The Impact of Renewable Energy Development on Energy Security: The Mediating Roles of Energy Portfolio Diversification and Supply Chain Resilience

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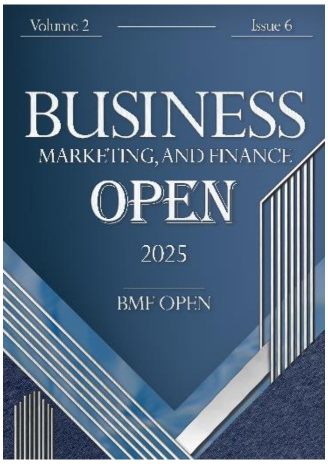

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Abstract: This study aimed to investigate the effect of renewable energy development on energy security and to examine the mediating roles of energy portfolio diversification and supply chain resilience among energy-sector professionals in Tehran. This applied, quantitative, cross-sectional study used a descriptive-correlational design and partial least squares structural equation modeling. The statistical population comprised managers, experts, policymakers, consultants, researchers, and technical specialists employed in energy-related governmental organizations, private companies, universities, and research centers in Tehran. A total of 384 participants were selected through a multistage sampling procedure. Data were collected using a structured questionnaire measuring renewable energy development, energy portfolio diversification, supply chain resilience, and energy security on a five-point Likert scale. Content and face validity were evaluated by experts and members of the target population, while internal consistency, convergent validity, and discriminant validity were assessed using Cronbach's alpha, composite reliability, average variance extracted, the Fornell–Larcker criterion, and heterotrait–monotrait ratios. Data were analyzed using SPSS version 27 and SmartPLS version 4. Renewable energy development had significant positive effects on energy portfolio diversification ($\beta = 0.631$, $p < 0.001$), supply chain resilience ($\beta = 0.587$, $p < 0.001$), and energy security ($\beta = 0.238$, $p < 0.001$). Energy portfolio diversification ($\beta = 0.284$, $p < 0.001$) and supply chain resilience ($\beta = 0.387$, $p < 0.001$) also significantly predicted energy security. The indirect effects of renewable energy development on energy security through energy portfolio diversification ($\beta = 0.179$, $p < 0.001$) and supply chain resilience ($\beta = 0.227$, $p < 0.001$) were significant, confirming complementary partial mediation. The model explained 64.5% of the variance in energy security. Renewable energy development strengthens energy security both directly and indirectly by broadening the energy portfolio and enhancing supply chain resilience, with supply chain resilience representing the stronger mediating mechanism.

Keywords: Renewable Energy Development; Energy Security; Energy Portfolio Diversification; Supply Chain Resilience; Structural Equation Modeling

1. Introduction

Energy security has become one of the most consequential concerns in contemporary economic development, public policy, and environmental governance. Modern societies depend on stable, affordable, accessible, and environmentally sustainable energy supplies to maintain industrial production, public services, transportation systems, digital infrastructure, household welfare, and national defense. However, geopolitical tensions, volatility in fossil-fuel markets, infrastructure failures, climate-related disruptions, technological dependencies, and the unequal geographical distribution of conventional energy resources have exposed the vulnerability of energy systems across both developed and developing countries. Energy security can therefore no longer be understood merely as the physical availability of fuel or electricity. It encompasses the reliability of supply, affordability of energy services, diversity of sources and technologies, resilience of infrastructure and supply networks, environmental compatibility, and the institutional capacity to anticipate and respond to disruptions. In the global context, energy-security strategies are increasingly shaped by interactions among geopolitical rivalry, national policy choices, market instability, technological transformation, and environmental commitments [1]. Accordingly, the transition toward more diversified and resilient energy systems has become a central component of national development strategies.

Dependence on a narrow range of fossil-fuel resources creates several interconnected risks. Countries that rely heavily on oil, natural gas, or coal may experience significant economic and operational difficulties when international prices increase, imports are interrupted, production facilities fail, or geopolitical disputes restrict access to critical energy supplies. Even energy-producing countries can face insecurity when their domestic energy systems are characterized by inefficient infrastructure, limited generating diversity, poor transmission capacity, or overdependence on a single resource. The experience of Iraq, for example, demonstrates that possessing substantial hydrocarbon reserves does not automatically guarantee a secure, reliable, and sustainable energy system when electricity infrastructure, institutional coordination, investment capacity, and policy implementation remain inadequate [2]. Similarly, the vulnerability of coal-dependent economies in Southeast Europe illustrates how concentrated generation structures and fragile electricity grids can expose national economies to supply disruptions, transition costs, and infrastructure risks [3]. These conditions highlight the necessity of moving beyond resource possession toward a broader conception of energy security based on adaptability, diversification, and resilience.

Renewable energy development has emerged as a major pathway for reducing these vulnerabilities. Solar, wind, biomass, geothermal, hydropower, and other renewable technologies can expand domestic generating capacity, reduce dependence on imported fuels, distribute energy production geographically, and contribute to climate-change mitigation. The transition toward renewable energy is also associated with technological innovation, employment creation, regional development, and improvements in environmental quality. Nevertheless, the contribution of renewable energy to energy security depends on the manner in which renewable technologies are integrated into national energy systems. Strategic energy planning must balance renewable resources with conventional generation, nuclear energy, storage technologies, grid flexibility, and demand-management mechanisms rather than treating any single technology as a complete solution [4]. Renewable energy development should therefore be understood as a multidimensional process involving investment, technological capability, supportive regulation, infrastructure expansion, market design, human capital, and long-term institutional commitment.

The importance of renewable energy has become particularly evident following recent energy crises. The European Union's experience after the unprecedented energy crisis demonstrated that exposure to imported fossil fuels can rapidly transform energy dependence into economic, political, and social vulnerability. In response, European energy policy increasingly emphasized renewable-energy deployment, efficiency, storage, interconnection, and the diversification of supply sources [5]. The Turkish experience likewise indicates that national renewable-energy action plans can produce measurable changes in energy production and policy outcomes when they are supported by coherent implementation mechanisms and sustained public commitment [6]. These examples suggest that renewable-energy policies can strengthen energy autonomy and reduce external exposure, but their effectiveness depends on implementation quality, complementary infrastructure, and alignment with the broader structure of the energy system.

The potential contribution of renewable energy is equally important in developing countries, where energy insecurity is frequently associated with inadequate electricity access, rapid population growth, fiscal constraints, weak transmission networks, and dependence on imported technologies. Affordable clean-energy transitions in these countries require combinations of decentralized generation, mini-grids, energy storage, energy-efficiency measures, appropriate financing, and locally adaptable technologies [7]. In Africa, the scale-up of renewable electrification requires not only favorable resource potential but also coordinated research, investment, institutional reform, regional integration, and improvements in electricity-market design [8]. Climate modeling can further improve renewable-energy planning by identifying variations in solar, wind, hydrological, and other resource potentials under changing environmental conditions [9]. Consequently, renewable-energy development must be grounded in reliable scientific assessment and translated into practical investment and infrastructure decisions.

National experiences reveal that the opportunities and barriers surrounding renewable energy differ considerably across political, economic, and geographical contexts. In South Africa, renewable-energy investment offers substantial potential for sustainable transition, yet financing limitations, policy uncertainty, grid constraints, and institutional challenges can delay implementation [10]. In Uganda, the direction of the renewable-energy landscape is influenced by regulatory arrangements, investment conditions, resource availability, technological access, and stakeholder participation [11]. Malaysia's energy transition similarly demonstrates the importance of policy coherence, innovation, green investment, and the integration of environmental objectives into long-term development planning [12]. In India, transforming coal-dependent regions requires renewable-energy opportunities to be aligned with just-transition policies that address employment, regional inequality, land use, and the socioeconomic consequences of structural change [13]. These cases indicate that renewable-energy development contributes most effectively to energy security when technological expansion is accompanied by institutional coordination and socially responsive transition planning.

