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Dimensionality reduction analysis of the renewable energy sector in Azerbaijan: nonparametric analyses of large datasets

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Abstract

Although the number of econometric analyses related to the renewable energy sector in Azerbaijan is increasing, studies on nonparametric dimensionality reduction are rather sparse. Principal component analysis (PCA) and multiple correspondence analysis (MCA) were chosen to fill this apparent research gap. As a result, a large dataset including the renewable energy sector and selected key macroeconomic indicators was evaluated. The PCA procedure yielded four distinct principle components reflecting the main macroeconomic variables, renewable energy production, industry-energy relations and natural resource revenues. The PCA method offers the possibility to examine the precise correlations and the underlying patterns between the displayed clusters of variables. Meanwhile, the MCA-based cross-country assessment of Azerbaijan's wind, solar and hydropower has struck somewhat pessimistic notes, as the country lags behind neighbouring and other post-Soviet countries (e.g. Estonia, Iran, Latvia, Russia) in developing its green energy sector. These findings are of great interest to policymakers, businesses and academics who wish to gain deep insight into the Azerbaijani economy in terms of renewable energy production. The practical value of the present work also lies in the fact that it analyses a multidimensional and relatively longitudinal dataset (1990–2022), which is an example of a methodological application of two nonparametric approaches.

Key words: Azerbaijani economy, energy transition, multiple correspondence analysis (MCA), nonparametric analysis, renewable energy, principal component analysis (PCA).

1. Introduction

Although developed nations lead the renewable energy, oil-rich countries are also keen to diversify their energy mix despite adoption barriers, including hydrocarbon subsidies, low electricity tariffs, fragmented policies, lack of renewable energy regulation and controlled electricity markets (Al-Sarihi and Mansouri, 2022). Azerbaijan is one of the oil-rich developing countries where renewable energy activities

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have recently increased due to new international agreements on the introduction of renewable energy technologies (Mehdiyev, 2022). Only hydropower generation is a well-founded field of alternative energy, which developed during the years of the Soviet Union, while solar and wind energy have experienced an upswing. As oil resources dwindle and global pressure for an energy transition increases, it is becoming increasingly important to understand the dynamics of the renewable energy sector. For this reason, the development of the renewable energy sector could provide additional opportunities to break away from oil dependence as the country's population grows and non-oil industrialization increases. Azerbaijan promises to be an interesting case study where there is tremendous potential for renewable energy development, while both the economic, political and institutional factors are unclear.

The objective of the current research is to examine the relationships and patterns between the renewable energy sector and various macroeconomic variables using principal component analysis (PCA) on the example of the Azerbaijani economy. The secondary research objective is to position Azerbaijan in comparison with selected Eurasian countries (both neighbouring and non-neighbouring) with respect to specific green energy sectors (e.g. wind, solar and hydropower) using multiple correspondence analysis (MCA). Both PCA and MCA allow for the identification of clusters of variables that share similar degrees of variance, a deeper understanding of the large dataset collected and a descriptive exploration of the qualitative nature of the energy transition. The research questions of this study are as follows: With which macroeconomic variables do the indicators for the renewable energy sector in Azerbaijan exhibit longitudinal covariance? What is the relative position of Azerbaijan in terms of specific renewable energy generation compared to the selected Eurasian countries (e.g. solar, wind, hydro)? Although the number of studies analysing the renewable energy sector in Azerbaijan is increasing, there are still research gaps that should be methodologically and empirically analysed in terms of the country's key macroeconomic variables and its position relative to other countries.

This paper contributes to the literature by systematically analysing the relationship between renewable energy and key macroeconomic variables in Azerbaijan between 1990 and 2022. By uncovering common trends and identifying clusters of variables, it provides insights into the complex dynamics and enables a comprehensive understanding of the dataset. It also clarifies which macroeconomic indicators correlate with renewable energy and assesses Azerbaijan's position on specific green energy sources. Furthermore, it provides a methodological exercise that serves as a benchmark study for future research with PCA and MCA.

The next section contains a literature review and the theoretical framework of the study. Section 3 explains the data and methodology, while Section 4 presents the results. Finally, conclusions are drawn in Section 5.

2. Literature review and theoretical framework

In general, scholars argue that Azerbaijan has many opportunities to improve its renewable electricity generation per capita (Vidadili et al., 2017), but this potential remains largely untapped due to slow technological improvements and unclear legal regulations (Mustafayev et al., 2022). With the adoption of the "State Program for the Utilization of Alternative and Renewable Energy Sources in the Republic of Azerbaijan," the Azerbaijani government has also shown its willingness to develop green energy and achieve a sustainable energy transition away from the fossil fuel-based economy (Hasanov, 2023). However, there are still numerous problems and challenges in the form of policy barriers, underdeveloped institutional mechanisms, weak regulations, limited storage capacity and an imbalance between supply and demand.

A large strand of emerging empirical studies (mainly parametric econometric methods) related to the renewable energy sector in Azerbaijan has been conducted by Mukhtarov et al. (2020), Huseynli and Huseynli (2022), Mukhtarov (2022), Kalyoncu et al. (2013), Huseynli (2022) and Hasanov et al. (2023). The general idea behind the above works is that it is possible to identify a casual relationship between economic growth, employment, production, financial development and renewable energy in Azerbaijan, indicating their importance for the national economic development agenda. Similarly, Guliyeva (2023) argued that a linear relationship exists between variables such as CO_2 emissions, energy consumption and economic growth in Azerbaijan using the ARDL method. Based on the same method, Acar et al. (2023) showed that economic growth and ecological footprint of Azerbaijan have an inverted U-shaped relationship with the environmental Kuznets curve. Acar et al. (2023) also claimed that financial development reduced the ecological footprint in Azerbaijan between 1996 and 2017. In addition, Mukhtarov and Aliyev (2022) claimed that institutional quality (represented by the variable government effectiveness) does not have a statistically significant impact on renewable energy production. The authors also pointed out that CO_2 emissions have a statistically insignificant relationship with renewable energy production.

