



CO₂ emission estimation in Central Asian countries by use of artificial intelligent methods

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ABSTRACT

Energy consumption and shares of different types of energy sources in the total energy supply play a critical role in CO₂ emissions in various countries. Aside from the energy-related factors, economic indicators such as Gross Domestic Product (GDP) can also influence emissions. In the present study, shares of different energy sources in total energy supply and GDP were utilized as inputs to propose a model for estimating CO₂ emissions in three Central Asian states, namely Kazakhstan, Uzbekistan, and Turkmenistan. In addition to the modelling outputs, the article likewise describes important characteristics of energy systems in target countries. Based on the comparison of CO₂ emissions per GDP unit, the study allowed identifying that this index in the target countries exceeds the global average, which necessitates urgent actions to reduce emissions. The input data for the research were obtained from the International Energy Agency (IEA) and World Bank. The study applied the Group Method of Data Handling (GMDH) and the Multilayer Perceptron (MLP) method. Both models showed significant performance in emissions estimation; however, according to the calculated values for the applied criteria, it was concluded that the GMDH led to better exactness compared to the MLP. The mean absolute relative deviations of the GMDH and MLP modes were approximately 3.69% and 4.28%, respectively. The R² value of the mentioned models were 0.9936 and 0.9929, respectively. In the majority of the cases for both models, relative deviations between the predicted and actual CO₂ emission were in the range of ±5%.

ARTICLE HISTORY

Received:

July 2, 2024

Accepted:

September 22, 2024

Published:

September 30, 2024

KEYWORDS

Artificial neural network, CO₂ emissions, Central Asian countries, GMDH, intelligent methods

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1. Introduction

There is a growing trend in the emission of greenhouse gases, mainly CO₂, due to various factors such as population growth, industrialization, increment in use of fossil fuels etc. Energy plays a critical role in the emission of greenhouse gases and must be considered for making policies for the mitigation of these gases. According to the report of the International Energy Agency (IEA) (CO₂ Emissions in 2023, A New Record High, but Is There Light at the End of the Tunnel, 2024), energy-related CO₂ emissions in the world increased by 1.1% in 2023. Over ten years ending with 2023, emissions of CO₂ in the world have elevated by slightly higher than 0.5% per year. Several approaches and pathways have been proposed for the reduction of energy-related CO₂ emission, including the deployment of renewable energies for power generation, transport, and heat production (Renewables, n.d.), development of cleaner energy technologies such as heat pumps for buildings heating and cooling (Heat Pumps, n.d.) and Electric Vehicles (EVs) for transport sector (Electric Vehicles, 2023), development of carbon capture systems (Carbon Capture, Utilisation and Storage, n.d.) etc. The development of models for the prediction of CO₂ emission and identification of the critical factors affecting the amount of greenhouse gas emissions help make proper policies towards the reduction of their emission. These policies must be based on complex dynamics between energy consumption, economic growth, and population dynamics. In a study (Turmunkh, 2021), the development of a sustainable energy strategy in Central Asia countries was presented. The author provides statistical analysis and recommendations for policymakers aiming to balance economic development with environmental sustainability in the region. Similar research on panel data econometrics, considering the time-series and cross-sectional dimensions is performed in (Yuldoshboy et al., 2022), the conclusion is made that economic activities also contribute to higher CO₂ emissions, reflecting the region's reliance on fossil fuels. The authors recommend investments in energy efficiency and renewable energy sources can be crucial to mitigate CO₂ emissions.

Central Asia's economy is deeply intertwined with fossil fuel production and consumption. The region is rich in fossil fuel resources, which plays a critical role in its economic development. Countries like Kazakhstan and Uzbekistan are major exporters of oil and natural gas, and their economies are significantly influenced by fluctuations in global energy markets. Studies have shown that the energy sector in Central Asia is heavily reliant on fossil fuels (Kuziboev et al., 2024; Radovanović et al., 2021), contributing to high levels of CO₂ emissions. In another study (Xiu, 2022), a significant positive correlation between CO₂ emissions and economic growth in Central Asian countries was reported. The elasticity of CO₂ emissions concerning GDP is estimated at 0.82, indicating that a 1% increase in GDP is associated with a 0.82% increase in CO₂ emissions.

Projections of CO₂ emissions in Central Asia indicate a continuing rise in emissions if current fossil fuel dependency persists. According to (Zhakiyev et al., 2023), the carbon dioxide emission is projected to 30% increase if no energy policy is utilized, therefore policy reforms and the adoption of renewable energy sources are critical to mitigating future emissions. Some positive forecasts are provided (Filipović et al., 2024), by estimating a 30% CO₂ reduction in three decades in Central Asia countries considering carbon pricing policy.

According to the literature review on CO₂ estimation in the Central Asia area, it can be stated that utilizing a panel data approach for CO₂ emission estimation comes with its own set of challenges. This approach can sometimes limit the complexity of the model, as it may struggle to fully capture the nuanced impacts of various socio-economic and technological factors over time and across different regions. The panel approach, while helpful for identifying overarching trends and relationships, might not adequately account for the specific local contexts or temporal dynamics that influence emissions. This can lead to potential biases or oversimplifications in the estimation process. Among different techniques and approaches applicable to the modelling of engineering and environmental problems, intelligent methods have some advantages such as the ability to model with relatively high accuracy, lower computation cost compared with the numerical simulation and fast performance. AI and other advanced technologies can play a crucial role in accurately estimating emissions and guiding effective policy decisions. The continued focus on regional cooperation and policy innovation will be essential in addressing the environmental challenges posed by fossil fuel dependency in Central Asia.

Intelligent methods such as Artificial Neural Network (ANN) are applicable in different energy-related fields of science. In greenhouse emissions estimation, ANN and deep learning neural networks are compared (Altikat, 2021). The study demonstrates that deep learning models are more effective than traditional neural networks in predicting CO₂ emissions. However, the techniques have been applied for a variety of systems in ANN-based approaches, such as performance prediction of renewable energy systems (Alhuyi Nazari et al., 2023), forecast of weather data affecting the outputs of energy systems such as wind turbines (Filik & Filik, 2017), energy consumption in different sectors (Luo et al., 2020) and estimation of energy price (Pindoriya et al., 2008). Good evidence is provided in (M. K. & V., 2020) with a multilayered ANN model that includes multiple hidden layers between input and output layers used to capture complex patterns in the data related to CO₂ emissions. The ANN model in (Rezaei et al., 2018a) demonstrated a high level of accuracy in predicting CO₂ emissions, showing a strong correlation between energy use and emissions. The study found that increases in energy consumption, particularly from non-renewable sources, lead to higher CO₂ emissions. Conversely, economic growth

driven by renewable energy sources was associated with lower emissions levels. In 2018, Rezaei et al. (Rezaei et al., 2018b) employed the Group Method of Data Handling (GMDH) to forecast the emission of CO₂ in four Nordic countries. Their model showed significant accuracy with an R² of 0.998. In 2019, Ahmadi et al. (Ahmadi, Jashnani, et al., 2019) developed a model by using shares of different energy sources utilized as primary energy supply in addition to Gross Domestic Product (GDP) as the inputs and GMDH as the intelligent technique for CO₂ emission estimation in five Middle Eastern countries. The Average Absolute Relative Deviation (AARD) of the predictive model proposed in their study was 2.3%. In 2020, Ghalandari et al. (Ghalandari et al., 2020) used data-driven techniques for CO₂ emission forecasting in four European countries. The use of various energy resources in addition to the GDP were inputs for the ANN-based models. Their models could estimate the CO₂ emission of the countries with an R² of 0.9999. Birjandi et al. (Komeili Birjandi et al., 2022a) used the Multilayer Perceptron (MLP) method with two different transfer functions namely radial basis and tansig for the estimation of CO₂ emission in countries in Southeast Asia. They reported that the use of the radial basis function in optimal structure leads to higher accuracy compared with the optimal model with the tansig function.

According to the literature review, it is concluded that intelligent methods, particularly ANN-based ones, are efficient and accurate tools for the prediction of CO₂ emission. Their accuracy is dependent on the architecture and applied methods and these factors should be considered to develop the precise model. This article focuses on the CO₂ emission modelling of three countries namely Kazakhstan, Uzbekistan and Turkmenistan in central Asia by use of ANN-based methods. The main novelty of the present work is the simultaneous consideration of these three countries for the development of a comprehensive model. Furthermore, some helpful information is provided on the key characteristics of their energy systems and policies considered for the future of their energy systems. In the following section, an overview of the energy systems and CO₂ emission status of these countries are provided. Afterwards, the applied methods are described. Subsequently, results and discussion are provided and finally, the conclusion is represented.

2. Overview of Energy Systems in Cases of the Study

Three countries, namely Kazakhstan, Uzbekistan, and Turkmenistan, located in central Asia are considered in the present study for modelling of CO₂ emission using ANN-based models. In this section, key features and policies related to the energy systems and environment of these countries are presented.

2.1. Kazakhstan

The Republic of Kazakhstan has a land area of 2,717,300 km² (Executive Summary, n.d.) and its population was around 19,621,000 in 2022 according to the World Bank data (Population, Total - Kazakhstan, n.d.). Gas and oil industries and associated sectors were responsible for 17% of GDP in 2020, oil provides the majority of the earnings of the country's exports and is the government revenue chief source (Executive Summary, n.d.). In 2021, oil products had the highest share in Total Final Consumption (TFC) that was followed by coal. High reliance on fossil fuels causes high CO₂ emissions per unit of GDP compared with the world and developed countries. In Figure 1, the emission of CO₂ between 1990 and 2021 is illustrated (Energy Statistics Data Browser, n.d.-a). It can be seen that although there was a sharp reduction in emissions between 1990 and 2001, there has been an increasing trend in recent years, particularly since 2015. Coal has the highest share in electricity generation in this country and it is followed by natural gas. The industry had the highest share in TFC of Kazakhstan between 2000 and 2019; however, from 2020 the share of the residential sector became higher than the industry sector (Energy Statistics Data Browser, n.d.-a).

Some policies have been made for the energy systems in Kazakhstan in recent decades. For instance, according to the law about the support of the utilization of renewable energy systems, which was adopted in 2009 and the latest amendment in 2021, feed-in tariff (FIT), grants and tax relief were introduced and rules were outlined for land allocation for renewable energy systems utilities (The Law About Support the Use of Renewable Energy Sources (Amended), 2022). Another policy, the law on Energy Conservation and Energy Efficiency, a strategic policy is designed to achieve a remarkable reduction in the energy consumption of industrial and municipal sectors. This law focuses on the enhancement of energy conservation, development of efficient infrastructures, and shifting towards green growth of the national economy (KAZAKHSTAN: Law No. 541-IV of 2012 on Energy Saving and Energy Efficiency (2019 Ed.), 2019). Another policy for the energy sector is entitled to energy efficiency classes of buildings. This policy focuses on the development of rules for the definition and revision of buildings' energy efficiency classes (Energy Efficiency Classes of Buildings, 2022). This policy can lead to improvement in the energy-saving in the buildings and reduction in the energy consumption and consequently decrease in emission of this sector. Furthermore, the United Nations Development Programme in Kazakhstan in partnership with this country's government and with financial help from the Global Environment Facility initiated programmes for supporting the medium- and small-sized enterprises carrying out the energy efficiency and renewable energy systems. The aim of this initiative is promotion of renewable energy projects on a small scale and decrement the financial burden of clean energy systems (Transition to Renewable

Energy Sources: Economic Benefits for Entrepreneurs in Kazakhstan, 2024). Between 2018 and 2020, the U.S. Agency for International Development (USAID) helped Kazakhstan leverage approximately 2 billion USD in private investment, leading to around 60 new projects on renewable energy which would decrease the emissions of CO₂ in this country by 11 Mt (Betting Big on Renewables, n.d.). Aside from the decarbonization, there are some investments and plans for the improvement of energy security in Kazakhstan. For instance, Central Asia Regional Economic Cooperation (CAREC) has invested around 8.9 billion USD in different projects that are mainly aimed at bilateral electricity trade expansion and enhancement of power networks in this region (Energy, 2023). Implementation of this plan would lead to the enhancement of energy security in the considered countries, e.g. Kazakhstan.

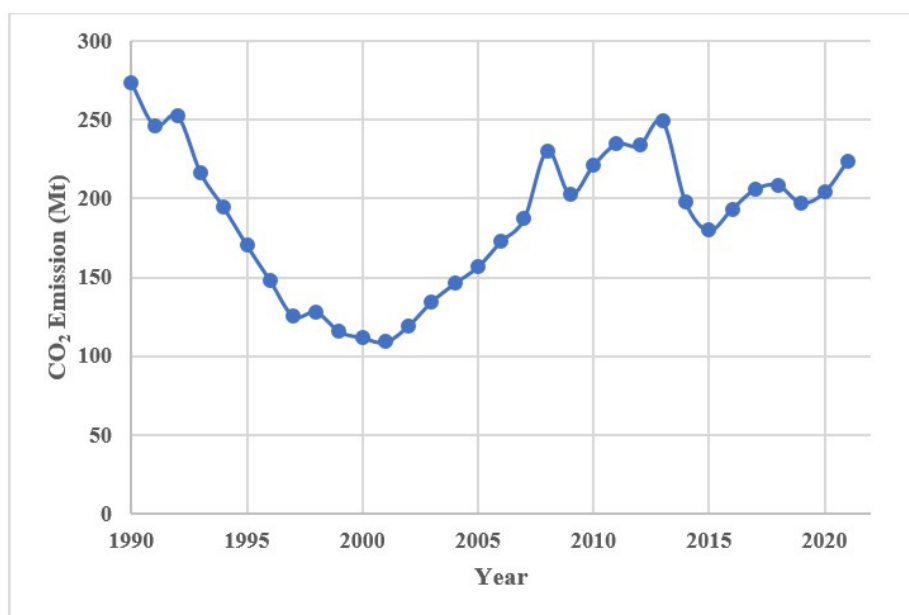


Figure 1. Total CO₂ emission in Kazakhstan between 1990 and 2021 (Energy Statistics Data Browser, n.d.-a).

2.2. Uzbekistan

The land area of Uzbekistan is around 447,400 km² (Uzbekistan (12/08), n.d.) and its population was approximately 35,648,000 in 2022 based on the data of the World Bank (Population, Total - Uzbekistan, n.d.). Despite being energy self-sufficient owing to its gas sector, the ageing infrastructure of this country struggles to face increasing domestic demand. Overuse, losses and financing remain problems in the energy sector of this country (Uzbekistan, n.d.). In this country, natural gas had the highest share in TFC and was followed by electricity in 2022 (Energy Statistics Data Browser, n.d.-b). CO₂ emission per unit of GDP in this country is high in comparison

with the world which can be attributed to the low efficiency of the systems and high reliance on fossil fuels. In Figure 2, Uzbekistan's CO₂ emission between 1990 and 2021 is represented. It can be seen that since 2015, there has been an increasing trend in the emission of CO₂. Natural gas has the highest share in electricity generation in Uzbekistan, and it was followed by hydropower in 2021. This year, the residential sector had the highest share in the TFC of Uzbekistan which was followed by the industry sector (Energy Statistics Data Browser, n.d.-b).

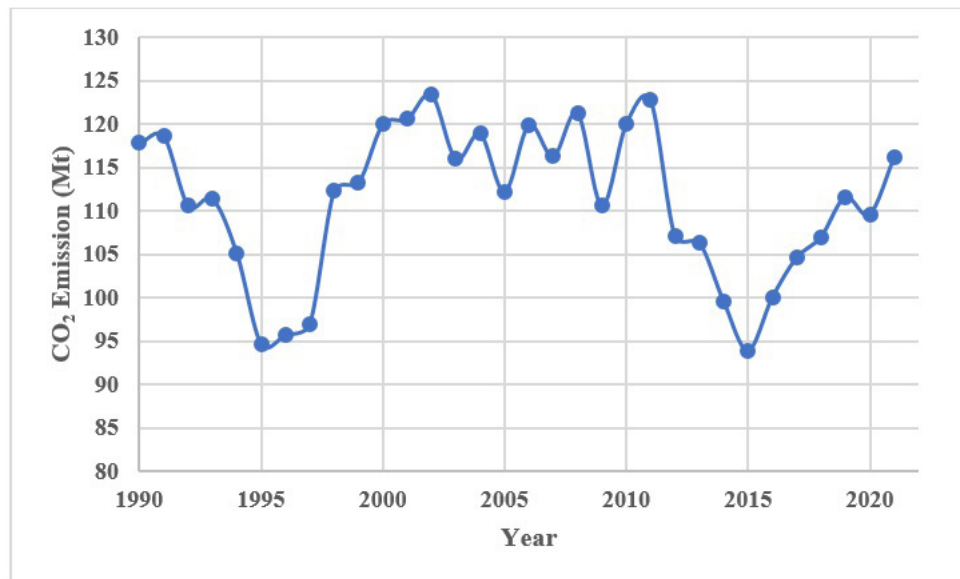


Figure 2. Total CO₂ emission in Uzbekistan between 1990 and 2021 (Energy Statistics Data Browser, n.d.-b).

Some policies and plans have been considered in the energy sector of Uzbekistan in recent years. The general items focused on by the government are designed in a way to achieve fuel independence by incrementing the natural gas and petroleum condensate output, creating raw materials base for the energy sector, maximising public access to electricity, liquefied and natural gas and the latest kinds of fuels, promotion of financial stability and attraction of more investment in this sector, utilization of energy resources in a more efficient way, development and legal framework for the energy sector and enhance the related financial-taxation system and promotion of competition in the energy sector (The Outlook for the Development of Renewable Energy in Uzbekistan, 2014). In addition to the general policies, some of the plans and policies are more specific. For instance, according to the Decree of the President of the Republic of Uzbekistan, primary directions for more development of the fuel and energy industry of the country are defined. There are different aims for it including the introduction of advanced resources and technologies applicable for energy saving in the economy and household sectors in

addition to the development of new energy sources (Decree of the President of the Republic of Uzbekistan “On Measures to Radically Improve the Management System of the Fuel and Energy Industry of the Republic of Uzbekistan” Dated 01.02.2019, №UP-5646, 2022). According to another policy, a law is presented that aims to strengthen the energy security of Uzbekistan, fuel diversification, and balance of energy in terms of electricity generation, heat and biogas utilizing renewable energies (Law of the Republic of Uzbekistan “On the Use of Renewable Energy Sources” Dated May 21, 2019, No. ZRU-539, 2022). Furthermore, this country set a 25% target for renewable energy generation by 2030 and carbon neutrality by 2050. USAID is cooperating with the stakeholders of the energy sector and the Ministry of Energy to initiate a Green Hydrogen Hub to support the efforts of the government to reach the mentioned goals (USAID Energizes Uzbekistan’s First Green Hydrogen Hub, n.d.).

2.3. Turkmenistan

Another case study of the present study is Turkmenistan located in Central Asia. The land area of this country is 469,930 km² and the population of this country was around 6,431,000 in 2022 (Population, Total - Turkmenistan, n.d.). The government of Turkmenistan was continuously investing in gas and oil to expand and modernize the heat and electricity sector by 2020. In addition, the energy sector is approximately fully subsidized (Turkmenistan, n.d.). The highest share of TFC belonged to natural gas in 2021 which was followed by the oil products (Energy Statistics Data Browser, n.d.-c). CO₂ emission per unit of GDP is high compared with the world and is higher than the two other countries considered in the present study. In Figure 3, the emission of CO₂ between 1990 and 2021 in Turkmenistan is illustrated. Between 1998 and 2011, there was a significant increase in emissions; however, its increasing trend has reduced in recent years. Among different sectors of this country, commercial and public services had the highest share of TFC in 2021 (Energy Statistics Data Browser, n.d.-c).

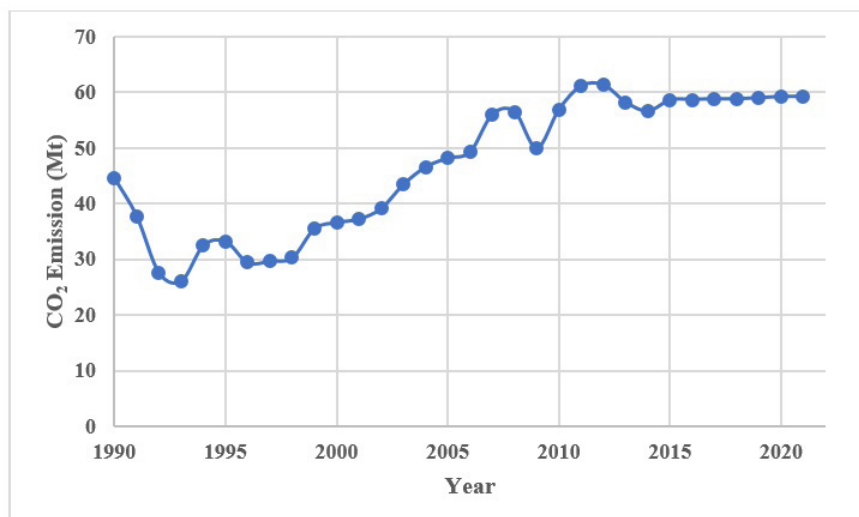


Figure 3. Total CO₂ emission in Turkmenistan between 1990 and 2021 (Energy Statistics Data Browser, n.d.-c).

There are some policies and plans for environmental protection and modification of energy systems in Turkmenistan. For instance, according to one of the policies on the protection of atmospheric air, a law is adopted to provide the set standards for air quality (On Protection of the Atmospheric Air, 2022). According to another policy, Turkmenistan's Nationally Determined Contribution (NDC) reflects decrement of 20% in the emission of greenhouse gases in 2030 in comparison with 2010 emissions under the business-as-usual scenario (Nationally Determined Contribution (NDC) to the Paris Agreement (2022 Update): Turkmenistan, n.d.). A project entitled "Sustainable Cities in Turkmenistan: Integrated Green Urban Development in Ashgabat and Avaza", which is funded by the UNDP and Global Environmental Fund aims to promote sustainable cities development and decrease unfavourable effects of urban growth in Turkmenistan (UNDP Continues to Support Turkmenistan in Improving Energy Efficiency and Developing Renewable Energy Sources, n.d.). As another international cooperation and support, USAID aids in the identification of opportunities related to renewable energy systems, helps in the development of large-scale and comprehensive low-carbon strategies in the sector of energy and takes part in the decrement of emissions of methane from the gas and oil sector (USAID Power Central Asia, n.d.).

3. Methods

There are various kinds and structures based on ANN for the development of predictive models. MLP is one of the most conventional ANN-based models that have been applied for the modelling of multiple systems and problems in recent decades. The general structure of an MLP ANN with one hidden layer is shown in Figure 4. A description of this model is presented here according to the study by Komeili et al. (Komeili Birjandi et al., 2022a). In various layers of this structure, neurons are located. Input information is received by the input layer and transferred to the next layer through the neurons. The communication ability of a neuron in comparison with the other neurons represents its weight. The quantity of neurons in each layer is associated with the weight value and value of the network's former layer. The principal processor component of this network is a neuron.

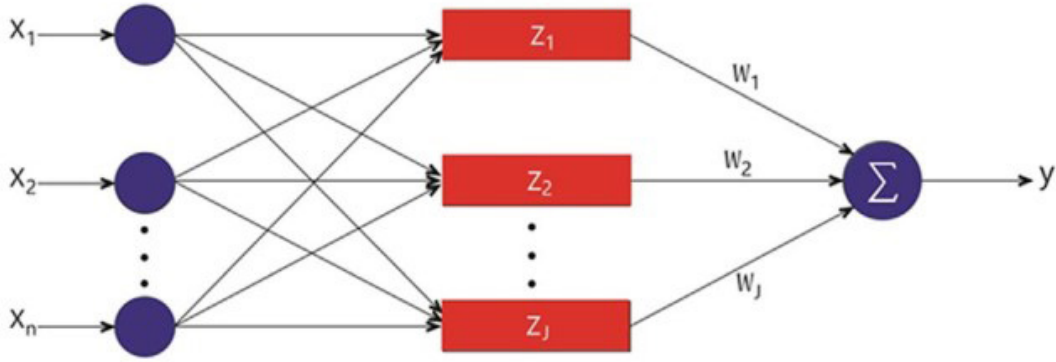


Figure 4. Structure of an MLP ANN with a single hidden layer (Komeili Birjandi et al., 2022a).

Considering X vector (X_1, X_2, \dots, X_n) as the network input, the weight of the neurons which stands for the j th neuron synapse power as ω_j , u_j as the linear combination of output and y_j as the network output, the following equations are used for determination of the output.

$$u_j = \sum_{i=1}^n \omega_{ji} X_i \quad (1)$$

$$y_j = \varphi(u_j + b_j) \quad (2)$$

$$v_j = u_j + b_j \quad (3)$$

In these equations, $\varphi(0)$ and b_j are activation function and bias, respectively. A variety of activation functions are applicable in this network. *tansig* as one of the most conventional activation functions, as presented in Equation (4) (Komeili Birjandi et al., 2022a), is applied in the present study.

$$\text{tansig}(x) = \frac{2}{1 + \exp(-2x)} - 1 \quad (4)$$

In the applied model, Levenberg-Marquardt is used as the training function for optimization of the network parameters. In addition, one hidden layer with different numbers of neurons is considered to obtain the optimal structure. The other hyperparameter values such number of epochs are selected based on the default value of MATLAB software.

Another technique applied in the present work for modelling is GMDH. This approach is described here according to the study by Kim et al. (Kim & Okuyucu, 2022). This method maps an input vector, $X=(x_1, x_2, \dots, x_n)$ to the forecasted value denoted by y_i as illustrated in Figure 5. It is anticipated to have as near as possible

the value of output to its actual value. M results determined for pairs of data in a network with single output and multiple inputs are observed as follows (Oh & Pedrycz, 2002).

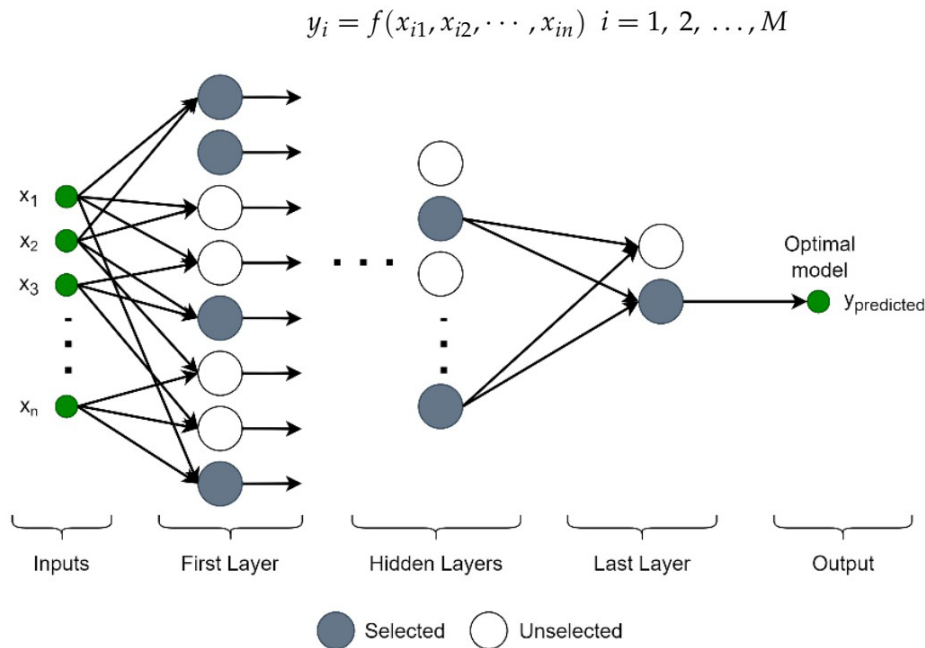


Figure 5. Schematic of GMDH ANN (Kim & Okuyucu, 2022)

The predicted value of the output, \bar{y} , from the inputs is represented as follows:

$$\bar{y}_i = \bar{f}(x_{i1}, x_{i2}, \dots, x_{in}) \quad i = 1, 2, \dots, M \tag{5}$$

The least-squares approach is utilized between the predicted and actual outputs to obtain the model. The following equation is used for minimization of the model error.

$$\sum_{i=1}^M (\bar{f}(x_{i1}, x_{i2}, \dots, x_{in}) - y_i)^2 \rightarrow \text{minimum} \tag{6}$$

This type of ANN is identified based on input and output factors emphasized in the form of the Kolmogorov-Gabor polynomial function, which is as Equation (7) (Farlow, 2020):

$$\bar{y} = a_0 + \sum_{i=0}^n a_i x_i + \sum_{i=1}^n \sum_{j=1}^n a_{ij} x_i x_j + \sum_{i=1}^n \sum_{j=1}^n \sum_{k=1}^n a_{ijk} x_i x_j x_k + \dots \tag{7}$$

Equation (7), a refers to the coefficients of a polynomial and $(i, j, k) \in 1, 2, \dots, n$. In general, this polynomial can be written in quadratic polynomial form with just two variables as follows (Elbaz et al., 2021):

$$y = G(x_i, x_j) = a_0 + a_1 x_i + a_2 x_j + a_3 x_i x_j + a_4 x_i^2 + a_5 x_j^2 \quad (8)$$

This model forecasts the output for each input parameter set and is applied for the prediction of the coefficient and decreased value of Root Mean Square Error (RMSE) between the forecasted and actual outputs. Minimization of RMSE is as Equation (9):

$$RMSE = \frac{\sum_{i=1}^M (\bar{y}_i - y_i)^2}{M} \rightarrow \text{Minimum} \quad (9)$$

In the principle form of this algorithm, all binary probabilities of the independent variables provide regression architecture utilizing the form of polynomials represented in Equation (8). The count of cells in the networks' hidden layer is calculated by $(n/2)$. Afterwards, the creation of M data triples is possible to form the actual output as (y_i, x_{ip}, x_{iq}) $(p, q) \in (1, 2, \dots, n)$. The obtained matrix is as follows:

$$\begin{bmatrix} x_{1p} & x_{1q} & \vdots & y_1 \\ x_{2p} & x_{2q} & \vdots & y_2 \\ \dots & \dots & \dots & \dots \\ x_{Mp} & x_{Mq} & \vdots & y_M \end{bmatrix} \quad (10)$$

GMDH algorithm essential form is written in matrix form and Equation (7) could be applied to rewrite it as follows:

$$Y = Aa \quad (11)$$

where $Y = \{y_1, y_2, \dots, y_M\}^T$ denotes the actual value of the output vector and $a = \{a_1, a_2, \dots, a_5\}$ is the vector of the unknown coefficient of the polynomial. The forecasted matrix for various p and q are as Equation (12).

$$A = \begin{bmatrix} 1 & x_{1p} & x_{1q} & x_{1p}x_{1q} & x_{1p}^2 & x_{1q}^2 \\ 1 & x_{2p} & x_{2q} & x_{2p}x_{2q} & x_{2p}^2 & x_{2q}^2 \\ \dots & \dots & \dots & \dots & \dots & \dots \\ 1 & x_{Mp} & x_{Mq} & x_{Mp}x_{Mq} & x_{Mp}^2 & x_{Mq}^2 \end{bmatrix} \quad (12)$$

The following normal equation must be solved for multi-regression analysis based on the least-squares method. For comparison of the models, Relative Deviation (RD) and Average Absolute Relative Deviation (AARD) are considered that are determined as follows (Komeili Birjandi et al., 2022b):

$$RD = \frac{y_{actual} - y_{modeled}}{y_{actual}} \quad (13)$$

$$AARD = \frac{\sum_{i=1}^n \left| \frac{y_{i,actual} - y_{i,modeled}}{y_{i,actual}} \right|}{n} \quad (14)$$

For the abovementioned parameters, it is preferred to have values closer to 0 as much as possible. Lower values of AARD and RD refers to higher accuracy of the proposed model and lower deviations between the predicted and actual outputs. In addition to these criteria, R^2 , calculated by use of Equation (15), is used as another parameter for evaluation (Komeili Birjandi et al., 2022b). Closer values to 1 means higher accuracy and for the current models (Dossumbekov et al., 2024), achieving R^2 values of higher than 0.95 would be acceptable.

$$R^2 = 1 - \frac{\sum_{i=1}^n (y_{i,actual} - y_{i,modeled})^2}{\sum_{i=1}^n (y_{i,actual} - \bar{y}_{actual})^2} \quad (15)$$

4. Results and Discussion

In the present study, two intelligent methods, namely GMDH and MLP ANN, are applied for the modelling of CO₂ emissions. GMDH Shell Software is used for the development of the GMDH model. The inputs of the proposed models are the total energy supply of different sources including 1. coal, 2. natural gas, 3. oil, 4. hydro, 5. biofuels and waste, 6. other renewables (wind, solar etc) and 7. GDP. The supplies of different energy sources are used as the inputs as the important factors of energy systems specifications and GDP is used as an economic index that can influence the emissions of greenhouse gases. The data are gathered for years between 1990 and 2021. The total number of datasets is equal to 96, that is not very big to make difficulties in analysis. Moreover, there is no missing data in the considered period. Furthermore, it is assumed that all of the obtained data are correct. Due to the mentioned reasons, no preprocessing is done for the present analysis and modelling (García et al., 2015, 2016). It should be noted that all of the raw data are used and no normalization is applied. Data related to the supply of different energy sources are obtained from the IEA website (Energy Statistics Data Browser, n.d.-c; Energy Statistics Data Browser, n.d.-a; Energy Statistics Data Browser, n.d.-b) and the GDP data are gathered from the WorldBank website (GDP (Current US\$) - Kazakhstan, n.d.; GDP (Current US\$) - Turkmenistan, n.d.; GDP (Current US\$) - Uzbekistan, n.d.). For training and testing of the proposed models, 70% and 30% of datasets were used, respectively. It should be indicated that validation dataset is not considered in the present study. In Figure 6, a comparison between the modelled and actual values of

CO₂ emission is presented. Most of the data are very close to Y=X line which means the prediction is precise and accurate. The R² value of this model for overall data is 0.9936. This value of R² is very close to 1 and it means that the precision of the model is acceptable. In Figure 7, RD of the different data versus the corresponding actual value of CO₂ emission is depicted. It can be observed that for the majority of cases, the value of RD is in the range of ±5%, indicating high precision of the model, and the maximum absolute value is around 20.5%. High values of RD in some years of the models have been reported in other studies on the similar problems. For instance, Ahmadi et al. (Ahmadi, Dehghani Madvar, et al., 2019). reported that for their model for CO₂ emission prediction in Latin American countries by use of PSO-LSSVM method, maximum value of RD was around 22%. The obtained values for the developed model in this study indicate that the model is acceptable for the estimation of CO₂ emission in the majority of the cases and could be applied for this purpose.

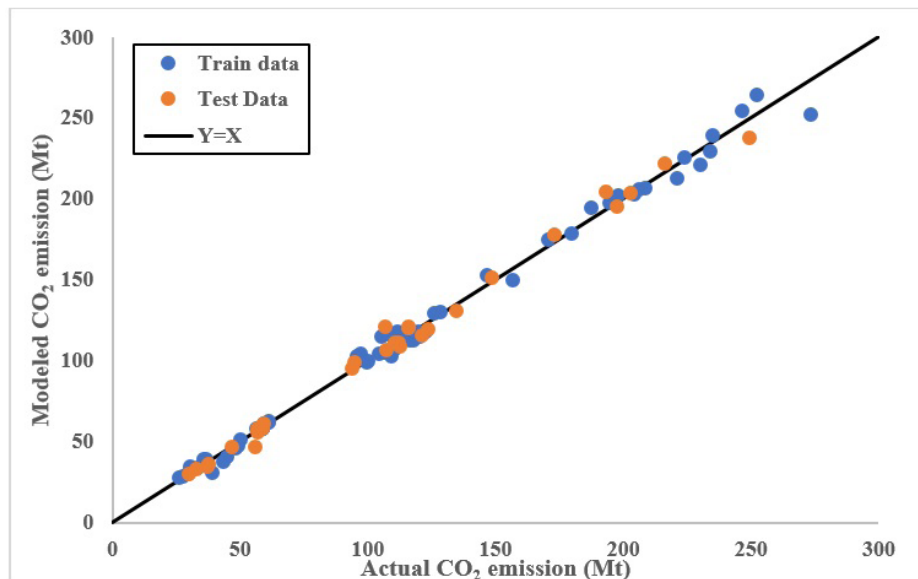


Figure 6. Comparison of modelled and actual values of CO₂ emission for the GMDH model.

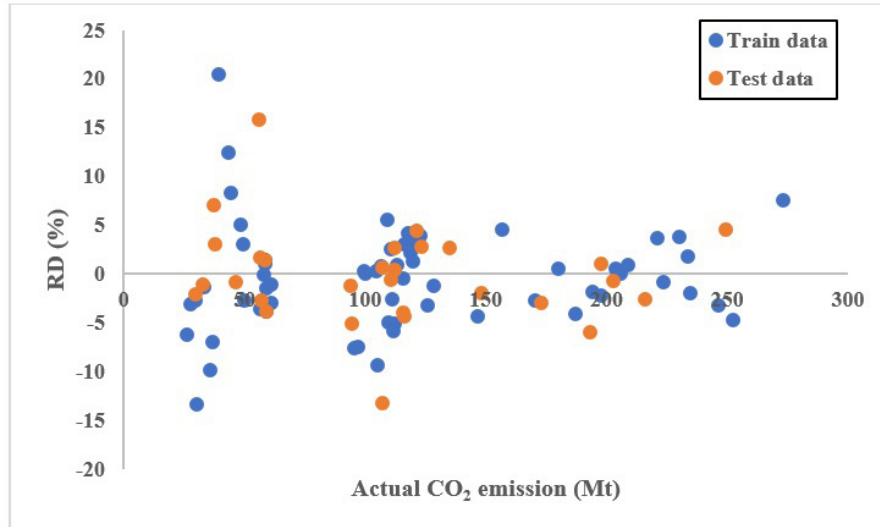


Figure 7. RD value vs actual values of CO₂ emission for the GMDH model.

Similar data are applied for the modelling of CO₂ emissions in the mentioned countries by use of MLP ANN. In the proposed model, just a single hidden layer is considered and various numbers of neurons, from 4 to 15, were applied to reach the maximum precision. In Table I, MSE values of different model structures are represented. It can be observed that the consideration of 5 neurons in the network provides the model with maximum precision among the tested networks. In this case, the MSE value of the network is 29.55 and R^2 is 0.9929. In Figure 8, the comparison is provided between the actual and modelled values for the MLP model it can be observed that the majority of the predictions are close to $Y=X$ line, meaning the high exactness of the model. Similar to the previous model, values of RD vs the actual value of the emission are depicted in Figure 9. It can be observed that the maximum absolute RD is higher than the GMDH model; however, the majority of the RD values are in the range of $\pm 5\%$. To have a better understanding of both models, the values of AARD for the models are compared in Figure 10. According to the obtained values of AARD, approximately 4.28% and 3.69% for the MLP and GMDH models, the latter model is a bit more accurate.



Table I. Values of MSE for different network structures.