The availability of renewable resources alone is insufficient. Countries must also possess the material, technological, financial, and organizational capabilities required to convert resource potential into reliable energy production. Nigeria has significant renewable-energy opportunities, including biomass and other locally available materials, yet their sustainable utilization requires a roadmap linking resource assessment, technological application, industrial capacity, research development, and policy support [14]. The evaluation of Nigeria's biomass policy further demonstrates that policy declarations do not necessarily produce effective utilization unless implementation frameworks, incentives, standards, and institutional responsibilities are clearly established [15]. Renewable energies can also strengthen sustainable energy governance and environmental policy by reducing emissions, supporting decentralized access, and creating alternatives to carbon-intensive development pathways [16]. Thus, the relationship between renewable energy and energy security is not automatic; it is mediated by the structural changes that renewable-energy development produces within the wider energy system.

One of the most important of these structural mechanisms is energy portfolio diversification. An energy system concentrated around a limited number of fuels, generating technologies, suppliers, or transportation routes is more susceptible to shocks than a system capable of substituting among multiple alternatives. Diversification can reduce the impact of resource shortages, price volatility, climatic variation, equipment failure, and geopolitical disruption by distributing risk across a broader set of energy options. Evidence from developing countries indicates that diversification beyond hydropower toward non-hydro renewable sources can improve energy security by reducing dependence on rainfall-sensitive generation and expanding the technological composition of electricity supply [17]. In Sri Lanka, the application of alternative energy sources has similarly been discussed as a sustainable strategy for reducing dependence on conventional resources and improving long-term system stability [18]. Energy portfolio diversification is therefore not simply a matter of increasing renewable capacity; it involves creating a balanced and flexible combination of technologies, suppliers, geographical locations, and delivery systems.

The effectiveness of diversification depends partly on the specific resources available within each context. Agricultural biomass represents a significant but unevenly distributed source of renewable energy in the European Union, and its contribution depends on production patterns, logistics, technological conversion, and regional agricultural structures [19]. Geothermal energy offers another diversification pathway, particularly in Eastern Africa, where regional integration could enable countries to share resources, infrastructure, technical capacity, and electricity markets [20]. Hydropower and water-energy resources may also support energy security, although their development can be constrained by environmental conditions, investment limitations, governance problems, and competition over water use, as observed in Aceh [21]. These examples demonstrate that portfolio diversification must be adapted to local resource endowments and supported by complementary infrastructure and regional cooperation.

Technological specialization also affects the trajectory of renewable-energy development. Countries differ in their capacity to manufacture, deploy, and maintain renewable-energy technologies, and these specialization patterns influence their competitive position and energy independence [22]. Renewable energy may become a driver of regional competitiveness when investment in generation is combined with industrial development, skills formation, innovation, and supportive market structures, as emphasized in analyses of the European Union's outermost regions [23]. Renewable-energy integration within major infrastructure initiatives can also improve energy efficiency and economic performance when energy planning, investment, and technology deployment are coordinated effectively, as illustrated by the China–Pakistan Economic Corridor [24]. These findings reinforce the argument that diversification has both security and development dimensions: it reduces energy-system concentration while simultaneously creating new technological and economic capabilities.

A second critical mechanism is supply chain resilience. Renewable-energy systems depend on complex supply networks involving minerals, manufactured components, electronic equipment, batteries, turbines, photovoltaic modules, transmission technologies, software, transportation services, maintenance capabilities, and specialized labor. Although renewable resources such as sunlight and wind are domestically available in many countries, the technologies required to capture and distribute them may depend on international supply chains. Price inflation, material shortages, shipping disruptions, trade restrictions, and geopolitical concentration in the production of critical components can therefore undermine renewable-energy deployment. Supply chain resilience refers to the ability to anticipate such disruptions, maintain essential operations, access alternative suppliers, recover from shocks, and adapt procurement and production systems over time. Research on renewable-energy markets has shown that supplier diversification, strategic inventory, flexible contracting, local sourcing, collaboration, and improved risk monitoring can reduce exposure to price inflation and supply interruptions [25].

Reliability engineering provides another foundation for resilient renewable-energy systems. Because solar, wind, storage, and grid-support technologies operate under varying environmental and technical conditions, their performance depends on preventive maintenance, failure analysis, redundancy, condition monitoring, and system-level reliability planning [26]. Climate-oriented management of district-heating enterprises similarly requires innovative resources, organizational adaptability, and investment strategies capable of responding to environmental and technological changes [27]. Supply chain resilience therefore extends beyond procurement. It includes the reliability of equipment, availability of spare parts, maintenance skills, information sharing, infrastructure redundancy, emergency procedures, and the institutional capacity to coordinate responses across the energy value chain.

Financial decision-making also shapes the resilience and scalability of renewable-energy investment. Renewable-energy projects often involve high initial capital costs, long payback periods, policy uncertainty, and exposure to changing technology prices. The use of data-driven financial analysis can improve investment selection, risk assessment, and resource allocation in sustainable-energy projects [28]. However, financial optimization must be integrated with broader energy-policy objectives. Developing countries frequently face institutional fragmentation, regulatory inconsistency, restricted access to capital, and inadequate technical capacity, all of which constrain the implementation of sustainable-energy policies [29]. Effective renewable-energy development consequently requires financing systems that account not only for expected returns but also for energy-security benefits, resilience, environmental externalities, and long-term public value.

Energy security is a multidimensional outcome that may vary across sectors. In agriculture, for example, the continuity, affordability, and accessibility of energy affect irrigation, mechanization, storage, processing, transportation, and food-system stability. The identification of vital indicators in agricultural energy security demonstrates that security must be evaluated through multiple operational, economic, and institutional dimensions rather than through a single supply measure [30]. A similar multi-indicator perspective has been used to assess Ghana’s energy security and environmental sustainability, emphasizing the need to integrate availability, affordability, accessibility, efficiency, and ecological consequences [31]. These approaches support the treatment of energy security as a latent, multidimensional construct influenced by the structure, diversity, and resilience of the energy system.

Despite the growing literature, important conceptual and empirical gaps remain. Many studies evaluate renewable-energy potential, policy development, investment barriers, or environmental effects without testing the mechanisms through which renewable-energy development enhances energy security. Other studies examine diversification or resilience independently, even though these mechanisms may operate simultaneously. A renewable-energy system may increase the number of energy sources but remain insecure if its equipment and materials depend on fragile supply networks. Conversely, a resilient supply chain may protect existing operations without correcting excessive dependence on a narrow energy portfolio. The development of a secure energy system therefore requires both portfolio-level diversification and supply-chain-level resilience. Research that integrates these mediators can provide a more complete explanation of why similar levels of renewable-energy investment may generate different energy-security outcomes across organizations and national contexts.

The Iranian energy system provides a particularly relevant setting for this issue. Iran possesses substantial fossil-fuel reserves as well as considerable solar, wind, biomass, geothermal, and small-hydropower potential. Nevertheless, electricity-demand growth, aging infrastructure, seasonal imbalances, environmental pressures, investment restrictions, technological dependence, and external economic constraints create persistent energy-security challenges. Tehran, as the country’s principal administrative, economic, academic, and policy center, contains a high concentration of energy-sector institutions, governmental organizations, research centers, consultants, private companies, and technical specialists. Examining the perceptions of professionals operating within this setting can clarify whether renewable-energy development is associated with stronger energy security and whether this association is transmitted through changes in the composition of the energy portfolio and the resilience of energy supply chains.

The theoretical model proposed in this study assumes that renewable-energy development has both a direct and an indirect effect on energy security. The direct effect may arise from increased domestic generating capacity, reduced fossil-fuel dependence, lower environmental exposure, distributed production, and technological modernization. The indirect effect through energy portfolio diversification reflects the capacity of renewable-energy expansion to broaden the mix of energy sources, technologies, suppliers, and locations. The indirect effect through supply chain resilience reflects the extent to which renewable-energy development promotes alternative sourcing, infrastructure flexibility, domestic capability, risk management, and recovery from disruption. By testing these relationships simultaneously, the study moves beyond a simple assessment of whether renewable energy is beneficial and instead examines the organizational and systemic mechanisms through which its benefits may be realized.

Accordingly, the aim of this study was to investigate the effect of renewable energy development on energy security and to examine the mediating roles of energy portfolio diversification and supply chain resilience among energy-sector professionals in Tehran.