Some studies, such as Ibadoghlu (2023; 2023), give a pessimistic outlook for the Azerbaijani renewable energy sector. They point to a decline in its share of total electricity generation and the reluctance of consumers and industry to adopt green energy technologies despite falling prices (Ibadoghlu, 2022). Although Azerbaijan is an energy exporter, the country is focusing on renewable energies and wants to increase their share of total energy production to 30% by 2030. This transition is in line with efforts to combat climate change and promote sustainable development (Mammadli, 2022).

Azerbaijan exhibits significant potential in renewable energy. The International Energy Agency (IEA, 2023) emphasizes its high potential for sustainable power generation and natural gas exports. Power generation capacity stood at 16% in 2018, expected to reach 30% by 2030 with energy market reforms. Technical potential is estimated at 3,000 MW for wind, 23,040 MW for solar, 380 MW for bio/waste energy, and 520 MW for small hydropower (IRENA, 2019).

Sound empirical research should be based on a solid, contemporary and effective theoretical foundation. For this reason, the theoretical framework of the present study is based on the metatheoretical framework proposed by Cherp et al. (2018), inspired by the contributions of Elionor Ostrom (2007, 2008). In simple terms, Cherp et al. (2018) claim that national energy transformations emerge through the interaction of three types of systems: techno-economic, socio-technical and political (see Figure 1). Techno-economic factors include energy markets that coordinate energy production, transformation, and ultimately production and consumption. Socio-technical aspects include the necessary knowledge, practices and networks that can be used in the energy transition. Finally, the political factors include the national energy-related policies that regulate and stimulate the energy transition. Cherp et al. (2018) point out that all of these three key aspects develop together and eventually lead to the energy transition. Therefore, capturing variables that cover these aspects both directly and indirectly (at least in the form of proxy variables) will provide unique insight into the research question at hand.

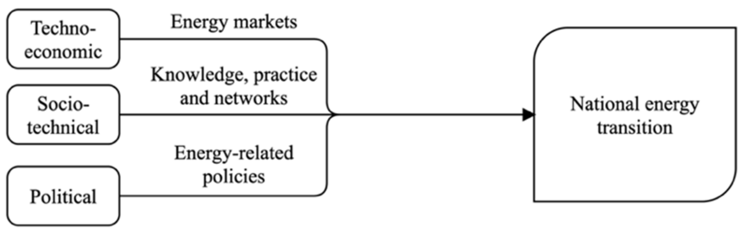

Figure 1: Theoretical framework of the current research
Source: Adapted from Cherp et al. (2018).

In the research design of the present study, due to the limited data available in the case of the Azerbaijani economy, it was not possible to consider every single aspect as precisely as Cherp et al. (2018) describe in their metatheoretical framework. Since the main objective of the work is to evaluate green energy from a multidimensional perspective, there were two major groups of variables, namely those related to renewable energy and economic variables. The latter were mainly formed considering the theoretical framework. For example, variables such as GDP, resource rents and oil rents were considered as techno-economic factors. Manufacturing value added, trade openness, etc. stood for the socio-technical dimension. Finally, institutional quality stands for the political aspects and is itself a composite index constructed for this study.

While additional details on the variables can be found in the Data and Methodology section, the theoretical model of the present study, which is guided by the literature review and theoretical framework, is based on the following motivation and rationale for the selection of variables: Following Mukhtarov et al. (2020), Huseynli and Huseynli (2022), Mukhtarov (2022), Kalyoncu et al. (2013), Huseynli (2022) and Hasanov et al. (2023), Ibadoghlu (2022; 2023), the variables of production, consumption, economic growth and industrial production were selected to measure their covariance with the renewable energy indicators. Similarly, following Acar et al. (2023) and other international publications (Jebli et al., 2020), CO_2 emission variables were collected to capture the environmental dimensions of the process, and institutional variables were developed as composite indices according to the discussion of Mukhtarov and Aliyev (2022) and Aydin (2019). Moreover, technological challenges, especially those related to technology transfer, highlights the inherent complexity associated with renewable energy technologies. By examining the role of technological change, the analysis can provide insights into overcoming barriers and transitioning to a more diversified and sustainable energy portfolio in Azerbaijan. For this reason, the index of technological change was also developed and included in this study.

Due to their immense importance and role in the Azerbaijani economy, oil and natural gas prices as well as economic structure variables (e.g. manufacturing, services, agriculture) and resource rents were also considered to examine their covariation with other variables in the PCA. Finally, the representation of the demand variable in its natural values typically refers to the total population of a given country. Therefore, both the total and urban population variables were included in the main list of variables.

3. Data and methodology

The phases of data analysis included data collection, data interpretation, data trimming, data analysis, clarification of the meaning of the results and overview of the PCA-based index values (see Figure 2). The data were collected from the World Bank, the State Statistical Committee of the Republic of Azerbaijan, etc. First, their descriptive statistics, normality and correlation analyses were performed to analyse the dataset descriptively (descriptive statistics is available upon request). Second, missing values were replaced and outlier values were trimmed (more on this later in this section). Third, PCA and MCA procedures were performed. Finally, the PCA-based index values were visualized. For this purpose, a total of 27 variables of interest were analysed, of which five are renewable energy related variables and 22 are macroeconomic variables covering the period between 1990 and 2022 for PCA. The period for MCA covers 2016–2022. The complete list of variables of interest, their definition, sources and abbreviations can be found in Table 1.