Number of neurons	Data set	MSE value
4	Train	736.94
	Test	459.23
	Overall	653.05
5	Train	35.50
	Test	22.74
	Overall	29.55
6	Train	59.51
	Test	30.58
	Overall	50.77
7	Train	67.33
	Test	15.18
	Overalls	51.57
8	Train	26.55
	Test	176.54
	Overall	71.86
9	Train	144.71
	Test	121.40
	Overall	137.67
10	Train	152.78
	Test	139.91
	Overall	148.89
11	Train	57.44
	Test	4109
	Overall	52.51
12	Train	71.70
	Test	25.99
	Overall	57.89
13	Train	116.54
	Test	7.32
	Overall	83.55
14	Train	43.67
	Test	8.06
	Overall	32.92
15	Train	696.00
	Test	569.56
	Overall	657.80

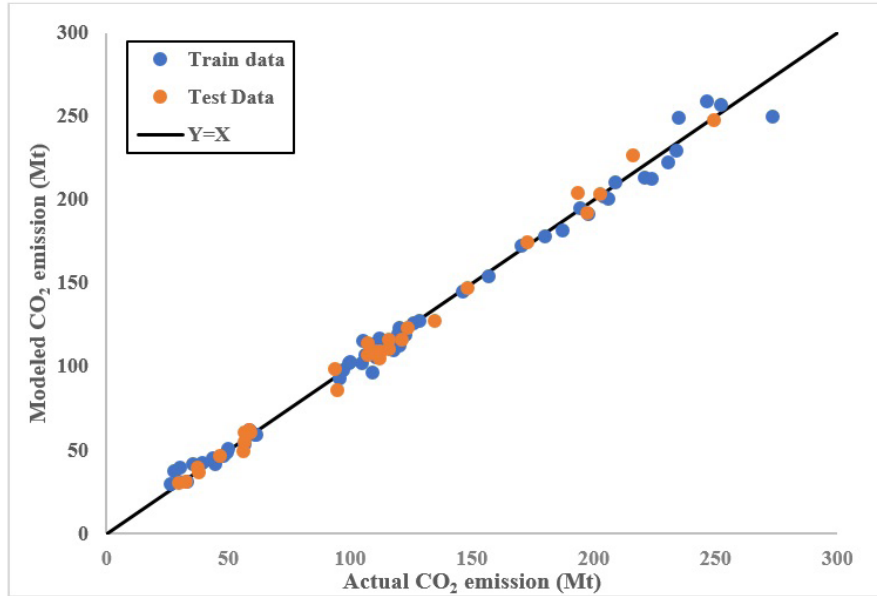


Figure 8. Comparison of modelled and actual values of CO2 emission for the MLP model.

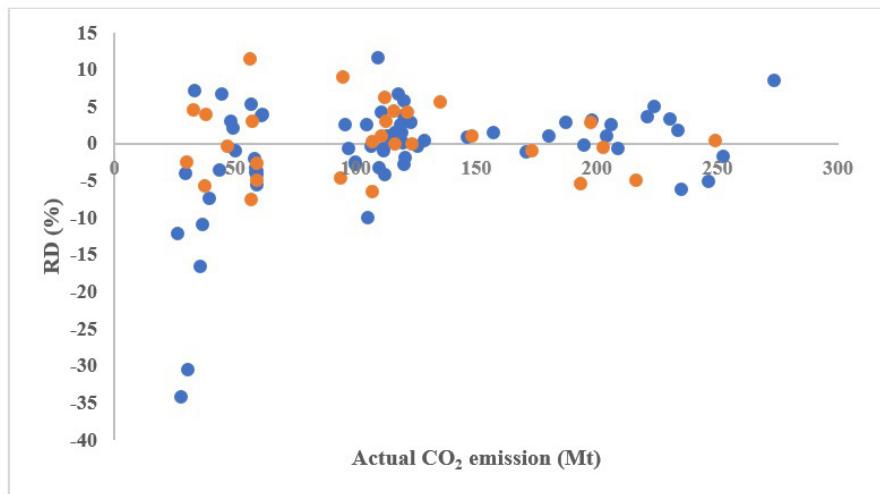


Figure 9. RD value vs actual values of CO2 emission for the MLP model.

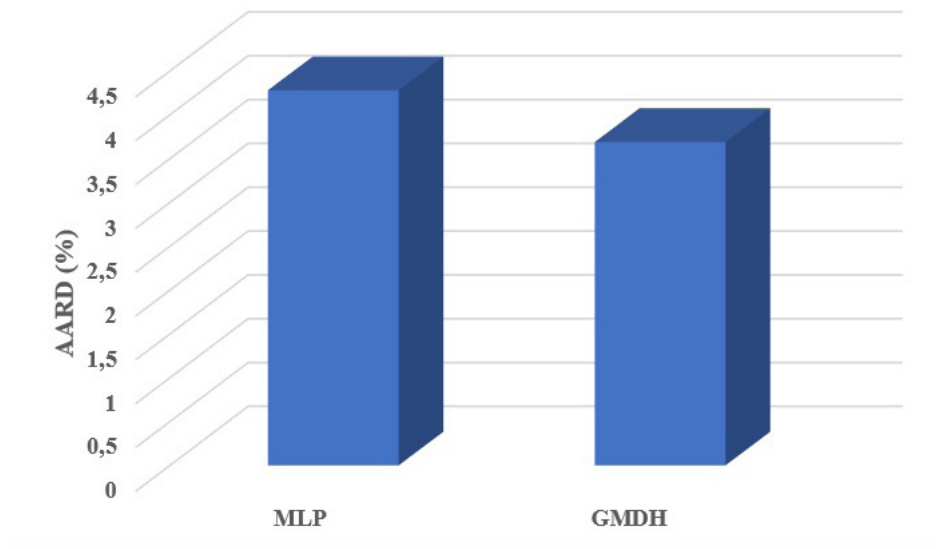


Figure 10. AARD of the proposed models.

According to the obtained values for R^2 , AARD and RD, it can be denoted that the proposed models have acceptable performance in the estimation of emissions. It should be noted that in the present model, it is assumed that the emission is a function of supplies of different energy sources and GDP while some other factors such as weather condition and social parameters could be effective on the emission. This assumption is considered due to the availability of the data and simplification of the proposed. The availability of all influential data on the emission of CO₂ and quantifying the detail specifications of the energy system specifications are among the most important limitations to propose more accurate and detailed models. The use of these models can be beneficial for policymakers and scholars to estimate emissions in upcoming years and evaluate different scenarios. By use of these models, different scenarios can be evaluated and compared in term of CO₂ emissions.

Algorithm synthesis ability via the learning process and obtaining solution of the cases of the nonlinear problems in addition to the models robustness are the principle advantages of ANNs; however, need to training process for each problem, necessity of applying multiple tests for finding the best structure and requirement for datasets with large size for network training are the main disadvantages of these techniques (Alhuyi Nazari et al., 2021; Navarro, 2013). In this regard, some other methods can be considered. In future studies, other intelligent methods including ANFIS, LSSVM etc could be tested and compared with the present model. In some cases, depending on the problems and their characteristics, the employment of other models can result in higher exactness and more accurate predictions. The main advantages of ANFIS are its reliable performance in capturing the nonlinear

architecture of a procedure and fast capacity of learning. Furthermore, this technique has both numerical and linguistic knowledge (Şahin & Erol, 2017). Ability of obtaining nonlinear solutions is among the most important advantages of SVM-based approaches; however, knowledge requirement related to the kernel function is the main problem of this method (Alhuyi Nazari et al., 2021). Aside from use of other methods, it would be an applicable recommendation to use different activation functions in the MLP model to investigate if those models could be more precise or not. In addition, it is suggested to consider more countries in the region to improve the comprehensiveness of the models.

5. Conclusion

In conclusion, this study highlights the intricate relationship between CO₂ emissions, influenced significantly by energy consumption patterns, energy source compositions, and economic indicators. CO₂ emission is dependent on a variety of factors and parameters; however, energy consumption and shares of different sources are very influential. In addition to them, GDP could be an affecting factor that should be considered in the estimation and forecasting of emissions. The main contribution of the present work is applying data-driven methods based on artificial intelligence to develop predictive models for the CO₂ emissions. This study considered three countries namely Kazakhstan, Uzbekistan and Turkmenistan as the cases. Sources such as IEA, the WorldBank and USAID were used for data gathering. It also provided valuable insights into the energy systems of these nations, along with their respective policies aimed at enhancing energy efficiency and reducing emissions. Central Asian countries are increasingly recognizing the pivotal role of economic policies and energy strategies in shaping their emission trajectories. Policies that integrate economic growth with sustainable energy practices are crucial. Measures such as incentivizing renewable energy investments, promoting energy efficiency in industries and households, and adopting cleaner technologies can significantly mitigate CO₂ emissions while fostering economic development.

The application of the Group Method of Data Handling (GMDH) and Multilayer Perceptron (MLP) models demonstrated strong performance in estimating emissions, with the GMDH showing a marginal advantage in accuracy over MLP. Comparison analysis indicated that both models have acceptable accuracy; however, making use of GMDH is preferred in terms of exactness compared with the MLP. The high coefficients of determination (R^2) and low average absolute relative deviations (AARD) for both models—0.9936 and 3.69% for GMDH, and 0.9929 and 4.28% for MLP—underscore their reliability. The proposed models can serve as valuable tools for predicting future emissions, offering insights that can inform policymakers in

formulating effective strategies for sustainable development and environmental stewardship. The policymakers can consider these models to evaluate different scenarios for prediction of emissions in future and compare them with each other. In future studies, other structures of networks and functions can be applied to develop more accurate models. Moreover, some other data-driven techniques such as LSSVM and ANFIS can be considered for modelling the emission of CO₂ to achieve more accurate predictions.

Acknowledgements

This research was supported by the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP23490690, BR21882258).

References

- Ahmadi, M. H., Dehghani Madvar, M., Sadeghzadeh, M., Rezaei, M. H., Herrera, M., & Shamshirband, S. (2019). Current Status Investigation and Predicting Carbon Dioxide Emission in Latin American Countries by Connectionist Models. *Energies*, 12(10), 1916. <https://doi.org/10.3390/en12101916>
- Ahmadi, M. H., Jashnani, H., Chau, K. W., Kumar, R., & Rosen, M. A. (2019). Carbon dioxide emissions prediction of five Middle Eastern countries using artificial neural networks. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*. <https://doi.org/10.1080/15567036.2019.1679914>
- Alhuyi Nazari, M., Mukhtar, A., Yasir, A. S. H. M., Rashidi, M. M., Ahmadi, M. H., Blazek, V., Prokop, L., & Misak, S. (2023). Applications of intelligent methods in solar heaters: an updated review. *In Engineering Applications of Computational Fluid Mechanics* (Vol. 17, Issue 1). Taylor and Francis Ltd. <https://doi.org/10.1080/19942060.2023.2229882>
- Alhuyi Nazari, M., Salem, M., Mahariq, I., Younes, K., & Maqableh, B. B. (2021). Utilization of Data-Driven Methods in Solar Desalination Systems: A Comprehensive Review. *Frontiers in Energy Research*, 0, 541. <https://doi.org/10.3389/FENRG.2021.742615>
- Altikat, S. (2021). Prediction of CO₂ emission from greenhouse to atmosphere with artificial neural networks and deep learning neural networks. *International Journal of Environmental Science and Technology*, 18(10), 3169-3178. <https://doi.org/10.1007/s13762-020-03079-z>
- Betting Big on Renewables. (n.d.). USAID. <https://www.usaid.gov/stories/betting-big-on-renewables#:~:text=From 2018 to 2020%2C USAID,the road for a year.>
- Carbon Capture, Utilisation and Storage. (n.d.). IEA. <https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage>
- CO₂ Emissions in 2023 A new record high, but is there light at the end of the tunnel? (2024).
- Decree of the President of the Republic of Uzbekistan “On measures to radically improve the management system of the fuel and energy industry of the Republic of Uzbekistan” dated 01.02.2019 №UP-5646. (2022). IEA. <https://www.iea.org/policies/13314-decree-of-the-president-of-the-republic-of-uzbekistan-on-measures-to-radically-improve-the-management-system-of-the-fuel-and-energy-industry-of-the-republic-of-uzbekistan-dated-01022019-up-5646>
- Dossumbekov, Y. K., Zhakiyev, N., Nazari, M. A., Salem, M., & Abdikadyr, B. (2024). Sensitivity analysis and performance prediction of a micro plate heat exchanger by use of intelligent approaches. *International Journal of Thermofluids*, 22(February), 100601. <https://doi.org/10.1016/j.ijft.2024.100601>

- Elbaz, K., Shen, S., Zhou, A., Yin, Z., & Lyu, H. (2021). Prediction of Disc Cutter Life During Shield Tunneling with AI via the Incorporation of a Genetic Algorithm into a GMDH-Type Neural Network. *Engineering*, 7(2), 238-251. <https://doi.org/10.1016/j.eng.2020.02.016>
- Electric Vehicles. (2023). IEA. <https://www.iea.org/energy-system/transport/electric-vehicles>
- Energy. (2023). CAREC. [https://www.carecprogram.org/?page_id=16#:~:text=Key Projects,support growth in ongoing trade.](https://www.carecprogram.org/?page_id=16#:~:text=Key%20Projects,support%20growth%20in%20ongoing%20trade.)
- Energy efficiency classes of buildings. (2022). IEA. <https://www.iea.org/policies/7040-energy-efficiency-classes-of-buildings>
- Energy Statistics Data Browser. (n.d.-a). IEA. <https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?country=KAZ>
- Energy Statistics Data Browser. (n.d.-b). IEA. <https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?country=UZB>
- Energy Statistics Data Browser. (n.d.-c). IEA. <https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?country=TKM>
- Executive summary. (n.d.). IEA. <https://www.iea.org/reports/kazakhstan-2022/executive-summary>
- Farlow, S. J. (2020). *Self-Organizing Methods in Modeling: GMDH Type Algorithms*. CRC Press, Boca Raton.
- Filik, Ü. B., & Filik, T. (2017). Wind Speed Prediction Using Artificial Neural Networks Based on Multiple Local Measurements in Eskisehir. *Energy Procedia*, 107, 264-269. <https://doi.org/10.1016/J.EGYPRO.2016.12.147>
- Filipović, S., Orlov, A., & Panić, A. A. (2024). Key forecasts and prospects for green transition in the region of Central Asia beyond 2022. *Energy, Sustainability and Society*, 14(1), 25. <https://doi.org/10.1186/s13705-024-00457-0>
- García, S., Luengo, J., & Herrera, F. (2015). *Data Preprocessing in Data Mining (Vol. 72)*. Springer International Publishing. <https://doi.org/10.1007/978-3-319-10247-4>
- García, S., Ramírez-Gallego, S., Luengo, J., Benítez, J. M., & Herrera, F. (2016). Big data preprocessing: methods and prospects. *Big Data Analytics*, 1(1), 9. <https://doi.org/10.1186/s41044-016-0014-0>
- GDP (current US\$) - Kazakhstan. (n.d.). WorldBank. <https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?locations=KZ>
- GDP (current US\$) - Turkmenistan. (n.d.). WorldBank. <https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?locations=TM>
- GDP (current US\$) - Uzbekistan. (n.d.). WorldBank. <https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?locations=uz>
- Ghalandari, M., Forootan Fard, H., Komeili Birjandi, A., & Mahariq, I. (2020). Energy-related carbon dioxide emission forecasting of four European countries by employing data-driven methods. *Journal of Thermal Analysis and Calorimetry*, 1-10. <https://doi.org/10.1007/s10973-020-10400-y>
- Heat Pumps. (n.d.). IEA. <https://www.iea.org/energy-system/buildings/heat-pumps>
- KAZAKHSTAN: Law No. 541-IV of 2012 on Energy Saving and Energy Efficiency (2019 Ed.). (2019). *Asia-Pacific Energy*. <https://policy.asiapacificenergy.org/node/135>
- Kim, M., & Okuyucu, O. (2022). Prediction of Undrained Shear Strength by the GMDH-Type Neural Network Using SPT-Value and Soil Physical Properties. *Materials*, 15, 6385. <https://doi.org/10.3390/ma15186385>
- Komeili Birjandi, A., Fahim Alavi, M., Salem, M., Assad, M. E. H., & Prabaharan, N. (2022a). Modeling carbon dioxide emission of countries in southeast of Asia by applying artificial neural network. *International Journal of Low-Carbon Technologies*, 17, 321-326. <https://doi.org/10.1093/ijlct/ctac002>

- Komeili Birjandi, A., Fahim Alavi, M., Salem, M., Assad, M. E. H., & Prabakaran, N. (2022b). Modeling carbon dioxide emission of countries in southeast of Asia by applying artificial neural network. *International Journal of Low-Carbon Technologies*, 17, 321-326. <https://doi.org/10.1093/ijlct/ctac002>
- Kuziboev, B., Saidmamatov, O., Khodjanizayov, E., Ibragimov, J., Marty, P., Ruzmetov, D., Matyakubov, U., Lyulina, E., & Ibadullaev, D. (2024). CO2 Emissions, Remittances, Energy Intensity and Economic Development: The Evidence from Central Asia. *Economies*, 12(4), 95. <https://doi.org/10.3390/economies12040095>
- Law of the Republic of Uzbekistan “On the use of renewable energy sources” dated May 21, 2019 No. ZRU-539. (2022). IEA. <https://www.iea.org/policies/13310-law-of-the-republic-of-uzbekistan-on-the-use-of-renewable-energy-sources-dated-may-21-2019-no-zru-539>
- Luo, X. J., Oyedele, L. O., Ajayi, A. O., Akinade, O. O., Owolabi, H. A., & Ahmed, A. (2020). Feature extraction and genetic algorithm enhanced adaptive deep neural network for energy consumption prediction in buildings. *Renewable and Sustainable Energy Reviews*, 131, 109980. <https://doi.org/10.1016/J.RSER.2020.109980>
- M. K., A. N., & V., M. A. (2020). Role of energy use in the prediction of CO2 emissions and economic growth in India: evidence from artificial neural networks (ANN). *Environmental Science and Pollution Research*, 27(19), 23631-23642. <https://doi.org/10.1007/s11356-020-08675-7>
- Nationally Determined Contribution (NDC) to the Paris Agreement (2022 Update): Turkmenistan. (n.d.). IEA. <https://www.iea.org/policies/17050-nationally-determined-contribution-ndc-to-the-paris-agreement-2022-update-turkmenistan>
- Navarro, R. I. (2013). Study of a neural network-based system for stability augmentation of an airplane Annex 1 Introduction to Neural Networks and Adaptive Neuro-Fuzzy Inference Systems (ANFIS).
- Oh, S., & Pedrycz, W. (2002). The design of self-organizing Polynomial Neural Networks. 141, 237-258.
- On protection of the atmospheric air. (2022). IEA. <https://www.iea.org/policies/11440-on-protection-of-the-atmospheric-air>
- Pindoriya, N. M., Singh, S. N., & Singh, S. K. (2008). An adaptive wavelet neural network-based energy price forecasting in electricity markets. *IEEE Transactions on Power Systems*, 23(3), 1423-1432. <https://doi.org/10.1109/TPWRS.2008.922251>
- Population, total - Kazakhstan. (n.d.). *WorldBank*. <https://data.worldbank.org/indicator/SP.POP.TOTL?locations=KZ>
- Population, total - Turkmenistan. (n.d.). *WorldBank*. <https://data.worldbank.org/indicator/SP.POP.TOTL?locations=TM>
- Population, total - Uzbekistan. (n.d.). *WorldBank*. <https://data.worldbank.org/indicator/SP.POP.TOTL?locations=UZ>
- Radovanović, M., Filipović, S., & Andrejević Panić, A. (2021). Sustainable energy transition in Central Asia: status and challenges. *Energy, Sustainability and Society*, 11(1), 49. <https://doi.org/10.1186/s13705-021-00324-2>
- Renewables. (n.d.). IEA. <https://www.iea.org/energy-system/renewables>
- Rezaei, M. H., Sadeghzadeh, M., Alhuyi Nazari, M., Ahmadi, M. H., & Astarai, F. R. (2018a). Applying GMDH artificial neural network in modeling CO2 emissions in four nordic countries. *International Journal of Low-Carbon Technologies*, 13(3), 266-271. <https://doi.org/10.1093/ijlct/cty026>
- Rezaei, M. H., Sadeghzadeh, M., Alhuyi Nazari, M., Ahmadi, M. H., & Astarai, F. R. (2018b). Applying GMDH artificial neural network in modeling CO2 emissions in four nordic countries. *International Journal of Low-Carbon Technologies*, 13(3), 266-271. <https://doi.org/10.1093/ijlct/cty026>
- Şahin, M., & Erol, R. (2017). A Comparative Study of Neural Networks and ANFIS for Forecasting Attendance Rate of Soccer Games. *Mathematical and Computational Applications* 2017, Vol. 22, Page 43, 22(4), 43. <https://doi.org/10.3390/MCA22040043>
- The Law About Support the Use of Renewable Energy Sources (amended). (2022). IEA. <https://www.iea.org/policies/5407-the-law-about-support-the-use-of-renewable-energy-sources-amended>

- The Outlook for the Development of Renewable Energy in Uzbekistan. (2014).
- Transition to renewable energy sources: economic benefits for entrepreneurs in Kazakhstan. (2024). *UNDP*. <https://www.undp.org/kazakhstan/stories/transition-renewable-energy-sources-economic-benefits-entrepreneurs-kazakhstan>
- Turkmenistan. (n.d.). *IEA*. <https://www.iea.org/countries/turkmenistan>
- Turmunkh, B.-E. (2021). Renewable and Non-Renewable Energy Consumption, Carbon Dioxide Emissions, and Economic Growth: Empirical Evidence from Central Asian Countries. *Journal of Economics and Development Studies*, 9(1). <https://doi.org/10.15640/jeds.v9n1a7>
- UNDP continues to support Turkmenistan in improving energy efficiency and developing renewable energy sources. (n.d.). *IEA*. <https://www.undp.org/turkmenistan/press-releases/undp-continues-support-turkmenistan-improving-energy-efficiency-and-developing-renewable-energy-sources>
- USAID Energizes Uzbekistan's First Green Hydrogen Hub. (n.d.). *USAID*. <https://uz.usembassy.gov/usaaid-energizes-uzbekistans-first-green-hydrogen-hub/>
- USAID Power Central Asia. (n.d.). *IEA*. <https://www.usaid.gov/central-asia-regional/fact-sheets/usaaid-power-central-asia>
- Uzbekistan. (n.d.). *IEA*. <https://www.iea.org/countries/uzbekistan>
- Uzbekistan (12/08). (n.d.). *U.S. Department of State*. <https://2009-2017.state.gov/outofdate/bgn/uzbekistan/113251.htm>
- Xiu, Z. Wei. (2022). Environmental implications of economic transition in Central Asia: A study of energy consumption and carbon emissions. *Top Academic Journal of Economics and Statistics*, 7(3), 19-39.
- Yuldoshboy, S., Karimov, M., & Kuralbaev, J. (2022). The association between CO2 and economic growth in Central Asian countries: Panel data approach. *Journal of Positive School Psychology*, 5587-5601.
- Zhakiyev, N., Khamzina, A., Zhakiyeva, S., De Miglio, R., Bakdolotov, A., & Cosmi, C. (2023). Optimization Modelling of the Decarbonization Scenario of the Total Energy System of Kazakhstan until 2060. *Energies*, 16(13), 5142. <https://doi.org/10.3390/en16135142>



Проблемы повышения энергоэффективности жилых многоквартирных зданий в условиях текущих цен на тепловую энергию в Казахстане

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АННОТАЦИЯ

Энергоэффективность является ключевым фактором при проектировании и эксплуатации зданий. В Республике Казахстан (РК), где здания занимают первое место по потреблению энергии (43 % от общего объема), жилой сектор играет важную роль, особенно в условиях холодного климата с продолжительными зимами. Основными факторами энергопотребления в жилых зданиях являются системы отопления и освещения. Анализ в рамках исследования, проведенный с использованием статистических методов, выявил причины высокого удельного расхода тепловой энергии, включая низкие тарифы и недостаток инвестиций в термомодернизацию зданий. В статье представлены результаты анализа энергопотребления в жилищном секторе Казахстана, а также основные причины высокого энергопотребления для отопления жилья, включая отсутствие инвестиций со стороны владельцев недвижимости в условиях низких цен на энергию в стране. Материалы, собранные автором в результате непосредственного участия в подготовке и реализации ряда пилотных проектов, демонстрируют потенциальный вклад технических мероприятий в общее сокращение энергопотребления в различных климатических условиях страны; позволили рассчитать рентабельность комплекса энергоэффективных мер для типового многоквартирного дома, а также сформулировать рекомендации по повышению энергоэффективности жилого сектора. Снижение энергопотребления в жилищном секторе будет способствовать сокращению выбросов парниковых газов, что особенно важно для достижения целей национальной климатической политики, включая Концепцию по переходу РК к «зеленой экономике», Определяемый на национальном уровне вклад (ОНУВ) и Стратегию достижения углеродной нейтральности РК до 2060 года. Результаты исследования основаны на данных, актуальных на конец 2021 г., и демонстрируют потенциал передовых технологий и целевых энергетических стратегий в смягчении последствий изменения климата.

Подана в редакцию:
29 марта 2024

Принята к публикации:
26 ноября 2024

Доступ онлайн:
7 декабря 2024

КЛЮЧЕВЫЕ СЛОВА

Энергоэффективность, жилые многоквартирные дома, тепловая энергия, энергопотребление, демонстрационные проекты, мониторинг эффектов, Казахстан

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1. Введение

Общая площадь жилищного фонда в Казахстане по состоянию на 2021 год составляет 387,7 млн. кв. м (О жилищном фонде, 2022) из которых 250,3 млн. кв. м (64,5 %) приходится на города. В городах Казахстана жилищный фонд широко представлен многоквартирными жилыми домами (МЖД), т.е. зданиями, включающими более одной квартиры, владельцами которых являются разные собственники, на долю которых приходится около 65 % общей площади ЖФ. По данным Бюро национальной статистики (О жилищном фонде, 2022) на 2021 год число многоквартирных жилых домов в стране составляет - 310 810 единиц с наибольшей концентрацией в городе Алматы и области, а также Восточно-Казахстанской и Карагандинской областях.

Представляет интерес история строительства этих домов. На рисунке 1 ниже представлена диаграмма, показывающая доли домов по году их постройки. Это интересно, поскольку здания, построенные до 1990 года в Казахстане создавались без энергосбережения и также не ремонтировались за последние 20-30 лет (Иванова, 2020). Таким образом общее число домов, возведенных до 1990 года в стране составляет не менее 82 % (см. рис. 1).

В Казахстане в настоящее время действует строительный норматив, регламентирующий предельное количество тепловой энергии, которое жилое здание должно потреблять на нужды отопления и вентиляции. Впервые подобный норматив действует с 2004 года, (документ СН РК 2.04-21-2004* «Энергопотребление и тепловая защита гражданских зданий» (Государственные нормативы..., 2006)). Новые стандарты энергоэффективности для зданий впервые определяют критерии, такие как потребление тепловой энергии на обогрев помещений в течение отопительного сезона, учитывая обмен воздуха, тепловые потери и расположение зданий.

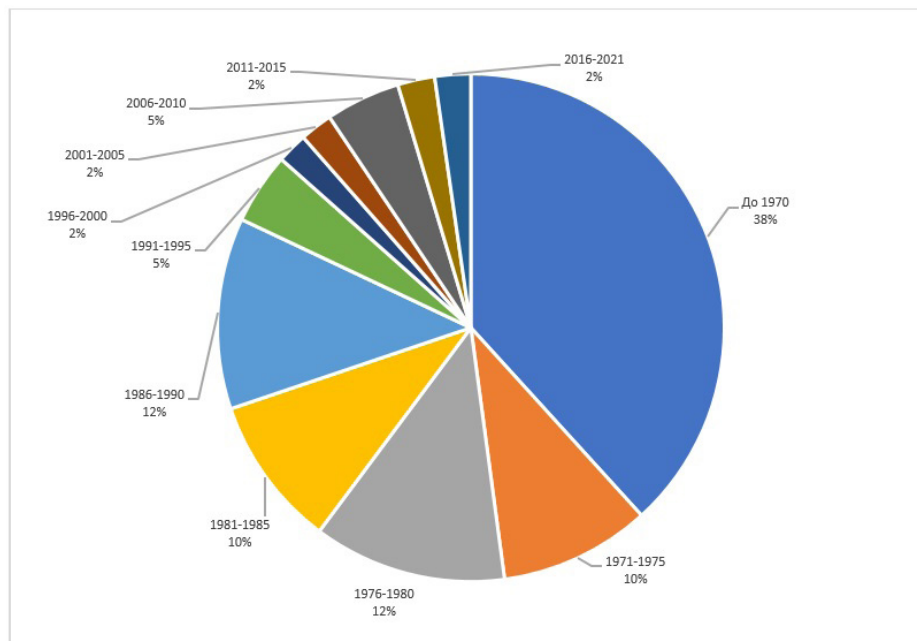


Рис. 1. Доля (%) МЖД по году постройки
(О жилищном фонде, 2022)

В соответствии с обновленными в 2011 году строительными стандартами, были внесены изменения в тепловую защиту зданий, в результате чего был принят СН РК 2.04-03-2011 (Государственные нормативы..., 2012). Этот документ ввел классификацию энергоэффективности зданий с использованием латинских букв от А до Е и дополнительные подклассы, такие как А++, В+, С+ и С-. Базовый показатель энергопотребления был ужесточен в среднем на 6%. По действующим нормам, новые жилые здания должны соответствовать как минимум классу С-, что соответствует уровню «Нормальный», в то время как уже существующие здания необходимо модернизировать для повышения их уровня энергоэффективности. Важным аспектом повышения энергоэффективности жилого сектора является снижение выбросов парниковых газов. В Казахстане данная задача интегрирована в ключевые стратегические документы, включая Концепцию перехода к зеленой экономике, Национально определяемые вклады (NDC) и Стратегию углеродной нейтральности к 2060 году. Особое внимание уделяется сокращению выбросов в секторе отопления, который занимает значительную долю в общем энергопотреблении страны. Реализация энергоэффективных мероприятий в жилом секторе позволяет как сократить расходы на энергоресурсы, так и внести вклад в выполнение климатических целей страны.

2. Обзор литературы

За последнее время в научной литературе опубликован ряд статей с тематиками близкими к рассматриваемым в настоящей статье. Так, в исследовании

Shevyakova и др. (2022) описаны проблемы внедрения энергосберегающих технологий в ЖКХ Казахстана. Основные препятствия включают низкий уровень тарифов, высокую изношенность сетей (70-80 %) и недостаток инвестиций. Для устранения этих проблем предложены меры, такие как модернизация оборудования и стимулирование инвестиций через государственные программы, например, "Нурлы Жер" и "Сильные регионы".

Исследование Tukhtamisheva и др. (2020) анализирует влияние низких цен на тепловую энергию на эффективность изоляции жилых зданий. При сохранении регулируемых цен отсутствует экономическое обоснование для внедрения более эффективных решений. Предложено использовать методику оптимизации тепловой изоляции, включая расчеты полной стоимости улучшений за жизненный цикл зданий, чтобы стимулировать более энергоэффективные стандарты строительства.

Assylbayev и др. (2023) отмечают необходимость повышения энергоэффективности как стратегического направления в условиях роста потребностей населения. Выделены климатические, экономические и социальные преимущества, включая сокращение выбросов, снижение затрат на энергопотребление и улучшение качества жизни. Предложено использовать налоговые стимулы и государственные инвестиционные программы для модернизации жилого фонда.

В исследовании Sharipov и др. (2021) анализируются проблемы энергосбережения в строительной отрасли Казахстана, включая высокую энергоемкость зданий и устаревшие строительные технологии. Авторы подчеркивают необходимость устранения законодательных и технических барьеров, совершенствования стандартов энергоэффективности, использования вторичных и возобновляемых источников энергии, а также внедрения эффективных систем вентиляции. Основными препятствиями остаются низкий уровень внедрения энергоэффективных технологий и слабый контроль за соблюдением стандартов на этапе проектирования и эксплуатации зданий.

Исследование Dyussebekova и др. (2022) показывает потенциал снижения энергопотребления через термомодернизацию зданий. Рассматриваются различные сценарии модернизации: от минимального (замена окон и утепление кровли) до значительного сокращения энергопотребления на 50 %. Авторы подчеркивают важность разработки политик и финансовых механизмов, таких как карбоновые офсеты, для стимулирования модернизации зданий.

Выводы из рассмотренной литературы подтверждают актуальность повышения энергоэффективности жилых зданий в Казахстане. Основные рекомендации включают: внедрение экономически оправданных стандартов тепловой изоляции; модернизацию существующего жилого фонда с учетом местных климатических условий; разработку стимулирующих мер для привлечения инвестиций. Эти работы поддерживают ключевые аспекты

настоящей статьи, подчеркивая связь между низкими ценами на энергию и недостаточной мотивацией к энергоэффективности, что достаточно подробно рассмотрено в статье ниже на примере пилотных проектов, в реализации которых принимал участие сам автор. Также, отметим, что сравнение статистических данных по энергопотреблению зданий, представленных в публикациях последних 3-4 лет, с данными 10-12-летней давности (в период активной реализации пилотных проектов), показывает, что ситуация с энергоэффективностью в стране существенно не изменилась. Это позволяет обоснованно использовать в данном исследовании более ранние данные, которые остаются актуальными и доступны для анализа.

3. Потребление энергии в секторе жилых зданий Казахстана

Большая часть жилищного фонда в казахстанских городах представлена многоэтажными домами, обеспеченными централизованным отоплением и электроснабжением, возведенными из кирпича, панельных и блочных конструкций, а также из железобетонного монолита (О жилищном фонде, 2022). С каждым годом такие здания все больше устаревают, что делает необходимым производить их ремонт и термомодернизацию для повышения энергоэффективности.

Правительство РК в 2011 году утвердило Программу модернизации жилищно-коммунального хозяйства Республики Казахстан на 2011-2020 годы одной из задач которой, было проведение ремонтов МЖД не менее чем в 10 % жилых зданий, требующих ремонта. Программа финансировалась Правительством РК на возвратной основе (жители возвращали беспроцентные кредиты в срок до 7 лет за мероприятия которые были выполнены в зданиях уполномоченными строительными организациями, подконтрольные акиматам городов и областей (местная администрация).

Благодаря усилиям международных организаций, реализующих в то время пилотные проекты, в частности, ПРООН, удалось включить в эту Программу мероприятия по термомодернизации жилых зданий в качестве обязательной меры при проведении капитальных ремонтов в зданиях (Panchenko N., Olshanskaya M., Gogunova I., Belyu A., 2013). Основанием для такого решения послужили энергоаудиты в жилых многоквартирных домах, проведенные государством и проектами международных организаций во всех регионах страны.

Эти энергоаудиты показали значительный удельный расход тепла в зданиях, который в среднем составил около 216-240 кВт·ч/м² в год (для сравнения: в европейских странах - 82-130 кВт·ч/м² в год). На рисунке 2 ниже на основе данных проведенных энергоаудитов в 2012-2013 гг. автором показаны сводные по регионам страны значения отклонений (в %) фактического удельного расхода тепловой энергии, потребляемой на нужды отопления, от требуемого по строительному нормативу (действовавшему на тот период времени).

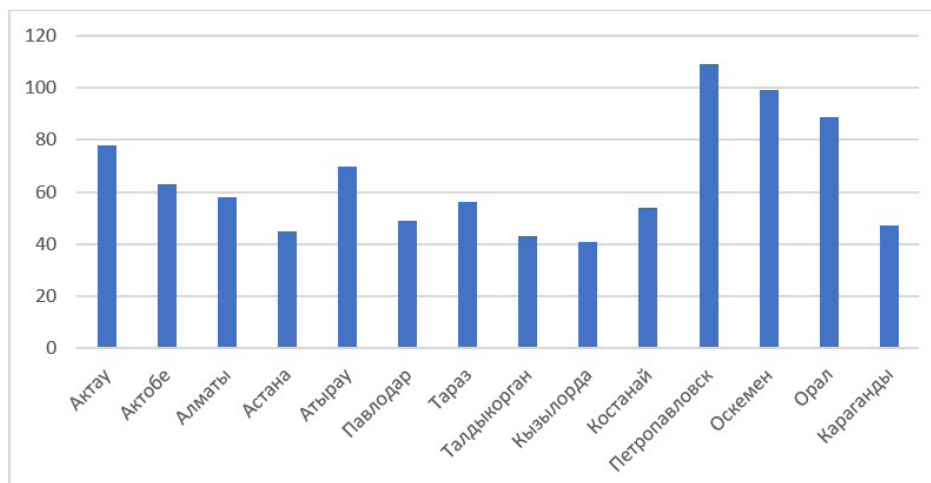


Рис. 2. Отклонение (%) фактического удельного энергопотребления для отопления жилых многоквартирных зданий от нормативного по регионам Казахстана - составлено автором на основе опубликованных данных энергоаудитов.

Как видно из рисунка 2, энергопотребление (на отопление) превышает минимальные требования норматива во всех регионах на 43-109 %. Наибольшие значения отклонений характерны для крайних северного, восточного и западного регионов Казахстана. В этих регионах удельное потребление тепловой энергии наибольшее и составляет 338, 284 и 250 кВт·ч/м² год - Петропавловск, Оскемен и Орал -соответственно. Высокие значения потребления тепловой энергии в многоквартирных жилых домах отмечаются и на юге, (в г. Алматы - 136 кВт·ч/м² в год (превышение 58 % по отношению к нормативному)), в г. Тараз - 142 кВт·ч/м² в год (превышение на 56 %), Актау - 126 кВт·ч/м² в год (превышение на 78 %).

Жесткие зимние условия, охватывающие большую часть Казахстана, а также длительное теплое и сухое лето в южных, центральных и западных регионах, требуют значительного использования тепловой энергии для обогрева зданий в холодное время года и электроэнергии для их охлаждения в летние месяцы. В этом причины высокого потребления тепловой и электрической энергии в городах Казахстане.

В период с 2011 по 2017 годы, благодаря сотрудничеству проектов ПРООН-ГЭФ и Правительства Республики Казахстан, было выполнено энергетическое обследование серии многоквартирных домов в различных населенных пунктах страны. Данные о потреблении энергии этими зданиями были собраны и представлены в таблице 1.

Таблица 1. Количество тепла (кВт/час на 1 м²), необходимого для отопления в МЖД в различных населённых пунктах Казахстана в сопоставлении с действующими строительными требованиями (Шрекенбах, Белый, 2022)

№ п/п	Этажность	Материал стен	Год постройки	Город	Фактическое потребление тепловой энергии (кВт·ч/м ² в год)	Требования СНиП РК для класса «С-» (не более кВт·ч/м ² в год)	Отклонение от норматива (%)	Класс энергоэффективности
1	9	ж/б панель	1988	Караганда	230	142	38	E
2	4	ж/б панель	1969	Алматы	264	97	63	E
3	5	кирпич		Астана	266	168	37	E
4	3	кирпич	1959	Караганда	290	166	43	E
5	5	ж/б панель	1971	Астана	212	168	21	D
6	5	ж/б панель	1971	Астана	184	168	9	D
7	5	ж/б панель	1971	Астана	211	168	20	D
8	5	ж/б панель	1971	Астана	209	168	20	D
9	5	ж/б панель	1971	Астана	198	168	15	D
10	5	ж/б панель	1987	Темиртау	235	160	32	E

Таблица составлена автором на основе информации, представленной в работах (Белый и др., 2013; Велуу и др., 2013).