2. Methodology

This study employed an applied, quantitative, cross-sectional, and descriptive-correlational research design. The primary objective was to investigate the effect of renewable energy development on energy security and to determine whether energy portfolio diversification and supply chain resilience mediated this relationship. A structural equation modeling approach was adopted because the proposed conceptual model included several latent variables and both direct and indirect relationships among the research constructs. The statistical population consisted of managers, senior experts, policymakers, consultants, researchers, and technical specialists working in energy-related organizations, governmental institutions, research centers, universities, and private companies located in Tehran, Iran. Eligible participants were required to possess at least a bachelor's degree in energy engineering, electrical engineering, mechanical engineering, industrial engineering, environmental sciences, economics, management, public policy, or another closely related discipline. They were also required to have at least three years of professional or research experience in renewable energy, energy planning, energy economics, energy security, electricity generation, energy supply chains, or energy policy. Individuals who did not have sufficient familiarity with the concepts examined in the study or who submitted incomplete questionnaires were excluded from the analysis.

A total of 384 participants were included in the final sample. This sample size was determined using Cochran's formula for large populations at a 95% confidence level, a 5% margin of error, and maximum population variability. To obtain the required number of usable responses, 430 questionnaires were initially distributed among eligible individuals. Of these, 397 questionnaires were returned, representing a response rate of 92.33%. Following the screening process, 13 questionnaires were excluded because of substantial missing data, patterned responses, or failure to satisfy the inclusion criteria. Consequently, data from 384 respondents were retained for the final statistical analysis. Participants were recruited through a multistage sampling procedure. First, major governmental, academic, research, and private-sector institutions involved in energy planning and renewable energy development in Tehran were identified. Subsequently, the institutions were classified according to their organizational sector, and potential participants were selected proportionately from each category. Within the selected institutions, purposive sampling was used to identify individuals with relevant professional knowledge and experience, after which eligible participants were invited to take part in the study. This procedure was intended to ensure the inclusion of respondents representing different dimensions of the energy system, including policy formulation, electricity generation, renewable energy investment, technology development, infrastructure management, procurement, logistics, and energy supply-chain planning.

Data collection was conducted through both printed and electronic questionnaires. Before distributing the research instrument, participants were informed about the objectives of the study, the voluntary nature of participation, the confidentiality of their information, and their right to withdraw from the research at any stage without penalty. No personally identifiable information was collected, and the responses were used exclusively for research purposes. Participants provided informed consent before completing the questionnaire. The average questionnaire completion time was approximately 15 to 20 minutes. To reduce common method bias, the participants were assured that there were no correct or incorrect answers, the items relating to predictor and outcome variables were presented in separate sections, and the order of selected items was varied. The questionnaires were also reviewed for missing values, outliers, response consistency, and unusually repetitive answer patterns before the final dataset was prepared.

Data were collected using a structured questionnaire consisting of two principal sections. The first section collected demographic and professional information, including age, gender, educational level, academic field, organizational affiliation, job position, and length of professional experience in the energy sector. The second section measured the four principal constructs of the conceptual model: renewable energy development, energy portfolio diversification, supply chain resilience, and energy security. All substantive items were measured using a five-point Likert scale ranging from 1, indicating “strongly disagree,” to 5, indicating “strongly agree.” Higher scores represented higher levels of the corresponding construct. The questionnaire was developed through a comprehensive review of the theoretical and empirical literature on renewable energy development, energy security, energy-source diversification, and supply-chain resilience. The initial item pool was also informed by established conceptual frameworks used in energy policy, sustainability, strategic management, and supply-chain studies. The wording of the items was adapted to the institutional and economic conditions of the Iranian energy sector.

Renewable energy development was operationalized as the extent to which renewable energy sources had been expanded, institutionalized, and integrated into the national and organizational energy system. The items assessed the growth of renewable electricity-generation capacity, investment in renewable energy infrastructure, access to advanced renewable technologies, policy and regulatory support, incentives for private-sector participation, development of technical expertise, integration of renewable resources into the electricity grid, and long-term commitment to reducing dependence on conventional fossil fuels. This construct reflected not only the physical expansion of renewable energy projects but also the institutional, technological, financial, and regulatory conditions required for their sustainable development.

Energy portfolio diversification was measured as the degree to which different energy sources, technologies, suppliers, and geographical channels were incorporated into the energy system to reduce excessive dependence on a limited number of resources. The relevant items evaluated the balance between fossil fuels and renewable sources, the use of multiple renewable technologies, the dispersion of energy-generation facilities, the diversity of energy suppliers, the availability of alternative sources during periods of disruption, and the flexibility of the energy mix in response to economic, political, technological, or environmental changes. Higher scores on this construct indicated that the energy system was less concentrated and more capable of replacing one energy source or supply channel with another when necessary.

Supply chain resilience was defined as the capacity of the energy supply chain to anticipate, absorb, respond to, recover from, and adapt to disruptive events. The corresponding items examined supplier flexibility, availability of alternative procurement sources, strategic storage capacity, infrastructure redundancy, domestic production capabilities, logistics flexibility, information-sharing mechanisms, risk-monitoring systems, coordination among supply-chain actors, emergency response capabilities, and the speed at which energy-related operations could return to normal following a disruption. The construct covered both short-term operational recovery and long-term adaptive capacity. Higher scores represented stronger preparedness for supply interruptions, geopolitical shocks, equipment shortages, transportation problems, natural hazards, cyber incidents, price volatility, and technological failures.

Energy security was operationalized as the ability of the energy system to provide adequate, reliable, affordable, accessible, and environmentally sustainable energy while remaining resistant to internal and external disruptions. The items assessed continuity of supply, stability of energy availability, affordability of energy services, reduction of import dependence, capacity to respond to peak demand, protection against supply interruptions, adaptability to geopolitical and market changes, environmental sustainability, and the long-term adequacy of energy resources and infrastructure. Energy security was therefore treated as a multidimensional construct encompassing availability, accessibility, affordability, reliability, resilience, and sustainability rather than merely the uninterrupted physical supply of energy.

The initial questionnaire was submitted to a panel of 12 experts in renewable energy, energy economics, energy policy, strategic management, and supply-chain management to evaluate its content validity. The experts assessed the relevance, clarity, necessity, comprehensiveness, and appropriateness of each item. Their recommendations were used to revise ambiguous expressions, remove repetitive items, and improve the conceptual coverage of the constructs. The content validity ratio and content validity index were calculated to confirm the necessity and relevance of the items. Items that did not meet the acceptable validity criteria were revised or removed. Face validity was subsequently evaluated through interviews with 15 members of the target population, who examined the clarity, readability, comprehensibility, and completion time of the questionnaire.

A pilot study was conducted with 40 energy-sector professionals who met the inclusion criteria but were not included in the final sample. The pilot data were used to evaluate the internal consistency and preliminary psychometric properties of the instrument. Cronbach’s alpha and composite reliability were calculated for each construct, with values of 0.70 or higher considered acceptable. Convergent validity was assessed using standardized factor loadings and average variance extracted. Factor loadings above 0.70 were considered desirable, although loadings between 0.40 and 0.70 were retained when their removal did not significantly improve composite reliability or average variance extracted and when the items were theoretically important. An average variance extracted value of at least 0.50 was regarded as evidence that the construct explained an adequate proportion of the variance in its indicators. Discriminant validity was evaluated using the Fornell–Larcker criterion, cross-loadings, and the heterotrait–monotrait ratio. Heterotrait–monotrait values below 0.85 were considered indicative of adequate distinction among the latent variables.

The collected data were analyzed using IBM SPSS Statistics version 27 and SmartPLS version 4. SPSS was used for data screening, coding, descriptive statistics, examination of missing values, identification of univariate outliers, and preliminary assessment of the distribution of the variables. The demographic and professional characteristics of the participants were summarized using frequencies, percentages, means, and standard deviations. The mean, standard deviation, minimum, maximum, skewness, and kurtosis were calculated for the principal research variables. Absolute skewness values below 3 and absolute kurtosis values below 10 were considered acceptable for subsequent multivariate analysis. Missing data were examined before the principal analysis. Questionnaires with substantial missing responses were excluded, whereas isolated missing values were addressed using appropriate statistical imputation procedures when the proportion of missing data was negligible and the pattern was considered random.

