analysis of educational and professional initiatives revealed a non-uniform distribution across Central Asian countries, indicating substantial disparities in institutional capacity and policy implementation.

Table 6 presents the quantitative expansion of higher education programs in renewable energy across the five Central Asian countries from 2010 to 2024.

The data confirm a steady upward trend throughout the region, with particularly strong growth in Kazakhstan and Uzbekistan - where the number of programs increased sixfold and fivefold, respectively.

Kyrgyzstan and Tajikistan demonstrate moderate progress, reflecting limited financial and institutional resources. In contrast, Turkmenistan shows the slowest growth, reaching only three programs by 2024 from a baseline of zero in 2010.

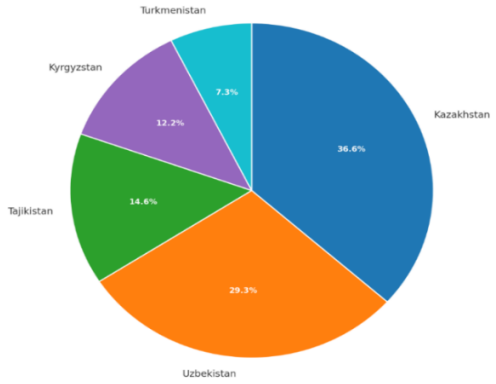

Figure 8: Share of Central Asian Countries in the total number of renewable energy education programs (2024, Pie Chart).

Overall, the regional total rose from 7 to 41 programs, evidencing an expanding educational infrastructure in the renewable energy domain. However, persistent cross-country disparities signal the need for stronger policy coordination, regional

partnerships, and investment in human capital development to achieve balanced progress across the region.

Figure 8 illustrates the distribution of Central Asian countries' shares in the total number of higher education programs focused on renewable energy as of 2024.

The results show a pronounced concentration in two leading countries:

- Kazakhstan accounts for approximately 36.6% (15 programs),
- Uzbekistan follows with 29.3% (12 programs).

Tajikistan and Kyrgyzstan represent the mid-range segment with 14.6% (6 programs) and 12.2% (5 programs), respectively, while Turkmenistan contributes 7.3% (3 programs).

This distribution highlights the uneven development of educational infrastructure across the region. The combined share of Kazakhstan and Uzbekistan exceeds two-thirds of all programs (≈66%), reflecting the concentration of institutional resources and strategic investments in these two countries.

To achieve regional balance, there is a need to expand educational initiatives in Kyrgyzstan, Tajikistan, and Turkmenistan. This could be achieved through cross-border partnerships, joint degree programs, and state-supported academic modernization aimed at strengthening human capital for the renewable energy transition.

3.4 Qualitative Results

An analysis of expert interviews revealed that the primary challenge in renewable energy education lies in the lack of practical training opportunities for students.

University instructors noted an acute shortage of modern laboratories and simulation facilities, while employers emphasized a disconnect between academic curricula and labor market needs [9]. These findings suggest that the educational systems in Central Asia are still largely theoretical, with limited exposure to hands-on industry applications.

Table 7 summarizes the results of expert interviews identifying the main barriers to workforce preparation for the renewable energy sector in Central Asia.

The most critical challenge is the shortage of laboratory infrastructure, reported by 69% of respondents on average. The issue is most acute in Turkmenistan (80%) and Kyrgyzstan (72%), reflecting underinvestment in technical facilities and experimental learning environments.

The weak connection between universities and employers emerges as another systemic barrier (58% region-wide), suggesting insufficient integration of applied research, internships, and co-designed curricula. The prevalence of outdated academic programs (52%) further limits the relevance of graduates' skills to evolving industry needs.

A substantial deficiency in digitalization of the educational process was also noted by 58% of experts, particularly in Turkmenistan (68%) and Tajikistan (64%), compared to somewhat lower figures in Kazakhstan and Uzbekistan (47-50%).

Overall, these findings confirm that the key problems are systemic, affecting all five countries of the region. They point to the need for a comprehensive modernization of curricula, strengthened university-industry partnerships, and accelerated digital transformation of educational infrastructure to align training outcomes with the demands of the renewable energy transition.