Представленные выше результаты свидетельствуют о высоком энергопотреблении в жилых многоквартирных домах Казахстана (даже в южных городах), что объясняется следующими факторами.

Во-первых, это техническое состояние существующего жилого фонда (прежде всего состояние ограждающих конструкций зданий, кровли, подвалов и инженерных систем зданий). В прошлом дома, построенные до 1990-2000 гг., как было показано выше, не отличаются энергоэффективностью, они не достаточно утеплены. Кроме этого, дома длительное время не ремонтировались, в большинстве домов системы отопления, горячего водоснабжения, канализации, освещения требуют капитального ремонта. В подавляющем большинстве обследованных жилых домов не было капитального ремонта кровли с момента постройки здания. Имеются значительные повреждения кровельного покрытия. Некоторые вентиляционные шахты разрушены. В разрушенных выводах вентиляционных колодцев скапливается мусор, который затрудняет воздухообмен помещений,

особенно в тёплый сезон. Здания, имеющие наибольшие проблемы относятся, как правило, к крупнопанельным, в которых межпанельные швы разошлись и требуют заделки и утепления. Как показала проведенная тепловизионная съемка объектов, потери тепла через ограждающие конструкции значительны.

Во-вторых, в большинстве зданий отсутствует автоматическое регулирование теплового потока (АТП) на отоплении и горячем водоснабжении, что исключает возможность экономного расходования тепловой энергии, особенно в переходные сезоны года. Также примерно 90 % установленных в подъездах светильников - энергозатратного устаревшего типа, что обуславливает большой расход электроэнергии на освещение мест общего пользования. Распределительные щиты электроснабжения находятся в неудовлетворительном состоянии.

В-третьих, это сложившаяся система управления и обслуживания жилыми многоквартирными зданиями. Долгое время (в советский период) содержанием жилых многоквартирных домов занималось государство, жители не были собственниками своих квартир и не несли полное бремя расходов на эти цели. После приватизации жилья в 90-х гг. прошлого века класс собственников жилья в стране так до конца и не сложился. Люди мало заботятся о состоянии общих инженерных коммуникаций дома, не привыкли вкладывать свои собственные средства для этих целей. Об этом свидетельствуют также проведенные с участием автора социологические исследования во время реализации пилотных демонстрационных проектов (Белый и др., 2014). Система, обязывающая это делать и в настоящее время до конца не продумана и не проработана. В результате многоквартирные дома продолжают устаревать и еще больше повышается их энергопотребление.

Впрочем, перечисленные причины высокой энергоёмкости сектора жилых зданий Казахстана характерны и для других стран региона, соседей и стран с похожей экономикой, что отражено в ряде работ (Вытчиков и др., 2014; Sarbaeva et al., 2021; Zhigulina et al., 2020 и др.).

4. Возможности снижения энергопотребления в жилищном секторе Казахстана

В рамках «Программы модернизации ЖКХ на 2011-2020» и параллельных - принятых Правительством Программ, а также пилотных проектов, поддержанных различными донорами, такими как ПРООН, ГЭФ, USAID, ЕБРР др. с 2011 года в жилом фонде страны проводились ремонтные работы разного уровня. Анализ и мониторинг проведенных ремонтных работ показывает, что в комплексе можно получить экономию от 20 до 40 % теплоснабжения на одном здании. Такие проекты, выполненные в разных регионах Казахстана, были направлены

в основном на пилотирование следующих технических решений: модернизация системы теплоснабжения и горячего водоснабжения путем установки автоматизированных тепловых пунктов (АТП); повышение термического сопротивления ограждающих конструкций зданий путем герметизации и ремонта межпанельных швов на фасадах, кровли, подвалов зданий, замены окон и дверей на энергосберегающие в местах общего пользования; внедрение и пилотирование цифровых платформ для мониторинга энергопотребления и ряд других. Результаты реализованных пилотных демонстрационных проектов в Казахстане приведены в работах (Belyu и др., 2013; Белый и др., 2014). Ниже в таблице 2 показан свод основных результатов некоторых реализованных пилотов, в том числе результаты проведенного мониторинга теплоснабжения.

Таблица 2. Оценка результативности реализованных пилотных демонстрационных проектов по повышению энергоэффективности жилых зданий в городах Казахстана

Период мониторинга	Вклад мероприятий в результат	Снижение потребления теплоэнергии на нужды отопления за отопительный сезон		Суммарная экономия денежных средств по оплате за потребленную тепловую энергию за 1 календарный год	
		Гкал	%	Доллар США*	%
Объект: город Караганда, 9-ти этажный панельный дом, 1985 г. постройки					
2010-2016 гг.	АТП, Кровля, окна, двери, фасад	248,1	34,9	3062,0	41,5
Объект: город Караганда, 3-х этажный кирпичный дом 1965 г. постройки					
2011-2013 гг.	АТП, фасад, окна, кровля	133,9	32	344,7	15,6
Объект: город Караганда, 9-ти этажный кирпичный жилой дом, 1979 г. постройки					
2010-2012 гг.	АТП	303,67	32,3	1852,4	30,8
Объект: город Алматы, 4-х этажный панельный дом 1969 г. постройки					
2011-2013 гг.	АТП	111,4	28,6	3183,8	41,5
Объект: город Темиртау, 5-ти этажный панельный дом 1987 г. постройки					
2019-2020 гг.	АТП, кровля, окна, фасад, подвал, инженерные сети, освещение	348,52	45	2036,2	40,5
Объект: город Астана, 5-ти этажный панельный дом 1974 г. постройки					
2020-2022 гг.	АТП, кровля, окна, фасад, подвал, инженерные сети, освещение	250	35	3 192	29

*Суммы экономии показаны в долларах США по курсу «доллар к тенге»

на 1 июля 2021 г.

Как видно из приведенных данных, процент экономии теплотенергии при реализации различных мероприятий находится в интервале от 28 до 45 % за отопительный сезон. Разный уровень экономии объясняется разным состоянием зданий, построенным в разные годы, разными типами применявшихся при строительстве технологий и решений и, следовательно, разными тепловыми потерями, а также разными техническими решениями, примененными при термомодернизации зданий в рамках пилотных проектов. Этот вывод согласуется, в частности, с выводами, изложенными в ряде публикаций, например в (Şıtağas и др., 2010; Filippidou и др., 2016). При этом, как известно, процент экономии тепла значительно возрастает при повышении комплексности термомодернизации зданий, т.е. совместного выполнения мер по инженерным системам и ограждающим конструкциям здания, что подтверждается собственными данными автора, изложенными в работе (Белый и др., 2014).

Важным замечанием, которое хочется отметить здесь - в Казахстане до сих пор отсутствуют пилотные проекты, которые могли бы продемонстрировать эффективность сплошного утепления фасада жилого здания. Первые такие проекты были выполнены еще в 2012 году в г. Актобе, однако, достоверность мониторинга данных проектов вызывает сомнение в результате завышенного по мнению автора процента полученной экономии (90 %). Другой пилот - несколько лет назад по типу «мокрый фасад» был утеплен многоквартирный жилой дом в Астане. Утепление продемонстрировало хороший эффект, но здание на котором был реализован пилот - это новое здание, построенное всего 5 лет назад и там уже применены многие энергоэффективные решения, так что определить эффективность мер по сплошному утеплению фасада для существующего жилого фонда на примере данного проекта не представляется корректным. На старых жилых зданиях (до 1990 года постройки) меры по сплошному утеплению фасада в Казахстане до сих пор не проводились и не оценивались. В этой связи далее будем говорить только о частичной модернизации фасада - а именно герметизации и ремонтам межпанельных швов зданий.

На основе результатов ранее реализованных пилотных проектов в Казахстане (Belyu и др., 2013; Белый и др., 2014), автором были рассчитаны вклады отдельных реализованных технических мероприятий в общее сокращение энергопотребления типового многоквартирного жилого здания (5 этажей, крупнопанельного типа с 80-тью квартирами). Наибольший эффект (суммарно до 75 %) дают мероприятия в подвале здания (модернизация отопления, утепление инженерных коммуникаций, перекрытия подвала), а также мероприятия на кровле - ее утепление и гидроизоляция (19 %). Другие мероприятия менее эффективны, их вклад составляет от 1 до 4 %. Тем не менее, эти мероприятия необходимы для создания теплового комфорта внутри помещения и эстетического вида модернизированного здания.

Выполнение такой комплексной работы с целью снижения энергопотребления наталкивается на серьезное препятствие в виде потребностей в значительных инвестициях. Ниже (рис. 3) приведен составленной автором график зависимости достигнутой величины энергосбережения в жилом здании от уровня инвестиций в него (из расчёта на 1 м² площади квартир), требуемых для выполнения термомодернизации. Зависимости, представленные ниже, определены по итогам реализации пилотных проектов в Казахстане (суммарно было охвачено анализом 10 пилотных проектов).

Как видно на графике, наиболее затратными мероприятиями (8,5-10 USD/м²), дающими незначительный эффект (1,5-2 %) являются герметизация межпанельных швов и обустройство неотапливаемых закрытых пространств на балконах (остекление). Также достаточно затратен ремонт кровли здания (9,5 USD/м²), но эффект от него значительно больше (23 %).

Проведение вышеупомянутых мероприятий в подобных типах жилых домов приводит к увеличению энергоэффективности до уровня "С" - "нормальный" в соответствии с текущими строительными нормами Казахстана (Государственные нормативы..., 2015). Основные расходы направляются на ремонт крыши, фасада и инженерных коммуникаций в жилом здании. Общая сумма требуемых вложений составляет более 69 миллионов тенге на каждое здание (приблизительно 162 тысячи долларов США по курсу на июль 2021 года). Учитывая, что в таком доме обычно располагается 80 квартир, каждому собственнику квартиры необходимо вложить в ремонт здания свыше 2 тысяч долларов США.

При этом экономический эффект от комплексной термомодернизации составляет всего немногим более 1,3 млн. тенге за год на все здание. Понятно, что даже простой срок окупаемости этих мероприятий превышает все разумные пределы (более 50 лет). Понятно, что такая ситуация обусловлена достаточно низкими тарифами на энергию в Казахстане: в качестве примера отметим, что стоимость 1 Гкал тепловой энергии в Астане составила на начало 2023 г. 2,4 тыс. тенге (около 5 долларов США), что в 10 раз меньше, чем, например, в странах Европы.

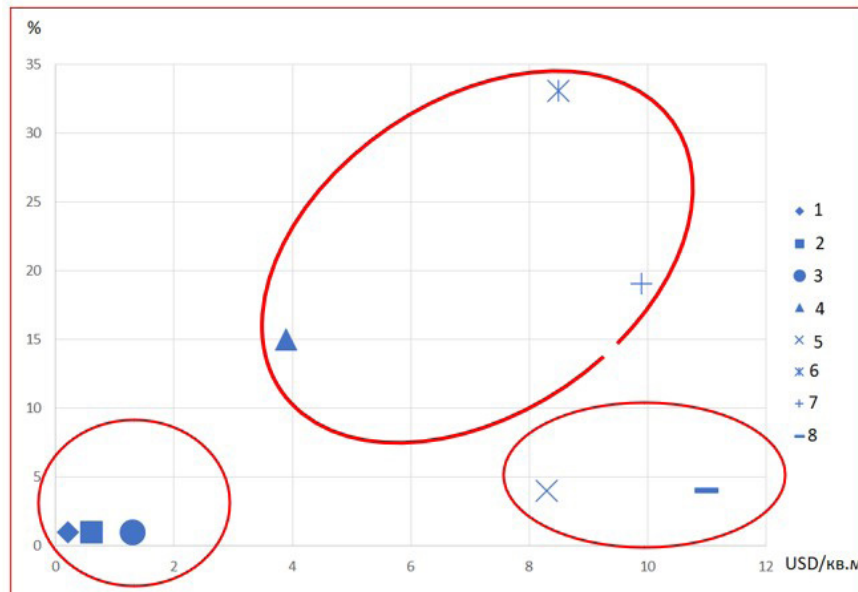


Рис. 3. Зависимость достигнутой величины энергосбережения (%) в жилом здании от уровня инвестиций (USD/1 кв. м), требуемых для выполнения отдельных мероприятий по термомодернизации жилого здания. 1 - Замена светильников в подъездах и другого дежурного освещения; 2 - Замена входных групп в подъездах (теплые тамбуры); 3 - Замена светопрозрачных конструкций в подъездах; 4 - Утепление подвала; 5 - Ремонт и герметизация межпанельных швов на фасаде; 6 - Монтаж Автоматизированного тепlopункта с заменой системы разводящих трубопроводов отопления и ГВС (горячая вода) по подвалу здания; 7 - Гидроизоляция и утепление кровельной системы; 8 - Остекление балконов.

5. Доступность услуг по термомодернизации домов в условиях низких цен на энергоносители

В связи с вышеизложенным справедлив вопрос о доступности потребителям в Казахстане расходов на термомодернизацию жилья сегодня. Вначале проанализируем из чего состоят расходы на коммунальные услуги. Для этого были проанализированы данные за 2021-2022 гг. для 1500 домохозяйств в трех городах Казахстана - Астана, Алматы и Атырау. В качестве исходных данных были использованы коммунальные счета (квитанции) за уплаченные коммунальные услуги как в отопительный, так и в неопотительный периоды года в квартирах многоэтажных жилых домов.

В исследуемых домохозяйствах была проанализирована структура коммунальных платежей, и особое внимание уделяется затратам на отопление и ГВС. Это объясняется тем, что именно затраты на теплоэнергию определяют класс энергоэффективности зданий в Казахстане, согласно действующим строительным нормам и правилам. Стоит отметить, что жители Казахстана оплачивают отопление лишь в период с середины октября до середины апреля, что соответствует продолжительности отопительного сезона в стране.

Исходя из проведенного анализа, было установлено (Белый, 2022), что в период отопительного сезона доля затрат на отопление и горячее водоснабжение варьируется от 25 % в Астане до 40 % в Алматы от общей суммы коммунальных платежей. Вне этого сезона расходы на горячее водоснабжение составляют лишь 3-5 % от коммунального бюджета. Когда учитываются затраты на отопление, горячее водоснабжение и электричество, они занимают от 34 % до 50 % коммунального бюджета в холодные месяцы и не более 35 % в теплые.

Для анализа финансовой нагрузки, связанной с оплатой коммунальных услуг домохозяйствами, в том числе за тепло, использовались статистические данные о доходах и расходах семей, предоставленные Национальным Бюро статистики за второй квартал 2021 года. Исходя из среднемесячных трат на содержание дома, выявлено, что в летние месяцы доля коммунальных платежей в трех городах колеблется от 7 до 10 процентов, а в зимние месяцы – от 11 до 13 процентов от общего бюджета домохозяйства.

Автором было проведено исследование, в ходе которого определено, что затраты на теплоэнергию занимают от 1,9 % до 3,6 % общих месячных расходов домохозяйств в холодный период года. Вне отопительного сезона, с апреля по октябрь, эти расходы снижаются до 0,96 % в Атырау и до 1,83 % в Алматы, что является весьма малой частью годового бюджета на коммунальные услуги.

Собранные данные указывают на то, что затраты на теплоэнергию составляют лишь незначительную часть расходов казахстанских домохозяйств. Это говорит о том, что интерес владельцев квартир к повышению энергоэффективности их домов, основанный исключительно на экономической выгоде, пока не проявляется. Большинство людей не склонны уделять внимание энергосбережению, поскольку текущие расходы на отопление невелики, в то время как затраты на реализацию мер по снижению энергопотребления остаются значительными.

В ходе исследования был проведен анализ, который позволил определить процентное соотношение общих затрат на коммунальные платежи и работы по термомодернизации (с учетом выплат по коммерческому кредиту) в общем доходе домохозяйств разных категорий в нескольких городах страны, результаты которого представлены в таблице 3.

Таблица 3. Величина (%) общих расходов на жилищно-коммунальные услуги и проведение термомодернизации у различных категорий домохозяйств в Казахстане (Белый, 2022)

№	Город	Среднестатистическое домохозяйство	Домохозяйство с двумя пенсионерами	Домохозяйство с одним пенсионером
1	Астана	18,50 (8,12)	20,07 (9,94)	31,30 (19,88)
2	Алматы	18,64 (7,28)	22,95 (9,94)	35,40 (19,88)
3	Атырау	20,65 (8,13)	23,20 (9,94)	34,98 (19,88)

Примечание:

В скобках показана доля затрат на термомодернизацию здания.

Расчеты были проведены:

- с учетом 30 %-ого сокращения энергии после термомодернизации здания;
- с учетом равных аннуитетных платежей для возврата взятого банковского кредита по ставке 14 % в течение максимально 5 лет .

В расчетах включены текущие затраты на основные коммунальные услуги, а также расходы по обслуживанию коммерческого кредита, взятого в коммерческом банке по ставке 14 % годовых на 5 лет с учетом ежемесячных аннуитетных платежей. Очевидно, что эти расходы составляют в среднем от 16 % до 19 % для семей с работающими членами, более 20 % для семей с двумя пенсионерами и более 30 % для семей с одинокими пенсионерами. При этом доля кредита на термомодернизацию составляет приблизительно половину от всех расходов данных домохозяйств.

Безусловно, для домохозяйств с пенсионерами требуется поддержка государства в форме частичной компенсации расходов, например, через предоставление жилищной помощи. Стоит отметить, что для домохозяйств с работающими собственниками в первом приближении доля коммунальных расходов (включая расходы на термомодернизацию) не считается критической по меркам многих европейских стран, где порогом часто является 25-30 % от общих расходов. Однако, учитывая среднюю заработную плату в Казахстане по сравнению с Европой, а также высокий процент расходов на продукты питания по проведенным социологическим опросам, становится ясно, что даже доля в 16-19 % на коммунальные расходы и термомодернизацию является значительной для определенной части населения, например, многодетных семей или семей с минимальным доходом. Таким образом, необходима продуманная помощь со стороны государства, основанная на доходах конкретного домохозяйства и ожидаемом уровне энергосбережения после термомодернизации. Важно учитывать положительный опыт других стран при разработке мер поддержки.

6. Заключение

Многokвартирные жилые здания в Казахстане являются важным направлением для сокращения энергопотребления, особенно в части достижения страной климатических обязательств. Как показал анализ имеющихся данных, энергопотребление для отопления этих зданий превышает минимальные требования норматива во всех регионах страны на 43-109 %. В то же время реализованные пилотные проекты продемонстрировали возможность добиться в среднем от 30 до 50 % экономии теплотребления на одном здании, что в условиях наблюдающегося в последнее время роста тарифов на тепловую и электрическую энергию весьма привлекательно для собственников. Снижение энергопотребления в существующих зданиях снижает и риски нехватки тепловой энергии в городах в условиях бурного нового строительства и уменьшает давление на инфраструктуру, особенно в зимний период. Это позволяет государству перенаправить ресурсы на модернизацию других ключевых инфраструктурных объектов.

Повышение энергоэффективности в секторе жилых зданий приводит к достижению и других - косвенных, в том числе, и социальных эффектов. Термомодернизация жилых многоквартирных зданий в Казахстане - это не только вопрос экономической целесообразности для собственника, но и вопрос обеспечения продления срока службы жилых домов, повышение безопасности проживания, повышение качества предоставления коммунальных услуг, повышение рыночной стоимости недвижимости и пр., что по мнению автора должно приводить к снижению социальной напряженности в обществе и повысить доверие населения к государственным реформам, хотя достоверно подтвержденных данных этой зависимости в стране пока нет. Выяснением этой связи может быть дополнительным исследованием автора, которое является темой отдельной научной статьи.

Повышение энергоэффективности многоквартирных жилых домов в Казахстане может иметь как прямые, так и косвенные политические последствия, которые отражаются на различных уровнях государственного управления, экономики и общества. Так, массовая практика увеличения энергоэффективности жилищного фонда снизит удельное потребление энергии, что в сочетании с принимаемыми мерами по декарбонизации всего сектора энергетики будет благоприятно сказываться на выполнении международных обязательств Казахстана по климату. Все это несомненно повысит репутацию страны на международной арене как партнера, приверженного устойчивому развитию и борьбе с изменением климата. Это также вероятно укрепит позиции Казахстана в переговорах с международными финансовыми институтами и организациями,

такими как Всемирный банк, Европейский банк реконструкции и развития и Зеленый Климатический Фонд для привлечения в страну дополнительных зелёных инвестиций.

Повышение энергоэффективности в жилом секторе сможет со временем уменьшить государственные расходы на субсидирование коммунальных услуг и энергетической инфраструктуры, что освобождает средства для других социально значимых проектов. Программы по повышению энергоэффективности обычно стимулируют спрос на специалистов в области строительства, проектирования, управления энергоресурсами и внедрения новых технологий. Это способствует созданию новых рабочих мест, особенно в секторе малого и среднего бизнеса и, как следствие, приводит к увеличению налоговых поступлений в бюджет.

Как известно, Казахстан сталкивается с серьезными вызовами, связанными с изменением климата. Повышение энергоэффективности не только снижает выбросы парниковых газов, но и делает здания более устойчивыми к экстремальным погодным условиям, что снижает риски для здоровья населения и инфраструктуры. Все это является дополнительным важным стимулом для массовой практики термомодернизации зданий в стране. Исходя из вышеизложенного, повышение энергоэффективности жилого сектора зданий становится важнейшей государственной задачей.

Однако, не весь набор энергосберегающих мероприятий, применяемый обычно на практике, может быть рекомендован к повсеместному применению в жилом фонде Казахстана. Исследования показали, что ремонтные работы на фасаде здания имеют скорее эстетический характер. Хотя необходимы дополнительные тестовые пилотные проекты по сплошному утеплению фасада для определения достоверного эффекта от их реализации в условиях Казахстана, обозначения их места в системе мероприятий.

Работа по улучшению энергоэффективности жилого сектора сталкивается с проблемой отсутствия надежной информации о фактическом состоянии жилых зданий. К сожалению, в стране отсутствует широко распространенная и методологически стандартизированная система сбора данных о потреблении энергии в каждом здании.

Независимо от набора мероприятий для выполнения задачи повышения энергоэффективности жилого фонда потребуются значительные финансовые ресурсы. По оценкам автора они могут составить порядка 10-12 млрд. долларов США на весь жилой фонд. Укрупненный расчет основан на учете стоимости мероприятий для термомодернизации «среднестатистического дома», конфигурация которого была основана на статистических данных (пятиэтажный панельный жилой дом, с 80-тью квартирами и общей площадью не превышающей 4,5 тыс. кв. м.). Для покрытия этих расходов очевидно потребуются заемные

средства, которые можно привлечь и использовать по назначению с применением финансовых механизмов поддержки потребителей через субсидирование и предоставление разумной грантовой поддержки, что успешно продемонстрировал опыт реализации различных пилотных проектов в Казахстане.

Не все население страны безболезненно сможет нести бремя расходов, необходимых на термомодернизацию своего жилища. Как показали расчеты, как правило, работающим (молодым) семьям такие расходы будут вполне по силам (вместе с коммунальными услугами они составят 18-20 % от совокупного дохода семьи). Однако неработающим, а также пенсионерам необходима будет поддержка государства через систему жилищной помощи.

В рамках проведения дальнейшей тематической работы автор планирует дополнить текущее исследование оценкой косвенных потенциальных выгод от энергосбережения в жилом секторе зданий, что может быть предметом отдельной статьи.

Список литературы

- Белый, А. (2022). Сколько стоит энергоэффективность в Казахстане? Извлечено из: <https://svestnik.kz/skolko-stoit-jenergojeffektivnost-v-kazahstane/?ysclid=lu6ynvxt7m5 86 16 7346>
- Белый, А., Друзь, Н., Задворных, Е. (2014). Возможности достижения социальных эффектов через повышение энергоэффективности многоквартирных жилых домов. Астана: ПРООН
- Белый, А., Задворных, Е., Друзь, Н., Шопаева, А., Хилленберг, Р., Валишева, И. (2013). Демонстрационная зона энергосбережения: Пилотный демонстрационный проект по повышению энергоэффективности системы теплоснабжения жилого многоквартирного здания: Аprobация модели «Все расчеты через КСК». Астана: ПРООН
- Витчиков, Ю., Беляков, И., Нохрина, Е. (2014). Утепление фасадов зданий при капитальном ремонте существующего жилого фонда Самарской области. Вестник СГАСУ. Градостроительство и архитектура. Вып. № 3(16). С. 103-110
- Государственные нормативы в области архитектуры, градостроительства и строительства. (2006). Строительные нормы РК. СН РК 2.04-21-2004* Энергопотребление и тепловая защита гражданских зданий. Астана: АО «КазНИИСА»
- Государственные нормативы в области архитектуры, градостроительства и строительства. (2012). Свод правил Республики Казахстан. СП РК 2.04-106-2012. Проектирование тепловой защиты зданий. Астана: АО «КазНИИСА»
- Государственные нормативы в области архитектуры, градостроительства и строительства. (2015). Строительные нормы РК. СН РК 2.04-04-2011. Тепловая защита зданий. Астана: АО «КазНИИСА»
- Иванова, Л. (2020). Развитие нормативных требований к тепловой защите зданий. Архитектура и дизайн № 1. С. 33-44. <https://doi:10.7256/2585-7789.2020.1.35796>
- О жилищном фонде. (2022). Статистический сборник на казахском и русском языках. Астана: Бюро национальной статистики Агентства по стратегическому планированию и реформам Республики Казахстан
- Шрекенбах, Л., Белый, А. (2022). К вопросу о системной организации модернизации многоквартирного жилого фонда в Казахстане для целей декарбонизации. Извлечено из: https://uyushma.uz/f/20220411_kaz_promhouse_article_eer_full_ru.pdf

- Assylbayev, A., Safronchuk, M., Niiazaliev, K., Brovko, N. (2023). Green Transformation and the Concept of Energy Efficiency in the Housing Sector. *Innovative Trends in International Business and Sustainable Management*. E.I. Lazareva, A.D. Murzin, B.A. Rivza, and V.N. Ostrovskaya, Eds., in *Approaches to Global Sustainability, Markets, and Governance*. Singapore: Springer Nature Singapore, 2023, pp. 567-577. https://DOI:10.1007/978-981-19-4005-7_61
- Belyy, A., Zadvornyykh, Y., Andreyev, D., Druz, N. (2013). Demonstration energy saving zone: Pilot projects to improve the energy efficiency of the heat consumption systems of buildings: ESCO mechanism testing in Karaganda city, Republic of Kazakhstan. Astana: UNDP
- Dyussebekova, N., Temirgaliyeva, N., Umyshev, D., Shavdinova, M., Schuett, R., Bektalieva, D. (2022). Assessment of Energy Efficiency Measures' Impact on Energy Performance in the Educational Building of Kazakh-German University in Almaty. *Sustainability*: vol. 14, no. 16, p. 9813, Aug. 2022, <https://DOI:10.3390/su14169813>
- Filippidou, F., Nieboer, N., Visscher, H. (2016). Energy efficiency measures implemented in the Dutch non-profit housing sector. *Energy and Buildings*. Volume 132, 15 November 2016, PP. 107-116. <https://DOI:10.1016/j.enbuild.2016.05.095>
- Panchenko, N., Olshanskaya, M., Goruynova, I., Belyy, A. (2013). Removing Barriers to Energy Efficiency in Municipal Heat and Hot Water Supply: Accomplishments & Lessons Learned from the UNDP/GEF Project in Kazakhstan. Astana: UNDP
- Sarbaeva, N., Omurbekova, M., Jeenbaev, U. (2021). The problems of increasing energy efficiency in residential buildings. *The Herald of KSUCTA*. Vol. 71. No. 1. - P. 142-146
- Sharipov, R., Tyulyubayeva, D., Shavdinova, M., Kudrevich, O., Yerzhanov, S. (2021). Practice and future of energy-efficient construction in the Republic of Kazakhstan. *J Appl Eng Science*: vol. 19, no. 1, pp. 1-8, 2021, <https://DOI:10.5937/jaes0-27404>
- Shevyakova, A., Petrenko, Y., Koshebayeva, G., Ulybyshev, G. (2022). Peculiarities of Housing and Communal Services and the Difficulties of Implementing Energy-Saving Technologies: The Case of Kazakhstan. *Energies*: vol. 15, no. 20, p. 7576, Oct. 2022, <https://DOI:10.3390/en15207576>.
- Šumarac, D., Todorović, M., Djurović-Petrović, M., Trišović, N. (2010). Energy efficiency of residential buildings in Serbia. *Thermal Science: Year 2010*, Vol. 14, Suppl., PP. S97-S113. <https://DOI:10.2298/TSCI100430017S>
- Tukhtamisheva, A., Adilova, D., Banionis, K., Levinskytė, A., Bliūdžius, R. (2020). Optimization of the Thermal Insulation Level of Residential Buildings in the Almaty Region of Kazakhstan. *Energies*: vol. 13, no. 18, p. 4692, Sep. 2020, <https://DOI:10.3390/en13184692>
- Zhigulina, A., Ponomarenko, A., Borodacheva, E. (2020). Problems of Energy Efficiency of Residential Buildings. *IOP Conf. Series: Materials Science and Engineering* 753 (2020) 032020. <https://DOI:10.1088/1757-899X/753/3/032020>

Enhancing energy efficiency of residential apartment buildings against current thermal energy prices in Kazakhstan

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<https://doi.org/10.29258/CAJSCR/2024-R1.v3-2/24-44.rus>

ABSTRACT

Energy efficiency represents a key factor in building design and operation. In the Republic of Kazakhstan (RK), where buildings occupy the first place (43 %) in terms of energy consumption, the residential sector plays an important role, especially considering its cold climate with long winters. Heating and lighting systems are the main elements of energy consumption in residential buildings. The statistical analysis within the framework of the study allowed revealing the drivers of high specific thermal energy consumption, including low tariffs and lack of investment in building thermal upgrading. The article presents the analytical findings on the energy consumption in Kazakhstan's housing sector, as well as describes the main reasons for high energy consumption for housing heating, inter alia low investment on behalf of property owners in the context of low energy prices. The materials collected by the author as a result of direct participation in the preparation and execution of several pilot projects demonstrate the potential contribution of technical measures to the overall energy consumption reduction in various climatic conditions across the country; made it possible to calculate the profitability of a set of energyefficiency measures for a standard apartment building, as well as formulate recommendations for improving energy efficiency in the residential sector. Curtailing energy consumption in the sector will contribute to reducing greenhouse gas emissions, which is especially important for achieving the goals of national climate policy, including the Concept for the Transition of the RK to a "Green Economy", Kazakhstan's Nationally Determined Contribution (NDC) and Strategy of the RK for Achieving Carbon Neutrality by 2060. The study outputs are based on the data as of late 2021 and show the potential of new technologies and targeted energy strategies to mitigate climate change impacts.

ARTICLE HISTORY

Received: March 29, 2024

Accepted: November 26, 2024

Published: December 7, 2024

KEYWORDS

Energy efficiency, residential multi-apartment buildings, heating energy, energy consumption, demonstration projects, monitoring effects, Kazakhstan

References

- Assylbayev, A., Safronchuk, M., Niiazalieva, K., Brovko, N. (2023). Green Transformation and the Concept of Energy Efficiency in the Housing Sector, in Innovative Trends in International Business and Sustainable Management, E.I. Lazareva, A.D. Murzin, B.A. Rivza, and V.N. Ostrovskaya, Eds., in Approaches to Global Sustainability, Markets, and Governance. Singapore: *Springer Nature Singapore*, 2023, pp. 567-577. https://DOI:10.1007/978-981-19-4005-7_61
- Belyy, A. (2022). Skol'ko stoit jenergojeffektivnost' v Kazahstane? [How much does energy efficiency cost in Kazakhstan], Retrieved from: <https://svestnik.kz/skolko-stoit-jenergojeffektivnost-v-kazahstane/?ysclid=lu6ynvxt7m586167346> (in Russian)
- Belyy, A., Druz', N., Zadvornyh, E. (2014). Vozmozhnosti dostizhenija social'nyh jeffektov cherez povyshenie jenergojeffektivnosti mnogokvartirnyh zhilyh domov [Opportunities to achieve social effects through increasing the energy efficiency of multi-apartment residential buildings], Astana: *PROON*. (in Russian)
- Belyy, A., Zadvornyh, E., Druz', N., Shopaeva, A., Hillenberg, R., Valisheva, I. (2013). Demonstracionnaja zona jenergosberezhenija: Pilotnyj demonstracionnyj proekt po povysheniju jenergojeffektivnosti sistemy teplopotreblenija zhilogo mnogokvartirnogo zdaniya: Aprobacija modeli «Vse raschety cherez KSK» [Demonstration zone of energy saving: Pilot demonstration project to increase the energy efficiency of the heating system of a multi-apartment residential building: Testing of the model "All calculations via KSK"]. Astana: *PROON*. (in Russian)
- Belyy, A., Zadvornykh, Y., Andreyev, D., Druz, N. (2013). Demonstration energy saving zone: Pilot projects to improve the energy efficiency of the heat consumption systems of buildings: ESCO mechanism testing in Karaganda city, Republic of Kazakhstan. Astana: *UNDP*
- Dyussebekova, N., Temirgaliyeva, N., Umyshev, D., Shavdinova, M., Schuett, R., Bektaliev, D. (2022). Assessment of Energy Efficiency Measures' Impact on Energy Performance in the Educational Building of Kazakh-German University in Almaty. *Sustainability*: vol. 14, no. 16, p. 9813, Aug. 2022, <https://DOI:10.3390/su14169813>
- Filippidou, F., Nieboer, N., Visscher, H. (2016). Energy efficiency measures implemented in the Dutch non-profit housing sector. *Energy and Buildings*. Volume 132, 15 November 2016, PP. 107-116. <https://DOI:10.1016/j.enbuild.2016.05.095>
- Gosudarstvennye normativy v oblasti arhitektury, gradostroitel'stva i stroitel'stva. (2006). Stroitel'nye normy RK. SN RK 2.04-21-2004 [Gosudarstvennye normativy v oblasti arhitektury, gradostroitel'stva i stroitel'stva. (2006). Stroitel'nye normy RK. SN RK 2.04-21-2004] Jenergotreblenie i teplovaja zashhita grazhdanskijh zdaniy [Energy consumption and thermal protection of civil buildings]. Astana: AO «KazNIISA». (in Russian)
- Gosudarstvennye normativy v oblasti arhitektury, gradostroitel'stva i stroitel'stva [State regulations in the field of architecture, urban planning and construction]. (2012). Svod pravil Respubliki Kazahstan. SP RK 2.04-106-2012. Proektirovanie teplovoj zashhity zdaniy. [Code of Practice of the Republic of Kazakhstan. SP RK 2.04-106-2012. Design of thermal protection of buildings]. Astana: AO «KazNIISA». (in Russian)
- Gosudarstvennye normativy v oblasti arhitektury, gradostroitel'stva i stroitel'stva [State regulations in the field of architecture, urban planning and construction]. (2015). Stroitel'nye normy RK. SN RK 2.04-04-2011. Teplovaja zashhita zdaniy [Building codes GC. SN RK 2.04-04-2011. Thermal protection of buildings]. Astana: AO «KazNIISA». (in Russian)
- Ivanova, L. (2020). Razvitie normativnyh trebovanij k teplovoj zashhite zdaniy [Development of regulatory requirements for thermal protection of buildings]. *Arhitektura i dizajn* [Architecture and design] № 1. S. 33-44. <https://DOI:10.7256/2585-7789.2020.1.35796> (in Russian)
- O zhilishhnom fonde [About the housing stock]. (2022). Statisticheskij sbornik na kazahskom i russkom jazykah [Statistical collection in Kazakh and Russian languages]. Astana: *Bjuro nacional'noj statistiki Agentstva po strategicheskomu planirovaniju i reformam Respubliki Kazahstan* [Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan]. (in Russian)

- Panchenko, N., Olshanskaya, M., Goruynova, I., Belyy, A. (2013). Removing Barriers to Energy Efficiency in Municipal Heat and Hot Water Supply: Accomplishments & Lessons Learned from the UNDP/GEF Project in Kazakhstan. Astana: *UNDP*
- Sarbaeva, N., Omurbekova, M., Jeenbaev, U. (2021). The problems of increasing energy efficiency in residential buildings. *The Herald of KSUCTA*. Vol. 71. No. 1. - P. 142-146
- Sharipov, R., Tyulyubayeva, D., Shavdinova, M., Kudrevich, O., Yerzhanov, S. (2021). Practice and future of energy-efficient construction in the Republic of Kazakhstan. *J Appl Eng Science*: vol. 19, no. 1, pp. 1-8, 2021, <https://DOI: 10.5937/jaes0-27404>
- Shevyakova, A., Petrenko, Y., Koshebayeva, G., Ulybyshev, G. (2022). Peculiarities of Housing and Communal Services and the Difficulties of Implementing Energy-Saving Technologies: The Case of Kazakhstan. *Energies*: vol. 15, no. 20, p. 7576, Oct. 2022, <https://DOI: 10.3390/en15207576>
- Shrekenbah, L., Belyj, A. (2022). K voprosu o sistemnoj organizacii modernizacii mnogokvartirnogo zhilogo fonda v Kazahstane dlja celej dekarbonizacii [On the issue of systemic organization of modernization of multi-apartment housing stock in Kazakhstan for the purposes of decarbonization]. Retrieved from: https://uyushma.uz/f/20220411_kaz_promhouse_article_eer_full_ru.pdf (in Russian)
- Šumarac, D., Todorović, M., Djurović-Petrović, M., Trišović, N. (2010). Energy efficiency of residential buildings in Serbia. *Thermal Science*: Year 2010, Vol. 14, Suppl., PP. S97-S113. <https://DOI:10.2298/TSCI100430017S>
- Tukhtamisheva, A., Adilova, D., Banionis, K., Levinskytė, A., Bliūdžius, R. (2020). Optimization of the Thermal Insulation Level of Residential Buildings in the Almaty Region of Kazakhstan. *Energies*: vol. 13, no. 18, p. 4692, Sep. 2020, <https://DOI:10.3390/en13184692>
- Vytchikov, Ju., Beljakov, I., Nohrina, E. (2014). Uteplenie fasadov zdanij pri kapital'nom remonte sushhestvujushhego zhilogo fonda Samarskoj oblasti [Insulation of building facades during major repairs of existing housing stock in the Samara region]. *Vestnik SGASU. Gradostroitel'stvo i arhitektura* [Urban development and architecture]. Vyp. № 3(16). S. 103-110. (in Russian)
- Zhiguli, A., Ponomarenko, A., Borodacheva, E. (2020). Problems of Energy Efficiency of Residential Buildings. *IOP Conf. Series: Materials Science and Engineering* 753 (2020) 032020. <https://DOI: 10.1088/1757-899X/753/3/032020>



Strategic environmental assessment in Uzbekistan: current trends, challenges and future prospects

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ABSTRACT

This study has examined Uzbekistan's environmental assessment framework, focusing on the challenges impeding Strategic Environmental Assessment implementation, as well as how international practices and pilot initiatives can guide the establishment of a robust and sustainable domestic SEA system. Through the analysis of legal documents, reports and pilot action outputs, the study has identified deficiencies in decision making and inconsistent mainstreaming of ecological matters into strategic planning. Thus, the major challenges include limited SEA awareness, insufficient baseline data, and weak legal and regulatory setting. Pilot projects, such as the Charvak Free Tourist Zone SEA, had revealed tangible concerns, including difficulties in engaging local stakeholders, data gaps, and unclear inter-agency roles. While these do represent significant obstacles, they also offer valuable lessons learnt for forging a comprehensive SEA scheme. Although the absence of a strong legal basis remains a critical limitation, there exist opportunities to enhance coordination, oversight, and stakeholder inclusivity. Uzbekistan can build on international SEA trends associated with public engagement and climate risk evaluation, while also learning from regional and cross-border actions. Collaborations across Central Asia, particularly in managing shared water and biodiversity resources, render additional opportunities for harmonizing environmental governance. The key priorities include the adoption of SEA legislation, capacity building through training and awareness programs, and the establishment of national networking and information exchange mechanisms. These steps are vital for fostering sustainable development, preserving natural resources, and building public trust in ecological governance. The study findings furnish actionable insights for policymakers and practitioners in Uzbekistan and other nations facing similar environmental assessment challenges.