Potential multicollinearity among the predictor variables was examined using tolerance values and variance inflation factors. Tolerance values greater than 0.20 and variance inflation factor values below 5 were interpreted as evidence that multicollinearity did not threaten the stability of the estimated coefficients. Harman's single-factor test and full collinearity assessment were used to examine the possibility of common method variance resulting from the self-report and cross-sectional nature of the data. Common method bias was considered unlikely when no single factor explained the majority of the total variance and when the full collinearity variance inflation factor values remained below the recommended threshold.

Partial least squares structural equation modeling was used to test the measurement and structural models. This method was selected because the research model involved multiple latent constructs, simultaneous mediation pathways, and a prediction-oriented assessment of energy security. The analysis was conducted in two successive stages. In the first stage, the measurement model was evaluated by examining indicator reliability, internal consistency reliability, convergent validity, and discriminant validity. Indicator reliability was assessed using standardized outer loadings. Internal consistency was examined through Cronbach's alpha, rho_A, and composite reliability. Values between 0.70 and 0.95 were considered acceptable. Convergent validity was established when the average variance extracted for each construct was at least 0.50. Discriminant validity was assessed through the Fornell–Larcker criterion and the heterotrait–monotrait ratio. Under the Fornell–Larcker criterion, the square root of the average variance extracted for each construct was required to exceed its correlations with the other constructs. Heterotrait–monotrait values below 0.85 were considered evidence of strict discriminant validity, while values below 0.90 were considered acceptable for conceptually related constructs.

In the second stage, the structural model was evaluated by examining collinearity, standardized path coefficients, coefficients of determination, effect sizes, predictive relevance, and overall model fit. The direct effect of renewable energy development on energy security was tested together with its effects on energy portfolio diversification and supply chain resilience. The effects of energy portfolio diversification and supply chain resilience on energy security were also examined. The coefficient of determination was used to assess the proportion of variance explained in each endogenous construct. Values of approximately 0.25, 0.50, and 0.75 were interpreted as weak, moderate, and substantial explanatory power, respectively, while recognizing that interpretation depends on the theoretical and empirical context of energy-policy research. The effect size statistic was used to determine the contribution of each exogenous variable to the explained variance of the endogenous constructs. Values of 0.02, 0.15, and 0.35 were interpreted as small, medium, and large effects, respectively.

Predictive relevance was examined using the blindfolding procedure. A cross-validated redundancy value greater than zero indicated that the model possessed predictive relevance for the corresponding endogenous construct. The model's out-of-sample predictive capacity was additionally assessed through the PLSpredict procedure by comparing the prediction errors of the partial least squares model with those of a linear benchmark model. The standardized root mean square residual was used as an approximate index of model fit, with values below 0.08 regarded as indicative of an acceptable fit between the empirical data and the proposed model.

The statistical significance of the direct, indirect, and total effects was evaluated using a nonparametric bootstrapping procedure with 5,000 resamples. Path coefficients were considered statistically significant when the corresponding t values exceeded 1.96 and the p values were below 0.05 in two-tailed tests. Bias-corrected 95% confidence intervals were also calculated. An effect was regarded as statistically significant when the confidence interval did not contain zero. The mediating roles of energy portfolio diversification and supply chain resilience were assessed by estimating the specific indirect effect of renewable energy development on energy security through each mediator. The total indirect effect was also calculated to determine the combined mediating contribution of the two variables.

The type of mediation was determined by simultaneously examining the significance and direction of the direct and indirect effects. Full mediation was inferred when the indirect effect was significant but the direct effect became nonsignificant after the mediators were included in the model. Partial mediation was inferred when both the direct and indirect effects remained significant. Complementary mediation was identified when the direct and indirect effects were significant and had the same direction, whereas competitive mediation was identified when the significant direct and indirect effects had opposite directions. The variance accounted for statistic was used as a supplementary indicator of mediation strength by calculating the ratio of the indirect effect to the total effect. Values below 20% were interpreted as indicating little or no mediation, values between 20% and 80% as partial mediation, and values above 80% as substantial or full mediation. All statistical tests were conducted at a significance level of 0.05.

3. Findings and Results

The final analysis was conducted using data obtained from 384 managers, experts, researchers, policymakers, consultants, and technical specialists working in energy-related organizations in Tehran. Of the participants, 252 individuals were male, representing 65.6% of the sample, and 132 were female, representing 34.4%. Regarding age, 72 participants, or 18.8%, were between 25 and 34 years old, 155 participants, or 40.4%, were between 35 and 44 years old, 111 participants, or 28.9%, were between 45 and 54 years old, and 46 participants, or 12.0%, were 55 years old or older. Therefore, the largest proportion of the respondents belonged to the 35–44-year age group, indicating that the sample was predominantly composed of professionals in the middle stages of their careers. In terms of educational attainment, 74 participants, equivalent to 19.3%, held a bachelor's degree, 202 participants, equivalent to 52.6%, held a master's degree, and 108 participants, equivalent to 28.1%, held a doctoral degree. Thus, more than four-fifths of the respondents possessed postgraduate qualifications, which supported their capacity to evaluate the technical, economic, managerial, and policy-related dimensions of renewable energy development and energy security.

With respect to organizational affiliation, 142 respondents, representing 37.0% of the sample, were employed in governmental organizations or public energy institutions, 96 respondents, representing 25.0%, worked in private energy companies, 88 respondents, representing 22.9%, were affiliated with universities or research centers, and 58 respondents, representing 15.1%, worked in consulting firms, professional associations, or other energy-related organizations. Regarding professional experience, 77 participants, or 20.1%, had between 3 and 5 years of relevant experience, 131 participants, or 34.1%, had between 6 and 10 years of experience, 102 participants, or 26.6%, had between 11 and 15 years of experience, and 74 participants, or 19.3%, had more than 15 years of experience. The mean professional experience of the participants was 10.84 years, with a standard deviation of 5.91 years. These characteristics demonstrated that the sample included respondents from diverse institutional sectors and that the majority had substantial academic qualifications and professional experience in renewable energy, energy planning, energy policy, electricity generation, energy economics, infrastructure management, or supply-chain activities.

Before evaluating the measurement and structural models, the data were screened for missing values, unusual response patterns, outliers, and distributional problems. The 13 questionnaires removed during the data-screening stage were excluded because they contained substantial missing information or repetitive response patterns. In the retained dataset, the proportion of missing values for individual items was less than 1%, and the remaining isolated missing values were replaced using the expectation-maximization method. Examination of standardized scores did not reveal any problematic univariate outliers exceeding the absolute value of 3.29. The absolute values of skewness ranged from 0.24 to 0.61, while the absolute values of kurtosis ranged from 0.18 to 0.73, indicating that the distributions of the main study variables did not display severe departures from normality. Variance inflation factor values for the predictor constructs ranged from 1.74 to 2.31, which were considerably below the threshold of 5 and indicated the absence of problematic multicollinearity. Harman's single-factor analysis showed that the first unrotated factor explained 37.64% of the total variance, which was below the 50% threshold. In addition, the full-collinearity variance inflation factor values were below 3.3. These findings suggested that common method variance was unlikely to represent a serious threat to the interpretation of the results.

Table 1. Descriptive Statistics and Correlations Among the Main Study Variables

Variable	Mean	Standard Deviation	Minimum	Maximum	Skewness	Kurtosis	1	2	3	4
Renewable energy development	3.68	0.65	1.71	5.00	−0.48	0.41	1.00			
Energy portfolio diversification	3.54	0.69	1.50	5.00	−0.36	0.18	0.63***	1.00		
Supply chain resilience	3.61	0.66	1.67	5.00	−0.24	−0.29	0.59***	0.54***	1.00	
Energy security	3.72	0.63	1.75	5.00	−0.61	0.73	0.67***	0.65***	0.68***	1.00

As presented in Table 1, the mean scores of all four research constructs were above the theoretical midpoint of 3.00, indicating that the respondents generally evaluated renewable energy development, energy portfolio diversification, supply chain resilience, and energy security at moderately favorable levels. Energy security obtained the highest mean score at 3.72, followed by renewable energy development at 3.68, supply chain resilience at 3.61, and energy portfolio diversification at 3.54. Although all constructs were evaluated above the scale midpoint, energy portfolio diversification received the lowest mean, suggesting that the diversity of energy sources, suppliers, technologies, and supply channels was perceived as relatively less developed than the other dimensions. The standard deviations ranged from 0.63 to 0.69, demonstrating an acceptable degree of variation in the participants' evaluations without evidence of excessive dispersion. The skewness and kurtosis coefficients were within acceptable limits and indicated no substantial univariate distributional problems.