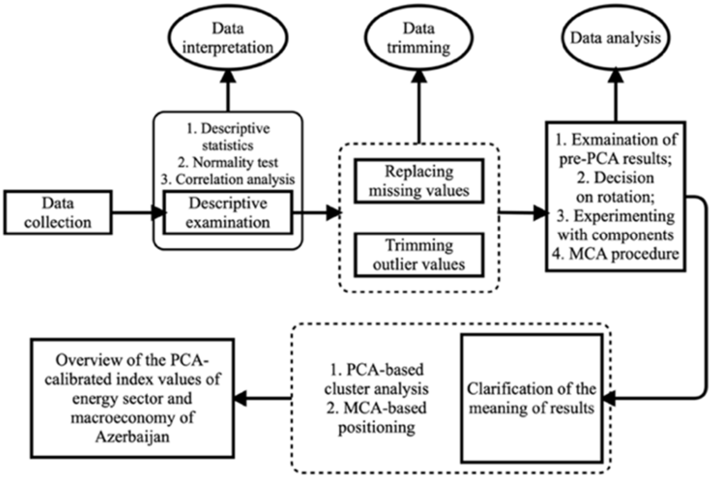

Figure 2: Conceptual framework of the data analysis process

Source: Author's own construction based on the research design.

Variables numbered from 1 to 4 represent renewable energy variables obtained from the Our World in Data platform. Starting from variable 6 onwards, the dataset comprises macroeconomic variables primarily sourced from the World Bank. Notably, two of these variables, namely TechCh and InsQ, are composite index variables specifically constructed for this study.

Table 1: List of the variables of interest used in principal component analysis

<table>
<tr><th>No.</th><th>Variable name</th><th>Abbreviation</th><th>Definition and measurement</th></tr>
<tr><td>1</td><td>Share of renewable energy in primary energy production</td><td>RenEn</td><td>Hydropower, solar energy, wind energy, geothermal energy, bioenergy, wave energy and tidal energy are categorized as renewable energy sources. Biofuels are not encompassed within these sources, in %.</td></tr>
<tr><td>2</td><td>Per capita electricity generated from renewable sources</td><td>RenElPc</td><td rowspan="2">Includes hydropower, solar energy, wind energy, geothermal energy, biomass, wave energy and tidal energy, constitutes the total of renewable electricity production, in kilowatt-hours.</td></tr>
<tr><td>3</td><td>Per capita consumption of renewable energy</td><td>ConRePc</td></tr>
<tr><td>4</td><td>Share of electricity from renewables</td><td>RenElShr</td><td>Production of electricity from hydropower, solar, wind, biomass and waste, geothermal, wave and tidal sources, in %.</td></tr>
</table>

Table 1: List of the variables of interest used in principal component analysis (cont.)

No.	Variable name	Abbreviation	Definition and measurement
5	Low-carbon energy consumption	LoCaEn	Low-carbon energy encompasses the aggregate of nuclear and renewable sources. Among the renewable sources are hydropower, solar energy, wind energy, geothermal energy, wave and tidal energy and bioenergy. Conventional biofuels are excluded from this categorization, in TWh – equivalent.
6	Oil prices	OilPr	USD per barrel, Brent trademark.
7	Natural gas prices	NatGasPr	Average German import price, in US dollars per megawatt-hour (MWh).
8	Total population	TotPop	The total population is determined using the de facto population definition, which includes all residents irrespective of their legal status or citizenship, in persons.
9	Urban population	UrPop	The total size of population living in urban areas, in persons.
10	Agriculture, forestry and fishing, value added	Agr	Economic structure variables. In other words, the percentage share of agriculture, forestry and fishing, industry, services and manufacturing value added in GDP, in %.
11	Industry (including construction), value added	Ind	
12	Services, value added	Serv	
13	Manufacturing, value added	Man	
14	Oil rents	OilRent	The difference between the value of total crude oil and production cost, in % of GDP.
15	Arable land	ArLand	Arable land refers to agricultural land that is suitable and utilized for growing crops. In hectares per person.
16	Consumer price index	CPI	in index values, 2010 = 100.
17	Foreign direct investment	FDI	net inflows, in % of GDP.
18	Gross Domestic Product	GDP	in current USD.
19	General government final consumption expenditure	GovExp	in % of GDP.
20	Gross capital formation	GrCapFor	
21	Trade openness	TrOpp	
22	Total natural resources rents	ResRents	

Table 1: List of the variables of interest used in principal component analysis (cont.)

No.	Variable name	Abbreviation	Definition and measurement
23	Energy use per person	EnUsPerPer	Energy use encompasses more than just electricity; it extends to various sectors of use, encompassing transportation, heating and cooking as well, in kilowatt-hours.
24	Per capita CO_2 emissions	CO_2Emm	Emissions of carbon dioxide (CO_2) originating from fossil fuels and industrial activities, excluding any effects resulting from changes in land use, in tons.
25	Primary energy consumption	PrEnCon	in terawatt-hours (TWh).
26	Technological change	TechCh	Principal component-based index value generated from the aggregation of four information communication variables, namely fixed telephone subscriptions, mobile cellular subscriptions, number of internet users and 4G network coverage.
27	Institutional quality	InsQ	Principal component-based index value generated from the aggregation of five variables, namely Human Rights Scores, Physical Integrity Rights Index, Private Civil Liberties Index, Political Civil Liberties and Individual Liberties and Equality Before the Law Index.

In general, there were only 12 missing values in the dataset, representing only 1.4% of the total observations (879 observations or data points in the 1990 and 2022 range from 27 variables). Some missing values were replaced by the mean of the series, while the missing values for the other variables were replaced by linearly interpolated values. The decision to use different methods to replace missing values depended on the relative position of the missing values—the beginning, middle or end of the time series.