ARTICLE HISTORY

Received:
June 18, 2024
Accepted:
December 5, 2024
Published:
December 25, 2024

KEYWORDS

environment,
environmental assessment,
legal framework,
policymaking, strategic
environmental
assessment, sustainable

1. Introduction

The expansion of Strategic Environmental Assessment (SEA) addresses the mounting demand for sustainable development (SD) and environmental considerations. SEA methodically evaluates ecological consequences to promote the SD narrative within policies, programs, and plans (PPPs) (Helbron & Palekhov, 2010; Jackson & Illsley, 2008; Nzioki & Kitulazzi, 2016). It likewise serves a comprehensive tool for accommodating environmental and health objectives in strategic decision-making aimed at alleviating adverse economic and regional development effects (Sabeva, 2015; UNECE, 2018). SEA considers environmental and health issues during the formulation of PPPs (Fischer et al., 2010; Uganda, 2006), promoting nature-sensitive development. SEA also pushes the evolution of worldwide SD by detecting and assessing potential ecological impacts (Song & Kim, 2007; UNECE, 2003). The SEA application and study have been thorough in the Global North; however, its effectiveness in countries like Uzbekistan is still uncertain. This study aimed to answer the following questions: What are the challenges and opportunities for implementing SEA in Uzbekistan, and how SEA can contribute to sustainable development? This analysis explored Uzbekistan's socio-political and environmental landscape to assist other countries encountering similar challenges.

The SEA Protocol and Espoo Convention represent essential legal SEA frameworks on a global scale (Koyano, 2020; Marsden, 2011; Mulder, 2011). Both advocate for sustainable progress and ecological stewardship, albeit in distinct domains. On the one hand, the Espoo Convention of February 25, 1991 requires environmental impact assessments and international consultations regarding transboundary ecological effects of major development projects (Koyano, 2020; Marsden, 2011). On the other hand, the SEA Protocol - ratified May 21, 2003 - emphasizes the importance of incorporating environmental dimensions in initial planning in designated regions. Public engagement and preliminary evaluations are deemed fundamental for achieving sustainable development (UNECE, 2003).

Moreover, Directive 2001/42/EC of June 27, 2001, commonly referred to as the SEA Directive, serves a core EU legal basis for strategic environmental assessment (Kläne & Albrecht, 2005; Sheate, 2003) and requires environmental assessment of plans and activities with significant ecological impacts (Feldmann et al., 2001). The Directive also highlights the importance of rendering due attention to environmental considerations while elaborating and executing SD-related plans and programs via informed decision-making (SEA Directive, 2001).

SEA plays a crucial role in shaping government initiatives across sectors, as well as informs decision-making in agriculture, forestry, fishery, energy, industry (including mining), transportation, regional development, waste and water

management, telecommunications, tourism, urban planning, and land use; although it does not automatically extend over other economic sectoral or municipal plans, or minor revisions. National governments are mandated to assess the need for SEA. It is essential to implement this process when a plan, program, or minor modification is likely to result in compelling environmental or health impacts. Along with financial/budgetary plans and programs, national defence and civil emergency plans and programs are SEA-exempt (Spar, 2012) - i.e. the SEA Protocol applies solely to newly introduced plans and programs by national and local public agencies, excluding any pre-existing strategic documents.

A systemic approach merges environmental objectives into planning and decision-making associated with PPPs (Ahmed et al., 2005; Corpade et al., 2012). The associated scoping identifies key ecological issues and stakeholder concerns after confirming an assessment necessity and scope. The initial assessment examines the environment and analyses impacts by reviewing possible outcomes, explores potential options, and formulates risk reduction strategies. SEA reports are exhaustive and detailed, featuring quality assurance measures to secure precision and adherence to standards (Saleh & Qutb, 2021; Souloutzoglou & Tasopoulou, 2020). Evaluation strategies scrutinize the execution and ecological effects, whereas discussions with regulatory bodies and community engagement ensure openness and ownership (Reicher et al., 2021).

That said, SEA remains inadequately reflected in Uzbekistan's national-level planning, even in the remit of striking infrastructural and industrial growth. The country is confronted with challenges such as water scarcity, land deterioration, and air pollution (Gafurova & Juliyev, 2021; Makhmudov et al., 2023; Tukhtayeva, 2020), as well as exhibits a notably high rate of water withdrawal per capita further exacerbating water scarcity (World Bank, 2020).

Against this backdrop, the nation has implemented environmental laws and sustainability initiatives aimed at improving its environmental governance, although making decisions without thoroughly inspecting their environmental aftermath compromises their intent. This research aimed to explore Uzbekistan's need to incorporate strategic environmental assessment into its development framework to tackle ecological challenges and foster sustainable progress.

To evaluate the target country's preparedness for SEA and its potential influence on sustainable development goals (SDGs), this investigation has employed a mixed-method strategy comprising a review of Uzbekistan's valid environmental policies, analysis of globally applied SEA frameworks, and consultation with regional environmental data.

This research offers empirical evidence regarding the function of SEA in promoting sustainable environmental governance in post-Soviet nations and, thus,

establishes a foundation for future comparative research as well as contributes to the discourse on the effectiveness of SEA in addressing environmental challenges in rapidly developing economies. This study emphasizes the significance of SEA in promoting sustainable development and adhering to international ecological standards; analyzes the challenges and opportunities that Uzbekistan government faces in implementing efficient environmental governance strategies; and manifests an inaugural examination of the application of SEA in Uzbekistan, closing a significant gap in the existing academic literature and offering novel insights into the nation's environmental assessment framework.

2. Methodology

A sweeping literature review was conducted to collect relevant information on SEA, with a particular emphasis on its prospective implementation in Uzbekistan, including to analyze existing literature, legal documents, and policy reports pertinent to SEA, utilizing a qualitative research design. Using the keywords such as “Uzbekistan”, “environmental governance”, “SEA”, and “Strategic Environmental Assessment”, the search strategy covered numerous academic databases, including Scopus, Web of Science, and Google Scholar. The search was limited to peer-reviewed articles, reports, and policy documents published in English from 2000 onwards to guarantee their relevance to the ongoing ecological challenges of Uzbekistan and the policy frameworks associated with current SEA practices.

Titles and abstracts were initially screened according to the predetermined criteria, and full texts were subsequently reviewed in detail to guarantee the inclusion of high-quality and substantial information on SEA frameworks, case studies from comparable contexts, and best practices in environmental governance. The criteria for source selection were as follows: relevance to SEA frameworks, applicability to Uzbekistan or analogous emerging economies, emphasis on legal enforcement, and alignment with best environmental governance practices. The process entailed the identification of pertinent sources that offered an all-inclusive understanding of SEA principles and practices.

The review allowed identifying a notable deficiency in the scientific literature regarding SEA in Uzbekistan - mere absence of thematic peer-reviewed articles. While SEA serves mainly as a tool for policy and development organizations, studies related to SEA from various contexts offer essential insights for its implementation in emerging economies such as the target country. This study has investigated SEA frameworks and their performance in comparable regions, addressing a scientific gap related to the applicability and potential impact of SEA within Uzbekistan's distinct socio-

environmental context. To address this discrepancy, numerous reports were generated by a variety of programs implemented in Uzbekistan. Those papers provided essential information and insights essential for understanding the current state and prospects of SEA in the country. Additionally, legal documents were obtained from the national legislative database of the Republic of Uzbekistan (www.lex.uz). Functioning as the sole official electronic medium for disseminating legal acts passed in the Republic of Uzbekistan (RUz), this resource represents the primary legal information repository of the state. It was essential for the acquisition of relevant legal documents on the national ecological assessment system. Additionally, online inquiries were conducted to identify supplementary reports and international legal documents, thereby expanding the scope of sources and guaranteeing a comprehensive compilation of relevant information.

A two-step procedure was utilized to identify the challenges and solutions outlined in the results section (Table II.). Thematic analysis was first applied to national legal documents, policy reports, and international SEA case studies to identify prevalent challenges and possible strategies. This analysis involved categorizing key themes related to sector-specific issues, legal and procedural barriers, and challenges in environmental governance in RUz. Secondly, the authors' firsthand experience in implementing experimental SEA projects in Uzbekistan contributed valuable insights to the findings, facilitating the incorporation of practical challenges and context-specific solutions. The integration of experiential insights and thematic analysis enabled a thorough understanding of the issues and potential solutions specific to the Uzbek context.

In order to facilitate an in-depth assessment, sources were selected based on their relevance to the primary concerns of SEA implementation, legal frameworks, environmental governance practices, and the unique context of the RUz. The harvested data underwent meticulous analysis to detect the most common themes, trends, and gaps in Uzbekistan's current SEA procedures. This approach provided a profound examination of SEA application in Uzbekistan's situation.

The review's credibility and integrity were maintained by rigorously adhering to ethical considerations that ensured accurate data representation and proper source referencing. The analysis was conducted impartially to provide a balanced and objective perspective on the subject matter, and all information sources were appropriately acknowledged.

2.1. Historical development and current global SEA status

The SEA can be traced back to the US National Environmental Policy Act (NEPA) of 1969 that had introduced the concept of Environmental Impact Statements (EIS) for major federal actions (Fundingsland Tetlow & Hanusch, 2012). Over the years,

the practice of SEA has significantly evolved, influenced by various international frameworks and agreements. In the late 1980s and early 1990s, several countries began implementing SEA provisions, often building on their existing EIA frameworks (Josimović et al., 2022). Those provisions were typically integrated into one of the four categories: EIA laws (e.g., the USA), planning regulations (e.g., Sweden), administrative orders or policy directives (e.g., Canada), or processes of policy appraisal and plan evaluation (e.g., the United Kingdom) (Fundingsland Tetlow & Hanusch, 2012). The adoption of SEA frameworks has been growing ever since with notable developments in international policies and directives.

The key milestones in SEA overall evolution include the adoption of the United Nations Economic Commission for Europe (UNECE) Protocol on SEA to the Convention on Environmental Impact Assessment in a Transboundary Context (Espoo Convention) in 2003 (Grout et al., 2018; Souloutzoglou & Tasopoulou, 2020). The Protocol emphasizes the importance of integrating ecological assessments into policies and programs. The European Union's SEA Directive 2001/42/EC, adopted in 2001, requires member states to ensure that certain plans and programs undergo environmental assessment, promoting SD by incorporating ecological considerations from the outset (European Union, 2001). SEA is applied across a wide range of strategic activities, including national, regional, and local PPPs (Baynova, 2021).

SEA gained global prominence following the EU Directive on SEA and SEA Protocol. East and Southeast Asian nations, including Hong Kong, China, Taiwan, Vietnam, South Korea, and Indonesia, have embedded SEA into their environmental assessment frameworks to examine ecological and social impacts of PPPs. SEA is widely utilized in Nepal, Pakistan, and India for various PPPs, notably in forest planning, hydropower development, drainage initiatives, coastal zone management, and industrial growth (Hossan et al., 2021).

In recent years, various worldwide trends have influenced the development and implementation of SEA frameworks. Public participation has emerged as an essential element, guaranteeing decision-making transparency and inclusivity. The introduction of digital instruments, including Geographic Information Systems (GIS) and remote sensing, has markedly improved data collection, analysis, and visualization capabilities. Moreover, SEA frameworks have been progressively integrating climate risk assessments to comply with the objectives of the Paris Agreement, highlighting both adaptation and mitigation solutions. Furthermore, transboundary SEA projects are also gaining prominence facilitating cross-country cooperation to tackle shared ecological issues and advance SD regionally.

In summary, SEA renders a structured path for mainstreaming environmental agenda in high-level decision-making, supporting SD, nature protection, and climate change mitigation.

2.2. Current environmental assessment system and SEA trends in Uzbekistan

The evolution of ecological assessment in the target country has been marked by the introduction of various legal acts to streamline and improve the associated procedures. Table I. below chronologically outlines the aforementioned legal documents, highlighting their key provisions and status. This historical context provides a foundation for understanding the existing framework and gaps still requiring attention to fully instill SEA into national development planning.

Table I. Evolution of legal documents in Uzbekistan's environmental assessment system.

Year	Legal Act	Key Provisions	Status
1992	Law "On Nature Protection" of the RUz	Establishes procedures for EIA (RUz, 1992)	Active
2000	Law "On Ecological Appraisal" of the RUz	Provides environmental appraisal guidelines (RUz, 2000)	Active
2018	Resolution of the Cabinet of Ministers of the RUz "On approving the Regulation on the state ecological appraisal"	Detailed regulations for state ecological appraisal implementation (RUz, 2018)	No longer valid
2019	Decree of the President of the RUz "On approving the 2030 Environmental Protection Concept of the RUz"	Describes initial steps to introduce the SEA mechanism into state sectoral policy, including plans, programs, and other strategic documents (RUz, 2019)	Active
2020	Resolution of the Cabinet of Ministers of the RUz "On further improvement of the EIA mechanism"	Latest update to refine and enhance the EIA process (RUz, 2020)	Active
2024	Law "On State Ecological Appraisal and Environmental Impact Assessment" of the RUz	Basis of SEA in Uzbekistan (RUz, n.d.)	Under development

Uzbekistan's ecological assessment system is predominantly structured around the EIA and State Ecological Appraisal (SEAUZ) models (Khotuleva et al., 2023). Within this system, developers are tasked with organizing and conducting EIAs, ensuring the completeness, accuracy, and quality of the environmental impact materials submitted for SEAUZ. The SEAUZ, carried out by the designated body, culminates in a mandatory conclusion determining whether a proposed activity can proceed

based on its potential ecological impacts. The conclusion is binding for all legal and physical entities involved in financing and implementing the project.

Nonetheless, considering these provisions, the ongoing practices demonstrate serious drawbacks, such as restricted public engagement, poor transparency, and lack of robust alignment with international standards. The importance of stakeholder engagement in SEA cannot be overstated, as it guarantees proper consideration of diverse perspectives, making the assessment process more inclusive and transparent. Yet, Uzbekistan still faces significant challenges in this regard, as evidenced by the Charvak FTZ pilot SEA. Stakeholder consultations during the project had pointed to gaps in awareness and participation, particularly among local authorities and community members alike, partly due to the absence of clear legal requirements for stakeholder involvement and lack of structured consultation mechanisms.

To bridge these gaps, the RUz could adopt best practices from international SEA frameworks, such as the use of participatory GIS for community mapping and digital tools for public consultations. These methods enable stakeholders to visualize potential environmental impacts and meaningfully contribute to the assessment. Establishing a formalized framework for stakeholder engagement with clear timelines and responsibilities would promote their systematic participation. The aforementioned steps are essential for building trust and fostering collaboration among all parties involved in SEA.

The present framework lacks specific requirements for SEAUZ documentation and processes, leading to insufficient integration of ecological assessments in strategic planning efforts. As a result, national strategic acts like development programs and sectoral strategies often bypass the rigorous ecological scrutiny necessary for ensuring sustainable development (Smutny et al., 2021). This gap results in fragmented and inconsistent environmental assessments incompatible with international standards, including these outlined in the SEA Protocol.

Today, Uzbekistan's legislation lacks a formal foundation for SEA execution, although the country has been taking steps to enhance its investment environment as part of its broader economic growth strategy.

The absence of SEA in these cases has revealed gaps in environmental planning, particularly in assessing cumulative impacts and fostering effective stakeholder engagement. By way of demonstrating a strong sustainability commitment, implementing SEA under such projects would echo Uzbekistan's priorities of nature conservation and enhancing its investor attractiveness.

Public participation in EIA and SEAUZ procedures is currently minimal and not systematically integrated, falling short of international norms. Public consultations are often non-mandatory and infrequent, thereby diminishing the community's ability to influence ecological decision-making.

The current system is likewise hampered by insufficient resources and lack of a clear institutional mandate to execute SEAs effectively (OSCE, 2021). This inadequacy is evident in the absence of detailed SEAUZ procedures, inter alia screening, scoping, and environmental reporting. Additionally, there is still ambiguity regarding the roles and responsibilities of different governmental bodies in the SEAUZ process, leading to inefficiencies and overlaps in environmental governance.

The limitations of Uzbekistan's current EIA and SEAUZ system are stark when compared to the comprehensive requirements of SEA as outlined in international frameworks such as the SEA Protocol. The lack of a systemic approach towards SEA means that strategic documents often fail to encompass broad nature-related considerations, resulting in decisions that may not fully account for long-term ecological impacts (OSCE, 2021). While EIA focuses on project-specific impacts, SEA is designed to evaluate the environmental effects of policies, plans, and programs at a higher strategic level. This higher-tier scope is crucial for SD, yet remains underdeveloped within Uzbekistan's current framework.

Moreover, the ongoing system's deficiency in terms of public participation and transparency represents a significant shortcoming. International SEA standards emphasize the importance of engaging the public and stakeholders early on and throughout the assessment process, ensuring that every voice is heard, and that decision-making is more democratic and informed. In contrast, Uzbekistan's existing processes do not adequately facilitate such engagement potentially curbing public trust and delivering suboptimal environmental outcomes.

2.2.1. Recent initiatives and law-making

During 2018-2021, in collaboration with UNECE and Organization for Security and Co-operation in Europe (OSCE), the national Ministry of Ecology, Environmental Protection and Climate Change (MEEPCC) undertook projects aimed at reviewing national legislation, proposing enhancements, and raising awareness regarding SEA. As part of these initiatives, the law on SEA was drafted and underwent review by relevant government agencies. Additionally, a needs assessment was conducted to evaluate the requirements for SEA implementation, leading to the elaboration of the Action Plan for SEA Execution in the RUz (Smutny et al., 2021).

The Law of the RUz "On State Ecological Appraisal and Environmental Impact Assessment" (anticipated in 2024) represents a significant step towards bridging this gap serving a core regulation on Strategic Environmental Assessment in the country. As of May 20, 2024, the act had undergone public discussion via the Portal for Discussing Draft Normative and Legal Documents (six proposals received), concluding the public discussion phase (RUz, 2024).

As per current legislation, it is imperative to ascertain the compatibility of diverse economic and other activities planned or ongoing within the country's territory with ecological standards as well as to assess their feasibility. The State Environmental Appraisal Center, operating under the MEEPCC auspices, conducts state ecological appraisal through its branches in the Republic of Karakalpakstan, constituencies, and the city of Tashkent.

2.3. Pilot SEA projects

In the absence of a functional national legal framework on SEA, in the RUz the strategic environmental assessment is currently only possible on a pilot or voluntary basis with a rather limited scope, thereby not fully leveraging the benefits of the mechanism. Given the situation, pilot SEA applications are particularly valuable for “testing” draft SEA provisions and building the necessary capacities. Several pilot SEAs supported by foreign institutions are currently in progress in Uzbekistan - for example, the German Society for International Cooperation (GIZ) conducted the SEA of the 2022-2023 Roadmap for the 2030 Concept of Forestry Development of the RUz (Decree of the President #PP-4850, 2020; Khotuleva et al., 2023).

Additionally, the project known as “Support for the Implementation of a Pilot Strategic Environmental Assessment” was executed by the Global Green Growth Institute (GGGI) in collaboration with the French Development Agency (AFD) and MEEPCC. That initiative focused on the Charvak Free Tourist Zone (FTZ), as detailed in Presidential Decree No. DP-5611 of January 5, 2019 (News, 2023). The Charvak FTZ project - launched in February 2023 and concluding in December 2024 - is situated in Bostonlik District of Tashkent Region and hallmarks the first practical implementation of SEA in Uzbekistan, and seeks to advance sustainable tourism by examining the prospects and obstacles in terms of applying strategic ecological evaluations in Uzbekistan.

The Charvak FTZ is a strategically designated area (Fig. 1.) created following Presidential Decree No. PF-5273 of December 5, 2017. Spanning 94,805 ha, the FTZ was established to capitalize on the region's tourism potential, improve recreational opportunities, and stimulate economic growth through modern investment strategies. The Charvak FTZ is a crucial element of Uzbekistan's holistic strategy of improving tourism infrastructure and fostering SD.

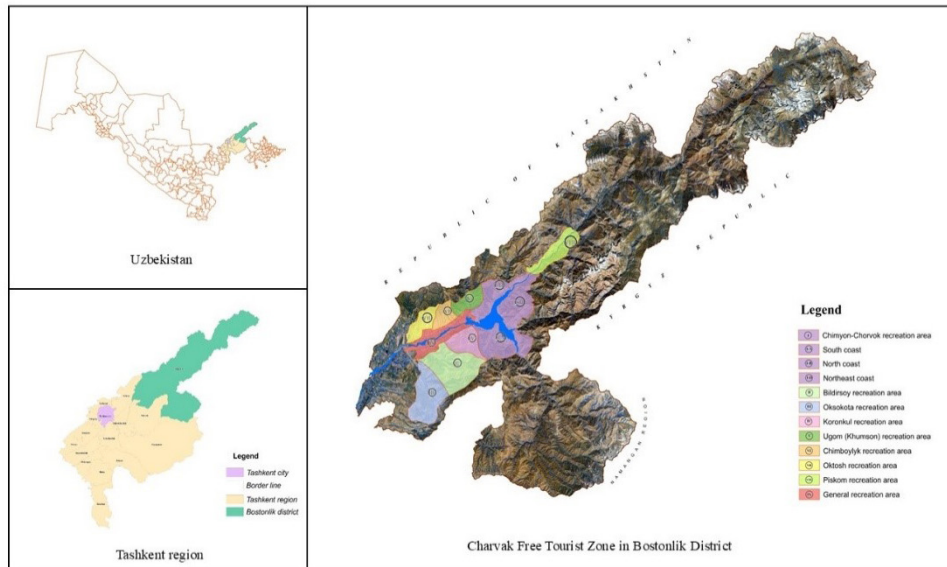


Fig. 1. Location map of the Charvak FTZ in Bostonlik District, Tashkent Region, Uzbekistan.

During the implementation of the pilot project, significant challenges arose, particularly as to stakeholder engagement, especially local authorities, throughout the SEA process. The issues encountered largely stemmed from the absence of explicit domestic regulations, i.e. not delineating the responsibilities of the parties involved in SEA execution. Consequently, the importance of voluntary participation was not consistently acknowledged. Furthermore, the lack of adequate information from public sources to assess the impacts on the nature and human health posed a problem. Coupled with the lack of a centralized database to support the required analyses, the absence of a structured SEA framework in Uzbekistan further complicated the situation.

The Charvak FTZ SEA outcomes outline a definitive strategy for tackling local ecological concerns. Significant obstacles - like landscape deterioration, biodiversity risks, water and air pollution and waste management challenges - necessitate immediate target actions. Considering the situation, the SEA put forward various strategies to mitigate adverse impacts, including the enforcement of robust sustainable land use and construction regulations, creation of designated eco-zones to safeguard sensitive habitats, and implementation of thorough waste management schemes. Further suggestions highlighted the importance of enhancing public transportation networks to mitigate air pollution and constructing sewage treatment plants to avert water contamination. The strategies outlined are designed to reduce environmental risks and promote the sustainable advancement of the Charvak FTZ.

3. Results and discussion

Effective execution of SEA in Uzbekistan encounters numerous substantial obstacles - the corresponding proposed solutions as per this study's findings are presented in Table II.

Table II. Main challenges of SEA in Uzbekistan and proposed solutions.

Main challenges	Proposed solutions from the research
Lack of national legislation to support SEA execution	Currently, there is no legal basis for applying SEA for PPPs in Uzbekistan. However, a preliminary legal document was drafted and underwent public discussion (as of June 3, 2024). It is essential to finalize and adopt this legal act as soon as possible.
Insufficient capacity to efficiently coordinate environmental assessment procedures among governmental authorities	Uzbekistan's authorities lack experience in coordinating SEA due to its novelty. To close this gap, blanket capacity-building is necessary.
Lack of procedural clarity and ambiguity surrounding the roles and responsibilities of the key actors involved in health impact assessment	Although the responsibilities and participation of the main actors in SEA implementation are clearer in terms of environmental assessment, the actor roles and participation in health impact assessment are not clearly defined. The new law should address this aspect.
Shortage of experts proficient in environmental and health analyses	Uzbekistan possesses a sufficient number of experts in EIA and State Ecological Appraisal (SEAUZ); however, there is a notable lack of experience of Strategic Environmental Assessment. To address this deficiency, it is imperative to organize training programs abroad for target experts to acquire international experience, and arrange training sessions involving globally recognized experts; furthermore, introducing SEA as a discipline at higher education institutions represents the primary solution to mitigate this issue.
Lack of necessary information, inadequate or poor-quality data in open sources, and difficulties in obtaining relevant information	Posting information necessary for SEA on the government website "Open Information Portal of the Republic of Uzbekistan", supplementing existing national information with regional and local information and ensuring their regular updates; further strengthening information dissemination by mandated organizations such as state bodies and scientific research institutes.

The suggested steps can greatly improve Uzbekistan's capacity to properly execute SEA, thus reinforcing environmental governance and advancing SD practices. Effective implementation of these solutions requires coordinated efforts on behalf of authorities and pertinent stakeholders, promoting a collaborative strategy towards SEA.

The insights from pilot SEA projects, such as the Charvak FTZ, provide valuable support for these findings. The Charvak FTZ pilot SEA - conducted in collaboration with GGGI and AFD - has highlighted several critical issues, including stakeholder engagement predicaments, particularly local authorities, due to poor familiarity with SEA processes and unclear responsibilities. Moreover, the absence of high-quality baseline data on environmental conditions like biodiversity and water resources limited the assessment's comprehensiveness. These shortcomings were compounded by the absence of a national SEA framework, leading to fragmented coordination among agencies and delayed decision-making. Despite these hindrances, the pilot demonstrated the importance of establishing a legal framework, improving data accessibility, and enhancing stakeholder engagement to ensure SEA's success in Uzbekistan.

Uzbekistan's development of its SEA framework is informed by international instruments, including the SEA Protocol to the Espoo Convention and EU SEA Directive. The draft SEA law of the RUz reflects international standards thereby laying groundwork for environmental assessments tailored to the nation's unique legal and governance context.

By incorporating the lessons learnt from the Charvak FTZ pilot project, Uzbekistan can close the existing gaps effectively. For instance, targeted trainings for stakeholders and public servants would raise their SEA awareness. Additionally, a centralized ecological database would boost the quality of future assessments. These practical measures are vital for aligning Uzbekistan's SEA practices with international norms while also customizing them to local conditions.

Uzbekistan has been harmonizing its practices with global standards while simultaneously adapting the SEA framework to suit local peculiarities, acknowledging the current capabilities of its institutions and existing environmental law. The insights obtained from domestic pilot SEA projects reiterate the findings of this study - the former demonstrate that the prevalent lack of familiarity with SEA among local stakeholders manifests a considerable burden to effective implementation, highlighting the necessity for targeted training and more explicit procedural guidelines.

By implementing target and contextually relevant responses to these challenges, Uzbekistan has the potential to endow a fully operational national SEA framework stimulating SD in line with international environmental governance models.

4. Future prospects

The future of SEA in Uzbekistan holds significant promise as the country is increasingly recognizing the importance of sustainable development and nature protection. As the country moves towards adopting holistic SEA legislation, it is

possible to note several emerging trends and opportunities. The anticipated Law of the RUz “On State Ecological Appraisal and Environmental Impact Assessment” - due in 2024 - represents a pivotal step in formalizing SEA practices. This legislation is poised to provide a robust legal foundation, thereby facilitating SEA mainstreaming into national PPPs.

Continuous efforts to build capacity among government authorities, planners, and stakeholders will be crucial for nurturing necessary skills and knowledge required for effective SEA execution. Additionally, international collaborations and partnerships could offer valuable expertise and resources, helping to boost institutional facility and best practices.

Implementing pilot SEA projects, as done currently with foreign support, will serve to “testing” and refining SEA procedures. Such pilot actions are instrumental in providing practical insights and lessons that can inform broader SEA application across various sectors in Uzbekistan. By examining the outcomes and methodologies of these pilot projects, stakeholders can identify effective strategies and potential pitfalls, thereby raising the overall cogency of SEA practices.

Leveraging advanced technologies like GIS and remote sensing can cardinally enhance SEA quality and efficiency. These technologies can facilitate improved data collection, analysis, and visualization, making SEA more potent in terms of identifying and mitigating ecological impacts. The integration of such technologies can also streamline the assessment process itself, providing more accurate and exhaustive environmental data to inform decision-making.

Enhancing public participation and transparency in the SEA process is critical for fostering trust and collaboration. Forging clear stakeholder engagement mechanisms and ensuring public access to relevant information is fundamental in this regard. Globally, there is a shift towards increased inclusivity in SEA processes, which Uzbekistan is incorporating by expanding the government website “Open Information Portal of the Republic of Uzbekistan”. This web portal can be further developed to serve as a platform for disseminating information and facilitating public input. By promoting transparency and inclusivity, Uzbekistan can ensure due consideration of diverse viewpoints, thereby elevating the legitimacy and validity of SEA outcomes.

Given Uzbekistan's strategic location in Central Asia, it possesses substantial potential for regional-level ecological cooperation. SEA has been globally used as a tool for transboundary environmental collaborations, and Uzbekistan's SEA framework could promote similar initiatives in Central Asia. Collective SEA initiatives with neighbouring countries could address transboundary environmental impacts and promote regional sustainability. In its turn, such co-action could lead to the emergence of harmonized ecological standards and practices, fostering a more integrated and effective nature management modus operandi across the region.

5. Conclusion

The detailed analysis of SEA in Uzbekistan pinpoints significant challenges and opportunities for bettering environmental governance and promoting sustainable development. The forthcoming Law of the RUz “On State Ecological Appraisal and Environmental Impact Assessment” is crucial for formalizing SEA practices and integrating them into national PPPs. Continual capacity-building through trainings, workshops and seminars is imperative for equipping government bodies, planners, and stakeholders with the necessary skillset. Calibrating these efforts with global SEA trends, such as strengthening public participation and increasing data transparency, will ensure that Uzbekistan’s SEA framework meets international standards.

Pilot SEA projects have demonstrated the potential to refine procedures and provide practical insights for broader application, as well as have contributed to the growing body of global knowledge, offering a model for SEA implementation in other emerging economies facing similar challenges. The case of the Charvak FTZ pilot SEA emphasizes the importance of addressing data gaps and engaging local stakeholders systemically. The project insights underscore the necessity to enhance inter-agency coordination and establish baseline environmental data to support effective SEA. Advanced technologies like GIS and remote sensing can aid data collection, analysis and visualization, improving the overall SEA efficiency and effectiveness. Following global shifts toward digital integration in SEA, these technologies will support Uzbekistan in conducting more data-driven and transparent assessments. Enhancing public participation and transparency via stakeholder engagement mechanisms and developing the “Open Information Portal of the Republic of Uzbekistan” will garner trust and collaboration.

Regional cooperation in Central Asia provides an additional dimension for leveraging SEA to achieve transboundary ecological objectives associated, for example, with shared water resources and biodiversity conservation. Establishing collaborative regional-level SEA frameworks can facilitate knowledge sharing and cross-adjust national sustainable development policies. Uzbekistan’s active participation in these efforts can set a precedent for regional environmental governance.

In summary, successful SEA implementation in Uzbekistan depends on legislative enhancements, capacity building, technological integration, public participation, and regional cooperation. Delivering on these tasks will improve ecological governance and support SD, ensuring the protection of natural resources for future generations.

Concluding, it is worth mentioning certain limitations that this study has faced. The analysis was predominantly based on secondary sources, such as legal documents, policy and pilot project outcome reports. Albeit abundant and substantive, these sources may not comprehensively reflect the latest or undocumented SEA related

developments within Uzbekistan. Further research should focus on integrating primary data collection methods, including interviews and field-based assessments, to validate findings and expand the analysis scope. Additionally, longitudinal studies could help evaluating the long-term impacts and adaptability of SEA in Uzbekistan, offering valuable insights for other countries with similar contexts.

Acknowledgments

The study team would like to express gratitude to the Global Green Growth Institute (GGGI) Uzbekistan for support and cooperation during the independent consultancy. Although this research was conducted independently, certain insights and information gathered during the consultancy were valuable in shaping this paper. The authors appreciate the opportunities and resources provided by GGGI Uzbekistan that have contributed to understanding the SEA framework in Uzbekistan.

References

- Ahmed, K., Mercier, J. R., & Verheem, R. (2005). Strategic environmental assessment - concept and practice. <https://api.semanticscholar.org/CorpusID:54819575>
- Baynova, T. (2021). Best Practices for Strategic Environmental Assessment and Application to the Ontario Long-Term Energy Plan. <https://doi.org/10.32920/ryerson.14646342.v1>
- Corpade, A.-M., Corpade, C., & Moldovan, C. (2012). Integrating Environmental Considerations into Transportation Planning through Strategic Environmental Assessment. <https://api.semanticscholar.org/CorpusID:210711170>
- European Union. (2001). Directive 2001/42/EC of the European Parliament and of the Council of 27 June 2001 on the assessment of the effects of certain plans and programmes on the environment. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32001L0042>
- Feldmann, L., Vanderhaegen, M., & Piroette, C. (2001). The EU's SEA Directive: status and links to integration and sustainable development. *Environmental Impact Assessment Review*, 21, 203-222. <https://api.semanticscholar.org/CorpusID:129729954>
- Fischer, T. B. (2005). Current SEA Practice in England. <https://api.semanticscholar.org/CorpusID:168049490>
- Fischer, T. B., Matuzzi, M., & Nowacki, J. (2010). The consideration of health in strategic environmental assessment (SEA). *Environmental Impact Assessment Review*, 30, 200-210. <https://api.semanticscholar.org/CorpusID:129837193>
- Fundingsland Tetlow, M., & Hanusch, M. (2012). Strategic environmental assessment: The state of the art. *Impact Assessment and Project Appraisal*, 30(1), 15-24. <https://doi.org/10.1080/14615517.2012.666400>
- Gafurova, L. A., & Juliev, M. (2021). Soil Degradation Problems and Foreseen Solutions in Uzbekistan. *Regenerative Agriculture*. <https://api.semanticscholar.org/CorpusID:237983658>
- Grout, L., Hales, S., French, N. P., & Baker, M. G. (2018). A Review of Methods for Assessing the Environmental Health Impacts of an Agricultural System. *International Journal of Environmental Research and Public Health*. <https://doi.org/10.3390/ijerph15071315>
- Helbron, H., & Palekhov, D. (2010). Strategic Environmental Assessment to Assess and Monitor Sustainable Resource Use in Progressive Development: Potentials and Limitations. <https://api.semanticscholar.org/CorpusID:110307932>

- Hossan, Md. S., Bari, Md. S., Rahman, Md. S., Hanif, Md. A., & Ali, Md. M. (2021). Strategic Environmental Assessment: Current Status, Practices and Challenges in Bangladesh. *International Journal of Environment and Climate Change*, 38-48. <https://doi.org/10.9734/ijecc/2021/v11i330375>
- Jackson, T., & Illsley, B. M. (2008). Using sea to mainstream sustainable development: Some lessons from Scottish practice. <https://api.semanticscholar.org/CorpusID:108459682>
- Josimović, B., Manić, B., & Krunic, N. (2022). Strategic Environmental Assessment as a Support in a Sustainable National Waste Management Program—European Experience in Serbia. *Energies*, 15(13). <https://doi.org/10.3390/en15134568>
- Khotuleva, M., Smutny, M., Artov, A., Saidmakhmudova, A., & Talipov, K. (2023). Strategic Environmental Assessment of the Roadmap for 2022-2023 to the Concept of Forestry Development of the Republic of Uzbekistan until 2030.
- Kläne, C., & Albrecht, E. (2005). Purpose and Background of the European SEA Directive. <https://api.semanticscholar.org/CorpusID:166736972>
- Koyano, M. (2020). The Espoo Convention in a Global Context: Its Contribution to the Development of International Environmental Law. <https://api.semanticscholar.org/CorpusID:263260478>
- Makhmudov, I. E., Mirzaev, A. A., Rajabov, A. Kh., Musaev, Sh. M., & Ulugbekov, B. B. (2023). Socio-Economic Impact on Water Conservation Implementation in Uzbekistan. *E3S Web of Conferences*. <https://api.semanticscholar.org/CorpusID:265265394>
- Marsden, S. (2011). The Espoo Convention and Strategic Environmental Assessment Protocol in the European Union: Implementation, Compliance, Enforcement and Reform. *Review of European Community and International Environmental Law*, 20, 267-276. <https://api.semanticscholar.org/CorpusID:154432787>
- Mulder, J. De. (2011). The Protocol on Strategic Environmental Assessment: A Matter of Good Governance. *Review of European Community and International Environmental Law*, 20, 232-247. <https://api.semanticscholar.org/CorpusID:154272843>
- Nzioki, N., & Kitulazzi, D. (2016). A REVIEW OF STRATEGIC ENVIRONMENTAL ASSESSMENT PROCESS AND ITS IMPLICATION IN REAL ESTATE DEVELOPMENT PROJECTS IN KENYA. <https://api.semanticscholar.org/CorpusID:203295377>
- Organization for Security, in Europe (OSCE), C., & United Nations Economic Commission for Europe (UNECE). (2021). Action Plan for Creation of a National System of Strategic Environmental Assessment (SEA) Uzbekistan.
- Reicher, O., Delgado, V., & Arumí, J. L. (2021). Use of Indicators in Strategic Environmental Assessments of Urban-Planning Instruments: A Case Study. In Sustainability. <https://doi.org/10.3390/su132212639>
- Republic of Uzbekistan. (n.d.). Law of the Republic of Uzbekistan “On State Ecological Expertise and Environmental Impact Assessment.” <https://regulation.gov.uz/uz/d/97210>
- Republic of Uzbekistan. (1992). Law of the Republic of Uzbekistan No. 754-XII “Concerning the Protection of Nature.” <https://www.lex.uz/uz/docs/-107115>
- Republic of Uzbekistan. (2000). Law of the Republic of Uzbekistan No. 73-II “On Ecological Expertise.” <https://www.lex.uz/uz/docs/-32955>
- Republic of Uzbekistan. (2018). Resolution of the Cabinet of Ministers of the Republic of Uzbekistan No. 949 “On the Approval of the Regulation on the State Ecological Expertise.” <https://lex.uz/docs/-4072890>
- Republic of Uzbekistan. (2019). Decree of the President of the Republic of Uzbekistan No. PF-5863 “On Approval of the Environmental Protection Concept of the Republic of Uzbekistan Until 2030.” <https://lex.uz/docs/-4574008>
- Republic of Uzbekistan. (2020). Resolution of the Cabinet of Ministers of the Republic of Uzbekistan No. 541 “On Further Improvement of the Environmental Impact Assessment Mechanism.” <https://lex.uz/docs/-4984499>

- Sabeva, M. (2015). Strategic Environmental Assessment: necessity, principles and specificities. *Review of Applied Socio-Economic Research*, 9, 90-102. <https://api.semanticscholar.org/CorpusID:55410198>
- Saleh, N., & Qutb, S. M. (2021). Role of Strategic Environmental Assessment Tools (SEA) to Guide Strategic Plans in Egypt: New Cities Case Study. *Svu-International Journal of Engineering Sciences and Applications*. <https://doi.org/10.21608/svusrc.2021.99106.1018>
- Sheate, W. R. (2003). The EC Directive on Strategic Environmental Assessment: A Much-Needed Boost for Environmental Integration. *European Energy and Environmental Law Review*. <https://api.semanticscholar.org/CorpusID:168185337>
- Smutny, M., Saidmakhmudova, A., Santer, E., Molodtsova, E., Melis, C., & Gachechiladze-Bozhesku, M. (2021). Strengthening National and Regional Capacities and Co-operation on Strategic Environmental Assessment (SEA) in Central Asia, Including as a Response to Climate Change: Uzbekistan Needs Assessment Report.
- Song, Y.-I., & Kim, H. (2007). Role and Implementation of SEA for Sustainable Society. <https://api.semanticscholar.org/CorpusID:264273478>
- Souloutzoglou, A., & Tasopoulou, A. (2020). The Methods and Techniques of Strategic Environmental Assessment. Comparative Evaluation of Greek and International Experience. *Sustainability*. <https://doi.org/10.3390/su12083310>
- Spar, K. (2012). Budget “Sequestration” and Selected Program Exemptions and Special Rules. <https://api.semanticscholar.org/CorpusID:153495138>
- State Committee of the Republic of Uzbekistan on Ecology, & Protection, E. (2023). News Article. <https://kerio.uznature.uz/en/site/news?id=3481>
- Tukhtaeva, Z. I. (2020). Air Pollution In Uzbekistan And The Solution For For Its Improvement. *The American Journal of Engineering And Techonology*. <https://api.semanticscholar.org/CorpusID:228969061>
- Uganda, I. (2006). STRATEGIC ENVIRONMENTAL ASSESSMENT (SEA). <https://api.semanticscholar.org/CorpusID:132214252>
- United Nations Economic Commission for Europe (UNECE). (2003). Protocol on Strategic Environmental Assessment (SEA).
- World Bank. (2020). Uzbekistan: Water Services and Institutional Support Project. <https://www.worldbank.org/en/news/press-release/2020/03/12/uzbekistan-water-services-and-institutional-support-project>



Communicating climate change to transform coping practices of farming audiences to sustainable adaptive capacity in Chad

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ABSTRACT

As any other Sub-Saharan country, Chad is highly vulnerable to climate variability and change. This research aimed to examine climate change communication pathways and the extent to which they have transformed and strengthened adaptive capacities of farmers based on the case of Mont Illi in Chad. Using a mixed methods approach, the data were collected from secondary and primary sources, accompanied by field missions. Qualitative and quantitative data analysis has revealed that climate change communication is key in the National Adaptation Plan, and institutions such as ANADER play a pivotal role in information dissemination. However, targeted communications are yet to transform coping practices of farmers, as 53% of them lack access to information; the other 47% receive it through radio (24%), from peer farmers (25%), agricultural federations (16%), technical agents (14%), television (7%), and the Internet (4%). Unlike in other areas where the media are crucial in information dissemination, farmers in Mont Illi have better access to information from other farmers, farming federations and traditional authorities. Cost effective and contextualized information has improved existing practices as well as facilitated rehabilitation of traditional knowledge systems for sustainable adaptation. Yet, in order to reinforce local adaptive capacities and transform farming practices through climate communications, actions should focus on strengthening institutions, agro-climatic extension and synergizing science with local knowledge in adaptation policy.