The correlation analysis showed that renewable energy development was positively and significantly correlated with energy portfolio diversification, $r = 0.63$, $p < 0.001$, supply chain resilience, $r = 0.59$, $p < 0.001$, and energy security, r = 0.67, $p < 0.001$. Energy portfolio diversification was also positively correlated with supply chain resilience, r = 0.54, $p < 0.001$, and energy security, r = 0.65, $p < 0.001$. Furthermore, supply chain resilience demonstrated the strongest bivariate relationship with energy security, r = 0.68, $p < 0.001$. These findings provided preliminary support for the proposed theoretical relationships. However, none of the correlations exceeded 0.80, which indicated that the constructs were related but empirically distinguishable and that multicollinearity was not likely to compromise the structural model estimates.

Table 2. Assessment of the Reliability and Convergent Validity of the Measurement Model

Construct	Number of Retained Items	Standardized Loading Range	Cronbach's Alpha	rho_A	Composite Reliability	Average Variance Extracted
Renewable energy development	8	0.72–0.86	0.91	0.92	0.93	0.62
Energy portfolio diversification	6	0.71–0.85	0.88	0.89	0.91	0.63
Supply chain resilience	9	0.70–0.87	0.92	0.93	0.94	0.63
Energy security	8	0.73–0.88	0.92	0.92	0.94	0.65

Table 2 presents the evaluation of indicator reliability, internal consistency, and convergent validity. Following the initial assessment of the measurement model, three items with standardized loadings below 0.60 were removed because their exclusion improved the internal consistency and convergent validity of the corresponding constructs without reducing their conceptual coverage. The final measurement model consisted of 31 indicators. Standardized factor loadings ranged from 0.70 to 0.88, and all retained indicators exceeded the minimum acceptable loading of 0.70. Bootstrapping analysis further indicated that all outer loadings were statistically significant at $p < 0.001$. These results demonstrated that each retained indicator explained a satisfactory proportion of the variance in its corresponding latent construct.

Cronbach's alpha coefficients ranged from 0.88 for energy portfolio diversification to 0.92 for both supply chain resilience and energy security. The rho_A coefficients ranged from 0.89 to 0.93, while composite reliability values ranged from 0.91 to 0.94. All reliability coefficients exceeded the recommended minimum of 0.70 and remained below 0.95, indicating strong internal consistency without evidence of item redundancy. The average variance extracted values ranged from 0.62 to 0.65, exceeding the recommended threshold of 0.50 for all constructs. Thus, each latent variable explained more than half of the variance in its indicators. Collectively, the factor-loading, reliability, and average variance extracted results confirmed the indicator reliability, internal consistency reliability, and convergent validity of the measurement model.

Table 3. Discriminant Validity Based on the Fornell–Larcker Criterion and Heterotrait–Monotrait Ratios

Construct	Renewable Energy Development	Energy Portfolio Diversification	Supply Chain Resilience	Energy Security
Renewable energy development	0.787	0.704	0.658	0.742
Energy portfolio diversification	0.630	0.794	0.612	0.734
Supply chain resilience	0.590	0.540	0.794	0.758
Energy security	0.670	0.650	0.680	0.806

Table 3 reports the results of the discriminant validity assessment. According to the Fornell–Larcker criterion, the square root of the average variance extracted for renewable energy development was 0.787, which was greater than its correlations with energy portfolio diversification, supply chain resilience, and energy security. Similarly, the square root of the average variance extracted was 0.794 for energy portfolio diversification, 0.794 for supply chain resilience, and 0.806 for energy security. In each case, the diagonal value exceeded the correlations between the corresponding construct and the other latent variables. These results indicated that every construct shared more variance with its own indicators than with any other construct included in the model.

The heterotrait–monotrait ratios ranged from 0.612 to 0.758. The highest ratio was observed between supply chain resilience and energy security at 0.758, while the lowest ratio was found between energy portfolio diversification and supply chain resilience at 0.612. All heterotrait–monotrait values were below the conservative threshold of 0.85. In addition, the bootstrapped 95% confidence intervals for the heterotrait–monotrait ratios did not include 1.00. Therefore, the four constructs demonstrated sufficient empirical distinctiveness. The combined evidence obtained from the Fornell–Larcker criterion, heterotrait–monotrait ratios, and examination of cross-loadings confirmed the discriminant validity of the measurement model and supported proceeding to the evaluation of the structural relationships.

Table 4. Results of the Structural Model and Direct-Effect Hypothesis Testing

Structural Relationship	Path Coefficient	Standard Error	t Value	p Value	95% Confidence Interval	Effect Size
Renewable energy development → Energy portfolio diversification	0.631	0.038	16.605	<0.001	[0.554, 0.701]	0.661
Renewable energy development → Supply chain resilience	0.587	0.041	14.317	<0.001	[0.503, 0.663]	0.527
Renewable energy development → Energy security	0.238	0.047	5.064	<0.001	[0.145, 0.329]	0.083
Energy portfolio diversification → Energy security	0.284	0.046	6.174	<0.001	[0.194, 0.374]	0.126
Supply chain resilience → Energy security	0.387	0.044	8.795	<0.001	[0.299, 0.472]	0.235

Endogenous Construct	R^2	Adjusted R^2	Q^2 Predictive Relevance
Energy portfolio diversification	0.398	0.396	0.269
Supply chain resilience	0.345	0.343	0.231
Energy security	0.645	0.642	0.443

As shown in Table 4, all hypothesized direct relationships were positive and statistically significant. Renewable energy development had a strong positive effect on energy portfolio diversification, $\beta = 0.631$, $t = 16.605$, $p < 0.001$. The confidence interval for this effect ranged from 0.554 to 0.701 and did not include zero. The corresponding effect size was 0.661, representing a large effect. This result indicated that greater development of renewable energy capacity, technology, infrastructure, investment, institutional support, and grid integration was associated with a substantial increase in the diversity of energy resources, technologies, suppliers, and geographical supply channels.

Renewable energy development also exerted a strong positive effect on supply chain resilience, $\beta = 0.587$, $t = 14.317$, $p < 0.001$. Its 95% confidence interval ranged from 0.503 to 0.663, while its effect size was 0.527, indicating a large contribution to the explanatory power of the supply chain resilience construct. This finding showed that the expansion and institutionalization of renewable energy could strengthen alternative sourcing opportunities, domestic technological capabilities, infrastructure redundancy, procurement flexibility, and the capacity of the energy supply chain to absorb and recover from disruptions.

The direct effect of renewable energy development on energy security was also statistically significant, $\beta = 0.238$, $t = 5.064$, $p < 0.001$. The confidence interval ranged from 0.145 to 0.329, confirming the stability of the positive relationship. The effect size was 0.083, which represented a small-to-moderate direct contribution after the two mediators had been entered into the model. This coefficient indicated that renewable energy development directly improved energy security by increasing the availability, reliability, sustainability, and domestic accessibility of energy. Nevertheless, the reduction in the magnitude of this direct path relative to the corresponding zero-order correlation suggested that a considerable portion of the relationship operated through energy portfolio diversification and supply chain resilience.

Energy portfolio diversification had a positive and statistically significant effect on energy security, $\beta = 0.284$, $t = 6.174$, $p < 0.001$. This relationship had a 95% confidence interval of 0.194 to 0.374 and an effect size of 0.126, indicating a small-to-moderate substantive effect. Accordingly, increasing the variety of energy sources, technologies, suppliers, geographical locations, and procurement channels enhanced the energy system's ability to respond to fluctuations in availability, demand, prices, geopolitical conditions, and environmental constraints.