The next part of the preliminary data analysis involved clarification of outlier values. The treatment of outliers in time series data is important because outliers can significantly distort the statistical properties and interpretation of the data in the PCA technique (Jolliffe and Cadima, 2016). Almost half of the 27 variables in the dataset had at least one outlier value in this study. To maintain data integrity, preserve statistical assumptions, minimize bias, achieve robustness, various methods and approaches (e.g. imputation of means, quantile-based flooring and capping, winsorization) were used to handle outliers. The decision was based on the location and frequency of outliers in time series.

The two main methods used in this work are PCA and MCA, both dimensionality reduction techniques that can be used to represent multivariate, large and longitudinal data in fewer—usually two or more—dimensions (Jolliffe, 2002). PCA is a multivariate technique that analyses datasets where observations are described by multiple correlating quantitative variables. Its goal is to extract the important information from the dataset, represent it as a set of new orthogonal variables called principal components (PCs), and display the similarity patterns of the observations and the variables (Hamid et al., 2016). PCA is a useful technique to capture the covariance in the original data and represent them as less correlated PCs. On the other hand, MCA can be generalized as PCA to deal with qualitative variables and as multiple factor analysis to deal with heterogeneous sets of variables (Van Rijckevorsel and De Leeuw, 1988). MCA is thus an exploratory method for representing multivariate data in two dimensions and, like PCA, is preferred for large datasets (Baxter et al., 1990).

Two main sources were used to conduct the PCA: Sarstedt and Mooi (2014) and Joint Research Center-European Commission (2008) "Handbook on constructing composite indicators: methodology and user guide." Both sources explain comprehensively and step by step how to apply PCA. For the MCA, the basic and theoretical suggestions of Kroonenberg and Greenacre (2004) were considered. Both PCA and MCA were conducted using SPSS version 26 software.

PCA was initially applied by preparing the dataset, which consisted of 27 variables associated with 891 observations (or 33 years for 27 variables). This process involved linearly projecting the data matrix to maximize variance. The significance of the correlation matrix was highlighted, and the optimization problem was addressed by determining eigenvalues along with their corresponding eigenvectors. Based on Wingdes et al. (2021), the formula for PCA used in this study is given below:

$$\begin{aligned} &\max var(\gamma_1^T x) = \gamma_1^T \Sigma \gamma_1 \\ &s.t. \quad \gamma_1^T \gamma_1 = 1 \end{aligned} \tag{1}$$

Lagrange multipliers approach was used to maximize $\gamma_1^T \Sigma \gamma_1$ subject to $\gamma^T \gamma = 1$

$$\gamma_1^T \Sigma \gamma_1 - \lambda(\gamma_1^T \gamma_1 - 1) \tag{2}$$

where λ is a Lagrange multiplier. The following is gained after differentiation with respect to γ_1:

$$(\Sigma - \lambda I_P)\gamma_1 = 0 \tag{3}$$

where Σ should be treated as covariance matrix and I_P is another form of $\Sigma\gamma_1 - \lambda\alpha_1 = 0$. Essentially, I_P is the $(p \times p)$ identity matrix. The maximization of the quantity happens as follows

$$\gamma_1^T \Sigma \gamma_1 = \gamma_1^T \lambda \gamma_1 = \lambda \gamma_1^T \gamma_1 = \lambda \tag{4}$$

In order to maximize λ, it is essential to make the corresponding eigenvector as large as possible. The process for determining the second component follows similar steps, as it is associated with the second-largest eigenvalue.

PCA and MCA entail preliminary analyses to adhere to the required methodological criteria. Firstly, the Kaiser-Meyer-Olkin measure of sampling adequacy (KMO) and Bartlett's sphericity test assess the suitability of the dataset for PCA. Typically, a KMO threshold of 0.500 is considered appropriate (Kalayci, 2005; Tastan and Yilmaz, 2008), with some dependency on variable types and sample size. In this study, 0.500 served as the focal criterion, aligning well with the study's nature. Secondly, the scree plot, communalities and total explained variance guided PCA progression. Variables with commonality values below 0.750 were excluded. Thirdly, Brown's (2009) recommendations dictated the choice of PCA rotation. To ensure robustness, Direct Oblimin rotation was preferred initially, checking for component correlations above 0.320. If met, oblique rotation was employed. This pragmatic approach aligned with Brown's (2009) guidance, ensuring practical and efficient outcomes.

Finally, MCA was performed at two levels: MCA of 2022 values and MCA of average annual percentage changes between 2014 and 2022. With this approach, we can see not only the current static values for a single year, but also how each country has accelerated its renewable energy production, including Azerbaijan.

4. Results

Throughout the PCA procedure, the significant loadings are those that exceed 0.300 (based on Brown, 2009). The MCA included attributes and countries. The attributes are specific renewable energy sources such as wind, solar and hydropower, while the countries were selected as Eurasian countries to position Azerbaijan in a relative and comparative manner.

4.1. Results of Dimensionality Reduction Analysis (or Principal Component Analysis)

The initial phase of PCA involved a meticulous examination of KMO values, Bartlet's sphericity test outcomes, and extraction results. In situations with large datasets, PCA often necessitates an iterative approach to potentially reduce variables, thus enhancing KMO values and cumulative variance. To attain optimal dimension reduction, a three-stage PCA was conducted. Initially, all variables were included. Subsequently, GovExp, GrCapFr, TrOpp and CO2Emm were excluded due to their low extraction values (see Table 2). To further optimize the process, in the third stage, FDI and Ser were also removed, as their extraction values were the lowest at 0.715 and 0.753, respectively. Consequently, KMO values exhibited incremental improvements, initially rising from 0.486 to 0.628 and then to 0.689. These transformations indicate both rapid and subsequent moderate enhancements in the dataset's suitability for PCA (see Figure 3, panel *a*).