ARTICLE HISTORY

Received:
October 18, 2024
Accepted:
December 12, 2024
Published:
December 27, 2024

KEYWORDS

climate change,
communication, adaptive
capacity, farming audiences,
Chaddevelopment

1. Introduction

Climate change has become a global phenomenon today, but the Sahel countries feel its effects the hardest due to the proximity of the desert and scarcity of natural resources. The international scientific community considers Chad one of the climate change hot spots in the world (Bedoum et al., 2017; FAO, 2021). The growing frequency and scale of extreme weather events like floods, droughts, heat waves and violent winds indicate that climate has been drastically altering over the recent decades in Chad (PANA, 2010; Baohoutou et al., 2014; IPCC, 2024). However, these phenomena will become even more intense and frequent in the coming decades. Indeed, climatic hazards negatively impact the functioning and productivity of agricultural systems and make communities and ecosystems increasingly vulnerable (World Bank, 2021). The agricultural sector occupies a preponderant place in Chad's economy, employs over 80% of the working population, and generates considerable farmer income (Third NCCC, 2020). Lake Chad, once the main location for the population to reside, has been drying up rapidly due to overuse and climate change. With mounting mean annual temperatures (by 0.7°C since the 1970s) and due to overexploitation and misuse, Lake Chad - formerly a source of livelihood for over 30 mln peasants - has shrunk by 90% during 1960-1990 (Bedoum et al., 2017; Adelphi, 2021). This has exacerbated crop failures, pasture degradation, water scarcity and conflicts leading to negative livelihood outcomes (Bedoum et al., 2017; FAO, 2021; Lamarche, 2023). It is therefore important to assess the country's capacity to adapt to climate change while considering effective communication and knowledge transfer as a prerequisite for sustainable adaptive action.

Chad's heritage in terms of climate information has evolved insignificantly over the past years. The First National Communication on Climate Change (NCCC) was submitted to the United Nation's Framework Convention on Climate Change (UNFCCC) in October 2001, and the Second NCCC - in June 2012. The National Action Plan for Adaptation to Climate Change (PANA-Chad) was developed in 2009 and submitted to the UNFCCC in February 2010. It comprises ten priority projects focusing inter alia on water management, crop intensification and diversification, management and restoration of soil fertility, education, information and communication on climate change (National Strategy for the Fight against Climate Change, SNLCC, 2017). The projects above with the total budget of US\$14.2 mln target three bioclimatic zones (Sudanian, Sahelian and Saharan) inside Chad (SNLCC, 2017). The Normal Action Program for Adaptation to Climate Change (PANA, 2010) was adopted under the theme of "traditional know-how in adaptation to the harmful effects of climate variability, past and current climate change". Domestic sectors highly vulnerable to climate include water resources, agriculture, livestock, fishing, and forestry.

Meanwhile, climate change communication represents a sensitive and delicate issue that institutions and stakeholders in the field face, and as such efforts to strengthen the performance of public policies and communication campaigns deserve particular attention.

In the context of climate resilience, the Chadian government is often supported by private associations, non-governmental organizations (NGOs), as well as agronomic and environmental institutions (SNLCC, 2017). Farmers need to adapt to the effects of current or expected climate change but for adaptation to be sustainable, it is necessary to communicate and interact with the main climate actors and thematic organizations (Zachary and Faulkner, 2016; Odeleye, 2018; Zafezeka et al., 2019). The ongoing targeted actions are insufficient and require a broader perspective. Central African countries have forged a trans-border approach to ensure regional collaboration rather than isolated policy frameworks (Fallah et al., 2024). Such inter-governmental liaising is inexistent in the Sub-Saharan Africa, and the previous research has not yet evaluated the efficiency of communications in building local farmer adaptive capacities in the Sub-Saharan African countries. This study aimed to bridge this scientific gap.

Today, the agricultural sector is highly vulnerable due to its dependence on nature, and the traditional coping systems utilized by the population are not sustainable (FAO, 2012). Effective adaptation requires a combination of scientific and traditional knowledge systems (FAO, 2011; Hobson and Niemeyer, 2011; Merzdorf et al., 2019). Chad still lacks a formal mechanism for centralizing information related on climate actions and fostering information exchange among various sectors concerned - be it inside the country or interacting with sub-regional, regional and international entities working on the same issues (TNCCC, 2020). Communication is carried out through a number of channels, including institutional, media, socio-traditional, participatory and educational (Ouédraogo et al., 2020). In rural areas, farmer-to-former extension approaches allow sharing knowledge and experiences (Mkisi, 2014; Prokopy et al., 2017; Zafezeka et al., 2019).

In Central Asian countries, climate change communication and education have been prioritized in policies. Studies by Sabyrbekov and Overland (2023) have revealed that knowledge is power and coping strategies get effectively transformed through knowledge transfer. The Comprehensive Action Plan for Climate Change Education targeting government institutions, academia, private sector, civil society, international organizations and local communities in countries like Kyrgyzstan manifests a solid foundation for adaptation. The Plan aims to mainstream climate change into formal education and training, including gender and indigenous knowledge systems (UNESCO, 2024). This has built the adaptive capacity of farmers in the country. On the contrary, the Sub-Saharan countries still face challenges in terms

of rendering easily accessible information and knowledge to enhance agricultural research and transform local-level coping practices.

The Mont-Illi Division is essentially a rural area with agro-pastoral activities as the main type of economic activity. Knowledge and information on adaptation are disseminated mainly in printed form; and the lack of sufficiently qualified climate experts does not allow adequate provision of climate products and services to rural producers. Studies by Bautista et al. (2017) and Evans et al. (2018) have pointed to the social media as effective platforms for climate change communication, yet the absence of Internet connection complicates not only the collection and transmission of meteorological data, but also the dissemination of climatological information and services among potential beneficiaries. Also, inadequate financial resources do not permit periodic meetings with planners and decision-makers to enable them to better understand the meaning and scope of meteorological information in order to better integrate it into their programs and action plans. According to Merzdorf et al. (2019), the illiteracy of most of the rural residents often leads to non-compliance with technical advice. The decline of certain institutions responsible for information dissemination and the lack of adequate technology also pose major problem (McGahey and Lumosi, 2018). For instance, poor fitting of researchers and agricultural extension entities with data and communication equipment limits climatic service provision (Moye et al., 2020).

Considering the challenges described above, this research targeted examining pathways in climate change communication and the extent to which they have transformed and strengthened farmer adaptive capacities using the case of Chad's Mont Illi Division.

2. Materials and methods

2.1. Study area

The Mont-Illi Division is located in the Mayo-Kebbi Region in Chad's southwest between lat. 3° and 7° north, and between long. 5° and 17° east of the Greenwich Meridian (Fig. 1). The local population is mainly engaged in crop farming and livestock rearing (Reyanbéle, 2023). Created in 2004 by Decree #115/PR/PM, the Division's capital is Fianga, and it has five sub-divisions: Fianga Rural, Hollom, Gamé, Kéra, Tikem, and Youé. According to the 2009 General Housing and Population Census, the division's estimated population is 228,366 people. As per the Köppen classification, the local climate is characterized by long dry season and short rainy season. The mean annual temperature amounts to 28°C and precipitation - to 606.9 mm, although droughts are common. Located between Cameroon and Chad, the Mont-Illi Division extends along the border separating the two countries around lat. 10° north

and long. 15° east. Its hydrological system includes Lakes Tikem and Youé and the Gourmouie River; water shortages are frequent. This part of Chad is dominated by the Toupouri (Tupuri) with the majority of their population living in the northern part of Cameroon.

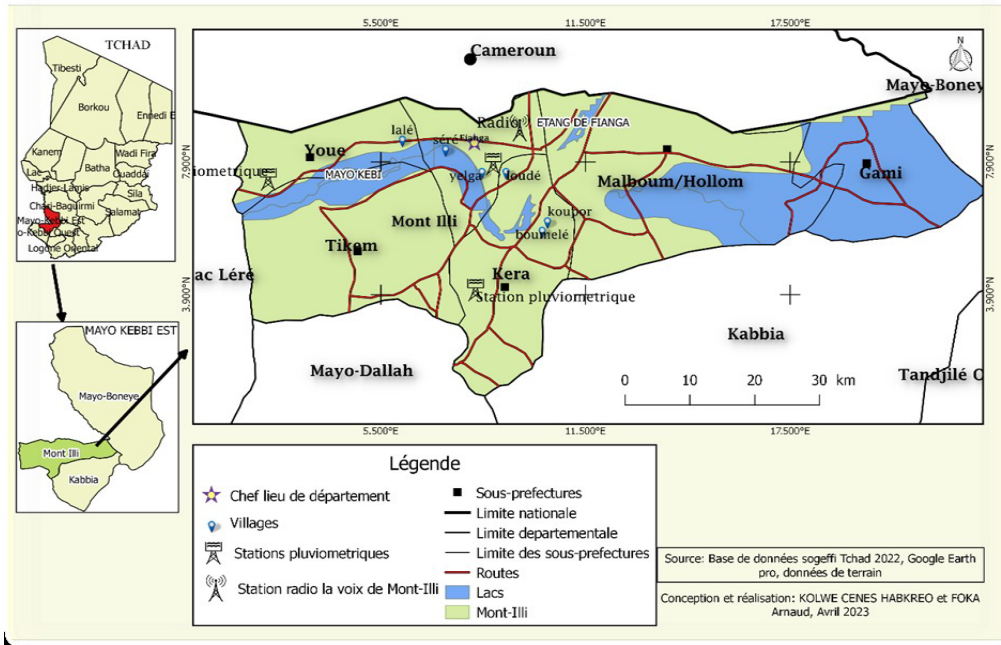


Figure 1. Location of the study area (source: Sogeffi data base, Chad 2022, Google Earth pro, Field data).

The Toupouri people are excellent breeders and farmers, and cultivate multiple crops like millet, peanuts, cereals, rice, potatoes, cassava and cotton to name just a few. Livestock breeding focuses on cattle, goats and poultry. However, the local livelihoods have significantly degraded in recent years under the combined effects of several factors, the most notable of which are climate change and rapid demographic growth (Reyanbélé, 2023). Altering climate has led to lower precipitation, in turn bringing down agricultural yields and pastureland, as well as exacerbating agro-pastoral conflicts for shrinking resources across the entire region (Lamarche, 2023)

2.2. Data collection and treatment

In terms of harvesting secondary and primary data, this research adopted a mixed methods approach. Documentary review consisted of consulting online articles, reports, archived articles, and dissertations in libraries and institutions such as the Research and Training Center for Development (CEFOD) in N'Djamena and National Agency for the Support of Rural Development (ANADER). Primary data were collected via household questionnaire surveys, key informant interviews and field observations.

As per the 2009 General Housing and Population Census, the population of Mont Illi was estimated at 228,366 inhabitants. Using the formula $[n=N/1+N(e)^2]$, the sample size of 350 was computed. Quantitative data were gathered using questionnaires administered to 350 randomly selected households engaged in agriculture. To get expert information, 16 in-depth interviews were conducted with journalists working at local radio stations (3), an agent from ANADER, CEFOD, head of agricultural posts (4), representatives of farmer groups (3), agricultural technicians (2), and traditional authorities (2). During interviews, voice notes were recorded using a dictaphone, and some interviews were conducted via telephone.

The data collected were processed both qualitatively and quantitatively. The voice notes recorded during the interviews were transcribed verbatim, coded and treated using the Atlas.ti software. The analysis were done according to the contents and themes identified in the research objectives. To lay emphasis on certain points, excerpts were extracted from the transcribed data to support figures from the household survey. In their turn, questionnaires were coded and processed quantitatively with the aid of Statistical Package for Social Sciences (SPSS) software. The outputs were generated in the form of percentages (%), tables and charts.

3. Results and discussion

3.1. Stakeholders in climate change communication

In Chad, the number and diversity of actors involved in the production and implementation of agro-climatic services are visible through their various interventions. The main actors involved in climate communications in the Mont-Illi Division operate at different levels: international, national, and divisional (local) (Table I.).

Table I. Stakeholders in climate change communication.

Category	Stakeholders involved	Role
International	Food and Agricultural Organization (FAO), Small Initiatives Program (PPI), World Bank, African Development Bank, etc.	Financing, provision of agro-climatic information and services, project support, training of agro-climatic agents
National	Academic institutions, ANADER, the media (radio, television, newspapers, etc.)	Generation of agro-climatological information, training of agro-climatic agents, weather forecasting, dissemination of information and climatic alerts

Table I. Cont.

Local	ANADER-Section, peasant groups (ex. Federation of Peasant Groups, Association of Youé (FEGAPY)), the media (community radio), local councils, etc.	Agricultural assistance, generation and dissemination of agro-climatic information, training
	Traditional authorities	Performing rites and rituals
	Farmers	Dissemination of indigenous knowledge and practices among themselves

Table I demonstrates a broad spectrum of actors producing and providing climate related services in the agricultural domain. Despite their status, they engage in certain concerted efforts in the field, as their sole objective is to reduce vulnerabilities and build adaptive capacities of farmers (end-users). The FAO plays an important role in this sense - the collaboration between its Mont-Illi divisional branch and the city of Bongor is effective; its interventions in training workshops have focused on issues related to agricultural production and food security. Since 2006, the Small Initiatives Program (PPI) has supported civil society organizations through funding small projects to preserve biodiversity and combat climate change. In Mont-Illi, the project carried out by the PPI in coordination with Local Orientation and Decision Bodies (ILOD) extends over approx. 27,000 ha of farmland and about 50 villages with nearly 65,000 inhabitants. Affected by years of severe drought and poor operating practices, local communities enjoy support and aid on behalf of numerous development programs, including in terms of resource management to ensure sustainable farmer livelihoods. These programs provide guidance on the various aspects of agro-sylvo-pastoral activities, areas fully protected for fishing, areas of pastoral regeneration and transhumance corridors.

At the national level, the Chadian government puts emphasis on training agricultural technicians. Institutions like the Technical School of Agriculture (ETA) in Bâ-Illi, University Institute of Agricultural Sciences (IUSAE) of Sarh, Agricultural Education Center (CETA) in Doyaba, Higher Institute of Agricultural Techniques (ISTA) in N'Djamena, Higher School of Agricultural Techniques and Forestry (ESTAF) in N'Djamena, Agro-Sylvo-Pastoral Training Center (CFAP) in N'Djamena train and build capacities of young Chadians on sustainable agricultural practices, especially smart agriculture.

The Rural Development Support Agency (ANADER) is also playing a key role in this respect. Created December 31, 2016 as per Law N035/PR/2016, ANADER is currently carving out a new mission in facilitating the intensification and diversification of agricultural products, training and structuring organizations of agricultural professionals for the effective management of collective actions, providing

advisory support to producers and their organizations in the field of management and maintenance of agricultural works. It also fosters research on crop and animal production. The Agency has already executed several joint targeted initiatives - Project to Strengthen Resilience to Food Insecurity and Nutrition in the Sahel (FAO P2RS), Natural Resources Management Project (PGRN), Project to Strengthen Climate Resilience and Sustainable Agricultural Productivity (Pro PAD), Rice Development Project in the Chari Logone Plain (PDRI-CL), and Regional Support Project for the Irrigation Initiative in the Sahel (PARIIS) - that have significantly improved farmers' adaptive capacities.

The General Directorate of National Meteorology (DGMN) is the national actor responsible for rendering meteorological and climatological services. In terms of meteorological/climatological products and services, DGMN produces and makes available to end users and partners the following information/products:

- agro-meteorological monitoring of agro-pastoral campaigns (10-day agro-meteorological bulletins, seasonal forecast bulletins, etc.);
- agro-meteorological assistance to producers (10-day agro-meteorological advice and operational agricultural calendars);
- weather monitoring and assistance to the general public (daily weather forecast bulletins).

Given that climatological data are often rare, DGMN also trains volunteer observers for rainfall and agro-meteorological stations, as well as holds seminars for farmers and breeders across the country to raise awareness on the importance of applying agro-meteorological information to boost agro-pastoral production. DGMN disseminates information among farmers through public and private media locally, and sometimes allows climate service providers to receive feedback from end users. The engaged media entities include the RNT National Radio physically located in N'Djamena and covering the entire division's territory, Terre Nouvelle Radio located in Bongor, and Voice of Mont Illi Radio (a local community radio station).

At the local level, there operate several federations of peasant groups and associations, also serving as centers for disseminating agro-climatic information, and sharing knowledge, good practices and experiences - Federation of Peasant Organizations for the Development of the Mont-Illi Basin (FOPDBI) created in 1992 with 60 groups (50 male, 10 female) and 4,318 members; Federation of Groups and Associations for the Development of Mouta (FEGAPDRM) created in 1992 bringing together 10 unions (5 unions of women's groups and 5 unions of men's groups), as well as 56 groups from 29 villages; Federation of Unions of Rural Groups and Associations of Tikem (FUGART) created in 1992 with 102 groups and 2,210 members; and, Federation of Peasant Associations for the Economic Development of Cabra (FAPDEC) created in 1994 with 622 members (including 122 women).

3.2. Information types and dissemination channels

The household survey revealed that in the Mont-Illi Division, agro-climatic information is popularized by a multidisciplinary team made up of agronomists, soil scientists, agricultural extension agents, climatologists, traditional authorities, and local farmers themselves. The type of information depends on the service provider (Fig. 2).

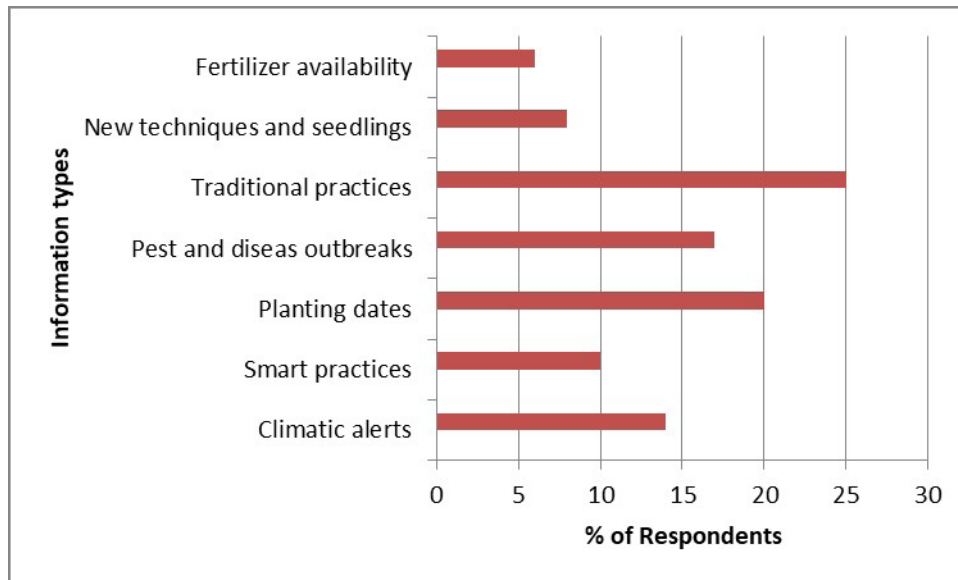


Figure 2. Types of agro-climatic information disseminated in Mont Illi.

Based on Fig. 2., the agro-climatic information disseminated among local communities is mainly related to: climatic alerts (14%), smart agricultural practices (10%), changes in agricultural calendar, especially planting dates (20%), pest and disease outbreaks and control methods (17%), traditional practices (25%), new techniques and improved seedlings (8%), and availability of fertilizers and other inputs (6%).

3.2.1. Climatic bulletins and alerts

Climatic alerts mainly cover rainfall repartition, especially the onset of the rainy season that marks the beginning of the planting season, and extreme events such as droughts and floods. Seasonal forecasts made by the National Meteorology Service (NMS) give the overall configuration of the rainy season. Weather experts observe seasonal trends and classify them either as normal rainy or as rainfall deficit seasons. If the forecast shows that the season will be in deficit, an alert report is sent to government authorities and local communities so that they can take appropriate measures. Seasonal forecasts are updated in early June, July and August, translated into agricultural advice by the multidisciplinary working group, and then transmitted

to different agents involved in extension to make them available to farmers via most appropriate channels. According to the 2020 report by ANADER, the date of the rainy season onset has been fluctuating over the years. The first rains are often recorded within the first decade of April but not always significant to trigger crop planting throughout the month. In some places, significant rainfall begins in May or June, allowing localized sowing throughout the division. The months of July and August receive the highest amounts of precipitation.

Extreme weather events such as floods and droughts are equally alerted by the NMS. The localities that are often victims of this phenomena are Kéra, Fianga, and Youé. Floods are frequently caused by torrential rains making rivers overflow. On the one hand, in the 2019/2020 ANADER report, the Mont-Illi Division recorded over 115 villages and over 10,472 ha of farmland affected by floods. The number of households severely affected by floods was estimated at 2,494. On the other hand, years of rainfall deficit and high probability of droughts are equally reported. These reports usually come out before the launch of the agricultural calendar in order to help farmers anticipate and take preventive actions.

3.2.2. Information on agricultural practices

Against the backdrop of climate variability and change, proper adaptation in the agricultural sector requires adoption of smart practices. To do this, farmers require technical know-how on the choice of land, cultivation techniques, irrigations schemes, proper fertilization use, etc. All these require rigorous training and information from farmers and extension agents. In addition, farmers should be able to identify agricultural threats, as well as know diseases and pests, proper phyto-sanitary control methods. These practices are often communicated to farmers by farming groups and federations. Agricultural federations allow a combination of scientific and traditional knowledge systems. For instance, farmers are provided current information on crops as well as their ecological requirements (Table II).

Table II. Ecological requirements of main crops and their cycle durations.

Crop type	Ideal temperature (°C)	Water requirements (mm)	Duration (days)
Corn	+18 à +30	500 à 1000	45 à 90
Groundnuts	+24 à +33	400 à 1200	50 à 100
Rice	+28 à +30	1000 à 1800	110-120
Sorghum	+12 à +30	*	90-150
Cow pea	+18 à +25	400 à 800	90-100
Penicillary	+25 à +30	200 à 800	75-100
Berber	+12 à +30	*	75-100

Source: Rural Development Support Agency (DSA/ANADER), 2020.

Table II shows the main crop types and their main growth drivers. Given rainfall unreliability, technical information on the optimal temperature and water needs of plants as well as the number of days required for the crop to mature permit farmers to plan their activities, including irrigation schemes, and reduce vulnerabilities to water shortages and heat stress. Equally, fertilization application extension agents provide technical information on fertilizer types, dosage and time of application. Most federations procure fertilizers and other inputs and sell them to federation members at cheaper rates. It is through their workshops and seminars that practical guides on fertilizer administration get disseminated.

3.2.3. Traditional/indigenous information and knowledge systems

Traditional information on agro-climatic phenomena in Mont-Illi relates to peasant perceptions, and indigenous knowledge systems are information and practices accumulated over the years of constant interaction with nature based on past experiences and practices transmitted through generations. Peasant perceptions are based on signs of nature, customs and traditions, as well as beliefs. Traditional knowledge and techniques are crucial in information dissemination among farmers, because farmer behavior, agro-climatic practices and strategies that they apply stem from empirical know-how, intentional experimentation and constructed know-how. As per the household survey, 76% of farmers claimed to be traditionally informed through the interpretation of nature, while 17% stated interpreting agro-climatic disasters using their traditions and customs. Accordingly to respondents, farmers interpreted rainfall deficit based on the drying up of certain plants and flowering behavior of certain plants; and forecasted the end of the planting season based on the appearance of winged ants and dragon flies. This information, usually perceived by traditional cattle herders, is shared among farmers and in groups.

In the Toupouri communities dominating in the study area, rites and beliefs are very important in environment conservation - they manifest a source of ancestral knowledge production and a means of communication among the “initiated” community members. For instance, during drought periods, a sacrifice is performed to appease the “gods”, as the belief is that prolonged droughts are a punishment from the “gods”. Rites and rituals are performed at the beginning of each planting seasons to ask for better yields. Equally, there are traditional techniques on soil fertilization, ploughing by animals, manufacturing of traditional insecticides and spraying of insect pests. For instances, the use of wood ash to send away pests and diseases is a common practice among the Toupouri, as well as the use of cattle dung to fertilize soil. Interestingly, during the interview it was revealed that cattle dung is not only useful as fertilizer but also allows conserving moisture for longer periods during water-scarce periods.

3.3. Dissemination channels and techniques

The household survey revealed that farmers get agro-climatic information through several channels (Fig. 3). This shows a combination of modern and traditional sources, but the level of accessibility and technology used determines the number of farming audiences attained.

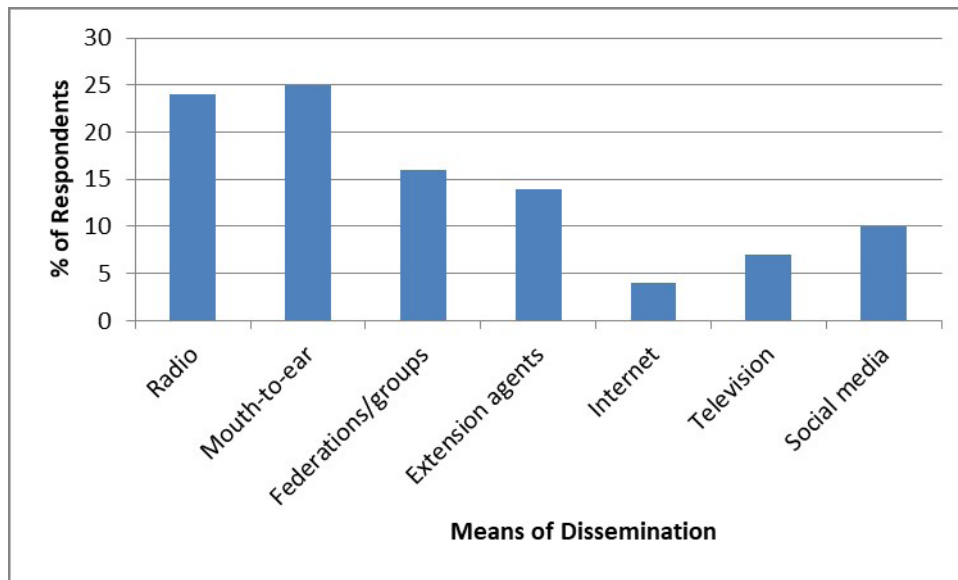


Figure 3. Channels used for disseminating agro-climatic information.

Fig. III shows that farmers receive information from the radio (24%), mouth-to-ear from other farmers (25%), agricultural federations (16%), extension agents (14%), social media (10%), television (7%), and the Internet (4%). The mouth-to-ear method of information sharing dominates. This fact demonstrates the role of traditional/local knowledge systems in climate change adaptation. The survey conducted under this study showed that farmers also use friends, neighbors or family members to get agro-climatic information and good practices. Farmers show solidarity through sharing information in funeral places, churches, in the field, during home visits and traditional ceremonies. Information relating to pest and disease outbreaks, as well as use of improved and drought resistant species is especially converged through this channel. Agricultural federations and extension agents utilize workshops, field demonstrations and seminars to ensure development of adequate skills among farmers while strengthening confidence, mastery of agricultural tools and understanding of planned adaptation strategies. Farmers in Mont-Illi are often assisted by ANADER agents, NGOs and other external actors through programs and projects. They also build capacity of extension agents on communication strategies and interactive approaches.

The community radio station - Voice of Mont Illi - broadcasts programs on the environment and climate change as well as relays information from the National Station, and equally runs programs in the local language. These programs attract a lot of farming audiences, as many use phones to listen to the radio. Though still timid, the use of the Internet and social media is becoming an important tool in information dissemination. The surveys revealed the information shared through the social media reaching the audience within a very short time. In every rural household, there is at least one mobile phone often used by several people. When farmers and extension agents receive climate information, they pass it on to other farmers through messages and voice notes. Farmer groups and federations likewise utilize WhatsApp groups to share useful information on a daily basis.

3.4. Nexus between effective communication and sustainable adaptive capacities of farmers

Climate change communication plays a crucial role in agricultural practices in terms of adaptation given the multiple challenges that farmers encounter. In the face of dwindling natural resources and poor yields due to climatic shocks, farmers adopt coping options which in most cases are autonomous and reactive. However, the study's findings revealed that short-term adaptation strategies are sometimes not sustainable or fail to produce the required results due to the lack of preparation and untimely interventions.

3.4.1. Amelioration of existing agro-climatic services and introduction of smart practices

Communications on climate change adaptation have improved access to new varieties and enhanced seedlings as well as information on crop type suitability and adaptability to changes in agro-ecological conditions (Fig. 4). Altering farming practices is also one of the advantages of climate communication. Agro-climatic information contributes to the choice of sowing dates and implementation of new techniques. Climate communication also makes it possible to improve technical performance, initially through the valorization of water, which has become a rare resource at certain periods in many villages. The household survey within the framework of this research revealed that with access to information farmers have adopted improved seedlings (30%), changed planting dates (18%), adopted drought resistant species (31%) and abandoned water-intensive crops (21%).



A. Drought resistant seed nursery.



B. Improved Irish potato variety.

Figure 4. Drought resistant seedlings and improved crop variety.

Agricultural practices make it possible to develop and increase yields, although to succeed farmers have to know how to determine the appropriate techniques. It is in this sense that agro-climatic information plays a major role at this level in the study area. Firstly, knowledge on the various factors involved in growth processes such as water, plant and animal species, pests and diseases, facilitate enhanced agricultural practices (A and B). This has already helped to build resilience of local farmers to climatic shocks. The use of information is largely linked to its accessibility and quality of current institutional offer. On the one hand, the existence of federations and local groups has valorized traditional agricultural practices - for instance, the use of fallow periods to enhance natural soil regeneration and animal dung application represent ancient techniques utilized for soil conservation. On the other hand, ANADER agents in collaboration with other institutions such as the FAO work on strengthening the use of modern technologies to better support smart agricultural practices (Fig. 5)



Figure 5. Materials offered by ANADER to support local farmers (source: ANADER, 2020).

Fig. 5. shows equipment offered to local residents to promote adoption of smart farming practices. The study revealed that 49% of farmers had received watering cans, 27% -- sprayers, 16% -- wheelbarrows, and 8% benefited from tractor services.

3.4.2. Rehabilitation of traditional knowledge systems

The Toupouri are an indigenous population with a plethora of traditional practices transmitted across generations. These knowledge systems can help the communities respond to the vagaries of weather, but the uncertainty of climatic phenomena requires rehabilitation of such practices. In order to do so, they should be recognized, documented and translated into policies. With strong traditional institutions, it becomes possible for these practices to be taken up by agricultural development operators rebranding and disseminating them among end-users. The interviews under the study revealed that the extent of climatic risks depends on the state of formations such as the availability of water resources and soil fertility. The agents involved in providing agro-climatic services make use of the endogenous knowledge of local farmers. The use of fallow techniques, crop association, seed selection, mutual cultural assistance and organic manure application undergo rehabilitation by agro-climatic technicians to combat climatic aberrations.

3.4.3. Building capacities of agricultural extension agents

Agricultural extension services aim to foster sharing of ideas and information, so as to influence decision making and reshape farming practices. Extension services should equally help farmers communicate among themselves. Yet, the efficacy of

these services depends on the capacities of the agents involved. It was revealed that over 50% of extension agents possessed little knowledge on climate change communications, while 20% lacked effective communication skills. Workshops and seminars organized by ANADER and NMS to enhance community effectiveness have ameliorated interventions in knowledge acquisition and sharing, as well as their competencies in carrying out field demonstrations. The use of modern information and communication technologies has become instrumental in training extension agents, allowing to respond to current trends and needs. This has helped them not to only communicate better but also to change their extension approaches. In Mont Illi, projects organized by the World Bank and African Development Bank in collaboration with local stakeholders have equipped extension workers with the required knowledge base and technologies to get climatic alerts at short notice. Also, these service providers have been taught how to accompany farmers in their endeavors by integrating their traditional knowledge into adaptation planning. By partnering with farmer groups and traditional institutions, they were able to change mindsets and belief systems that had shown limitations in the face of current climatic and other environmental stressors.

3.5. Challenges in using agro-climatic information to enhance sustainable adaptive capacity

Aware of the importance of agro-climatic information in building adaptive capacity, the Chadian government has demonstrated political will by mobilizing local and international actors, policies and resources to ensure that information reaches the end-users. Nevertheless, the study's household survey allowed identifying a number of pending challenges (Fig.6).

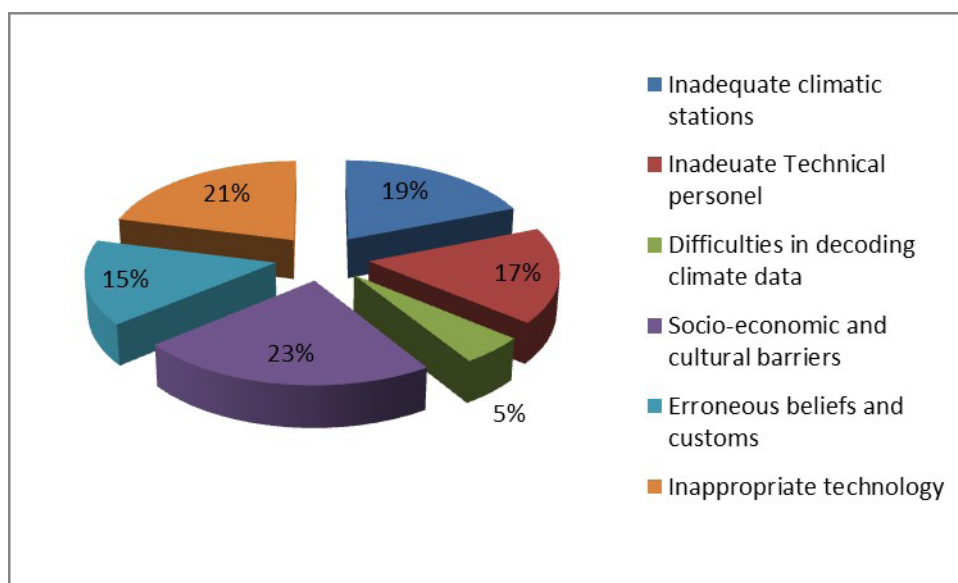


Figure 6. Challenges that farming audiences face in using agro-climatic information for adaptation.

As per Fig. 5. the ongoing challenges are multiple and include inadequate and lack of up-to-date climatic stations for in-situ data collection (19%), socio-economic and cultural issues such as inadequate financing and illiteracy (23%), insufficient technology such as cell phones and water pumps (21%), unqualified dissemination personnel (17%), erroneous traditional beliefs and pseudoscience (15%), and inability of farmers to decode and understand the transmitted information (5%). These factors affect farmers' ability to receive, accept, diffuse and translate information into adaptive practices.

3.5.1. Poor state of the observation network for collecting and transmitting climate data

The current meteorological observation network in Chad is not only obsolete but also does not cover the entire country's territory, impeding the reliability of the data harvested. According to the ANADER data management service, each year two to three stations stop transmitting climate data due to malfunction of the stations themselves or degradation of climate devices. As such, local stations rely on other national agencies and disaster relief NGOs for support. The Mont Illi Division has inadequate observation instruments and limited data on past and future climate conditions (Table III).

Table III. Weather stations in Mont Illi and scale of data available.

Station	Latitude	Longitude	Data availability and scale		
			Annual	Monthly	Daily
FIANGA S/PR EF	9.91	15.13	1980-2009	1980-2009	2000-2013
YOUE	9.90	14.93	1980-2009	1980-2009	2000-2013
KERA	8.91	17.08	1980-2009	1980-2009	2000-2013
TIKEM	9.81	15.05	1980-2009	1980-2009	2000-2013
FIANGA	9.93	15.18	1980-2009	1980-2009	2000-2013
FIANGA CFPA	9.88	15.11	1980-2009	1980-2009	2000-2013

Source: Ministère de l'Environnement de l'Eau et de la Pêche, MEEP (2020).