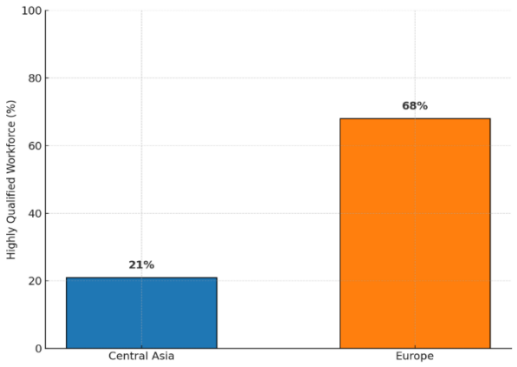

Figure 9: Comparison of the share of highly qualified personnel in Central Asia and Europe (2024, Bar Chart).

Figure 9 compares the proportion of highly qualified specialists in the renewable energy sector between Central Asia and Europe as of 2024. The results show a pronounced disparity:

- Central Asia - 21%;
- Europe - 68%.

The sharp visual contrast between the bar heights highlights the systemic gap in workforce competence and institutional preparedness. The European educational and professional ecosystem sustains a high level of skill formation, ensuring a consistent supply of experts for the renewable energy industry, while Central Asia remains in the early phase of capacity development.

Table 7: Main barriers to human capital development (Based on Expert Interviews, % of Respondents).

Barrier	Uzbekistan	Kazakhstan	Kyrgyzstan	Tajikistan	Turkmenistan	Regional Average
Lack of laboratory equipment	65%	58%	72%	70%	80%	69%
Weak link with employers	54%	49%	60%	62%	67%	58%
Outdated curricula	48%	42%	55%	53%	61%	52%
Lack of digital technologies	50%	47%	59%	64%	68%	58%

The diagram supports the conclusion that accelerated workforce development is essential for the Central Asian region. Bridging this gap will require systemic measures, including the modernization of university curricula, expansion of practical training infrastructure, integration of digital learning technologies, and strengthened partnerships with employers and international universities.

According to IRENA [3], the share of highly qualified personnel in Europe is approximately 68%, whereas in Central Asia it remains at only 21%, revealing a deep imbalance that demands urgent reforms in education quality, institutional governance, and international collaboration.

Table 8: Comparative Analysis of Key Indicators (2024).

Indicator	Europe	North America	East Asia	Central Asia
Share of highly qualified personnel (%)	68	65	58	21
Number of university programs	150	120	110	41
Number of retraining centers	95	88	60	10
Adoption of digital technologies (%)	72	70	61	34

Table 8 provides a comparative overview of key indicators of human capital development in the renewable energy sector across Europe, North America, East Asia, and Central Asia in 2024.

The data clearly demonstrate that Central Asia lags behind all other regions across every dimension. The share of highly qualified specialists stands at 21%, compared to 68% in Europe, 65% in North America, and 58% in East Asia.

A similar pattern is observed for the number of university programs (41 in Central Asia vs. 150 in Europe) and the availability of retraining centers (10 vs. 95 and 88, respectively). The digitalization of education and training also remains limited, with only 34% adoption in Central Asia, compared to over 70% in developed regions.

These discrepancies highlight structural and institutional challenges, including underinvestment in higher education, insufficient integration of digital tools, and weak linkages between academia and industry. To close this gap, Central Asian countries must implement targeted reforms, focusing on:

- Expanding and updating renewable energy curricula.
- Establishing modern laboratories and competence centers.
- Integrating digital technologies and simulation tools.
- Promoting international academic partnerships and mobility programs.

Such interventions would help align the region's educational ecosystem with global standards and create a sustainable pipeline of specialists for the rapidly expanding renewable energy sector.

3.5 Country-Specific Analysis of Human Capital Development in Central Asia

This subsection provides a detailed country-level assessment of renewable energy human capital development across all five Central Asian nations (Table 9). The goal is to move beyond regional generalizations and present a clearer differentiation of institutional capacity, education systems, and workforce potential.

Uzbekistan. Uzbekistan has demonstrated the fastest institutional modernization in the region. Since 2019, more than 12 university programs in renewable energy have been launched, supported by the Green Economy Strategy (2019-2030).

-

Table 9: Comparative overview of human-capital development across Central Asia (2024).