Table 2: Communalities of the three-stage dimension reduction analysis

Variable	Extraction	Variable	Extraction	Variable	Extraction
RenEn	0.918	RenEn	0.927	RenEn	0.925
RenElP	0.801	RenElPc	0.881	RenElPc	0.911
ConRenPc	0.821	ConRenPc	0.892	ConRenPc	0.919
LoCaEn	0.921	LoCaEn	0.945	LoCaEn	0.947
RenElShr	0.874	RenElShr	0.909	RenElShr	0.933
NatGasPr	0.819	NatGasPr	0.832	NatGasPr	0.814
OilPr	0.910	OilPr	0.915	OilPr	0.896
TotPop	0.936	TotPop	0.928	TotPop	0.921
FDI	0.836	FDI	0.715		
GDP	0.925	GDP	0.922	GDP	0.913
GovExp	0.749				
GrCapFor	0.727				
TrOpp	0.626				
ResRents	0.849	ResRents	0.892	ResRents	0.950
EnUsPerPer	0.891	EnUsPerPer	0.917	EnUsPerPer	0.938
CO2Emm	0.675				
PrEnCon	0.934	PrEnCon	0.884	PrEnCon	0.887
TechCh	0.961	TechCh	0.959	TechCh	0.956
InsQ	0.725	InsQ	0.788	InsQ	0.783
UrbPop	0.930	UrbPop	0.924	UrbPop	0.915
Agr	0.957	Agr	0.953	Agr	0.948
Ind	0.940	Ind	0.946	Ind	0.925
Ser	0.757	Ser	0.753		
Man	0.896	Man	0.916	Man	0.915
OilRent	0.876	OilRent	0.914	OilRent	0.960
ArLand	0.762	ArLand	0.785	ArLand	0.789
CPI	0.890	CPI	0.882	CPI	0.874

Source: Author's own calculations based on the collected dataset.

Notes: Extraction Method: Principal Component Analysis.

Figure 3, panel *b*, illustrates the alterations in cumulative variance across PCA stages. The exclusion of variables with limited contributions to PCs led to enhancements in both individual and overall cumulative variances. In essence, during the third stage, the primary component elucidated 44.0% of the dataset's main variance, as opposed to 36.9% in the initial stage. Simultaneously, the fourth component attained a cumulative variance of 90.6%, marking a noteworthy increase of 5.8 percentage points relative to the initial stage outcomes.

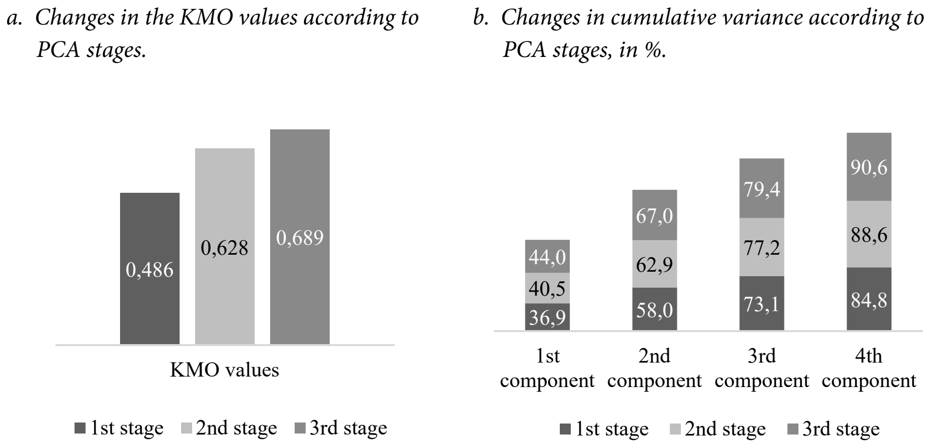

Figure 3: Graphical representation of the pre-PCA procedure of three-stage dimension reduction analysis

Source: Author's calculations based on the collected dataset.

Direct Oblimin rotation showed component correlations below 3.200 (see Table 3), prompting the choice of the Varimax method for rotation. Furthermore, all stages, guided by scree plot values, suggested retaining four PCs, supported by statistically significant results from Bartlett's test of sphericity, denoting substantial correlations among the variables of interest (see Table 4).

Table 3: Component correlation matrix

Component	1	2	3	4
1	1			
2	0.183	1		
3	0.127	–0.092	1	
4	0.106	–0.268	0.027	1

Source: Author's own calculations based on the collected dataset.

Notes: Extraction method: principal component analysis; rotation method: Oblimin with Kaiser normalization.

Table 4: Results of Bartlett's test of sphericity and scree plot analysis

Specification	Bartlett's test of sphericity			Scree plot
	Approximate Chi-square	df	Significance	
1st stage	1907.65	351	0.000	4
2nd stage	1697.45	253	0.000	4
3rd stage	1567.36	210	0.000	4

Source: Author's own calculations based on the collected dataset.

Table 5 presents the results of the third stage PCA, dividing the dataset into four PCs. The first PC exhibits noteworthy positive loadings from TechCh (0.941), GDP (0.925), TotPop (0.917), UrbPop (0.895), CPI (0.880), OilPr (0.872), NatGasPr (0.807) and Ind (0.793). Notably, TechCh, GDP and population-related variables hold substantial loadings above 0.800. Conversely, negative loadings appear on the first PC, including Agr (–0.933), AgLand (–0.872), Man (–0.834), InsQ (–0.693) and EnUsPerPer (–0.321). This reflects a significant decline in the agricultural and manufacturing sectors within Azerbaijan's economy, resulting in negative correlations with the positively loaded variables. A similar trend is observed for agricultural lands and institutional quality, although energy use per person exhibits a weaker association. In essence, the first PC encompasses key macroeconomic variables of Azerbaijan.