Table III shows that six observation stations had operated in Mont Illi. The measurements performed by these stations date back to 2009 (for monthly and annual data) and 2013 (for daily data), i.e. these stations have not generated any data for the last decade, because the equipment at the stations got either spoiled or became outdated. Faced with these discrepancies, local stations depend on the NMS for information and climatic alerts making local-level information dissemination not timely.

3.5.2. Inadequate technology and qualified personnel

Proper information generation and dissemination require adequate technology at the production centers and at the level of end-users. At the level of climatic stations, the non-functioning of observation stations had prompted the use of satellite data requiring complex software. However, the technical know-how and skilled personnel necessary to make satellite data exploitable are insufficient and sometimes completely absent. The state of information and communication technologies among farming audience poses yet another challenge. Although each household has at least one person with a cell phone, those who own these tools are mostly the youths, the majority of which are not interested in agriculture. The use of the social media to disseminate information is also hindered by other factors such as unsteady electricity supply and mobile connection. The generation of reliable agro-climatic services adapted to user needs requires sufficient number of highly qualified personnel. It was revealed that entities responsible for producing information do not have enough technical staff, and the age of the available few does not allow them to properly utilize modern communication technologies. In such a situation, farmers are forced to deal with auxiliary staff and non-professional observers, or rely on traditional facts to adapt to climatic hazards (Agricultural agent, personal communication, February, 2024).

3.5.3. Difficulties in decoding and understanding climatic information

Talking to farmers who have access to climatic bulletins and alerts, they acknowledged that climate related information is not communicated in simple and easy to understand terms. For instance, a farmer said -

“... alerts are shared in our forum at times, but we are not able to understand the technical jargon associated with agro-climatic information and how to use some of the technical guides proposed by agricultural technicians...” (Farmer, personal communication, February, 2024).

They also deplore the irregularity of training workshops and discrimination in the selection of participants. In this light, findings from the household survey revealed that 21% of farmers experienced difficulties understanding climatic alerts, while over 45% had no confidence in agricultural extension agents and the information they shared. Another 30% did not care about alerts and related information because of their low French language proficiency; and 6% stated that the broadcasts to communicate and promote agro-climatological products and services were done at inappropriate time as well as never targeted those in dire need due to corruption and favoritism. These factors made it difficult for interviewees to accept and implement agro-climatic information.

3.5.4. Socio-economic and cultural barriers

The analysis of the social representation of farmers, educational level and income situation permits better understanding the ways farmers use agro-climatic information in their agricultural practices. The household survey revealed that 54% of the population had completed primary education, 17% completed secondary education, and 19% had a university or professional degree, while another 10% did not go to school at all. Such low level of education among farming audiences hinders their ability to decode information and adopt technical prescriptions from extension agents. Education and training shape peasant's perception of climatic services and their interaction with extension services as revealed by farmers in the following excerpts:

"... Most of us farmers are not literate, and the agents who come to us do not understand the realities we experience. They just come to finish their days and leave thinking they have done their job, but we don't understand them at all. Every year the scenario is the same. From this perspective, we view them as a non-event. After they leave, we still continue with our old habits. Besides, we know our old habits better than them..." (Head of farmer association, personal communication, March, 2024).

"... I can barely cover the needs of my family, so why should I care about something that can cost me. I trust in God. If it rains heavily then so be it. If there is a rainfall deficit, why should I seek information? If there is no rain, will they be able to create artificial rain for us?..." (Farmer, personal communication, February, 2024).

This perception of farmers about extension agents, which is culturally inclined, has implications for the adoption of agro-climatic services and practices. Denial of such services has been attributed to poverty, as farmer income is inadequate for them to implement adaptation such as purchasing improved seeds and adopting novel irrigation techniques. The annual income of farmers is low - more than 80% of the community members earn from 100,000 to 350,000 FCFA. This situation largely explains the low demand for agro-climatic services among farmers. The acquisitions of new farmland requires significant investment, preventing farmers from expanding their plots. Thus, the cultivated areas remain insignificant (over 50% of farmers cultivate less than one hectare). In turn, the small farm size limits the deployment of innovations and long term projects.

3.5.5. Erroneous beliefs and pseudoscience

Climate change is perceived differently by different communities, often leading to misinformation. In Mont Illi, there are people who intentionally deny the existence of climate change and scientific methods proposed to adapt to or mitigate its impacts. They attribute climate change to the "anger of gods" or misfortune that

require cleansing of the land. These beliefs have reached the level of pseudoscience, making farmers deny the efficacy of policies intended to address the challenges, as well as the credibility of climate scientists and extension agents. For example, an extension said -

“... it is a challenging situation with us in the fields. How can they fight climate change by performing sacrifices and organizing traditional ceremonies? Someone needs to address this misinformation...” (Extension agent, personal communication, March, 2024).

The Toupouri make up the local indigenous community with its own traditional knowledge systems assisting in reading weather changes, including the belief that traditional sacrifices can avert adverse meteorological events (Fig.7).



A. The “Few Kake” or Cock sacrifice.



B. The “Féo Kagué” ceremony.

Figure 7. The cock sacrifice and festival to appease the “gods” for rainfall.

The festival depicted in the images above represents an important event in the lives of the Toupouri, and has certain implications for managing environmental challenges. The “Few Kake” (Image A) as it is usually called is done to thank the “god of rain” for the agricultural yields obtained in each household and implore his goodness for better production for the next farming season or year. In its turn, the “Féo Kagué” (Image B) ceremony is an opportunity for the community to invoke the spirits of their ancestors while imploring their blessing for an abundant harvest during the year. The crux of the matter is that believers in such practices tend to refute scientific information and techniques that could actually assist them in responding to the whims and caprices of climate.

4. Discussion

Information is power, and climate change communication is prerequisite for effective adaptation and mitigation. Given its high level of climatic vulnerability and the negative impacts registered over the recent years in the vital sectors such as agriculture, water and energy, Chad - after signing and ratifying the UNFCCC in 1993 - developed its Third NCCC in November 2020 following its Second NCCC (SCNCC, 2013), and First NCCC (CNI, 2001). As per the Chadian constitution, the government has taken regulatory measures integrating climate change in policies, programs, projects and development plans in the key economic sectors, including agriculture - the main source of livelihood for the population. The application of these legal texts and implementation of corresponding target actions oblige development actors and local communities to take into account the measures planned in national communications and the National Strategy for the implementation of the UNFCCC. Taking agriculture as the main stay of the population, this study revealed the existence of diverse actors and stakeholders involved in the production and dissemination of agro-climatic knowledge and practices in order to improve the adaptability of farming audiences.

International (FAO, World Bank, African Development Bank), national (ANADER, National Meteorological Service) and local actors (local councils, agricultural federations, traditional authorities) make concerted efforts to boost farmer adaptive capacities. These findings are corroborated by Hobson and Niemeyer (2011), Mkisi (2014), Prokopy et al. (2017), and Zafezeka et al. (2019), portraying the importance of coordinated climate change communication actions. This approach will enable blending of scientific and traditional knowledge - the model which has been thoroughly examined and critiqued in extensive scholarly literature (Egeruoh-Adindu, 2022; Lauter, 2023; Moye, 2024; Kongnso, 2024).

The types of information and the channels utilized for its dissemination are crucial and can shape the perceptions of audiences as well as build their adaptive capacities. In Mont Illi, climatic alerts (14%), smart agricultural practices (10%), changes in the agricultural calendar (20%), pest and disease outbreaks and control methods (17%), traditional beliefs and practices (25%), new techniques and improved seedlings (8%), and availability of fertilizers and other inputs (6%) are the types of agro-climatic information disseminated to the population. Dissemination channels include radio (24%), mouth-to-ear (25%), agricultural federations (16%), extension agents (14%), social media (10%), television (7%) and the Internet (4%). The media, including traditional and social media, play a pivotal role in public communication (Carvalho, 2010) of climate change needs, which represents a diverse landscape that takes into consideration the interest of all groups, especially most vulnerable ones. Classical methods of communication and knowledge sharing might be discriminatory,

as in the majority of African communities only the elites and upper social class have access to information. However, Evans et al. (2018) demonstrated that political actors and elites alone cannot lead to collective social change for the environment and climate change. As such, in most developing countries the agricultural sector has focused on agricultural extension approaches and farming associations to disseminate climate change information using non-formal education methods. Extension services transfer cost effective and contextualized technologies and smart practices through field visits, trainings and field demonstrations (Chindong, 2008; Mkisi, 2014; Odeleye, 2018; Tumbo et al. 2018).

Effective climate change communication and knowledge sharing empower farming audiences and enhance their adaptive capacities. In Mont Illi, climate change communication has allowed ameliorating existing agro-climatic services and paved the path for the adoption of smart practices, rehabilitating current traditional practices and building capacity of extension agents. For instance, with access to information, farmers have adopted improved seedlings (30%) and drought resistant species (31%), changed planting dates (18%), and abandoned water-intensive crops (21%). These findings concur with the studies by McGahey and Lumosi (2018) and Ouédraogo et al. (2020) holding that climate change communication is pivotal in adopting sustainable adaptive options. However, many factors influence the ability of farming audiences to accept and adopt climate change information. This research allowed identifying the lack of up-to-date climatic stations (19%), socio-economic and cultural reasons (23%), inappropriate technology (21%), unqualified extension agents (17%), erroneous traditional beliefs and pseudoscience (15%), and the inability of farmers to decode and understand the transmitted information (5%) as the main limiting factors requiring attention of climate change communicators (Tumbo et al., 2018; Moye et al., 2020; and Ouédraogo et al., 2020).

Like Sub-Saharan Africa, Central Asia is facing adverse climate impacts in critical sectors such as agriculture, water, and energy (Sabyrbekov and Overland, 2023; Miholjicic-Ivkovic, 2024; Fallah et al., 2024), yet the latter was able to employ a different approach within a similar context. Unlike Chad that had developed a national adaptation policy, the countries of Central Asia had endorsed a regional climate adaptation strategy. Kyrgyzstan, Kazakhstan, Tajikistan, Turkmenistan, and Uzbekistan had forged an adaptation strategy prioritizing information sharing and political dialogue. With regional stakeholder collaboration, the Initiative Climat International (iCI) aims to enhance collaboration and knowledge sharing for effective adaptation through consultations, workshops, and regional conferences (iCI, 2024).

That said, Uzbekistan's 3rd National Communication on Climate Change (2016) criticizes the fact that climate change issues are addressed solely on websites of government bodies or non-governmental organizations and are insufficiently covered

by the media (Center of Hydrometeorological Services, 2016). Given that climate change is transboundary, regional collaborations provide an excellent basis for sustainable adaptation actions - an approach that can also work for the countries of Lake Chad basin. Climate change education and communication are at the heart of adaptation policies in Central Asia. For instance, in 2021, the government of Kyrgyzstan presented the Comprehensive Action Plan for Climate Change Education that targets public institutions, academia, private sector, civil society, international organizations and local communities. The Plan aims to mainstream climate change into formal education and training, including gender and indigenous knowledge systems (UNESCO, 2024). Faced with these challenges, the IPCC (2015) opined that the effects of climate change in Africa are exacerbated by low adaptive capacities, and as such effective communication and knowledge sharing can reshape existing practices and improve farmer adaptive capacities.

5. Conclusion

This study aimed to examine the extent to which climate communications and knowledge sharing can enhance sustainable adaptive capacities of farming audiences. Using the case of the Mont Illi Division in Chad, a mixed methods approach was applied for data collection and analysis. The study's findings indicate that climate change communication occupies a central place in adaptation policies in Chad. With already three NCCCs between 2001 and 2020, the national government has demonstrated political and integrated communication as a central pillar in the national adaptation plan. The involvement of international, national and local actors has paved the way for disseminating a variety of information types via diverse channels. Information types include climatic alerts, changes in agricultural calendar, transfer of technologies and smart practices, and availability of improved seedlings. Unlike in other areas where the media play a central role in dissemination, farming audiences in Mont Illi have more access to information from farming federations and traditional authorities. The use of extension services in the transfer of contextualized technologies and training seminars, field visits and demonstrations to share good practices have significantly contributed to building adaptive capacity.

Nevertheless, challenges abound. The production of climate services is hindered by the absence of weather stations, limited qualified personnel, information inaccessibility, inadequate financing to purchase inputs, and erroneous traditional beliefs. All these curb farmers' ability to accept information and shift their practices. To ensure sustainable adaptive capacities, it is necessary to strengthen institutions providing information at all levels, reinforce agricultural extension approaches, and integrate traditional knowledge systems into adaptation while putting clarity on its importance and limits.

References

- Adelphi. (2021). Lake Chad Risk Assessment: The role of climate change in the current crisis, “Lake Chad Risk Assessment Project”, Republic of Chad
- Baohoutou, L., Abdoulaye, B., Clobite, B., Mbanghoguinan, A., and Issak, A. (2014). Impact de la variabilité pluviométrique et de la sécheresse au sud du Tchad: effets du changement climatique, *Revue Ivoirienne des Sciences et Technologies*, <https://doi.org/10.4236/ahs.2013.22012>
- Bautista, A., Manalo, J., Jayson, C., Berto, T., Hallares, F., and Saludez, J. (2017). Climate Change communication in the rice sector, DA-Philippine Rice Research Institute Maligaya, *Science City of Muñoz*, 3119 Nueva Ecija, ISBN NO. 978-621-8022-33-1
- Bedoum, A., Clobite, B., Bell Jean, P., Issak, A., Robert, M., and Laohoté, B. (2017). Évolution des indices des extrêmes climatiques en République du Tchad de 1960 à 2008, *Atmosphere-Ocean*, 55:1, 42-56, DOI: [10.1080/07055900.2016.1268995](https://doi.org/10.1080/07055900.2016.1268995)
- Carvalho, A. (2010). Media(ted) discourses and climate change: a focus on political subjectivity and (dis) engagement. *Wiley Interdisc Rev Clim Change* 1(2):172-179, <https://wires.onlinelibrary.wiley.com/doi/10.1002/wcc.13>
- C H S. (2016). Third National Communication of the Republic of Uzbekistan under the United Nations Framework Communication on Climate Change, Tashkent, Republic of Uzbekistan
- Chindong, P. (2008). Information circulation in rice production: The case of UNVDA and Ndop rice farmers, Cameroon, *Masters Dissertation*, Van Hall Larenstein, University of Applied Sciences, Wageningen, The Netherlands, <https://edepot.wur.nl/1195>
- DSA/ANADER. (2020). Rapport de Campagne agricole 2019-2020. Direction de la Statistique Agricoles et l'Agence Nationale d'Appui au Développement Rural. Ministère de l'Agriculture, N'Djamena Tchad. <https://www.scirp.org/reference/referencespapers?referenceid=2988272>
- Egeruoh-Adindu, I. (2022). Leveraging Indigenous Knowledge for Effective Environmental Governance in West Africa. *Beijing Law Review*. 2022;13:931-947, <https://doi.org/10.4236/blr.2022.134060>
- Evans, H., Lauren, D., and Ruth, T. (2018). Communicating Climate Change: Theories and Perspectives, https://doi.org/10.1007/978-3-319-69838-0_7
- FAO. (2021). Mise à jour de la contribution déterminée nationale (cdn), République du Tchad, Policy, lex-faoc219739, <http://https://unfccc.int>
- FAO, (2012). Volet sécurité alimentaire du document national de protection sociale. Profil des urgences au Tchad. Représentation de la FAO au Tchad. Cadre de Programmation Pays, https://www.fao.org/fileadmin/user_upload/faoweb/chad/docs/Representation_de_la_FAO_au_Tchad_Final.pdf
- FAO. (2011). The Role of Information and Communication Technologies for Community-Based Adaptation to Climate Change, Communication for Sustainable Development Initiative - CSD, Technical Paper, Rome, Italy, https://www.fao.org/uploads/media/ap606e_2.pdf
- Fallah, B., Didovets, L., Rostami, M and Mehdi, H. (2024). Climate change impacts on Central Asia: Trends, extremes and future projection. *International Journal of Climatology*, DOI: [10.1002/joc.8519](https://doi.org/10.1002/joc.8519)
- Hobson, K., and Niemeyer, S. (2011). Public responses to climate change: The role of deliberation in building capacity for adaptive action. *Global Environmental Change*, 21(3). 957-71. DOI: [10.1016/j.gloenvcha.2011.05.001](https://doi.org/10.1016/j.gloenvcha.2011.05.001).
- ICI. (2024). “Capacity development for climate policy” is supporting its partner countries in the implementation of their Regional Climate Change Adaptation Strategies. <https://www.international-climate-initiative.com/en/iki-media/news/regional-climate-change-adaptation-strategy-in-central-asia/>
- IPCC, (2014): Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp

- IPCC, (2015). Climate Change 2014: Synthesis report. Core Writing Team, R. Pachuni, L.A. Meyers (Eds), Contribution of working groups 1, 11, & 111 to the fifth assessment. *Report of the intergovernmental panel on climate change IPCC*, Geneva Switzerland.
- Kongnso, E. (2024). "Mainstreaming Indigenous Knowledge of Pastoralists into Climate Change Policies in Cameroon". *International Journal of Environment and Climate Change* 14 (10):557-70. <https://doi.org/10.9734/ijecc/2024/v14i104508>
- Lamarche, A. (2023). Climate-fueled Violence and Displacement in the Lake Chad Basin: Focus on Chad and Cameroon, Report, *Refugees International*, <https://communityconnect.cblt.org/topic/report-climate-fueled-violence-and-displacement-lake-chad-basin-focus-chad-and-cameroon>
- Lauter, O. (2023). Challenges in combining indigenous and scientific knowledge in the arctic, *Polar geography*. 2023;46:1, 62-74, <https://doi.org/10.1080/1088937x2023.2233578>
- McGahey, D., and Lumosi, C. (2018). climate change communication for adaptation: mapping communication pathways in semi-arid regions to identify research priorities, *Journal of Sustainable Development in Africa* (Volume 20, No.1, 2018), ISSN: 1520-5509
- Merzdorf, J., Pfeiffer, J., and Forbes, B. (2019). "Heated Discussion: Strategies for Communicating Climate Change in a Polarized Era," *Journal of Applied Communications: Vol. 103: Iss. 3*. <https://doi.org/10.4148/1051-0834.2269>
- Miholjic-Ivkovic, N. (2023). Impact of climate change on migration trends in rural Central Asia, *Central Asian Journal of Sustainability and Climate Research* (2024) 3(1):74-95, <https://doi.org/10.29258/CAJSCR/2024-R1.v3-1/74-95.eng>
- Ministère de l'Environnement de l'Eau et de la Pêche, MEEP. (2020). Troisième Communication Nationale du Tchad sur le changement climatique. *Ministère de l'Environnement et de l'Eau*, 220 p. <https://unfccc.int/sites/default/files/resource/RAPPORT%20TCN%202020.pdf>
- Ministère de l'Environnement de l'Eau et de la Pêche, MEEP, (2009). Seconde Communication Nationale du Tchad sur le changement climatique (SCNCC). *Ministère de l'Environnement et de l'Eau*, 220 p. <https://unfccc.int/sites/default/files/resource/tcdnc2.pdf>
- Mkisi, B. (2014). "The Role Of Agricultural Extension In Smallholder Farmer Adaptation To Climate Change In Blantyre District, Malawi" (2014). *Open Access Theses*. 353. https://docs.lib.purdue.edu/open_access_theses/353
- Moye, E., Nsahlai L., and Kiming I. (2020). Agricultural Extension Approaches and Climate Change Communication Within the Ndop Rice Sector, North West Region, Cameroon. *International Journal of Social, Political and Economic Research*, 7(2), 125-141. <https://doi.org/10.46291/IJOSPERvol7iss2pp125-141>
- Odeleye, G. (2018). Extension's role and stakeholders' intervention in climate change advocacy, *International Journal of Agriculture, Environment and Food Sciences*, e-ISSN : 2618-5946 DOI: 10.31015/jaefs.18030
- Ouédraogo, I., Diouf, N., Gnalenba, A., Zougmore, R., and Ndiaye, O. (2020). Diffusion des informations climatiques et météorologiques au Sénégal. Document de capitalisation des acquis du projet USAID/CINSERE. Programme de Recherche du CGIAR sur le Changement Climatique, l'Agriculture et la Sécurité Alimentaire (CAAFS). Wageningen, Pays Bas, 20 pages., <https://hdl.handle.net/10568/115155>
- PANA, (2010). Programme d'Action National d'Adaptation aux changements climatiques (PANA-Tchad), pp. 92. https://unfccc.int/sites/default/files/resource/CHAD-NAP_FR_web.pdf
- Prokopy, S., Wendy-Lin, B., Gary, B., and Power, R. (2017). Agricultural Extension and Climate Change Communication, *Oxford Research Encyclopedia of Climate Science*, DOI:10.1093/acrefore/9780190228620.013.429
- Reyanbélé, N. (2023). L'UNICEF et la prise en charge des enfants vulnérables dans la région du Mayo Kebbi-est au Tchad (1960-2020), *Mémoire en Histoire des Relations Internationales*, Université de Yaoundé 1, Cameroon
- Sabyrbekov, R., and Overland, I. (2023). Measuring the Capacity for Adaptation to Climate Change in Central Asia, *Central Asian Journal of Sustainability and Climate Research* (2023) 2(1):83-104, <https://doi.org/10.29258/CAJSCR/2023-R1.v2-1/83-104.eng>

- SNLCC .(2017). Stratégie Nationale de Lutte contre les Changements Climatiques au Tchad (SNLCC). Available at <http://extwprlegs1.fao.org/docs/pdf/Cha186306.pdf>
- Tumbo, D., Nicholaus, M., Kadege, G., Malongo, R., Haug, R., and Camilius, A. (2018). Exploring Information Seeking Behavior of Farmers' in Information Related to Climate Change Adaptation Through ICT (CHAI), *International Review of Research in Open and Distributed Learning* Volume 19, Number 3, <https://doi.org/10.19173/irrodl.v19i3.3229>
- UNESCO, (2024). Kyrgyzstan, Climate change communication and education. Education Profiles, <https://education-profiles.org/central-and-southern-asia/kyrgyzstan/~climate-change-communication-and-education>
- World Bank. (2021): Climate Change Knowledge Portal: Observed Climate Data, CRU TS4.07 0.5-Degree, DOI: <https://doi.org/10.57966/tw2k-9h36>
- Zachary, M., and Faulkner, W.(2016). Communicating Climate Change to Agricultural Audiences, College of Agriculture and Life Sciences, Virginia Tech, *Publication BSE-203P*, https://www.pubs.ext.vt.edu/content/dam/pubs_ext_vt_edu/BSE/BSE-203/BSE-344.pdf
- Zafezeka, M., Paramu, L., Mudhara, M., and Obert, J. (2019). Climate Change Mainstreaming in Extension Agents Training Curricula: A Case of Mopani and Vhembe District, Limpopo Province, South Africa, *Journal of Asian and African Studies*, DOI: [10.1177/0021909619857098](https://doi.org/10.1177/0021909619857098)



Factors shaping corporate green economy practices in Kyrgyzstan and Georgia

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ABSTRACT

Environmental practices by private businesses are important for transiting to green economy. Against the backdrop of scarce empirical literature on green economy practices in the Central Asian Region, this study aims to examine factors affecting corporate green economy practices in Georgia and Kyrgyzstan using the most recent enterprise survey dataset, as well as contribute to the discussion of the green economy driving factors from enterprises' perspective. Green economy practices are assessed based on CO₂ monitoring and energy management actions. The study's empirical findings suggest that along with general business characteristics access to finance and energy costs drastically impact the adoption of green economy routines in the private sector. Interestingly, the use of foreign technology and international certification have demonstrated positive effects only in the sample of Georgia, without any statistically significant manifestations in Kyrgyzstan. Moreover, only large firms have shown positive trends in adopting CO₂ monitoring and energy management measures. These findings imply the need for adjusting targeted green economy state policies to specific country contexts.

ARTICLE HISTORY

Received:
October 25, 2024
Accepted:
December 20, 2024
Published:
December 29, 2024

KEYWORDS

green economy, sustainable development, CO₂, Kyrgyzstan, Georgia

1. Introduction

Climate change poses complex challenges for economies to adjust to and mitigate the corresponding effects. Both from consumers' and producers' perspectives, resource-efficient behavior is required (Thøgersen, 2021). On the one hand, producers globally face risks associated with extreme weather events and other related operational and long-term risks; on the other hand, compliance with government environmental regulations puts additional pressure on them via mounting corporate operational costs (Tingey-Holyoak et al., 2024; Unepfi, 2023). Green economy practices by firms are essential for achieving sustainable development objectives (Weick, 2016).

Climate change is an issue of planetary scale with no exception for developed countries or the Global South, and financing climate adaptation efforts continues to be an important topic of discussion. The establishment of state-funded institutions to promote sustainable development, including support for technological innovation of enterprises to reduce greenhouse gas (GHG) emissions and promote energy-saving production, is essential across jurisdictions (Guo et al., 2020). However, adaptation to environmental challenges and transition to green economy is costly for most enterprises in developing nations (International Monetary Fund, 2022). In addition, the dominance of small and medium-sized enterprises (SMEs) in developing countries complicates the deployment of green economy innovations due to the insufficient capacities and resources of most SMEs compared to large enterprises (Rodrigues & Franco, 2023).

The empirical literature suggests that green corporate practices are driven by a multitude of factors, ranging from company characteristics to state environmental regulations (Alraja et al., 2022; Harakati et al., 2024; Jun et al., 2019; Siewers et al., 2024). However, there is a lack of understanding of the factors behind firms' behavior towards green practices in the context of developing countries, given various constraints that small and medium enterprises face.

Central Asian economies are considered extremely vulnerable to climate change, and sustaining economic growth requires government policy to meet multiple challenges, including protecting the environment, reducing GHG emissions, as well as the business community and environment internally adapting to the emerging conditions (Brollo, 2023; Vakulchuk et al., 2023). Yet, the literature on green economy for the region is rather limited. To the best knowledge of the authors, no studies so far have focused on the sustainable development practices of enterprises specifically in Central Asian economies, although rare investigations include target countries in larger samples and examine the impacts of environmental trends on general economic indicators (Brunelli et al., 2022; Isiksal et al., 2022).

To contribute to filling this gap, this study has aimed to analyze the factors affecting green economy practices of private firms in Georgia and Kyrgyzstan using the World Bank Enterprise Surveys (WBES) 2023 data. Along with firm characteristics, the dataset includes the Green Economy Module allowing to evaluate factors affecting the adoption of CO₂ monitoring and energy management measures. Thus, this study contributes to the discussion of green economy driving factors from enterprises' perspectives, an almost not explored matter for the Central Asian Region and Georgia. Moreover, given the challenges related to data availability to examine the climate change topic in developing countries, the use of the most recent firm-level dataset with specific questions on sustainability practices enriches the understanding of potential barriers for green transition. In its turn, the empirical analysis based on the data from Kyrgyzstan and Georgia underlines the importance of the institutional context varying by country.

2. Literature review

Environmental innovations by enterprises play a pivotal role in explaining green economy dynamics. Studies indicate that environmentally friendly innovations by firms depend on different factors ranging from company characteristics to specific local business operation conditions, and government regulations. Among them, participation in external economic activities often manifests itself as a strong factor affecting green economic activities in the private sector. Thus, while examining this relationship based on the global data, including the Central Asian Region, Siewers et al. (2024) found that enterprises with higher participation in global value chains demonstrated a more efficient use of energy and monitoring of CO₂.

Using India's data, Ali and Singh (2024) revealed a significant correlation between the size of a firm and adoption of green economy practices. They concluded that the impact of enterprise characteristics varies by firm size. For instance, female ownership positively affects adoption in large firms but negatively in SMEs. However, lean operations, research and development (R&D) spending, and international quality certification positively influence the adoption of green practices in both SMEs and large companies.

Some other firm characteristics, including managerial features and labor force composition, are likewise argued as significant drivers of environmentally sensitive behavior among enterprises. Harakati et al. (2024), examining the role of CEO's gender on climate change adaptation in Mediterranean countries, showed that entities with female CEOs had a stronger commitment to environmental regulations, such as CO₂ emission control. Yet, studies indicate that not only internal corporate features but also relevant government policies may explain green practices by firms.

For instance, the study by Jun et al. (2019), focusing on the case of Pakistan, argued that - along with internal factors of firms, such as skilled labor and managerial approaches to green practices - awareness about green products in the relevant market and existence of government support are important for SMEs in leveraging green innovation.

Government efforts to mitigate environmental challenges have some effect on enterprises adopting more environmentally friendly practices. Thus, Lin & Ho (2011) found that among logistics firms in China regulatory pressure and state support successfully stimulated green practices, whereas uncertainties related to the environment and complexity of green practices hindered their adoption. Public environmental policies may have an effect on the financial aspects of enterprises. Based on the data for firms in China during 2007-2020, Li et al. (2022) found that the CO₂ emission trading system had a positive impact on the cash holdings of firms, with the effect more expressed in enterprises subject to more rigorous government monitoring and enjoying fewer investment opportunities.

Previous empirical studies also indicate that environmental concerns and state regulations have implications beyond firm's internal financial behavior and may spill over to the financial market. Perdichizzi et al. (2024) examined the relationship between CO₂ emissions and corporate values using the data for European private businesses. The authors argued a negative relation between CO₂ emissions by firms and their market value, as high intensity of GHG emissions may lead to higher environmental liability risks. Yet, this causal relationship may not be present or be weak in developing countries, where financial markets are not fully matured to reflect environmental conditions and regulations.

On the opposite, even without the corresponding government regulations environmental concerns, including climate change effects, may represent a distinct exogenous modifier of corporate behavior. The study by Benincasa et al. (2024), investigating the coping strategy of firms in the face of climate change damages - focusing on the sample of both developing and developed economies - argued that companies experiencing losses due to weather conditions demonstrated a higher probability of applying green practices and investing in long-term assets.

Other studies suggest that the movement towards a sustainable green economy is closely related to technological innovation intensity in a market (for instance, Alraja et al., 2022), i.e. Low technological innovation in an economy may not be favorable for wider green economy practices.

Investment in green economy practices can be beneficial for firms by boosting their performance. Petreski et al. (2024) investigated the impacts of investment in environmentally sustainable practices on labor productivity in central and Southeast Europe, as well as the Commonwealth of Independent States (CIS). They found that

such investments had a strong effect on labor productivity, especially in firms with prevailing low-skill labor force. Moreover, they underlined regional differences as well - SMEs in Central European countries demonstrated higher labor productivity effects than those in Southeast Europe and CIS countries.

Central Asia is no exception in terms of the climate change challenges that the region is facing, and the priority of green economy objectives is underlined by national policy frameworks, regional cooperation agendas, as well as the increasing vulnerability to climate-related risks. And yet, the literature on green economy in the region is rather scarce. The literature review revealed no research focusing specifically on corporate green economy practices inside the region although, as mentioned above, several empirical investigations encompassed Central Asian states in larger country samples. Some studies explored the relationship of environmental indicators with economic trends. For instance, Isiksal et al. (2022) studied the role of human capital in the relationship between natural resources, economic expansion, and CO₂ in Central Asian countries. The authors argued that exploitation of natural resources would inflate emissions, and that raising environmental awareness would facilitate the positive impact of human capital on improving the environment. Ergasheva et al. (2023), focusing on ESG investment in Russia and Central Asian states, stressed the importance of green finance instruments in the region. Brunelli et al. (2022), examining environmental auditing in Central Asia, concluded the need for active elaboration and implementation of government enforcement and regulation towards environmental standards. The aim of this study, focusing on the green economy practices of firms in Georgia and Kyrgyzstan, is to contribute to better understanding the dynamics of private sector involvement in sustainable development efforts by providing a comparative analysis of the two countries - one from Central Asia and one from the Caucasus.

3. Green economy in Georgia and Kyrgyzstan

As in the majority of developing countries, green economy mechanisms in Georgia and Kyrgyzstan are not fully developed albeit existing national strategies and targets to achieve green economy objectives related to GHG emission reduction, green energy, and energy efficiency. In fact, Georgia's strategy on SME development comprises measures to mainstream environmental practices, as well as anticipates alignment with international standards in the long run. The overview of the green economy transition experiences of both target countries indicates prevalence of activities related to endorsing national strategies incorporating green economy targets and passing green legislation. Alongside with these, the countries have been taking active steps to introduce financial measures to support green investments,

encourage environmentally friendly business practices, and reduce cost barriers for firms transitioning to sustainable operations. Thus, following the post-COVID-19 period, the recovery plan in Georgia included green stimulus mechanisms and introduction of sustainable finance principles (OECD, 2022). In a similar vein, Kyrgyzstan's Green Economy Development Program envisages mechanisms to support the transition to an inclusive green economy, such as sustainable finance measures, fiscal stimuli, and sustainable public procurement. In particular, at the policy level, it is noted that climate change creates conditions for inequality among the population, including gender disparity in accessing labor market opportunities. This challenge underscores the importance of comprehensive actions to ensure a just transition in both target countries (Government of Georgia, 2021; Ministry of Economy and Commerce of the Kyrgyz Republic).

The introduction of Environment, Social and Governance (ESG) standards represents one of the recent milestones in the realm of sustainable development goals (SDGs) within the region's financial sector. The National Bank of Georgia has drafted the ESG Reporting and Disclosure Principles and is publishing the Sustainable Finance Report (National bank of Georgia, 2024). The National Bank of Kyrgyzstan has likewise developed and adopted the roadmap for the implementation of ESG in the banking sector (24.kg, 2024). Along with this, targeted activities are taking place in several other economic sectors oriented towards low-carbon transition, such as clean energy, energy-efficient buildings, green transportation, etc. Although both countries' practices confirm the priority of SDGs in relevant strategic documents, data evidence suggests the need for urgent and active domestic measures to reduce emissions and increase energy efficiency. The production-based CO₂ emissions index shows a strong increase, especially after 2010 (see Figure 1). The same indicator shows a declining trend for the European OECD countries. In most developing countries, improving public welfare requires ramping up production, including in the sectors which are intensive CO₂ emitters. Meeting these sustainable development requirements - less pollution and higher incomes - necessitates the efficient use of energy resources. Yet, as shown in Figure 2, energy productivity in Georgia rapidly dropped after 2001 - most likely due to the increased reliance on energy-intensive sectors, outdated infrastructure, and limited efficiency measures, with a slight improvement only after 2020. The situation in Kyrgyzstan did not change substantially over the review period, with only a minor difference between the values in 2000 and in 2022. In contrast, the OECD group's curve indicates a long-term improvement in energy productivity. The stagnating trend in Georgia and Kyrgyzstan points to higher energy consumption for producing relatively smaller volumes of goods and services. Furthermore, it underlines the importance of rolling out energy-saving technologies in both the manufacturing and household sectors.

The latter is clearly demonstrated in Figure 3 - energy intensity per capita exhibits an analogous improving long-term trend for the OECD group, whereas in Georgia it shows rising intensity over the last decade, resulting in a value exceeding “one” (1). Despite some fluctuations, in Kyrgyzstan there is a small increase in energy intensity per capita in 2022 compared to the early 2000s.

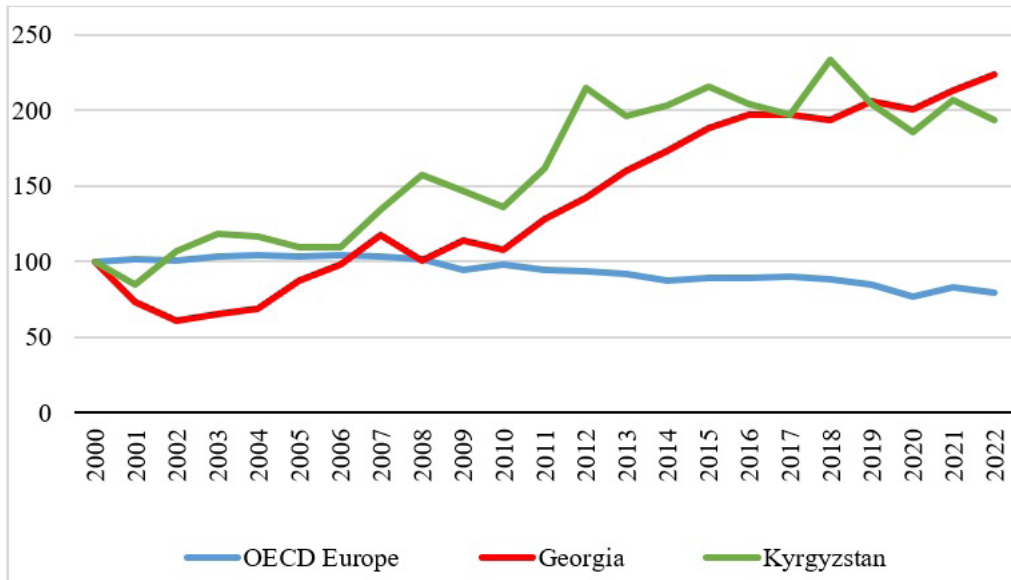


Figure 1. Production-based CO₂ emissions (Index, 2000).

Source: OECD, 2022.

Figure 1 illustrates a significant upturn in production-related CO₂ emissions in Georgia and Kyrgyzstan, contrasting with a consistent decline in OECD Europe. This upward trend indicates an increase in the environmental externalities of industrial and energy-intensive sectors. These developments intensify the regulatory pressure on firms to implement cleaner production technologies, invest in emission-reducing innovations, and meet global standards in order to obtain green finance and access to export markets.

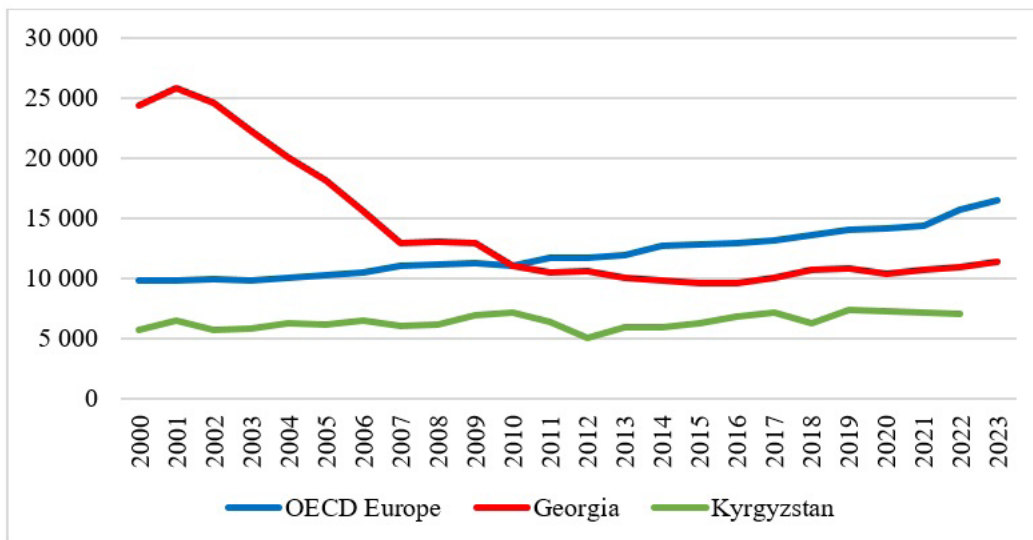


Figure 2. Energy productivity, GDP per unit of TES (US dollars per ton of oil equivalent, 2015).