Supply chain resilience produced the strongest direct effect on energy security among the variables entered simultaneously into the final energy-security equation, $\beta = 0.387$, $t = 8.795$, $p < 0.001$. Its confidence interval extended from 0.299 to 0.472, while the effect size was 0.235, representing a moderate effect. This result demonstrated that energy security depended substantially on the ability of the energy supply chain to anticipate disturbances, maintain critical operations, access alternative suppliers, mobilize strategic reserves, coordinate responses, and restore normal performance after disruptions.

Renewable energy development explained 39.8% of the variance in energy portfolio diversification and 34.5% of the variance in supply chain resilience. The combined effects of renewable energy development, energy portfolio diversification, and supply chain resilience explained 64.5% of the variance in energy security, representing substantial explanatory power. The adjusted coefficient of determination for energy security was 0.642, which was only slightly lower than the unadjusted value and suggested that the model's explanatory capacity was not artificially inflated by the number of predictors. The cross-validated redundancy values were positive for all three endogenous constructs, with Q^2 values of 0.269 for energy portfolio diversification, 0.231 for supply chain resilience, and 0.443 for energy security. These values confirmed that the structural model possessed meaningful predictive relevance, particularly for the principal dependent variable of energy security.

The model also demonstrated acceptable approximate fit. The standardized root mean square residual was 0.061, which was below the recommended threshold of 0.08. The normed fit index was 0.913, indicating an acceptable correspondence between the proposed model and the observed data. The root mean square residual covariance was 0.097, and the discrepancy measures for the estimated model were below their bootstrapped 95% upper confidence limits. These findings supported the overall adequacy of the proposed structural model.

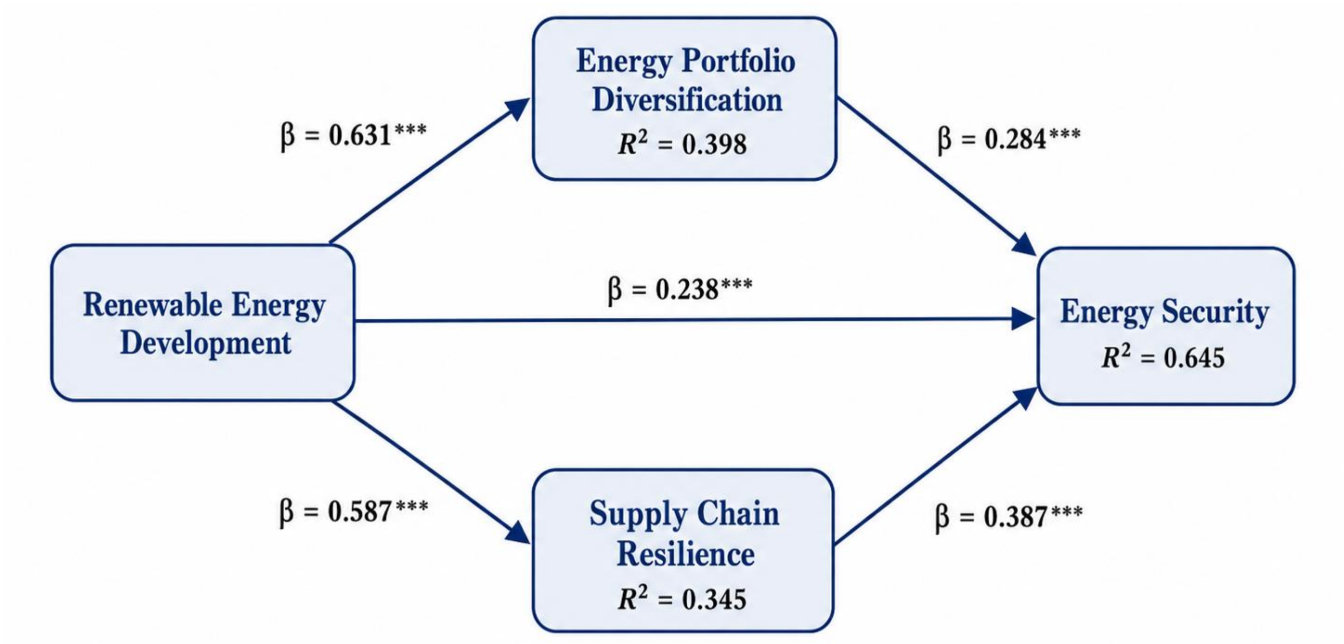

Figure 1. Final Structural Model of the Relationships Among Renewable Energy Development, Energy Portfolio Diversification, Supply Chain Resilience, and Energy Security

Figure 1 presents the standardized coefficients of the final structural model. The model illustrates that renewable energy development influenced energy security through three complementary pathways. The first pathway was the direct relationship between renewable energy development and energy security, with a standardized coefficient of 0.238. The second pathway operated through energy portfolio diversification, in which renewable energy development predicted diversification with a coefficient of 0.631 and diversification subsequently predicted energy security with a coefficient of 0.284. The third pathway operated through supply chain resilience, in which renewable energy development predicted resilience with a coefficient of 0.587 and resilience predicted energy security with a coefficient of 0.387. All displayed paths were statistically significant at $p < 0.001$. The figure also indicates that 39.8% of the variance in energy portfolio diversification, 34.5% of the variance in supply chain resilience, and 64.5% of the variance in energy security were explained by the model. The relative magnitude of the coefficients showed that supply chain resilience represented the stronger of the two mediating mechanisms, although both mediators made meaningful and statistically significant contributions to the relationship between renewable energy development and energy security.

Table 5. Bootstrapping Results for the Mediating Effects of Energy Portfolio Diversification and Supply Chain Resilience

Indirect Relationship	Indirect Effect	Standard Error	t Value	p Value	95% Confidence Interval	Variance Accounted For	Mediation Interpretation
Renewable energy development → Energy portfolio diversification → Energy security	0.179	0.033	5.424	<0.001	[0.118, 0.248]	27.8%	Complementary partial mediation
Renewable energy development → Supply chain resilience → Energy security	0.227	0.034	6.676	<0.001	[0.164, 0.298]	35.2%	Complementary partial mediation
Total indirect effect	0.406	0.049	8.286	<0.001	[0.314, 0.505]	63.0%	Substantial partial mediation

Direct effect after inclusion of mediators	0.238	0.047	5.064	<0.001	[0.145, 0.329]	37.0%	Direct effect remained significant
Total effect of renewable energy development on energy security	0.644	0.035	18.400	<0.001	[0.571, 0.708]	100.0%	Strong total effect

Table 5 reports the results of the mediation analysis based on 5,000 bootstrap resamples. The specific indirect effect of renewable energy development on energy security through energy portfolio diversification was positive and statistically significant, $\beta = 0.179$, $t = 5.424$, $p < 0.001$. The bootstrapped 95% confidence interval ranged from 0.118 to 0.248 and did not contain zero. Therefore, energy portfolio diversification significantly mediated the relationship between renewable energy development and energy security. The variance accounted for by this specific indirect pathway was 27.8%, indicating that more than one-quarter of the total effect of renewable energy development on energy security was transmitted through the diversification of energy sources, technologies, suppliers, and procurement channels.

The indirect effect through supply chain resilience was also positive and statistically significant, $\beta = 0.227$, $t = 6.676$, $p < 0.001$. Its bootstrapped confidence interval ranged from 0.164 to 0.298. This indirect effect was larger than the indirect effect through energy portfolio diversification, indicating that supply chain resilience represented the stronger mediating mechanism in the model. The variance accounted for by this pathway was 35.2%, demonstrating that more than one-third of the total relationship between renewable energy development and energy security was explained by improvements in the energy supply chain's preparedness, flexibility, absorptive capacity, recovery speed, and adaptive capability.

The combined indirect effect through both mediators was 0.406 and was statistically significant, $t = 8.286$, $p < 0.001$. The confidence interval for the total indirect effect ranged from 0.314 to 0.505 and excluded zero. The direct effect of renewable energy development on energy security remained statistically significant after the inclusion of energy portfolio diversification and supply chain resilience, $\beta = 0.238$, $p < 0.001$. The total effect was 0.644, indicating a strong overall positive influence of renewable energy development on energy security. The combined variance accounted for by the two mediators was 63.0%, while the remaining 37.0% of the total effect was attributable to the direct pathway.