Indicator	Uzbekistan	Kazakhstan	Kyrgyzstan	Tajikistan	Turkmenistan
University programs	12	15	5	6	3
Retraining centers	7	10	3	2	1
Highly qualified personnel (%)	23	32	18	16	12
Digitalization level (%)	45	52	28	25	18
Private-sector involvement (%)	20	35	10	8	5
Main challenge	Labs & mismatch	Regional inequality	Funding	Infrastructure	Low openness

The key characteristics are as follows:

- Establishment of new solar and wind engineering departments at TSTU and Turin Polytechnic University;
- Opening of professional retraining centers in Tashkent, Samarkand, and Bukhara;
- Active partnerships with EU universities (Erasmus+, DAAD);

Rapid development of digital platforms for remote engineering training.

However, challenges persist.

- Limited laboratory infrastructure outside major cities;
- Skills mismatch between graduates and employer requirements;
- Insufficient private-sector involvement in curriculum development.

Overall, Uzbekistan is a regional leader in educational expansion but still needs stronger industry-academia integration.

Kazakhstan. Kazakhstan has the most structured and well-funded renewable energy education system in Central Asia.

Key strengths:

- The largest number of programs (15 university programs, 60+ modules).
- High involvement of private companies (Samruk-Energy, Eni Plenitude) in training initiatives;
- Modern laboratories and competence centers established in Almaty, Astana, and Shymkent;
- Substantial public funding (3.2-3.5% of GDP allocated to education).

Barriers include:

- Geographic imbalance - rural regions have limited access to modern training.
- Dependence on international instructors for advanced modules.
- Bureaucratic constraints in accreditation of new programs.

Kazakhstan has a well-developed but uneven system that requires decentralization and further digital expansion.

Kyrgyzstan. Kyrgyzstan has demonstrated moderate yet notable progress.

Positive developments:

- Growth from 1 to 5 university programs (2010-2024).
- Strengthening hydropower-focused curricula aligned with national energy priorities.
- Support from international donors (UNDP, JICA) for laboratory upgrades.

Key challenges:

- Severe funding shortages - less than 1.8% of GDP allocated to higher education.
- Outdated equipment in universities outside Bishkek.
- Limited digitalization and simulation tools.
- Weak cooperation with private hydropower companies.

Kyrgyzstan's system is promising but requires substantial investment and modernization.

Tajikistan. Tajikistan has significant renewable potential (especially hydropower); however, human capital development remains constrained.

Strengths:

- Gradual expansion to 6 university programs in 2024.
- Increasing government interest in green-skills training.
- Active collaboration with World Bank energy-education projects.

Limitations:

- Very limited laboratory infrastructure - over 70% of surveyed staff report lacking modern tools.
- High dependence on donor support for training programs.
- Weak alignment between university curricula and hydropower industry needs.
- Low digital readiness.

Tajikistan's main barrier is inadequate technical facilities, which slow progress despite political commitment.

Turkmenistan. Turkmenistan remains the slowest mover in human capital development for renewable energy.

Observations:

- Only 3 university programs currently exist.
- Renewable energy is not yet fully integrated into national education strategies.
- Limited accessibility of institutional data and low transparency of academic reform.
- Very low digitalization and absence of competence centers.

Constraints:

- Weak industry-academia collaboration.
- High dependence on foreign specialists for installation and maintenance of renewable-energy equipment.
- Minimal participation in international academic partnerships.

Overall, Turkmenistan requires systemic reforms and increased openness to accelerate green skill development. Summary of Country-Specific Differences.

4 DISCUSSION

4.1 Interpretation of Findings

The results presented in the previous section indicate that the human capital base in the renewable energy sector of Central Asian countries is still in a formative stage.

While the number of university programs has grown considerably in recent years, the quality of training and alignment with international standards remain limited. The gap between regional leaders (Kazakhstan and Uzbekistan) and countries where progress has been slower (Kyrgyzstan, Tajikistan, Turkmenistan) remains significant.

This finding aligns with broader international research showing that regions with low institutional support and limited investment in education tend to fall behind in workforce quality and technological innovation [1].