Source: OECD, 2022.

As shown in Figure 2, the low and generally steady energy productivity in Georgia and Kyrgyzstan in recent years indicates that enterprises are producing comparatively less economic output per unit of energy utilized. Enhancing energy efficiency is essential for businesses aiming to reduce operational expenses and satisfy sustainability standards increasingly expected by investors and governments. This inefficiency may indicate outdated technologies and insufficient incentives for energy-efficient attempts.

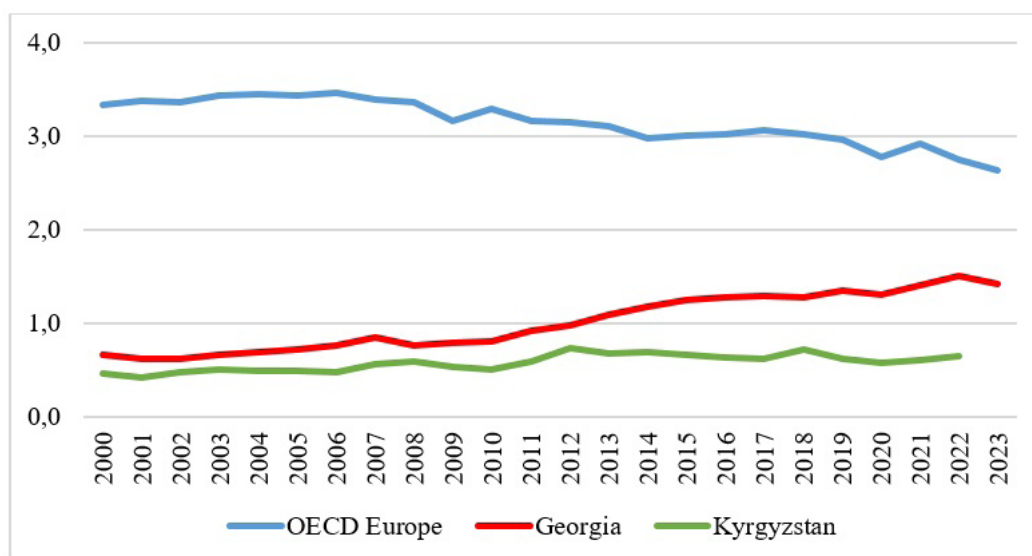


Figure 3. Energy intensity per capita (Tons of oil equivalent per person).

Source: OECD, 2022.

The notable rise in per capita energy consumption depicted in Figure 3 for both Georgia and Kyrgyzstan, especially evident in Georgia, shows a growing energy demand. The pattern indicates that firms experience crucial constraints, such as inadequate access to energy-efficient infrastructure and technologies. This situation highlights the importance of adopting energy-saving practices to allow businesses to maintain cost competitiveness while also complying with evolving environmental standards. Consequently, businesses are incentivized to adopt energy-saving practices and invest in modern and efficient technologies to maintain cost-effectiveness, as well as satisfy increasingly stringent environmental regulations.

These data indicate that carbon emissions are rapidly growing while energy productivity is falling, and the population consumes more energy in Georgia and Kyrgyzstan. Nevertheless, these developments do not distinguish between residential and production sectors' energy consumption and CO₂ emissions. It is often argued that both households and enterprises play a role in these developments, but it is enterprises - as key economic growth drivers - that are expected to be more energy-efficient and emit less carbon dioxide. Green policies are a government priority, and both target governments have launched various measures to forge favorable conditions for a broader application of green economy practices among private sector actors by setting environmental standards via direct regulations and financial reporting norms. However, the relevant literature argues that beyond state regulatory efforts there are other important factors affecting the adoption of sustainable development practices by firms.

4. Methodology

4.1. Analytical approach

To investigate the determinants of environmental and energy management practices at the firm level, this study utilized a logistic regression (logit) model estimating the probability of adopting CO₂ monitoring and energy management measures. The basic logistic regression model, exploring the linear relationship of explanatory covariates X with the predicted logit, is specified as follows (Pampel, 2020):

$$\text{logit}(p) = \text{Ln}\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_k X_k + \varepsilon$$

, where p represents the probability of a firm adopting a specified measure,

X_1, X_2, \dots, X_k denote the explanatory variables,

β_0 is the intercept term,

And ε represents the error term.

The coefficients $\beta_1, \beta_2, \dots, \beta_k$ are estimated using maximum likelihood estimation procedures.

The calculations use two binary dependent variables. The first variable indicates whether a firm has monitored its CO₂ emissions over the past three years. The value of “one” (1) denotes that the firm has engaged in CO₂ monitoring, while “zero” (0) indicates that it has not. The second dummy dependent variable indicates whether a firm has adopted energy management measures over the last three years to reduce emissions, waste, or pollution. The set of explanatory variables include various indicators related to corporate characteristics. A detailed description of the variables is given in Table I. The age of firm, or years since establishment, may have an important effect on sustainability practices. Older firms may have established frameworks and resources, yet might be more resistant to change, whereas younger firms may be more agile and open to innovation. Therefore, the effect of firm age might be nonlinear, and in order to incorporate this potential effect the square of the firm age is included among the explanatory variables (Karymshakov et al., 2019). Firm size is another potential important factor, as larger companies generally have more financial and operational capacities to implement environmental practices. They may also face greater regulatory scrutiny, pushing them to adopt sustainability measures. Conversely, smaller enterprises - while resource-constrained - may still adopt energy-efficient practices in a cost-effective manner.

The manager’s experience influences how firms approach sustainability. For instance, experienced managers are more likely to recognize the strategic value of environmental initiatives, drawing on a broad range of challenges and solutions in the process. Furthermore, manager’s gender can also shape firm’s environmental decisions - studies suggest that female managers tend to prioritize long-term sustainability goals, often driving more environmental actions (Ullah et al., 2022). Thus, the study team factored in both gender and experience of the top manager, measured as the number of years she/he has worked in the sector to which the firm belongs. As mentioned above, foreign market experience and connections with foreign partners significantly influence corporate performance. To approximate this potential effect, the calculations included two dummy variables. The first one indicates whether a firm is using a foreign-licensed technology, since the utilization of foreign-licensed technologies may have implications for technological and operational improvements, which could positively influence their environmental performance too. This variable can also reflect the degree of internationalization and competitiveness of a firm linked to a higher likelihood of adopting practices that align with sustainability standards. The second variable refers to whether a firm has a quality certification as a potential indicator of external standards effecting corporate environmental practices. Quality certifications signal a firm’s commitment to high operational and environmental standards, driving them to adopt best practices, including energy management and CO₂ monitoring. Companies with certifications such as ISO14001

or ISO50001 are likely to already have environmental management systems in place, making them more fit for engaging in sustainable practices (Fronzel et al., 2018). Enterprises, following their profit maximizing behavior, may simply adopt energy-saving measures due to the higher costs of energy consumption for their production activities. High electricity costs create a strong economic incentive for businesses to adopt energy-saving measures, reduce consumption, and comply with environmental regulations. Therefore, in the estimations the study team considers the electricity cost ratio, which helps to explore the influence of operational costs on corporate sustainability practices, i.e. offering insights into how economic pressures stimulate the adoption of energy management and environmental monitoring systems.

The financial resources that firms may use represent one of the fundamental factors for sustainable practices. In this study, the corporate financial potential is based on the indicator of whether a firm has a credit line or loan. Enterprises with access to loans can more easily fund the technologies and processes needed for sustainability initiatives. Apart from the internal firm characteristics, the sectors of the economy where firms operate may demonstrate varying performance in response to environmental changes due to both internal characteristics and different regulatory and operational requirements. Businesses in high-emission sectors, such as manufacturing in general, are more likely to face these regulations. In the empirical model, companies are classified as per four main sectors of the economy: food, non-food manufacturing, trade, and services.

Table I. Description of variables (World Bank, n.d.).

Variable	Description
Dependent variables:	
CO2 monitoring	1 - firm has monitored its CO2 emissions over the last three years, 0 - otherwise
Energy management adoption	1 - firm has adopted energy management measures to reduce emissions, waste, or pollution in the last three years, 0 - otherwise
Explanatory variables:	
Firm age	Number of years from the year that firm began operations to 2023
Squared firm age	Square of the firm age
Manager experience	Number of years of experience of the top manager in the sector
Female manager	1 - top manager is female, 0 - otherwise
Capital city	1 - firm is located in the capital city, 0 - otherwise
Electricity cost ratio	Percentage share of the firm's total annual electricity cost relative to total annual sales in 2022
International certification	1 - firm has an internationally recognized quality certification, 0 - otherwise

Table I. Cont.

Foreign technology	1 - firm uses technology licensed from a foreign-owned company (excluding office software), 0 - otherwise
Access to finance	1 - firm has a line of credit or loan from a financial institution, 0 - otherwise
Firm size	1 - small firm, 2 - medium-sized firm, 3 - large firm (based on the number of employees: small = 5-19, medium = 20-99, large = 100 or more)
Firm sector	1 - food, beverages, and tobacco; 2 - manufacturing; 3 - trade and wholesale; 4 - services
Country	1 - Georgia; 2 - Kyrgyz Republic

4.2. Data source

This study has utilized the firm-level data from the 2023 World Bank Enterprise Surveys (WBES) for Georgia and the Kyrgyzstan. The survey dataset includes corporate characteristics including innovation, access to finance, corruption, infrastructure, energy, business-government relations, barriers to growth, and performance indicators. Notably, the 2023 WBES includes the Green Economy Module, which assesses firms' adoption of sustainable practices and climate change mitigation measures. For this analysis, the datasets for Georgia and the Kyrgyz Republic were merged based on the variables specified in the empirical models. The resulting combined dataset comprised 946 firms, including 592 from Georgia and 354 from Kyrgyzstan. This dataset represents the most recent information available for these countries, offering a valid perspective on sustainability practices at the firm level. The dataset includes responses from businesses operating in diverse industries, providing information on corporate characteristics, managerial attributes, financial access, and technological capabilities.

Table II provides descriptive statistics for the total sample, as well as the breakdown by country. On average, 22% of companies in the total sample monitor their CO₂ emissions, with Georgia demonstrating a higher percentage compared to Kyrgyzstan. Georgia also demonstrates a higher share of energy management adoption than the Kyrgyz Republic. These differences may reflect regional variations in environmental awareness or regulatory pressure, which could influence corporate sustainability practices. The average firm age in Kyrgyzstan is 19.5 years and 12.7 years in Georgia, suggesting the former having a higher proportion of enterprises with longer years since establishment.

Enterprises across the two target countries do not show large variation in their managerial characteristics - managerial experience is almost similar, with slightly more experienced managers in Kyrgyzstan. Female managers make up 20.5% of the

total sample, with a higher percentage in Georgia, which could indicate domestic gender dynamics in leadership positions between the examined countries.

The location of businesses also varies, with the concentration of firms in the capital city higher in Kyrgyzstan. Additionally, companies in Kyrgyzstan, on average, have a slightly higher electricity cost ratio than these in Georgia, which might encourage the adoption of more energy-efficient practices. Finally, the data for Georgia exhibits a notably higher proportion of companies with quality certifications and access to credit, potentially linked to greater international exposure or stronger integration into global markets. These factors could facilitate the adoption of sustainability measures, such as CO₂ monitoring and energy management.

Table II. Descriptive statistics.

Variable	Total sample	Georgia	Kyrgyz Republic
Number of observations	946	592	354
Dependent Variables			
CO ₂ monitoring (% of firms)	22.30	24.80	18.10
Energy management adoption (% of firms)	27.10	28.00	25.40
Explanatory Variables			
Firm age (years)	15.23	12.67	19.50
Squared firm age	344.30	227.10	539.70
Manager experience (years)	18.21	17.65	19.12
Firms managed by female (% of firms)	20.50	21.60	18.60
Firms located in capital city (% of firms)	41.40	38.20	46.90
Electricity cost ratio (% of total sales)	3.80	3.70	4.00
Firms using foreign technology (% of firms)	16.40	16.20	16.70
Firms having quality certificates (% of firms)	18.40	23.00	10.70
Firms having line of credit or loan (% of firms)	45.90	57.10	27.20
firm size			
Small (% of firms)	49.30	50.70	46.90
Medium (% of firms)	33.40	30.20	38.70
Large (% of firms)	17.30	19.10	14.40

Table II. Cont.

firm sector			
Food, beverages, and tobacco (% of firms)	17.90	21.80	11.30
Manufacturing (% of firms)	23.40	15.90	35.90
Trade and wholesale (% of firms)	24.50	27.20	20.10
Services (% of firms)	34.20	35.10	32.80

Authors' calculations based on the enterprise surveys data (World Bank, n.d.).

5. Estimation results

To account for potential differences between the target countries, the analysis was conducted separately for the total sample and for the subsamples of Georgia and Kyrgyzstan. These models were estimated with robust standard errors to address potential heteroscedasticity. Table III presents the average marginal effects from the logit models analyzing the probability of firms adopting CO₂ monitoring. Firm age demonstrates a significant negative effect on the likelihood of implementing CO₂ monitoring in the total sample, suggesting that older firms are less likely to adopt such practices. However, the squared term is positive and significant, indicating a potential U-shaped relationship - i.e. that very mature companies might eventually adopt these practices. Yet, this relationship is not statistically significant in the individual country sample estimations.

Firms located in capital cities are significantly less likely to monitor CO₂ emissions across all models. This finding is contradictory to the general expectation, as urban areas typically have stricter regulations. One possible explanation may be that enterprises in capital cities may prioritize other competitive pressures or rely on existing infrastructure and services, potentially leading to less focus on independent environmental initiatives. Another possible explanation could be related to market dynamics and customer demands. Urban businesses might operate in highly competitive environments, where immediate profitability and operational efficiency are prioritized over long-term sustainability practices. In addition, such companies might rely more on service-based industries, which generally have lower direct emissions and may not feel the same urgency to deploy CO₂ monitoring as these operating in emission-intensive sectors typically located outside the capital city.

Table III. Estimation results for logit models on the probability of adopting CO2 monitoring (marginal effects).

	Total sample	Georgia	Kyrgyz Republic
Firm age	-0.00674** (0.00341)	-0.00654 (0.00581)	-0.00671 (0.00506)
Squared firm age	0.000118** (0.0000545)	0.000139 (0.000131)	0.000110 (0.0000683)
Capital city	-0.147*** (0.0345)	-0.195*** (0.0448)	-0.0864* (0.0518)
Manager experience	0.00162 (0.00147)	-0.00106 (0.00195)	0.00655*** (0.00237)
Female manager	-0.0204 (0.0367)	-0.0249 (0.0452)	-0.0287 (0.0588)
Access to finance	0.0121 (0.0318)	-0.0410 (0.0379)	0.0914** (0.0452)
Foreign technology	0.0680* (0.0358)	0.0515 (0.0468)	0.0792 (0.0524)
International certification	0.0837** (0.0348)	0.0930** (0.0426)	0.00974 (0.0751)
Electricity cost ratio	0.493** (0.193)	0.232 (0.280)	0.718*** (0.243)
Firm size (small - reference category)			
Medium	0.0812** (0.0317)	0.0769* (0.0429)	0.102** (0.0496)
Large	0.203*** (0.0473)	0.223*** (0.0491)	0.165** (0.0651)
Firm sector (food, beverages, and tobacco - reference category)			
Manufacturing	-0.0524 (0.0484)	-0.0900 (0.0573)	0.0588 (0.0670)
Trade and wholesale	-0.143*** (0.0487)	-0.221*** (0.0576)	0.0615 (0.0774)
Services	-0.0927** (0.0448)	-0.0883* (0.0471)	-0.0625 (0.0743)
Country	+	+	+
Number of observations	802	512	290
Pseudo r-squared	0.122	0.134	0.180

Standard errors are in parentheses. ***, **, and * indicate statistical significance of 1%, 5%, and 10%, respectively. Authors' calculations based on the enterprise surveys data (World Bank, n.d.).

The lack of a significant effect of managerial experience in the total sample might indicate that CO2 monitoring is influenced more by external factors - such as regulatory pressures, market demands, or financial resources - than by the expertise of the top manager. However, the positive and significant effect in the Kyrgyz Republic suggests that experienced managers may be better at leveraging environmental practices, navigating regulatory requirements, or securing sustainability-focused resources from financial institutions.

Access to credit or loans is positively associated with the monitoring of CO₂ emissions in Kyrgyzstan, which may reflect more robust environmental standards on behalf of financial institutions in the country compared to Georgia. Banks and other financial institutions can require borrowers to adopt environmentally sustainable measures as a condition for financing. This suggests that access to finance is an effective tool to incentivize businesses to engage in CO₂ monitoring and other green practices. The use of foreign-licensed technology is positively associated with CO₂ monitoring in the total sample, indicating that firms adopting advanced foreign technologies are more likely to engage in environmental practices like CO₂ monitoring. Yet, this relationship is not significant in the country-specific models, suggesting that the effect may be driven by broader trends that do not hold consistently across individual countries. On the opposite, companies possessing international quality certifications are significantly more likely to adopt CO₂ monitoring, particularly in Georgia. This finding confirms the expectation that certification such as ISO14001 reinforces corporate commitment to environmental standards and encourages the implementation of sustainable practices. In Georgia, the emphasis on international certifications may be more prominent, driving businesses toward adherence to global environmental practices due to the country's strategic approach to integrating with EU standards. These results are consistent with previous studies (Sam & Song, 2022; Arocena et al., 2021; Hu et al., 2024) that also revealed a positive association between the adoption of international quality certifications and improvements in corporate environmental performance, including CO₂ emission monitoring and reduction.

Estimation results show that operational cost pressures related to electricity drive firms to adopt CO₂ monitoring practices. A higher electricity cost ratio significantly increases the likelihood of businesses in Kyrgyzstan adopting measures to monitor CO₂, highlighting that enterprises facing greater energy-related expenses are more motivated to implement sustainability measures to reduce operational burden. Firm size is one of the important factors in explaining business performance. This finding aligns with previous studies that indicate that increased energy prices result in better energy use and lower CO₂ emissions by companies (Brucal & Dechezleprêtre, 2021).

Estimation results likewise indicate that mid-size and large firms are significantly more likely to adopt CO₂ monitoring practices compared to small enterprises. This effect is consistent across all samples and indicates that larger firms are better equipped to allocate resources toward sustainability initiatives. They may also have more complex operations necessitating greater attention to environmental impacts. At the same time, these findings reflect the potential difficulties for small and even some medium-sized enterprises in meeting sustainable development requirements. This result matches prior studies showing that larger companies are

more likely to adopt environmental practices (Reis et al. 2020; Bodjongo et al., 2023; Ali & Singh, 2024). Finally, firm sector analysis reveals that those working in the trade, wholesale and service sectors are less likely to implement CO₂ monitoring, particularly in Georgia, compared to those in the food, beverages, and tobacco sector. This could reflect sector-specific differences in environmental awareness, regulation, or perceived benefits of CO₂ monitoring, with some industries potentially facing fewer external pressures to engage in sustainability practices. Interestingly, the estimations based on Kyrgyzstan's sample do not demonstrate any significance by economic sectors, which may imply that enterprises are adopting green practices as measured by CO₂ monitoring and energy management measures universally, without any sectoral differences. The factors affecting corporate energy-consuming behavior can differ between countries, sectors, or firm characteristics. Table IV presents the average marginal effects from the logit models on the probability of adopting energy management practices. For reference, the corresponding logit coefficients are reported in the Appendix.

Table IV. Estimation results for logit models. On the probability of energy management adoption (marginal effects).

	Total sample	Georgia	Kyrgyz Republic
Firm age	-0.00886** (0.00363)	-0.0192*** (0.00578)	-0.00177 (0.00555)
Squared firm age	0.000115** (0.0000571)	0.000389*** (0.000121)	0.0000121 (0.0000745)
Capital city	-0.0979*** (0.0344)	-0.164*** (0.0433)	-0.0149 (0.0547)
Manager experience	0.00209 (0.00156)	0.000389 (0.00191)	0.00421 (0.00280)
Female manager	-0.0636 (0.0407)	-0.0977** (0.0474)	0.00962 (0.0651)
Access to finance	0.0502 (0.0337)	0.0194 (0.0398)	0.0920* (0.0535)
Foreign technology	0.0450 (0.0407)	0.0295 (0.0527)	0.0728 (0.0632)
International certification	0.0662* (0.0383)	0.0854* (0.0448)	-0.136 (0.101)
Electricity cost ratio	0.332* (0.177)	-0.0678 (0.307)	0.587** (0.254)
Firm size (small - reference category)			
Medium	0.0706** (0.0349)	0.118*** (0.0435)	0.0178 (0.0562)
Large	0.169*** (0.0513)	0.175*** (0.0576)	0.226*** (0.0729)

Table IV. Cont.

Firm sector (food, beverages, and tobacco - reference category)			
Manufacturing	-0.000382 (0.0534)	0.000716 (0.0615)	0.0654 (0.0789)
Trade and wholesale	-0.164*** (0.0494)	-0.202*** (0.0598)	-0.0434 (0.0935)
Services	-0.0699 (0.0480)	-0.0429 (0.0510)	-0.0697 (0.0842)
Country	+		
Number of observations	802	512	290
Pseudo r-squared	0.0839	0.122	0.109

Standard errors are in parentheses. *, **, and * indicate statistical significance of 1%, 5%, and 10%, respectively. Authors' calculations based on the enterprise surveys data (World Bank, n.d.).

In the total sample, firm age shows a significant negative affect on the adoption of energy management practices. However, the positive and significant squared term for firm age suggests a potential U-shaped relationship. Thus, businesses do not consider energy management as a priority within a few years since establishment, but after some time - becoming more mature - companies may eventually implement energy management practices. Nevertheless, this trend is statistically significant in the sample of Georgia only. Businesses located in capital cities are generally less likely to adopt energy management practices, and this result is consistent across the total sample and in Georgia. The negative effect is especially strong in Georgia, where enterprises operating in the capital city are significantly less likely to implement energy management practices. In the Kyrgyz Republic, however, the effect is not significant, indicating that location plays a more substantial role in the former than in the latter. There is no significant relationship between managerial experience and adoption of energy management practices in any of the country models. Additionally, the presence of a female manager does not significantly influence the likelihood of adopting energy management practices in the total sample. Yet, in Georgia, businesses with female managers are less likely to implement energy management practices, suggesting that gender dynamics may influence decision-making processes in this country. Access to finance is positively associated with the adoption of energy management practices in both the total sample and Kyrgyzstan. Therefore, it can be argued that financial resources - potentially from international financial organizations or green financing initiatives - play a crucial role in facilitating the adoption of energy management practices. These findings are consistent with prior studies (Iram and Zhang, 2022; Zhou et al., 2022; Bouchmel et al., 2024) that highlight positive impacts

of better access to finance on investments in energy-efficient technologies. These findings underline the key role of financial access in enabling energy management practices. The use of foreign-licensed technology does not have a significant impact on the adoption of energy management practices, either in the total sample or in the country-specific models for Georgia and Kyrgyzstan. Analogous to CO₂ monitoring estimations, businesses with international quality certifications in the total sample and in Georgia are more likely to adopt energy management practices. These results align with prior research (Laskurain et al., 2017; Arocena et al., 2021; Otrachshenko et al., 2023), which also report a positive correlation between international quality system certifications and improvements in corporate environmental performance, including energy management. To an extent, this could reflect institutional differences between the two target countries. The electricity cost ratio is positively associated with energy management adoption in the total sample, with a particularly strong effect in the Kyrgyz Republic. Firms with higher electricity costs are more keen to adopt energy management practices to reduce operational expenses. This effect is statistically significant in Kyrgyzstan, where high energy costs likely drive companies to implement measures enhancing their energy efficiency and reducing costs. In Georgia, the effect is negative but not statistically significant. The positive relationship between higher electricity costs and the likelihood of adopting energy management practices is similar to previous studies (Kök et al., 2016; Naimoglu, 2023), which argue that higher energy prices incentivize enterprises to improve energy efficiency.

Larger companies are more apt to adopt energy management practices compared to smaller entities, and this effect holds consistently across all samples. Both medium and large enterprises are significantly more likely to adopt energy management practices than small ones, perhaps due to greater resources required for sustainability initiatives and deploying energy management systems. Firms in the trade and wholesale sector are significantly less inclined to adopt energy management practices than these in the food sector, especially in Georgia. In Kyrgyzstan, sectoral differences are not statistically significant, suggesting that sector-specific factors have a limited impact on adoption.

6. Conclusions

This study has investigated the factors affecting corporate green economy practices in Georgia and the Kyrgyz Republic using the most recent World Bank's enterprise survey dataset. Green economy practices were measured by whether firms adopted CO₂ monitoring and energy management measures. To explore the determinants of environmental and energy management practices at the firm

level in the two target countries, the empirical approach was based on a logistic regression model. The study findings suggest that along with corporate managerial characteristics, access to finance, foreign technology, international certification and energy costs are important for green economy practices by businesses. Enterprises with a broader financial access demonstrate a higher probability of implementing sustainable development practices, and those facing higher energy costs are inclined to introduce energy management measures. On the one hand, this effect is in line with the corresponding previous literature on corporate behavior, yet it does not indicate intrinsic motivation among companies for sustainable development, but can be rather explained as a cost-reducing approach for profit maximizing. On the other hand, the effect of foreign economic mechanisms significantly influences the adoption of green economy practices through foreign technology and international certification. Moreover, these effects vary by firm size, with larger enterprises displaying positive trends in adopting CO₂ monitoring and energy management measures.

One potential limitation of this study is that the authors did not fully address the possible endogeneity. Efficient dealing with the issue requires more data and information both at the firm level and about local context. Moreover, given the cross-sectional data used in the study, an additional analysis of time-varying corporate characteristics - that might be important for their green economy practices - may be necessary. Future research entailing longitudinal data analysis may provide more insights on the corporate behavior dynamics in the target countries.

The study's empirical findings have several policy implications. First, promotion of sustainable development practices depends on a country-specific context. The comparison of results between Georgia and Kyrgyzstan points to potential positive effects of the internationalization of economic dynamics on green economy practices. International standards for environmental protection and SDGs expressed in financial system standards can be an effective tool. From this standpoint, ESG and other loan requirements in the financial system of Central Asian economies manifest an efficient instrument for stimulating enterprises towards green economy.

Second, though environmental regulations set by governments are not clearly specified in this study's empirical model, they represent the most direct state policy tool. Efficient application of state regulatory measures may inaugurate conditions for businesses to embrace green economy practices.

Third, dealing with environmental regulations and adopting new technologies or measures are costly for enterprises in emerging economies, especially for medium and small operators. Lack of managerial capacity and financial resources to meet environmental standards may create a significant burden for such companies. Government policies on green economy transition should therefore account for a potential differentiated support based on firm size. Specifically, smaller businesses

may require more financial assistance or fiscal relief to offset the high costs associated with adopting green measures. This suggests that state policies should offer targeted financial support for smaller entities, such as loans under favorable conditions or fiscal relief measures, rather than providing uniform assistance across all firm sizes. Larger companies may still require support, but it might be at a lesser level compared to smaller entities.

Fourth, the cost of energy can be an effective tool for forcing enterprises to take effective energy management measures. However, high energy cost may have a negative effect on the production potential of the private sector. Along with energy management enforcement mechanisms, it is important to promote the use of alternative energy resources. In addition, higher energy consumption intensity in both target countries flags residential energy consumption as an important focus of energy saving strategies.

References

- 24.kg. (2024, October 7). National Bank approves roadmap for implementation of ESG principles. https://24.kg/english/316015_national_bank_approves_roadmap_for_implementation_of_esg_principles/
- Ali, J., & Singh, S. (2024). Does the size of the firm matter in determining the adoption of green economy practices in India? *International Journal of Social Economics*, 52(4), 561-577. <https://doi.org/10.1108/ijse-11-2023-0918>
- Alraja, M. N., Imran, R., Khashab, B. M., & Shah, M. (2022). Technological Innovation, Sustainable Green Practices and SMEs Sustainable Performance in Times of Crisis (COVID-19 pandemic). *Information Systems Frontiers*, 24(4), 1081-1105. <https://doi.org/10.1007/s10796-022-10250-z>
- Arocena, P., Orcos, R., & Zouaghi, F. (2021). The impact of ISO14001 on firm environmental and economic performance: The moderating role of size and environmental awareness. *Business strategy and the environment*, 30(2), 955-967, <https://doi.org/10.1002/bse.2663>
- Benincasa, R., Betz, F., & Gattini, L. (2024). How do firms cope with losses from extreme weather events? *Journal of corporate finance*, 84, 102508. <https://doi.org/10.1016/j.jcorpfin.2023.102508>
- Bodjongo, M. J. M., Fofana, M., & Epse Essomme, F. K. O. (2023). Firm size and pro-environmental behavior in Cameroon. *Environmental Economics*, 14(1), 47. [http://dx.doi.org/10.21511/ee.14\(1\).2023.05](http://dx.doi.org/10.21511/ee.14(1).2023.05)
- Bouchmel, I., Ftiti, Z., Louhich, W., & Omri, A. (2024). Financing sources, green investment, and environmental performance: Cross-country evidence. *Journal of environmental management*, 353, <https://doi.org/10.1016/j.jenvman.2024.120230>
- Brollo, N. G., Teodoru, I. R., Karapetyan, N., Ustyugova, Y., van Houtte, J., Jonas, J., Shi, W., Arzoumanian, S., Tintchev, K. I., Tuuli, M., Saliba, F., Talishli, F., El-Said, M., & Fernanda. (2023, June 8). Paving the way to more resilient, inclusive, and greener economies in the Caucasus and Central Asia. <https://www.imf.org/en/publications/departmental-papers-policy-papers/issues/2023/05/26/paving-the-way-to-more-resilient-inclusive-and-greener-economies-in-the-caucasus-and-532116>
- Brucal, A., & Dechezleprêtre, A. (2021). Assessing the impact of energy prices on plant level environmental and economic performance: Evidence from Indonesian manufacturers. *OECD environment working papers*, (170), 0_1-47, <https://doi.org/10.1787/9ec54222-en>
- Brunelli, S., Murzakhmetova, A., & Falivena, C. (2022). Environmental auditing in rural areas: Current patterns and future challenges in Central Asia. *Sustainability*, 14(22), Article 22. <https://doi.org/10.3390/su142215163>

- Ergasheva, S. T., Zinovyeva, I. S., Abdurashitov, A. A., Kopytina, Y. A., & Makarova, T. V. (2023). ESG investments in support of the development of the green economy in Russia and Central Asia. In E. G. Popkova & B. S. Sergi (Eds.), *ESG management of the development of the green economy in Central Asia* (pp. 419-428). *Springer International Publishing*. https://doi.org/10.1007/978-3-031-46525-3_44
- Fronzel, M., Krättschell, K., & Zwick, L. (2018). Environmental management systems: Does certification pay? *Economic analysis and policy*, 59, 14-24. <https://doi.org/10.1016/j.eap.2018.02.006>
- Government of Georgia. (2021). Georgia's 2030 Climate Change Strategy and Action Plan. *Food and agriculture organization of the united nations*. <https://faolex.fao.org/docs/pdf/geo209870.pdf>
- Guo, R., Lv, S., Liao, T., Xi, F., Zhang, J., Zuo, X., Cao, X., Feng, Z., & Zhang, Y. (2020). Classifying green technologies for sustainable innovation and investment. *Resources, Conservation and Recycling*, 153, 104580. <https://doi.org/10.1016/j.resconrec.2019.104580>
- Harakati, R., Ghazouani, I., & Hlioui, Z. (2024). CEO gender and climate change commitment: The mediating effect of environmental regulation perception. *Corporate Social Responsibility and Environmental Management*, 31(5), 4630-4650. <https://doi.org/10.1002/csr.2809>
- Hu, Y., Tu, T., & Lei, Z. (2024). Impact of corporate environmental goals on compliance behaviors in European Union food industry: A cross-country analysis. *Journal of Cleaner Production*, 444, 141212. <https://doi.org/10.1016/j.jclepro.2024.141212>
- International Monetary Fund. (2022, September 23). Poor and vulnerable countries need support to adapt to climate change. Retrieved from <https://www.imf.org/en/Blogs/Articles/2022/03/23/blog032322-poor-and-vulnerable-countris-need-support-to-adapt-to-climate-change>
- Iram, R., & Zhang, J. (2022). Assessing the role of financial inclusion and financial development to improve energy and environmental efficiency. *Environmental Science and Pollution Research*, 29(33), 49948-49965. <https://doi.org/10.1007/s11356-022-18942-4>
- Isiksal, A. Z., Assi, A. F., Zhakanov, A., Rakhmetullina, S. Z., & Joof, F. (2022). Natural resources, human capital, and CO2 emissions: Missing evidence from the Central Asian states. *Environmental Science and Pollution Research*, 29(51), 77333-77343. <https://doi.org/10.1007/s11356-022-21227-5>
- Jun, W., Ali, W., Bhutto, M. Y., Hussain, H., & Khan, N. A. (2019). Examining the determinants of green innovation adoption in SMEs: A PLS-SEM approach. *European Journal of Innovation Management*, 24(1), 67-87. <https://doi.org/10.1108/ejim-05-2019-0113>
- Karymshakov, K., Sulaimanova, B., & Aseinov, D. (2019). Determinants of innovation activity of small and medium-sized enterprises in small Post-Soviet countries. *Business and Economics Research Journal*, 10(1), 1-12.
- Kök, A. G., Shang, K., & Yücel, Ş. (2016). Impact of electricity pricing policies on renewable energy investments and carbon emissions. *Management Science*, 64(1), 131-148. <https://doi.org/10.1287/mnsc.2016.2576>
- Laskurain, I., Ibarloza, A., Larrea, A., & Allur, E. (2017). Contribution to energy management of the main standards for environmental management systems: The case of ISO 14001 and EMAS. *Energies*, 10(11). <https://doi.org/10.3390/en10111758>
- Li, W., Chen, X., Huang, J., Gong, X., & Wu, W. (2022). Do environmental regulations affect firm's cash holdings? Evidence from a quasi-natural experiment. *Energy Economics*, 112, 106151. <https://doi.org/10.1016/j.eneco.2022.106151>
- Lin, C.-Y., & Ho, Y.-H. (2011). Determinants of green practice adoption for logistics companies in China. *Journal of Business Ethics*, 98(1), 67-83. <https://doi.org/10.1007/s10551-010-0535-9>
- Naimoglu, M. (2023). The effect of energy prices, energy losses, and renewable energy use on CO2 emissions in energy-importing developing economies in the presence of an environmental Kuznets curve. *Environmental Science and Pollution Research*, 30(20), 58755-58772. <https://doi.org/10.1007/s11356-023-26656-4>
- National Bank of Georgia. (2024, October 12). *Sustainable finance*. <https://nbg.gov.ge/en/page/sustainable-finance>

- OECD. (2022, october 3). Green Economy Transition in Eastern Europe, the Caucasus and Central Asia. OECD Green Growth Studies. *OECD Publishing*. <https://doi.org/10.1787/c410b82a-en>
- Otrachshenko, V., Hartwell, C. A., & Popova, O. (2023). Energy efficiency, market competition, and quality certification: Lessons from Central Asia. *Energy Policy*, 177. <https://doi.org/10.1016/j.enpol.2023.113539>
- Pampel, F. C. (2020). Logistic regression: a primer (2nd ed.). *SAGE publications*
- Perdichizzi, S., Buchetti, B., Cicchiello, A. F., & Dal Maso, L. (2024). Carbon emission and firms' value: Evidence from Europe. *Energy Economics*, 131, 107324. <https://doi.org/10.1016/j.eneco.2024.107324>
- Petreski, M., Tanevski, S., & Stojmenovska, I. (2024). Employment, labor productivity and environmental sustainability: Firm-level evidence from transition economies. *Business Strategy & Development*, 7(1), e347. <https://doi.org/10.1002/bsd2.347>
- Reis, C., Benvenuti, L., Campos, L., & Uriona, M. (2020). The influence of company size on energy management systems adoption: A system dynamics model. *Brazilian Business Review*, 17(5), 579-600. <https://doi.org/10.15728/bbr.2020.17.5.6>
- Rodrigues, M., & Franco, M. (2023). Green innovation in small and medium-sized enterprises (SMEs): A qualitative approach. *Sustainability*, 15(5), Article 5. <https://doi.org/10.3390/su15054510>
- Sam, A. G., & Song, D. (2022). ISO 14001 certification and industrial decarbonization: An empirical study. *Journal of Environmental Management*, 323. <https://doi.org/10.1016/j.jenvman.2022.116169>
- Siewers, S., Martínez-Zarzoso, I., & Baghdadi, L. (2024). Global value chains and firms' environmental performance. *World Development*, 173, 106395. <https://doi.org/10.1016/j.worlddev.2023.106395>
- Stockholm Environment Institute. (2024, september 27). Green goals and economic gains: shedding light on Georgia's energy and climate strategy. <https://www.sei.org/features/green-goals-Georgia-climate/#:~:text=the%20primary%20objective%20of%20formulating,green%20development%2c%20and%20innovative%20technologies>
- The Ministry of Economy and Commerce of the Kyrgyz Republic. (n.d.). Draft program for the development of a green economy in the Kyrgyz Republic until 2028. <https://mineconom.gov.kg/ru/direct/302/335>
- The Ministry of Economy and Sustainable Development of Georgia. (2022). SME development strategy of Georgia 2021-2025. https://www.economy.ge/uploads/files/2017/ek_politika/sme_strategy/2022/sme_strategy_2021_2025_eng.pdf
- Thøgersen, J. (2021). Consumer behavior and climate change: Consumers need considerable assistance. *Current opinion in behavioral sciences*, 42, 9-14. <https://doi.org/10.1016/j.cobeha.2021.02.008>
- Tingey-Holyoak, J., Cooper, B., Crase, L., & Pisaniello, J. (2024). Business strategies to counter climate change risks to long lived production assets. *Journal of Cleaner Production*, 459, 142553. <https://doi.org/10.1016/j.jclepro.2024.142553>
- Ullah, F., Jiang, P., Ntim, C. G., Shahab, Y., & Jiang, X. (2022). Female directors' foreign experience and environmental and sustainable performance. *Asia-Pacific Journal of Financial Studies*, 51(2), 169-193. <https://doi.org/10.1111/ajfs.12369>
- UNEP FI. (2023, April). Climate risks in the Industrials Sector. <https://www.unepfi.org/themes/climate-change/climate-risks-in-the-industrials-sector/>
- Vakulchuk, R., Daloz, A. S., Overland, I., Sagbakken, H. F., & Standal, K. (2023). A void in Central Asia research: Climate change. *Central Asian Survey*, 42(1), 1-20. <https://doi.org/10.1080/02634937.2022.2059447>
- Weick, V. (2016). Green economy and sustainable development. In *Waste Management and the Green Economy* (pp. 121-150). *Edward Elgar Publishing*. <https://doi.org/10.4337/9781783473816.00016>
- World Bank. (n.d.). Enterprise Surveys. Retrieved from [2022, September 10] <https://www.enterprisesurveys.org>
- Zhou, J., Yin, Z., & Yue, P. (2023). The impact of access to credit on energy efficiency. *Finance Research Letters*, 51. <https://doi.org/10.1016/j.frl.2022.103472>

Appendix

Table a1. Estimation results for logit models on the probability of adopting co2 monitoring (estimated coefficients).