Table 5: Rotated component matrix of the analysis

Specification	Components			
	1	2	3	4
TechCh	0.941	–0.228	0.052	–0.121
Agr	–0.933	–0.046	0.274	–0.036
GDP	0.925	–0.222	0.018	0.082
TotPop	0.917	–0.261	–0.029	–0.100
UrbPop	0.895	–0.303	0.089	–0.121
CPI	0.880	–0.284	–0.060	–0.122
OilPr	0.872	0.018	–0.032	0.365
ArLand	–0.872	0.089	–0.112	0.097
Man	–0.834	0.077	0.454	–0.085
NatGasPr	0.807	0.060	–0.097	0.388
Ind	0.793	0.299	–0.259	0.374
InsQ	–0.693	–0.150	–0.522	0.087
LoCaEn	0.017	0.954	0.049	0.185
RenElPc	–0.161	0.928	0.022	0.153
ConRenPc	–0.237	0.917	0.019	0.145
RenElShr	–0.203	0.897	–0.181	0.232
RenEn	–0.029	0.818	–0.482	0.147
PrEnCon	0.057	–0.188	0.919	–0.056
EnUsPerPer	–0.321	–0.050	0.904	0.122
ResRents	0.029	0.301	0.033	0.926
OilRent	0.051	0.380	–0.009	0.902

Source: Author's own calculations based on the collected dataset.

Notes: Extraction method: Principal Component Analysis; Rotation Method: Varimax with Kaiser Normalization; Rotation converged in 5 iterations.

The second PC predominantly represents the renewable energy sector, with LoCaEn (0.954), RenElPc (0.928), ConRenPc (0.917) and RenElShr (0.897) as primary, positively correlated and highly loaded variables. They also exhibit positive correlations with ResRents (0.301) and OilRent (0.380), which aligns with Azerbaijan's economic realities, where resource revenues heavily influence nearly everything, including renewable energy development. UrbPop (−0.303) is the sole negative loading variable in the second PC, indicating an adverse correlation with the aforementioned renewable and non-renewable energy variables. Interestingly, this suggests that while urban population increased, renewable energy sector growth did not follow the same trajectory.

The third PC displays significant loadings from PrEnCon (0.919), EnUsPerPer (0.904) and Man (0.454), all contributing positively. Conversely, InsQ (−0.522) and RenEn (−0.482) exhibit negative loadings on this component. It appears that the third PC primarily represents industrial energy usage, as the main loaders are associated with energy consumption and the manufacturing sector. In other words, this PC signifies the interplay between industry and energy, contrasted by a negative correlation with institutional quality and the proportion of renewable energy in primary energy production. In essence, both consumer-focused renewable energy generation and industrial energy production appear insufficient to meet the demand.

The fourth PC elucidates the role of non-renewable resource rents in Azerbaijan's economy. Notably, all significant loadings are positive, with ResRents (0.926) and OilRent (0.902) as the primary contributors. Additionally, OilPr (0.365), NatGasPr (0.388) and Ind (0.374) exhibit moderate positive loadings on the fourth PC. Given Azerbaijan's oil-centric economy, these findings align with expectations, essentially categorizing the fourth component as "natural resource rents."

To aid visual comprehension, PCA was repeated with a fixed number of PCs set to two, resulting in Figure 4. This representation offers clearer clustering of key economic and renewable energy sector variables compared to the three or four-dimensional counterparts. The first PC features NatGasPr, OilPr, GDP, TechCh, CPI and TotPop as major positive loaders, negatively correlated with ArLand, InsQ, Man, Agr and EnUsPerPer. Notably, Ind loads significantly on both the first and second PCs, highlighting its importance as it bridges both renewable and non-renewable energy sectors within the industry.

In the second PC, RenElShr, RenElPc, ConRenPc, LoCaEn, RenEn, OilRent and ResRents load positively and significantly, whereas PrEnCon is the sole negative and significant loader. This finding aligns with the declining trends in renewable energy-related variables since 2006, contrasted with the rising trend in primary energy consumption. Interestingly, PrEnCon exhibited no significant negative loading on the PC in the initial analysis stage. It appears that the second PC in the two-component solution mirrors the second PC in the initial approach.

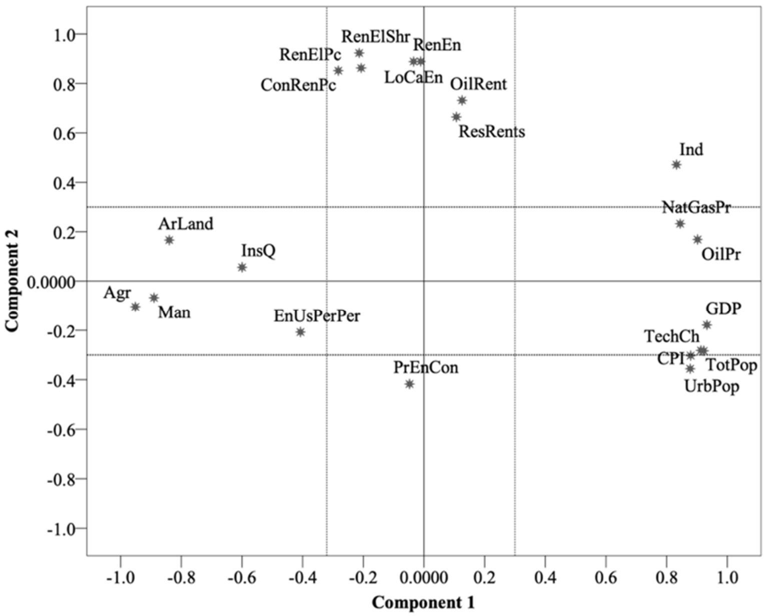

Figure 4: Two-dimensional component loadings, 1990–2022

Source: Author's calculations based on the collected dataset.