It is also important to note that Central Asia possesses substantial renewable resource potential - abundant solar radiation, wind corridors, and hydropower reserves - yet the shortage of skilled specialists represents a serious barrier to translating this potential into sustainable growth. Without a qualified workforce, large-scale green projects risk being delayed, underutilized, or overly dependent on foreign expertise.

Thus, the discussion underscores the strategic necessity of developing a competitive and interdisciplinary human capital base as a cornerstone for the region's green energy transition.

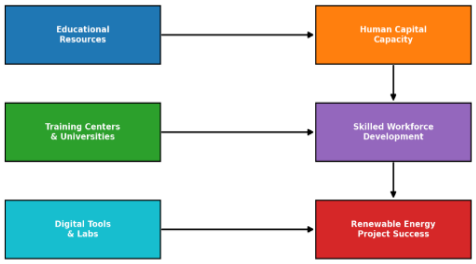

Figure 10: Conceptual model of the relationship between educational resources and the effectiveness of Renewable Energy deployment in Central Asia.

Figure 10 presents a conceptual model illustrating the relationship between educational resources and the effectiveness of renewable energy implementation in the Central Asian region.

On the left side of the diagram are the key sources of educational resources - universities, training centers, and digital laboratories. These institutions constitute the foundation for human capital formation, providing the technical and managerial competencies necessary for the energy transition.

The right side of the model depicts the transformation process: educational resources strengthen human capacity, enhance the supply of qualified specialists, and ultimately improve the implementation performance of renewable energy projects.

The diagram highlights that the level of human capital directly determines the effectiveness of renewable energy deployment. Conversely, insufficient educational infrastructure can significantly slow the regional energy transition. This conceptual relationship underscores the strategic importance of investing in education and workforce training as a prerequisite for successful green transformation.

4.2 Comparison with International Experience

A comparative analysis (see Table 10 and Fig. 9) demonstrates that Central Asian countries lag far behind Europe and North America across key indicators of educational quality, digitalization, and

workforce competence. This reinforces the urgent need for systemic reforms in the regional educational strategies for renewable energy workforce development.

Table 10 compares key aspects of workforce training systems between Central Asia and developed regions (Europe and North America) as of 2024.

Table 10: Comparative differences in workforce training (Central Asia vs. Developed Regions, 2024).

Indicator	Europe	North America	Central Asia
Share of highly qualified personnel (%)	68	65	21
Private sector participation in educational initiatives (%)	55	49	12
Investment in education (% of GDP)	4.5	5.0	2.1
Use of digital technologies in education (%)	72	70	34

The proportion of highly qualified specialists in Central Asia remains critically low - only 21%, compared to 68% in Europe and 65% in North America. This reflects a pronounced deficit in human capital and a lack of alignment between educational outcomes and labor market needs.

A particularly important differentiating factor is the weak involvement of the private sector in educational initiatives: only 12% of Central Asian training programs involve business participation, compared to 55% in Europe and 49% in North America. This demonstrates limited engagement of employers in curriculum design, internships, and co-financing of training programs.

Furthermore, investment in higher education across Central Asia remains substantially lower - 2.1% of GDP, compared with 4.5% in Europe and 5.0% in North America. The adoption of digital technologies in the educational process is also limited to 34%, almost half the level observed in advanced economies (72% and 70%).

These findings underscore that the key structural weaknesses of Central Asian educational systems include:

1) Low private sector engagement.
2) Insufficient public investment in higher education.
3) Slow digital transformation of training infrastructure.

Together, these factors significantly constrain the region's ability to produce a competitive renewable energy workforce and limit its readiness for the green transition. Addressing these challenges requires systemic reforms - modernization of curricula, stronger public-private partnerships, and comprehensive digital integration - to align the regional human capital framework with global standards.

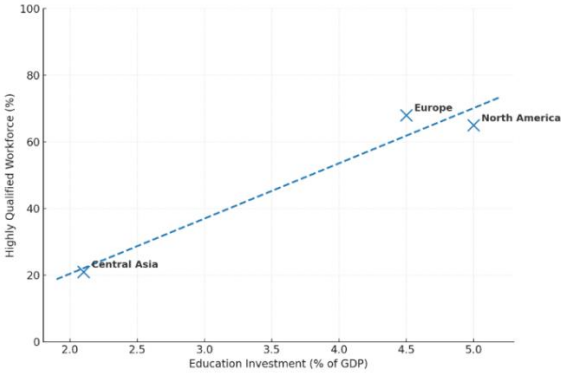

Figure 11: The impact of educational investment levels on the share of qualified personnel (Regional Comparison, Scatter Plot).