Because the direct effect and both indirect effects were statistically significant and operated in the same positive direction, the mediation pattern was classified as complementary partial mediation. Therefore, the expansion of renewable energy did not improve energy security solely through its immediate contribution to energy availability, sustainability, or reduced fossil-fuel dependence. A substantial portion of its influence occurred because renewable energy development increased the diversity of the energy portfolio and strengthened the resilience of the energy supply chain. At the same time, the persistence of a significant direct effect demonstrated that renewable energy development continued to influence energy security through additional mechanisms not fully captured by the two mediators, such as reduced exposure to international fuel-price volatility, greater domestic energy production, technological innovation, environmental sustainability, distributed generation, and improved long-term adequacy of energy resources.

To compare the relative strengths of the two mediating pathways, the difference between the specific indirect effects was calculated. The indirect effect through supply chain resilience exceeded the effect through energy portfolio diversification by 0.048. Bootstrapping showed that this difference was statistically significant, with a 95% confidence interval ranging from 0.011 to 0.091 and $p = 0.014$. Accordingly, although both variables transmitted a significant portion of the effect of renewable energy development on energy security, strengthening supply chain resilience appeared to be a relatively more influential pathway. This finding suggested that the contribution of renewable energy to energy security depended not only on increasing the number and variety of energy sources but also on ensuring that the equipment, technologies, materials, logistics networks, suppliers, maintenance capacities, storage systems, and institutional coordination required for renewable energy production could withstand and recover from disruptions.

The PLSpredict analysis provided further evidence regarding the model's predictive performance. For the majority of the energy-security indicators, the root mean squared prediction errors generated by the partial least squares model were lower than those generated by the linear regression benchmark. The Q^2_predict values for all energy-security indicators were greater than zero and ranged from 0.281 to 0.417. These results demonstrated medium-to-high out-of-sample predictive power. Therefore, the proposed model was not only capable of explaining the observed relationships in the study sample but also showed acceptable potential for predicting energy-security evaluations in comparable groups of energy-sector professionals.

Overall, the results supported all proposed relationships in the conceptual model. Renewable energy development significantly increased energy portfolio diversification and supply chain resilience and directly improved energy security. Energy portfolio diversification and supply chain resilience each exerted independent positive effects on energy security and significantly mediated the effect of renewable energy development. Supply chain resilience emerged as the strongest immediate predictor of energy security and the stronger of the two mediators. The substantial coefficient of determination for energy security, the positive predictive-relevance values, the acceptable approximate model-fit indices, and the statistically significant direct and indirect effects collectively demonstrated that the proposed model provided a strong explanation of how renewable energy development contributed to energy security among energy-sector organizations and professionals in Tehran.

4. Discussion and Conclusion

The present study examined the effect of renewable energy development on energy security and assessed the mediating roles of energy portfolio diversification and supply chain resilience among energy-sector professionals in Tehran. The findings showed that renewable energy development had a positive and statistically significant direct effect on energy security. Renewable energy development also significantly predicted energy portfolio diversification and supply chain resilience, while both mediating variables exerted significant positive effects on energy security. Furthermore, the indirect effects through energy portfolio diversification and supply chain resilience were statistically significant, confirming complementary partial mediation. Supply chain resilience emerged as the stronger mediator and the strongest direct predictor of energy security in the final structural model. Together, renewable energy development, energy portfolio diversification, and supply chain resilience explained a substantial proportion of the variance in energy security, indicating that the proposed model provided a strong account of the mechanisms through which renewable energy development may reinforce the security of the energy system.

The first major finding was that renewable energy development directly enhanced energy security. This result indicates that expanding renewable generation capacity, investing in renewable infrastructure, improving technological capabilities, supporting grid integration, and establishing favorable institutional and regulatory conditions can strengthen the availability, reliability, affordability, and sustainability of energy supply. Renewable technologies can reduce dependence on a limited range of fossil fuels and create domestic alternatives to imported or externally vulnerable energy resources. This interpretation is consistent with evidence showing that renewable-energy action plans can improve national energy outcomes when they are implemented through coherent policy and institutional frameworks [6]. It also accords with the post-crisis experience of the European Union, where accelerated renewable-energy development became a central strategy for reducing dependence on external fossil-fuel supplies and improving long-term energy autonomy [5].

The positive direct relationship also reflects the capacity of renewable energy to decentralize generation and reduce the exposure of the energy system to disruptions affecting large conventional facilities or imported fuel routes. Solar, wind, biomass, geothermal, and small-scale hydropower installations can distribute energy production across different locations and provide alternative sources during periods of supply stress. The findings are therefore aligned with studies emphasizing renewable energy as a critical element of sustainable energy governance, climate policy, and national energy independence [16]. They also support the argument that renewable energy can contribute to more affordable and accessible energy transitions when supported by suitable technologies, storage systems, mini-grids, and investment structures [7]. In this sense, renewable energy development strengthens energy security not only by adding generation capacity but also by altering the spatial, technological, and institutional configuration of the energy system.

Nevertheless, the relatively smaller direct path from renewable energy development to energy security after the mediators were included suggests that renewable capacity alone is insufficient. The security benefits of renewable energy depend substantially on whether development produces broader structural transformations. This interpretation is compatible with research showing that countries possessing large energy-resource endowments may still experience energy insecurity when infrastructure, institutional coordination, financing, and implementation capacities remain inadequate [2]. Similarly, the challenges observed in South Africa indicate that renewable-energy potential does not automatically translate into a secure transition when grid limitations, financing barriers, and policy uncertainty constrain deployment [10]. Therefore, renewable-energy projects contribute most effectively to security when they form part of an integrated strategy involving diversification, infrastructure modernization, supply-chain planning, and institutional reform.

The second major finding was that renewable energy development strongly increased energy portfolio diversification. This result suggests that the expansion of renewable resources broadens the composition of the energy system by introducing new fuels, technologies, suppliers, geographical locations, and generation models. A diversified portfolio reduces dependence on a single resource and creates substitution possibilities when one component becomes unavailable, expensive, or technically unreliable. The finding is directly consistent with research demonstrating that diversification toward non-hydro renewable energy sources can improve energy security in developing countries by reducing excessive dependence on a narrow generation base [17]. It also supports evidence from Sri Lanka, where alternative energy sources have been identified as an important strategy for reducing conventional-energy dependence and improving sustainable energy availability [18].

Renewable energy development can generate diversification at several levels. At the resource level, it introduces solar, wind, biomass, geothermal, and other alternatives to oil and natural gas. At the technological level, it expands the range of generation, storage, conversion, and demand-management technologies. At the geographical level, it permits the distribution of energy production across areas with different climatic and resource characteristics. At the supplier level, it can enable the participation of private firms, regional producers, local communities, and distributed-energy operators. These mechanisms are consistent with research emphasizing differences in national specialization patterns in renewable-energy technologies and the importance of developing country-specific technological capabilities [22]. They also align with the argument that renewable energy can become a source of regional competitiveness when energy investment is linked to innovation, industrial development, and market diversification [23].

The significant positive effect of energy portfolio diversification on energy security further showed that a broader energy mix improves the capacity of the system to withstand economic, climatic, geopolitical, and operational shocks. When energy supply depends on several technologies and resources, disruption in one component can be partially compensated for by others. This is especially important where hydropower is exposed to rainfall variability, fossil fuels are subject to international price volatility, or imported components are vulnerable to political restrictions. The energy potential of agricultural biomass in the European Union illustrates how locally available resources can supplement existing energy systems, although their contribution depends on regional production and logistical capacity [19]. Similarly, regional geothermal integration in Eastern Africa demonstrates how cross-border cooperation and resource sharing can diversify electricity systems and strengthen sustainable development [20]. The present findings thus reinforce the view that diversification is a central mechanism connecting renewable-energy development with energy security.