4.2. Results of Multivariate Correspondence Analysis

Figure 5 displays the initial MCA findings, encompassing four attributes tied to specific renewable energy sources: solar, wind, hydropower and nuclear. The analysis encompasses 24 countries, allowing a comparative assessment of Azerbaijan's standing. Despite considerable renewable energy potential, Azerbaijan exhibits subpar performance in hydropower, wind and solar energy. For instance, neighbouring countries like Russia and Iran surpass Azerbaijan in hydropower production, and post-Soviet nations such as Ukraine, Estonia and Belarus outperform Azerbaijan in solar energy production. Hungary stands as a notable leader in this regard since the Hungarian government has been proactively advocating the advancement of solar energy through diverse initiatives and policies. In fact, as of the conclusion of 2022, Hungary possessed slightly over 4,000 MW of photovoltaic capacity, marking a substantial surge compared to the levels recorded a decade earlier (Eurobserv-er, 2023). In fact, Hungary's commitment to a clean energy transition has even been recognized by the International Energy Agency (2022). Additionally, Lithuania leads in wind power production, with Mongolia, Türkiye and Poland displaying strong results, while Azerbaijan's wind power generation in 2022 remains limited. Lituania's leading position has been attributed to its geographical position and government's support (Evwind, 2023).

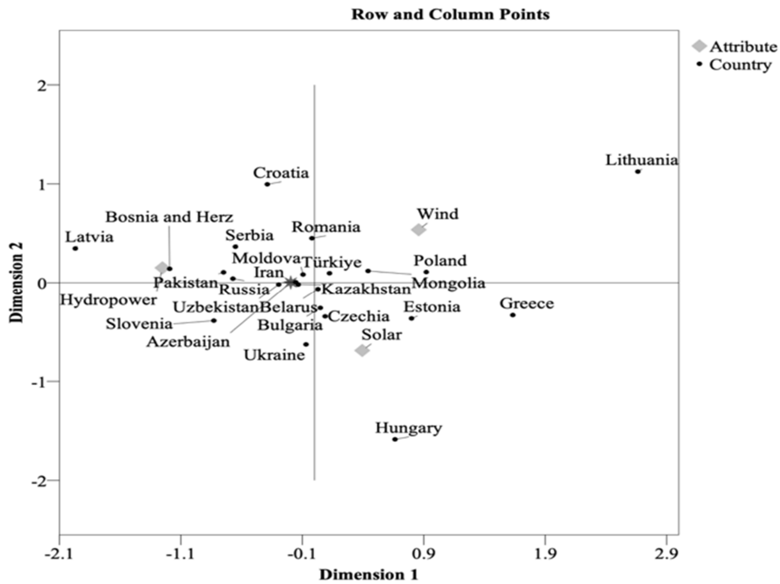

Figure 5: Multiple correspondence analysis of the renewable energy production by source across selected countries, only in 2022.*Source: Author's calculations based on the collected dataset*

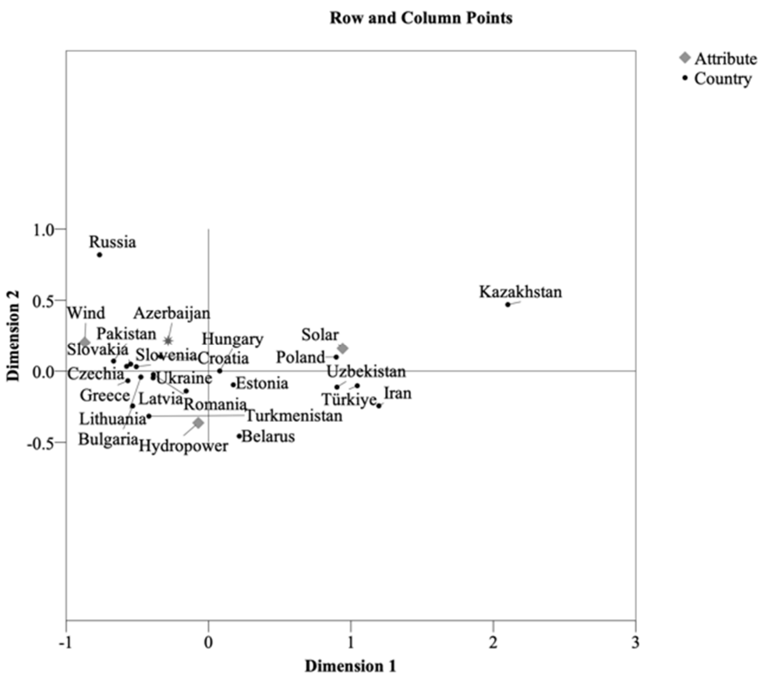

Figure 6: Multiple correspondence analysis of the renewable energy production by source across selected countries, based on annual average percentage changes, 2014–2022

Source: Author's calculations based on the collected dataset.

Azerbaijan's average annual growth rates in solar, wind and hydropower are concerning, showing a considerable gap in solar energy development compared to Kazakhstan, Uzbekistan, Iran and Türkiye. In this aspect, Azerbaijan lags behind Estonia, Hungary and Belarus but surpasses Slovakia, Pakistan, Latvia, Lithuania, Bulgaria and others (see Figure 6). Meanwhile, Azerbaijan's wind energy development improved from 2014 to 2022, akin to Croatia and Russia but behind Pakistan, Czechia, Slovakia and Greece. However, hydropower development lags behind compared to Belarus, Turkmenistan, Bulgaria, Romania and Ukraine, with Azerbaijan outperforming only Russia in this regard.