Figure 11 illustrates the relationship between investment in education (as % of GDP) and the share of highly qualified personnel (%) across three macro-regions - Central Asia, Europe, and North America.

The data reveal a clear gradient: Central Asia (2.1% - 21%) lies in the lower quadrant of the graph, while Europe (4.5% - 68%) and North America (5.0% - 65%) cluster markedly higher along the qualification axis. The spatial dispersion of points underscores a pronounced gap between developing and advanced regions.

A dotted linear-regression line indicates a positive association: the higher the share of investment in education, the greater the proportion of highly qualified specialists. This relationship suggests that targeted increases in educational expenditure-specifically directed toward curriculum modernization, laboratory infrastructure, and digital learning environments-are statistically linked with the advancement of workforce competence in the renewable-energy sector.

Overall, the figure confirms a direct correlation between investment intensity and human-capital quality. In Central Asia, where public spending on higher education averages only 2.1 % of GDP, the professional-qualification indicators remain substantially below those of Europe and North America. These disparities highlight the critical

importance of sustained investment in human-capital formation as a foundation for a successful green-energy transition.

4.3 Key Barriers and Challenges

Based on the expert interviews (see Table 7), four systemic barriers were identified as the principal constraints to workforce development in the renewable-energy sector of Central Asia:

1) Insufficient laboratory infrastructure - most technical universities lack modern experimental facilities and simulators, limiting practice-oriented training and innovation capacity.
2) Limited digital integration - digital tools, data platforms, and online learning technologies remain underdeveloped, constraining both teaching quality and remote learning accessibility.
3) Weak university-industry linkages - cooperation between academia and employers is sporadic; few joint programs, internships, or co-funded research projects exist.
4) Outdated curricula - educational programs remain oriented toward traditional energy disciplines and have not yet incorporated cross-cutting "green-skills" modules (renewable-systems design, environmental impact assessment, energy-data analytics).

These challenges are structural rather than episodic and collectively reduce the region's ability to supply a competent and innovation-ready workforce. Overcoming them will require a combination of institutional reforms, public-private partnerships, and targeted international cooperation, ensuring that educational modernization aligns with the technological demands of the emerging green economy.

Figure 12 visualizes the systemic barriers to workforce development in the Central Asian countries. The diagram organizes these constraints into three interconnected dimensions-institutional, infrastructural, and technological-showing how their interaction produces cumulative effects on the quality of human capital formation.

On the left side, four key groups of constraints are highlighted:

- Institutional Weaknesses (policy fragmentation, limited governance capacity);
- Infrastructure Gaps (shortage of laboratories and competence centers).
- Technological Lag (slow adoption of digital tools and data platforms).
- Industry-Academia Disconnect (weak cooperation with employers and low engagement of the private sector).

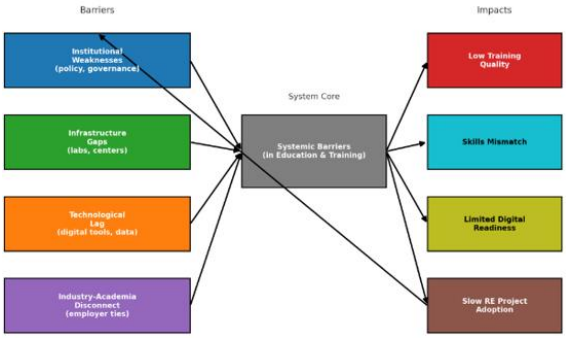

Figure 12: Systemic barriers in workforce development in Central Asia.

These factors converge in the central node, labeled Systemic Barriers in Education and Training, emphasizing their mutually reinforcing nature.

On the right side, the diagram presents the outcomes of these barriers:

- Low Training Quality.
- Skills Mismatch.
- Limited Digital Readiness.
- Slow Renewable Energy (RE) Project Adoption.