The mediation analysis showed that energy portfolio diversification transmitted a significant part of the total effect of renewable energy development on energy security. This means that renewable energy improved security partly because it reduced the concentration of the energy portfolio. The result explains why merely increasing renewable capacity may produce limited security gains if development remains concentrated in one technology or region. For example, excessive dependence on hydropower can create vulnerability to drought, while overreliance on solar generation without adequate storage may expose the system to intermittency and peak-demand mismatches. Challenges associated with water-energy development in Aceh demonstrate that renewable resources may themselves be constrained by environmental, financial, and governance conditions [21]. Strategic energy planning must therefore balance different renewable and non-renewable options, storage capacity, grid flexibility, and potentially nuclear generation in accordance with national needs [4].

The third principal finding was that renewable energy development had a strong positive effect on supply chain resilience. This result indicates that renewable-energy expansion can promote alternative procurement channels, domestic production capabilities, technical learning, infrastructure redundancy, strategic storage, and coordination among energy-sector actors. As renewable industries develop, organizations may become better able to identify multiple suppliers, maintain essential components, and respond flexibly to disruptions. The result is aligned with research showing that resilient renewable-energy supply chains require supplier diversification, flexible contracting, inventory management, local sourcing, collaborative relationships, and risk-monitoring systems [25]. It is also consistent with the emphasis placed on local material availability and technological application in developing sustainable renewable-energy roadmaps [14].

The development of resilient renewable-energy supply chains is especially important because renewable technologies remain dependent on global networks for critical minerals, batteries, turbines, photovoltaic modules, electronic equipment, and specialized maintenance services. The availability of a renewable natural resource does not guarantee energy independence if the technologies required to exploit it are imported from a small number of foreign suppliers. The present finding therefore highlights the importance of combining renewable deployment with local manufacturing, technical education, maintenance capability, and strategic procurement. Reliability engineering can further strengthen this process through preventive maintenance, redundancy, failure prediction, and continuous monitoring of renewable-energy equipment [26]. Likewise, climate-oriented management of district-heating enterprises shows that resilient energy organizations require innovative resources and adaptive managerial capacity, rather than infrastructure investment alone [27].

Supply chain resilience also had the strongest direct effect on energy security among the predictors in the final model. This finding implies that the ability to anticipate, absorb, recover from, and adapt to disruptions is particularly important for maintaining secure energy services. Even a diversified energy system may remain vulnerable if spare parts are unavailable, logistical networks are disrupted, maintenance personnel are insufficient, or critical technologies depend on single-source procurement. Resilience allows the system to convert energy-resource diversity into sustained operational performance. This interpretation accords with research on the vulnerability of electricity grids and coal-dependent economies, which demonstrates that weak infrastructure and limited adaptive capacity can amplify the effects of energy shocks [3]. It is also compatible with broader assessments of energy security that emphasize the interaction of geopolitical dynamics, national policy, infrastructure, and institutional preparedness [1].

The stronger mediating effect of supply chain resilience compared with energy portfolio diversification suggests that the operational continuity of the energy system may be more decisive than the numerical diversity of its resources. Diversification creates alternatives, but resilience determines whether these alternatives can be mobilized effectively during disruption. For example, solar and wind technologies may broaden the energy mix, but their security contribution will remain limited if storage systems, grid connections, replacement components, or technical services are unavailable. The findings therefore support an integrated interpretation in which diversification provides structural options and resilience provides the capability to use those options under pressure. This distinction is especially important in contexts exposed to trade restrictions, currency volatility, financing constraints, and technological dependence.

The substantial total indirect effect found in the study confirms that most of the influence of renewable energy development on energy security occurred through these two mechanisms. This finding extends earlier studies that have often examined renewable-energy policy, energy diversification, or supply-chain challenges separately. Sustainable-energy transitions in Uganda, for instance, have been shown to depend on interacting institutional, technological, and investment conditions [11], while Malaysia's transition experience underscores the importance of coordinated policy, green investment, and innovation [12]. The present model integrates these perspectives by showing that renewable development improves security when it simultaneously changes the composition of the energy portfolio and strengthens the capacity of the supply chain to withstand disruption.

The findings also have implications for the socioeconomic and regional dimensions of energy transition. Renewable-energy development may contribute to energy security while creating new industries, employment opportunities, and regional development pathways. However, these outcomes require transition policies that address workers, communities, land use, and regional inequalities, particularly in fossil-fuel-dependent areas. Evidence from India's coal landscapes demonstrates the importance of aligning renewable-energy expansion with just-transition strategies and sustainable development objectives [13]. Renewable-energy investments must therefore be evaluated not only in terms of generating capacity but also according to their contribution to local capability, social stability, industrial diversification, and long-term resilience.

The findings further indicate that financial and policy decisions play a central role in translating renewable potential into security outcomes. Data-driven financial analysis can improve the selection and management of sustainable-energy investments, particularly where capital is limited and projects involve substantial uncertainty [28]. At the same time, developing countries face regulatory instability, fragmented institutions, limited access to finance, and technical capacity constraints that can weaken renewable-energy policies [29]. The positive relationships identified in this study should therefore not be interpreted as evidence that all renewable-energy investments automatically improve security. The quality of investment, institutional coordination, technology selection, and supply-chain design determines the extent of the resulting benefits.

The multidimensional nature of energy security also helps explain the strength of the proposed model. Renewable-energy development, portfolio diversification, and supply-chain resilience can simultaneously affect availability, affordability, reliability, environmental sustainability, and adaptability. Multi-index assessments of energy security and environmental sustainability emphasize that progress in one dimension does not necessarily guarantee progress in others [31]. Sectoral evidence from agriculture likewise shows that energy security depends on multiple technical, economic, and institutional indicators [30]. The present results support this multidimensional perspective by demonstrating that energy security is produced through an interconnected system of resources, technologies, institutions, and operational capabilities.

The study had several limitations that should be considered when interpreting its findings. First, the cross-sectional design prevented definitive causal conclusions, because all variables were measured at a single point in time. Second, the data were collected through self-report questionnaires, and the results may therefore have been influenced by respondents' perceptions, professional interests, or socially desirable answers. Third, the sample was restricted to energy-sector professionals in Tehran, which may limit the generalizability of the findings to other provinces, rural areas, operational facilities, or countries with different institutional and energy conditions. Fourth, the study examined two mediating variables, whereas other mechanisms, including technological innovation, energy storage capacity, regulatory quality, investment stability, grid modernization, and public acceptance, may also explain the relationship between renewable energy development and energy security. Finally, the model was based on perceptual measures rather than objective indicators such as outage duration, import dependence, generation costs, renewable capacity, supplier concentration, or recovery time following disruptions.

Future studies should employ longitudinal designs to examine how renewable-energy development, portfolio diversification, supply-chain resilience, and energy security change over time. Comparative research across provinces, countries, and different institutional settings would help determine whether the relationships found in this study remain stable under different economic, technological, and political conditions. Researchers should combine survey data with objective energy-system indicators and administrative records to reduce dependence on self-reported evaluations. Future models could also investigate additional mediators and moderators, including energy storage, regulatory quality, geopolitical risk, technological capability, domestic manufacturing, digital supply-chain visibility, investment stability, and organizational learning. Qualitative interviews with policymakers, investors, grid operators, and renewable-energy firms could provide deeper insight into the mechanisms underlying the statistical relationships. Finally, alternative structural models should examine possible reciprocal relationships, such as whether greater energy security itself stimulates additional renewable-energy investment.

Energy policymakers and organizational decision-makers should treat renewable-energy development as part of an integrated security strategy rather than as an isolated capacity-expansion program. Investments should be distributed across multiple renewable technologies and geographical areas to avoid replacing dependence on fossil fuels with dependence on a single renewable resource. Energy organizations should develop multiple supplier relationships, maintain strategic inventories of critical components, improve preventive maintenance, and establish emergency procurement and recovery procedures. Greater priority should be given to domestic manufacturing, technical training, energy storage, grid modernization, and digital monitoring of supply-chain risks. Public and private investment decisions should evaluate projects according to their contribution to diversification and resilience in addition to financial return and generating capacity. Coordination among governmental agencies, universities, private firms, grid operators, and research centers should also be strengthened so that renewable-energy expansion contributes to a reliable, adaptable, and secure national energy system.

Authors' Contributions

Authors equally contributed to this article.

Ethical Considerations

All procedures performed in this study were under the ethical standards.

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Conflict of Interest

The authors report no conflict of interest.

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