4.3. Index of Renewable Energy Sector in Azerbaijan

Figure 7 summarizes the dimension reduction analysis of Azerbaijan's economy concerning the renewable energy sector. Factor 1 predominantly represents macroeconomic variables, reflecting overall economic growth and per capita energy use. Factor 2 mainly loads renewable energy variables and resource rents, showing volatility and an overall decline. Factor 3 indicates industry-energy relations, displaying a positive upward trend since 2010 after disruptions in the 1990s. Factor 4, reflecting natural resource rents, is volatile with peaks in 2007 and 2008, lacking a clear trend due to unpredictable oil and natural gas prices and the associated rents in Azerbaijan.

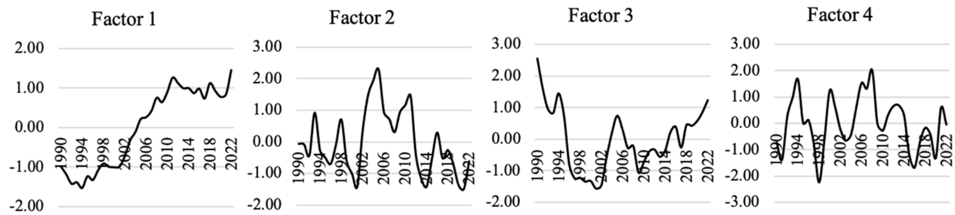

Figure 7: Principal component-based factor scores, in index values, 1990–2022

Source: Author's own calculation based on the collected dataset.

5. Conclusions

Using PCA and MCA approaches as nonparametric dimensionality reduction methods, this study examined two aspects of the Azerbaijani economy: first, what type of underlying relationships (i.e., covariance) exists between a number of macro-economic variables and variables from the renewable energy sector; second, how Azerbaijan's relative performance in specific renewable energy sectors such as wind, solar and hydropower compares to other selected Eurasian countries (e.g. Kazakhstan, Latvia).

The PCA results effectively segmented the initial dataset of 22 variables (originally 27) into four principal components representing distinct aspects: macroeconomic indicators (PC 1), the renewable energy sector (PC 2), industry-energy dynamics (PC 3) and natural resource rents (PC 4). PC 1 and PC 3 exhibited consistent positive trends between 1990 and 2020, as indicated by their index values. In contrast, PC 2 and PC 4 displayed volatility without discernible trends. Notably, certain economic metrics like FDI, trade openness, services value added, gross capital formation, government expenditure and CO_2 emissions held limited significance in the PCA, and their exclusion notably enhanced the quality of the analysis by elevating KMO values and cumulative variance explained. Moreover, the MCA results showed that Azerbaijan's abundant renewable energy potential is currently underutilized and lags behind that of other similar post-Soviet countries. These analyses illustrated the methodological exercise of dimensionality reduction in a relatively longitudinal dataset using a small and resource-rich economy from the perspective of renewable energy sector development.

The PCA results unveil several key findings. Firstly, as the Azerbaijani economy recuperated from transition shocks of the 1990s and witnessed an oil boom, energy consumption per capita declined, institutional quality deteriorated, and the contributions of manufacturing and agriculture to value-added diminished (evident from the significant loadings on PC 1). Secondly, there is a strong connection between renewable and non-renewable energy variables, indicating interdependence, where funding for the renewable energy sector often stems from the non-renewable sector's revenue generation capability. Thirdly, renewable energy struggles to keep pace with escalating energy demands, particularly in industrial sectors, amidst declining institutional quality. Lastly, PC 4 demonstrates that even within a dataset encompassing 22 variables, oil and gas-related factors significantly cluster around industrial activities, reflecting the nation's heavy reliance on oil-based export revenues and domestic value added.

The theoretical implications of the current study are as follows. First, economic diversification and reliance on non-energy sectors might contribute to more sustainable energy consumption patterns in small and dependent economies such as Azerbaijan. Second, the strong connection between renewable and non-renewable energy variables underscores the interdependence in Azerbaijan's energy landscape. Third, the MCA results, revealing Azerbaijan's underutilized renewable energy potential compared to other Eurasian countries, have profound theoretical and policy implications. The comparative perspective emphasizes that countries with more or less similar geographical and natural conditions differ in their renewable energy performance, which underlines the role of institutional and political factors in theory building.

The study yields several crucial policy implications for Azerbaijan, a country with substantial untapped potential in solar, wind and hydro energy and a commitment to greener energy sources. While optimism surrounds this transition, challenges persist that foreign investments alone cannot resolve. First, actionable policies, not just rhetoric, are needed to accelerate renewable energy development. Setting specific targets for renewable energy in production and consumption is vital. Additionally, a revised electricity pricing policy can incentivize solar energy adoption. Second, amidst Azerbaijan's role as a gas supplier to the EU, a comprehensive, long-term energy policy is crucial, considering diversification and a favourable business environment to reduce commodity dependency. Third, the energy sector's vulnerability to international commodity price fluctuations necessitates broader economic diversification. Addressing economic, legal and technical obstacles promptly is essential for sustainable renewable energy growth. Lastly, fostering environmental awareness among key stakeholders and authorities is critical to transition from fossil fuels to green energy. Effective communication on green energy, recycling and environmental risks is vital for progress.

The generalizability of the results obtained in this study is underpinned by the methodological rigor and versatility of the analytical techniques used, namely PCA and MCA. These methods can be applied to countries where the renewable energy sector is still at an early stage of development and where there is a lack of understanding of the sector in terms of the complex socioeconomic relationships.

There are some limitations and areas that should be explored in the future. Nonparametric methods provide insights but do not allow causal inferences due to limited functional specifications, control and precision. Context-specific results limit generalizability beyond Azerbaijan. Endogeneity problems remain, especially in energy economic analyses, which complicates policy analysis. Future research should integrate parametric and nonparametric approaches, examine longer time periods and consider policy implications. Expert interviews could complement quantitative analysis and provide nuanced perspectives on renewable energy dynamics and policy impacts.

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