A feedback arrow runs from Slow RE Project Adoption back to Institutional Weaknesses, illustrating a negative feedback loop in which the delayed implementation of renewable-energy projects perpetuates institutional inefficiencies and obstructs reform.

Thus, the model demonstrates that solving the human-capital deficit requires simultaneous institutional, infrastructural, and technological transformations, combined with stronger university-industry partnerships and integrated governance mechanisms.

4.4 Practical Significance of the Findings

The results of this study have direct policy relevance for the design of educational and institutional strategies in the Central Asian region. They demonstrate that without modernization of educational infrastructure and deeper integration of the private sector, the region risks remaining on the periphery of the global green-energy transition.

Table 11 outlines the key directions for reform in the system of workforce preparation for the

renewable-energy sector and specifies practical measures for their implementation.

A top priority is curriculum modernization, which should incorporate interdisciplinary modules that integrate energy engineering, environmental management, and digital technologies. This approach will prepare a new generation of specialists capable of addressing the technological and ecological challenges of the energy transition.

Table 11: Potential directions for workforce development reform.

Reform Area	Specific Measures
Curriculum Modernization	Introduction of interdisciplinary modules combining energy, ecology, and digitalization.
Infrastructure Enhancement	Establishment of modern laboratories and competence centers.
Digital Integration	Deployment of simulators, online learning, and IoT-based training platforms.
Business Partnerships	Dual education programs, internships, and corporate training.
International Cooperation	Joint master's programs, exchange schemes, and academic mobility initiatives.

The second direction involves strengthening educational infrastructure through the establishment of modern laboratories and competence centers, enabling practice-oriented learning and experimentation.

The third reform area is digital integration, which includes the deployment of simulators, online learning platforms, and IoT-based systems for remote training and performance monitoring.

The fourth direction, partnership with business, aims to develop dual-education schemes, internships, and corporate retraining programs, bridging the gap between theoretical education and market needs.

Finally, international cooperation should focus on joint degree programs, student and faculty exchanges, and academic mobility, ensuring the transfer of global best practices and international accreditation of regional programs.

Together, these initiatives constitute a comprehensive reform strategy, combining educational, technological, and institutional measures to enhance the region's human-capital competitiveness in the renewable-energy domain.

All aggregated datasets, coding schemes, and regression output tables used in this study are provided as Supplementary Material (Appendix A-C) to enable transparency, reproducibility, and further comparative analysis.

5 CONCLUSIONS

This study, devoted to the development of a qualified workforce in the green-energy sector of Central Asia, has identified both positive dynamics and systemic constraints requiring long-term solutions.

Using a mixed-methods approach-including statistical analysis, comparative benchmarking, expert interviews, and case studies-the research provides a comprehensive assessment of the region's educational and workforce infrastructure, as well as its alignment with international experience.

The findings indicate that while the number of university programs and retraining centers has grown steadily-particularly in Kazakhstan and Uzbekistan-the overall quality of workforce preparation remains low. Only 21% of specialists in the renewable-energy field possess advanced qualifications, compared to 68% in Europe and 65% in North America.

The main barriers include inadequate laboratory infrastructure, weak integration of digital technologies in the learning process, misalignment of curricula with labor-market demands, and limited private-sector involvement in educational initiatives.

The comparative analysis confirms a strong positive correlation between education investment and workforce quality. Central Asia, allocating just 2.1% of GDP to higher education-compared with 4.5-5.0% in Europe and North America-faces structural risks such as skills mismatch, low digital readiness, and slower adoption of renewable-energy projects.

Nevertheless, the study also identifies significant opportunities. The region possesses abundant renewable resources (solar, wind, and hydropower) and growing governmental commitment to green economic policies. To realize this potential, active educational reform is essential. The priority areas include curriculum renewal, infrastructure strengthening, digital transformation, public-private partnerships, and international collaboration.

Ultimately, the primary challenge for Central Asian countries is to shift from quantitative expansion to qualitative enhancement of educational initiatives. Only through comprehensive modernization of the workforce development system can the region close the gap with advanced economies and secure successful integration into the global renewable-energy transition.

The findings affirm that human capital is the pivotal factor of sustainable energy transformation. Without substantial investment in education and training, the transition to a green economy in Central Asia will remain constrained and uneven.

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