	Total sample	Georgia	Kyrgyz Republic
Firm age	-0.0429** (0.0217)	-0.0399 (0.0353)	-0.0524 (0.0400)
Squared firm age	0.0007** (0.0004)	0.0008 (0.0008)	0.0009 (0.0005)
Capital city	-0.938*** (0.229)	-1.186*** (0.293)	-0.674* (0.407)
Manager experience	0.0103 (0.009)	-0.0065 (0.012)	0.051*** (0.0191)
Female manager	-0.130 (0.233)	-0.152 (0.275)	-0.224 (0.456)
Access to finance	0.0773 (0.202)	-0.250 (0.232)	0.713** (0.354)
Foreign technology	0.433* (0.230)	-0.250 (0.232)	0.618 (0.416)
International certification	0.533** (0.224)	0.567** (0.263)	0.0760 (0.586)
Electricity cost ratio	3.135** (1.230)	1.414 (1.702)	5.598*** (1.965)
Firm size (small - reference category)			
Medium	0.536*** (0.208)	0.469* (0.262)	0.798** (0.388)
Large	1.182*** (0.264)	1.358*** (0.321)	1.291** (0.527)
Firm sector (food, beverages, and tobacco - reference category)			
Manufacturing	-0.290 (0.265)	-0.548 (0.352)	0.458 (0.526)
Trade and wholesale	-0.897*** (0.309)	-1.346*** (0.366)	0.480 (0.607)
Services	-0.539** (0.252)	-0.538* (0.289)	-0.488 (0.581)
Country	+		
Constant	-0.923** (0.368)	-0.225 (0.440)	-2.989*** (0.750)
Number of observations	802	512	290
Pseudo r-squared	0.122	0.134	0.180

Notes: Standard errors are in parentheses. ***, **, and * indicate statistical significance of 1%, 5%, and 10%, respectively.

Source: World Bank, 2024.

Table a2. Estimation results for logit models on the probability of energy management adoption (estimated coefficients).

	Total Sample	Georgia	Kyrgyz Republic
Firm age	-0.049** (0.020)	-0.110*** (0.034)	-0.0107 (0.034)
Squared firm age	0.0006** (0.0003)	0.002*** (0.0007)	0.00007 (0.0005)
Capital city	-0.543*** (0.195)	-0.935*** (0.262)	-0.0902 (0.331)
Manager experience	0.012 (0.009)	0.002 (0.011)	0.025 (0.017)
Female manager	-0.353 (0.227)	-0.557** (0.271)	0.0581 (0.393)
Access to finance	0.279 (0.187)	0.111 (0.227)	0.555* (0.327)
Foreign technology	0.250 (0.226)	0.168 (0.301)	0.439 (0.385)
International certification	0.368* (0.214)	0.487* (0.259)	-0.822 (0.618)
Electricity cost ratio	1.840* (0.990)	-0.387 (1.751)	3.540** (1.576)
Firm size (Small - reference category)			
Medium	0.401** (0.197)	0.673*** (0.253)	0.107 (0.339)
Large	0.880*** (0.258)	0.998*** (0.338)	1.364*** (0.470)
Firm sector (Food, Beverages, and Tobacco - reference category)			
Manufacturing	-0.002 (0.258)	0.004 (0.351)	0.395 (0.478)
Trade and Wholesale	-0.951*** (0.287)	-1.153*** (0.348)	-0.262 (0.563)
Services	-0.359 (0.241)	-0.245 (0.291)	-0.421 (0.509)
Country	+		
Constant	-0.750** (0.333)	0.0188 (0.414)	-1.959*** (0.638)
Number of observations	802	512	290
Pseudo R-squared	0.0839	0.122	0.109



Оценка выбросов CO₂ в странах Центральной Азии с применением искусственного интеллекта

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Данная версия является переводом статьи “CO₂ emission estimation in Central Asian countries by use of artificial intelligent methods”, опубликованной в журнале 30 сентября 2024 г.

АННОТАЦИЯ

Энергопотребление и доли различных видов энергии в общем объеме энергоснабжения играют решающую роль в объеме выбросов CO₂ в различных странах. Помимо факторов, связанных с энергетикой, такие экономические показатели, как валовой внутренний продукт (ВВП), также могут влиять на выбросы. В настоящем исследовании доли различных источников энергии в общем энергоснабжении и ВВП были использованы в качестве входных данных для модельной оценки выбросов CO₂ в трех государствах Центральной Азии, а именно в Казахстане, Узбекистане и Туркменистане. В дополнение к результатам моделирования в статье также описываются важные характеристики энергетических систем целевых стран. На основе сравнения выбросов CO₂ на единицу ВВП исследование позволило выявить, что данный индекс в целевых странах превышает среднемировое значение, что обуславливает необходимость принятия срочных мер по сокращению выбросов. Исходные данные для исследования были получены от Международного энергетического агентства (МЭА) и Всемирного банка. В исследовании были применены следующие методы: групповой метод обработки данных (Group Method of Data Handling, GMDH) и метод многослойного перцептрона (Multilayer Perceptron, MLP). Обе модели показали хорошие результаты в оценке выбросов, однако в соответствии с расчетными значениями для примененных критериев был сделан вывод о том, что использование GMDH дает более точные результаты по сравнению с MLP. Средние абсолютные относительные отклонения моделей GMDH и MLP составили приблизительно 3,69 % и 4,28 % соответственно. Значения R² для упомянутых моделей составили 0,9936 и 0,9929 соответственно. В большинстве случаев для обеих моделей относительные отклонения между прогнозируемыми и фактическими выбросами CO₂ находились в диапазоне ±5 %.

КЛЮЧЕВЫЕ СЛОВА

искусственная нейронная сеть, выбросы CO₂, страны Центральной Азии, GMDH, интеллектуальные методы

1. Введение

В настоящее время наблюдается рост выбросов парниковых газов, главным образом CO₂, что обусловлено такими факторами, как рост численности населения, индустриализация, увеличение использования ископаемого топлива и др. Энергетика играет ключевую роль в выбросах парниковых газов и должна учитываться при разработке политики по их сокращению. Согласно отчету Международного энергетического агентства (IEA) «CO₂ Emissions in 2023: A New Record High, but Is There Light at the End of the Tunnel» (2024), выбросы CO₂, связанные с энергией, увеличились на 1,1 % в 2023 г. За последние десять лет выбросы CO₂ в мире росли со среднегодовым темпом более чем на 0,5 %. Для сокращения выбросов CO₂, связанных с энергией, были предложены различные подходы, включая использование возобновляемых источников энергии для генерации электроэнергии, транспорта и производства тепла (Renewables, n.d.), разработку более чистых технологий, таких как тепловые насосы для обогрева и охлаждения зданий (Heat Pumps, n.d.) и электрические транспортные средства (Electric Vehicles, 2023), а также развитие систем улавливания углерода (Carbon Capture, Utilisation and Storage, n.d.). Разработка моделей для прогнозирования выбросов CO₂ и определения ключевых факторов, влияющих на количество парниковых газов, способствует формированию эффективной политики по их сокращению. Эта политика должна учитывать сложную динамику между энергопотреблением, экономическим ростом и демографией.

В исследовании Turmunkh (2021) представлена стратегия устойчивого энергопотребления для стран Центральной Азии. Автор проводит статистический анализ и дает рекомендации для политиков, стремящихся сбалансировать экономическое развитие с экологической устойчивостью. Аналогичное исследование на основе панельных данных (Yuldoshboy et al., 2022) показало, что экономическая активность также способствует увеличению выбросов CO₂, отражая зависимость региона от ископаемого топлива. Авторы рекомендуют инвестиции в энергоэффективность и возобновляемые источники энергии как ключевые меры для смягчения выбросов CO₂.

Экономика Центральной Азии тесно связана с производством и потреблением ископаемого топлива. Регион богат ресурсами ископаемого топлива, что играет важную роль в его экономическом развитии. Такие страны, как Казахстан и Узбекистан, являются крупными экспортерами нефти и природного газа, а их экономики существенно зависят от колебаний на мировых энергетических рынках. Исследования показали, что энергетический сектор Центральной Азии сильно зависит от ископаемого топлива (Kuziboev et al., 2024; Radovanović et al., 2021), что приводит к высоким уровням выбросов CO₂. Другое

исследование (Xiu, 2022) выявило значительную положительную корреляцию между выбросами CO₂ и экономическим ростом в странах Центральной Азии. Эластичность выбросов CO₂ по отношению к ВВП оценена на уровне 0,82, что указывает на то, что 1 % роста ВВП связан с увеличением выбросов CO₂ на 0,82 %.

Прогнозы выбросов CO₂ в Центральной Азии указывают на их продолжительный рост, если сохранится текущая зависимость от ископаемого топлива. Согласно данным (Zhakiyev et al., 2023), выбросы углекислого газа могут увеличиться на 30 %, если не будет внедрена энергетическая политика. Поэтому реформы в этой области и внедрение возобновляемых источников энергии критически важны для сокращения выбросов в будущем. В то же время положительные прогнозы (Filipović et al., 2024) предполагают, что введение политики ценообразования на углерод может сократить выбросы CO₂ на 30 % в течение трех десятилетий в странах Центральной Азии.

Согласно обзору литературы по оценке выбросов CO₂ в Центральной Азии, использование подхода панельных данных имеет свои ограничения. Этот метод иногда усложняет модель, поскольку он может не в полной мере учитывать тонкие воздействия различных социально-экономических и технологических факторов с течением времени и в разных регионах. Хотя панельный подход полезен для выявления общих тенденций и взаимосвязей, он может не учитывать специфические локальные контексты или временную динамику, влияющие на выбросы, что приводит к потенциальным искажениям или упрощениям в процессе оценки. Среди различных методов, применимых для моделирования инженерных и экологических проблем, интеллектуальные методы обладают рядом преимуществ: высокой точностью, низкими вычислительными затратами по сравнению с численным моделированием и высокой скоростью работы. Искусственный интеллект (ИИ) и другие передовые технологии играют важную роль в точной оценке выбросов и принятии эффективных политических решений. Постоянное внимание к региональному сотрудничеству и инновациям в политике будет ключевым для решения экологических проблем, связанных с зависимостью Центральной Азии от ископаемого топлива.

Интеллектуальные методы, такие как искусственные нейронные сети (Artificial Neural Network - ANN), находят применение в различных областях науки, связанных с энергетикой. В оценке выбросов парниковых газов сравнены ANN и глубокие нейронные сети (Altikat, 2021). Исследование показало, что в прогнозировании выбросов CO₂ модели глубокого обучения более эффективны, чем традиционные нейронные сети. Кроме того, эти методы применялись для различных систем в подходах, основанных на ANN, например, для прогнозирования производительности возобновляемых источников энергии (Alhuyi Nazari et al., 2023), прогнозирования погодных данных, влияющих на работу энергосистем,

таких как ветряные турбины (Filik & Filik, 2017), оценки энергопотребления в различных секторах (Luo et al., 2020) и прогнозирования цен на энергию (Pindoriya et al., 2008). В работе М. К. & V. (2020) представлена многослойная модель ANN с несколькими скрытыми слоями между входными и выходными уровнями, которая позволяет улавливать сложные закономерности в данных, связанных с выбросами CO₂. Модель ANN в работе Rezaei et al. (2018a) продемонстрировала высокую точность в прогнозировании выбросов CO₂, показав сильную корреляцию между потреблением энергии и выбросами. Исследование установило, что увеличение потребления энергии, особенно из невозобновляемых источников, приводит к более высоким выбросам CO₂, тогда как экономический рост, основанный на возобновляемых источниках энергии, ассоциировался с более низкими уровнями выбросов. В 2018 г. Rezaei et al. (2018b) применили метод группового учета аргументов (GMDH) для прогнозирования выбросов CO₂ в четырех странах Северной Европы. Их модель продемонстрировала значительную точность с коэффициентом детерминации (R^2) 0,998. В 2019 г. Ahmadi, Jashnani, et al. (2019) разработали модель с использованием долей различных источников энергии, а также ВВП в качестве входных данных и GMDH в качестве интеллектуальной техники для оценки выбросов CO₂ в пяти странах Ближнего Востока. Среднее абсолютное относительное отклонение (AARD) предложенной модели составило 2,3%. В 2020 г. Ghalandari et al. (2020) использовали основанные на данных методы для прогнозирования выбросов CO₂ в четырех европейских странах. Их модели, которые включали различные энергоресурсы и ВВП в качестве входных данных, могли оценивать выбросы CO₂ с коэффициентом детерминации 0,9999. Komeili Birjandi et al. (2022a) применили метод многослойного перцептрона (MLP) с двумя различными функциями переноса – радиальной базисной функцией и *tansig* – для оценки выбросов CO₂ в странах Юго-Восточной Азии. Они обнаружили, что использование радиальной базисной функции в оптимальной структуре приводит к более высокой точности по сравнению с моделью, использующей функцию *tansig*.

Согласно обзору литературы, можно сделать вывод, что интеллектуальные методы, особенно основанные на ANN, являются эффективными и точными инструментами для прогнозирования выбросов CO₂. Их точность зависит от архитектуры и применяемых методов, и эти факторы следует учитывать при разработке точной модели. В данной статье основное внимание уделено моделированию выбросов CO₂ в трех странах Центральной Азии – Казахстане, Узбекистане и Туркменистане – с использованием методов на основе ANN. Главная новизна работы заключается в одновременном учете данных по этим трем странам для разработки комплексной модели. Кроме того, представлена полезная информация о ключевых характеристиках их энергетических систем

и политике, направленной на развитие этих систем в будущем. В следующем разделе представлен обзор энергетических систем и состояния выбросов CO₂ в указанных странах. Затем описываются применяемые методы, обсуждаются результаты и представляются выводы исследования.

2. Обзор энергетических систем в рамках исследования

В настоящем исследовании для моделирования выбросов CO₂ с использованием моделей на основе ANN рассматриваются три страны Центральной Азии: Казахстан, Узбекистан и Туркменистан. В этом разделе представлены ключевые характеристики и политические меры, связанные с энергетическими системами и экологией этих стран.

2.1. Казахстан

Республика Казахстан занимает площадь 2 717 300 км² (Executive Summary, n.d.), а численность ее населения в 2022 г. составляла около 19 621 000 человек, согласно данным Всемирного банка (Population, Total - Kazakhstan, n.d.). В 2020 г. нефтегазовая промышленность и связанные с ней секторы обеспечивали 17 % ВВП. Нефть составляет основную часть доходов от экспорта страны и является главным источником доходов государственного бюджета (Executive Summary, n.d.). В 2021 г. нефтепродукты занимали наибольшую долю в конечном потреблении энергии (TFC), за ними следовал уголь. Высокая зависимость от ископаемого топлива приводит к значительным выбросам CO₂ на единицу ВВП по сравнению с мировыми и развитыми странами. На Рисунке 1 представлены данные о выбросах CO₂ в Казахстане в период с 1990 по 2021 г. (Energy Statistics Data Browser, n.d.-a). Несмотря на резкое снижение выбросов в период с 1990 по 2001 г., с 2015 г. наблюдается тенденция к их увеличению. Уголь занимает наибольшую долю в генерации электроэнергии, за ним следует природный газ. В период с 2000 по 2019 г. промышленный сектор был основным потребителем энергии в Казахстане, однако с 2020 г. доля потребления в жилом секторе превысила промышленный сектор (Energy Statistics Data Browser, n.d.-a).

В последние десятилетия в Казахстане были приняты меры для реформирования энергетической системы. Например, в 2009 г. был принят закон о поддержке использования возобновляемых источников энергии, в который были внесены поправки в 2021 г. Закон предусматривает введение тарифов на закупку энергии, грантов, налоговых льгот и установление правил выделения земли для объектов возобновляемой энергетики (The Law About Support the Use of Renewable Energy Sources (Amended), 2022). Другой закон, касающийся энергосбережения и энергоэффективности, направлен на значительное снижение потребления энергии в промышленном и муниципальном секторах. Этот закон акцентирует

внимание на развитии энергоэффективной инфраструктуры и переходе к «зеленому» росту национальной экономики (KAZAKHSTAN: Law No. 541-IV of 2012 on Energy Saving and Energy Efficiency (2019 Ed.), 2019).

Еще одна политика связана с энергоэффективностью зданий. Она включает разработку правил для определения и пересмотра классов энергоэффективности зданий (Energy Efficiency Classes of Buildings, 2022). Эта инициатива способствует экономии энергии в зданиях, снижению ее потребления и, следовательно, уменьшению выбросов в этом секторе. Программа развития ООН в Казахстане в партнерстве с правительством страны и при финансовой поддержке Глобального экологического фонда инициировала программы поддержки средних и малых предприятий, внедряющих энергоэффективные и возобновляемые энергетические системы. Целью этой инициативы является продвижение проектов возобновляемой энергии малого масштаба и снижение финансовой нагрузки от использования чистых энергетических систем (Transition to Renewable Energy Sources: Economic Benefits for Entrepreneurs in Kazakhstan, 2024). В период с 2018 по 2020 г. Агентство США по международному развитию (USAID) привлекло около 2 млрд долл. частных инвестиций, что позволило реализовать около 60 новых проектов в области возобновляемой энергетики, снизив выбросы CO₂ в стране на 11 млн тонн (Betting Big on Renewables, n.d.). Помимо декарбонизации, Казахстан предпринимает шаги для повышения своей энергетической безопасности. Например, Центральноеазиатское региональное экономическое сотрудничество (CAREC) инвестировало около 8,9 млрд долл. в различные проекты, направленные на расширение двусторонней торговли электроэнергией и улучшение сетей электроснабжения в регионе (Energy, 2023). Реализация этого плана повысит энергетическую безопасность в Казахстане и других странах региона.

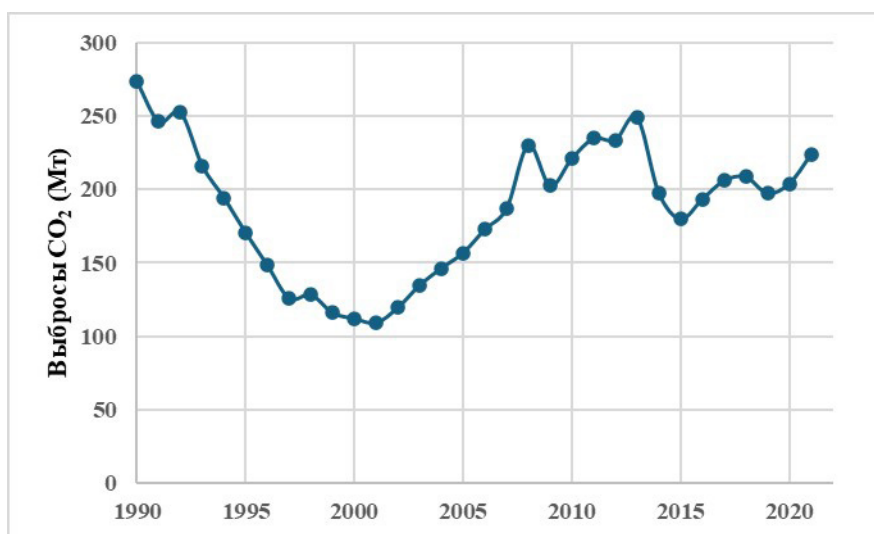


Рисунок 1. Общая эмиссия CO₂ в Казахстане в период с 1990 по 2021 г. (Energy Statistics Data Browser, n.d.-a)

2.2. Узбекистан

Площадь Узбекистана составляет около 447 400 км² (Uzbekistan (12/08), n.d.), а численность населения в 2022 г. составляла примерно 35 648 000 человек, согласно данным Всемирного банка (Population, Total - Uzbekistan, n.d.). Несмотря на энергетическую самодостаточность благодаря газовому сектору, устаревшая инфраструктура страны сталкивается с трудностями в удовлетворении растущего внутреннего спроса. Чрезмерное использование, потери и недостаток финансирования остаются основными проблемами энергетического сектора Узбекистана (Uzbekistan, n.d.). В 2022 г. природный газ занимал наибольшую долю в конечном потреблении энергии (TFC), за ним следовало электричество (Energy Statistics Data Browser, n.d.-b). Выбросы CO₂ на единицу ВВП в Узбекистане высоки по сравнению с мировыми показателями, что объясняется низкой эффективностью систем и высокой зависимостью от ископаемого топлива. На Рисунке 2 представлены данные о выбросах CO₂ в Узбекистане в период с 1990 по 2021 г. Начиная с 2015 г. наблюдается возрастающая тенденция выбросов CO₂. Природный газ занимает наибольшую долю в производстве электроэнергии в Узбекистане, за ним следует гидроэнергетика (данные за 2021 г.). В этом же году жилой сектор имел наибольшую долю в конечном потреблении энергии, за ним следовал промышленный сектор (Energy Statistics Data Browser, n.d.-b).

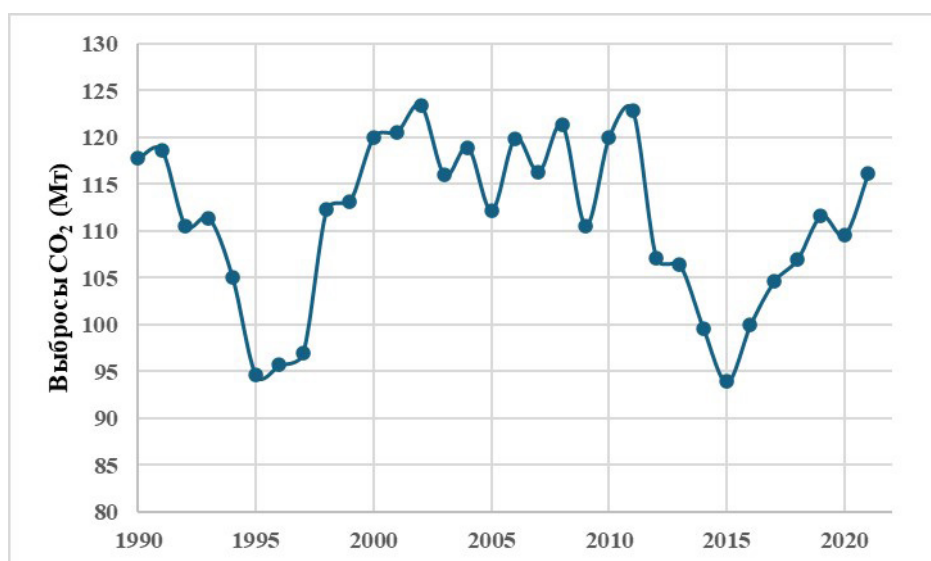


Рисунок 2. Общая эмиссия CO₂ в Узбекистане в период с 1990 по 2021 г. (Energy Statistics Data Browser, n.d.-b)

В последние годы в энергетическом секторе Узбекистана были рассмотрены различные стратегии и планы. Общие меры, принятые правительством, направлены на достижение топливной независимости за счет увеличения добычи природного газа и газового конденсата, создания сырьевой базы для

энергетического сектора, обеспечения максимального доступа населения к электроэнергии, сжиженному и природному газу, а также к современным видам топлива. Кроме того, уделяется внимание укреплению финансовой стабильности, привлечению инвестиций в этот сектор, эффективному использованию энергетических ресурсов, развитию правовой базы для энергетического сектора, совершенствованию системы налогообложения и финансового регулирования, а также продвижению конкуренции в энергетическом секторе (The Outlook for the Development of Renewable Energy in Uzbekistan, 2014). В дополнение к общей политике были разработаны и более конкретные планы. Например, согласно Указу Президента Республики Узбекистан, определены основные направления дальнейшего развития топливно-энергетической отрасли страны. Среди целей - внедрение передовых ресурсов и технологий, способствующих энергосбережению в экономике и бытовом секторе, а также развитие новых источников энергии (Указ Президента Республики Узбекистан «О мерах по радикальному совершенствованию системы управления топливно-энергетической отраслью Республики Узбекистан» от 01.02.2019 № UP-5646, 2022). В соответствии с другой политикой представлен закон, направленный на укрепление энергетической безопасности Узбекистана, диверсификацию топлива и балансировку энергетики в таких областях, как производство электроэнергии, тепла и биогаза с использованием возобновляемых источников энергии (Закон Республики Узбекистан «Об использовании возобновляемых источников энергии» от 21 мая 2019 года, № ZRU-539, 2022). Кроме того, страна поставила цель достичь доли 25 % генерации энергии из возобновляемых источников к 2030 г. и углеродной нейтральности к 2050 г. USAID сотрудничает с заинтересованными сторонами энергетического сектора и Министерством энергетики для создания центра зеленого водорода (Green Hydrogen Hub) в поддержку усилий правительства по достижению этих целей (USAID Energizes Uzbekistan's First Green Hydrogen Hub, n.d.).

2.3. Туркменистан

Еще одним объектом исследования является Туркменистан, расположенный в Центральной Азии. Площадь страны составляет 469 930 км², а численность населения в 2022 г. составила около 6 431 000 человек (Population, Total - Turkmenistan, n.d.). Правительство Туркменистана на протяжении многих лет активно инвестировало в газовую и нефтяную отрасли для расширения и модернизации сектора тепла и электроэнергии к 2020 г. Кроме того, энергетический сектор практически полностью субсидируется (Turkmenistan, n.d.). В 2021 г. наибольшая доля в конечном потреблении энергии принадлежала природному газу, за которым следовали нефтепродукты (Energy Statistics Data

Browser, n.d.-c). Выбросы CO₂ на единицу ВВП в Туркменистане высоки по сравнению с мировыми показателями и превышают аналогичные показатели двух других стран, рассмотренных в данном исследовании. На Рисунке 3 представлены данные о выбросах CO₂ в Туркменистане в период с 1990 по 2021 г. В период с 1998 по 2011 г. наблюдалось значительное увеличение выбросов, однако в последние годы эта тенденция замедлилась. Среди различных секторов наибольшую долю конечного потребления энергии в 2021 г. занимали коммерческие и общественные услуги (Energy Statistics Data Browser, n.d.-c).

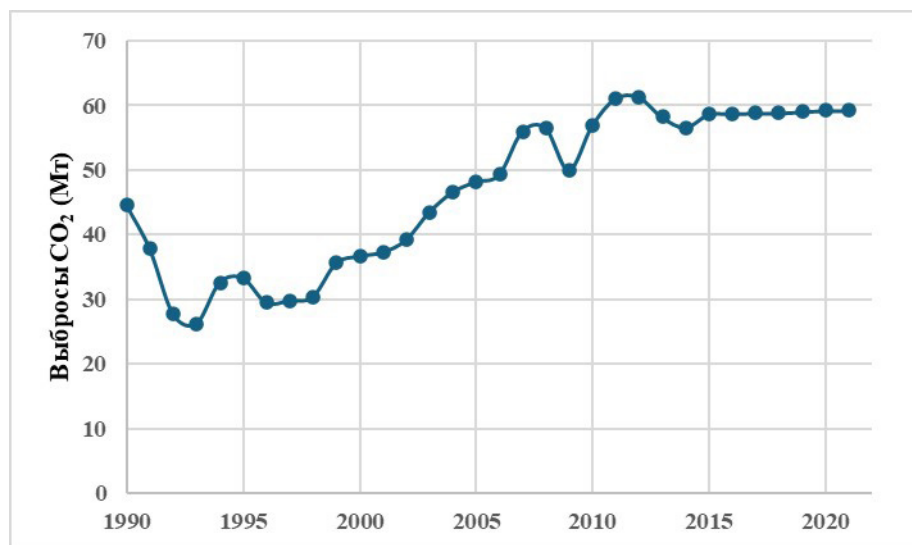


Рисунок 3. Общая эмиссия CO₂ в Туркменистане в период с 1990 по 2021 г. (Energy Statistics Data Browser, n.d.-c)

В Туркменистане реализуются различные стратегии и планы, направленные на защиту окружающей среды и модернизацию энергетических систем. Например, в рамках одной из программ по охране атмосферного воздуха был принят закон, устанавливающий стандарты качества воздуха (On Protection of the Atmospheric Air, 2022). Согласно другому документу, Определяемый на национальном уровне вклад (NDC) Туркменистана предусматривает сокращение выбросов парниковых газов на 20 % к 2030 г. по сравнению с уровнем 2010 г. в сценарии «бизнес как обычно» (Nationally Determined Contribution (NDC) to the Paris Agreement (2022 Update): Turkmenistan, n.d.). Проект под названием «Устойчивые города в Туркменистане: комплексное развитие зеленых городов в Ашхабаде и Авазе», финансируемый Программой развития ООН (UNDP) и Глобальным экологическим фондом, направлен на продвижение устойчивого развития городов и снижение негативных последствий городского роста в Туркменистане (UNDP Continues to Support Turkmenistan in Improving Energy Efficiency and Developing Renewable Energy Sources, n.d.). Кроме того, в рамках международного сотрудничества и

поддержки USAID оказывает помощь в выявлении возможностей, связанных с возобновляемыми источниками энергии, содействует разработке масштабных и комплексных низкоуглеродных стратегий в энергетическом секторе и участвует в сокращении выбросов метана из газового и нефтяного сектора (USAID Power Central Asia, n.d.).

3. Методы

Существует множество типов и структур, основанных на ANN, которые используются для разработки прогнозных моделей. Одной из наиболее распространенных моделей на основе ANN является многослойный перцептрон (MLP), который на протяжении последних десятилетий применялся для моделирования различных систем и решения множества задач. Общая структура MLP с одним скрытым слоем представлена на Рисунке 4. Описание этой модели приводится на основе исследования Komeili Birjandi et al. (2022a). В различных слоях структуры расположены нейроны. Входная информация поступает через входной слой и передается на следующий слой через нейроны. Способность нейрона передавать информацию по сравнению с другими нейронами характеризуется его весом. Количество нейронов в каждом слое связано со значением веса и значениями предыдущего слоя сети. Основным вычислительным элементом этой сети является нейрон.

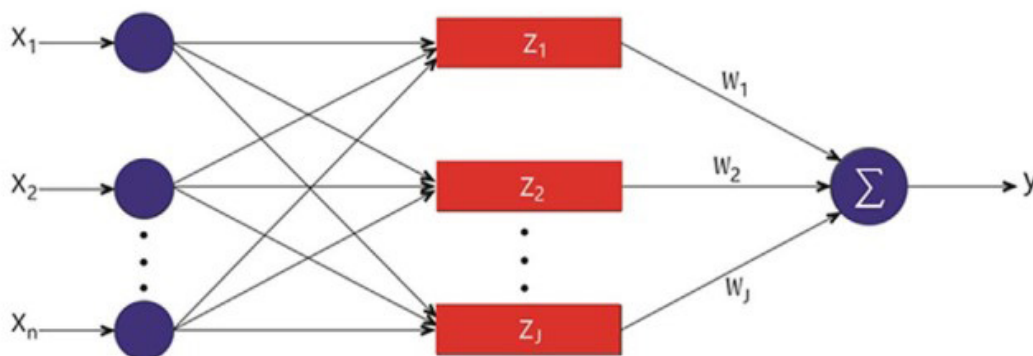


Рисунок 4. Структура многослойного перцептрона (MLP ANN) с одним скрытым слоем (Komeili Birjandi et al., 2022a)

Принимая вектор X (X_1, X_2, \dots, X_n) в качестве входа сети, вес нейронов, соответствующий мощности синапса j -го нейрона, обозначается как ω_j , u_j представляет линейную комбинацию выходов, а y_j является выходным значением сети. Для определения выходного значения используются следующие уравнения:

$$u_j = \sum_{i=1}^n \omega_{ji} X_i \quad (1)$$

$$y_j = \varphi(u_j + b_j) \quad (2)$$

$$v_j = u_j + b_j \quad (3)$$

В этих уравнениях $\varphi(0)$ и b_j обозначают функцию активации и смещение соответственно. В данной сети могут применяться различные функции активации. Одна из наиболее распространенных функций активации, *tansig*, используется в данном исследовании и представлена следующим выражением (Komeili Birjandi et al., 2022a):

$$\text{tansig}(x) = \frac{2}{1 + \exp(-2x)} - 1 \quad (4)$$

Для оптимизации параметров сети в применяемой модели используется метод обучения Левенберга - Марквардта. Также рассматривается один скрытый слой с различным количеством нейронов для определения оптимальной структуры. Значения других гиперпараметров, таких как количество эпох, устанавливаются в соответствии с настройками по умолчанию в программном обеспечении MATLAB. Другой метод, применяемый в данном исследовании для моделирования, — это метод группового учета аргументов (GMDH). Этот подход описан на основе исследования Kim & Окуууси (2022). Метод сопоставляет входной вектор $X = (x_1, x_2, \dots, x_n)$ с прогнозируемым значением, обозначаемым как \bar{y} , как показано на Рисунке 5. Предполагается, что прогнозируемое значение максимально близко к фактическому значению выхода. Множество M определяется для пар данных в сети с одним выходом и несколькими входами (Oh & Pedrycz, 2002).

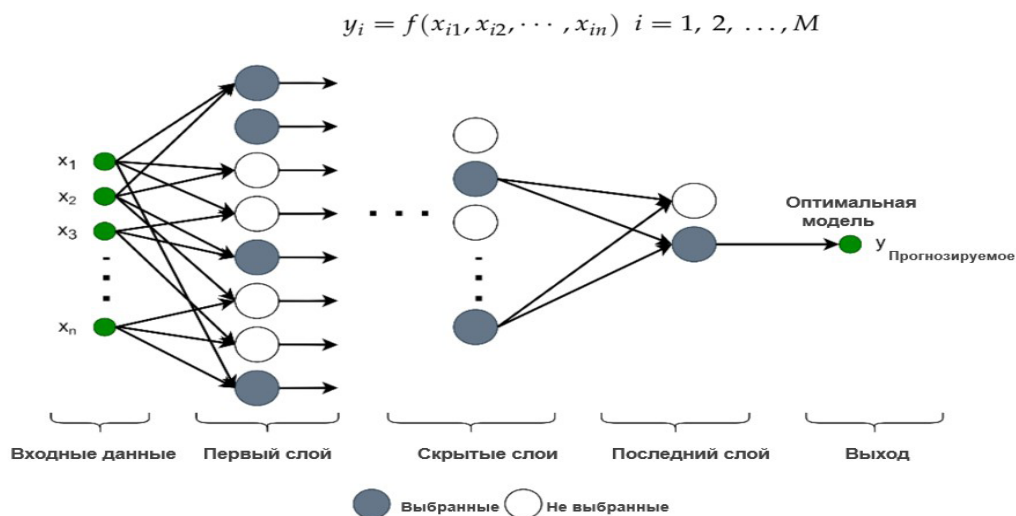


Рисунок 5. Схема GMDH ANN (Kim & Окуууси, 2022)

Предсказанное значение выхода \bar{y} из входных данных представляется следующим образом:

$$\bar{y}_i = \bar{f}(x_{i1}, x_{i2}, \dots, x_{in}) \quad i = 1, 2, \dots, M \quad (5)$$

Метод наименьших квадратов используется для сопоставления прогнозируемых и фактических выходных данных и получения модели. Следующее уравнение применяется для минимизации ошибки модели:

$$\sum_{i=1}^M (\bar{f}(x_{i1}, x_{i2}, \dots, x_{in}) - y_i)^2 \rightarrow \text{минимум} \quad (6)$$

Этот тип ANN определяется на основе входных и выходных факторов, представленных в форме полиномиальной функции Колмогорова - Габора, которая записывается следующим образом (Farlow, 2020):

$$\bar{y} = a_0 + \sum_{i=1}^n a_i x_i + \sum_{i=1}^n \sum_{j=1}^n a_{ij} x_i x_j + \sum_{i=1}^n \sum_{j=1}^n \sum_{k=1}^n a_{ijk} x_i x_j x_k + \dots \quad (7)$$

В уравнении (7) a обозначает коэффициенты полинома $(i, j, k) \in (1, 2, \dots, n)$. В общем случае этот полином может быть записан в квадратичной полиномиальной форме с использованием только двух переменных следующим образом (Elbaz et al., 2021):

$$\bar{y} = G(x_i, x_j) = a_0 + a_1 x_i + a_2 x_j + a_3 x_i x_j + a_4 x_i^2 + a_5 x_j^2 \quad (8)$$

Эта модель прогнозирует выходные значения для каждого набора входных параметров и используется для определения коэффициентов и уменьшения значения среднеквадратичной ошибки (Root Mean Square Error - RMSE) между прогнозируемыми и фактическими выходами. Минимизация RMSE определяется следующим образом:

$$RMSE = \frac{\sum_{i=1}^M (\bar{y}_i - y_i)^2}{M} \rightarrow \text{минимум} \quad (9)$$

В базовой форме данного алгоритма все бинарные вероятности независимых переменных формируют регрессионную архитектуру, используя полиномиальную форму, представленную в уравнении (8). Количество ячеек в скрытом слое сети рассчитывается как $(n/2)$ (число комбинаций). Затем возможно создание M тройных наборов данных для формирования фактического выхода, представленного как

(y_i, x_{ip}, q_{iq}) , где $(p, q) \in (1, 2, \dots, n)$. Полученная матрица представлена следующим образом:

$$\begin{bmatrix} x_{1p} & x_{1q} & \vdots & y_1 \\ x_{2p} & x_{2q} & \vdots & y_2 \\ \dots & \dots & \dots & \dots \\ x_{Mp} & x_{Mq} & \vdots & y_M \end{bmatrix} \quad (10)$$

Основная форма алгоритма GMDH записывается в матричной форме, и уравнение (7) может быть переписано следующим образом:

$$Y = Aa, \quad (11)$$

где $Y = \{y_1, y_2, \dots, y_M\}^T$ обозначает фактические значения выходного вектора, $a = \{a_1, a_2, \dots, a_5\}$ представляет собой вектор неизвестных коэффициентов полинома. Прогнозируемая матрица для различных p и q представлена в уравнении (12).

$$A = \begin{bmatrix} 1 & x_{1p} & x_{1q} & x_{1p}x_{1q} & x_{1p}^2 & x_{1q}^2 \\ 1 & x_{2p} & x_{2q} & x_{2p}x_{2q} & x_{2p}^2 & x_{2q}^2 \\ \dots & \dots & \dots & \dots & \dots & \dots \\ 1 & x_{Mp} & x_{Mq} & x_{Mp}x_{Mq} & x_{Mp}^2 & x_{Mq}^2 \end{bmatrix} \quad (12)$$

Следующее нормальное уравнение должно быть решено для многомерного регрессионного анализа на основе метода наименьших квадратов. Для сравнения моделей используются относительное отклонение (Relative Deviation RD) и среднее абсолютное относительное отклонение (Average Absolute Relative Deviation AARD), которые определяются следующим образом (Komeili Birjandi et al., 2022b):

$$RD = \frac{y_{actual} - y_{modeled}}{y_{actual}} \quad (13)$$

$$AARD = \frac{\sum_{i=1}^n \left| \frac{y_{i,actual} - y_{i,modeled}}{y_{i,actual}} \right|}{n} \quad (14)$$

Для вышеуказанных параметров предпочтительны значения, как можно более близкие к 0. Более низкие значения AARD и RD указывают на более высокую точность предлагаемой модели и меньшие отклонения между прогнозируемыми и фактическими выходами. В дополнение к этим критериям для оценки используется коэффициент детерминации (R^2), который рассчитывается с использованием уравнения (15) (Komeili Birjandi et al., 2022b). Значения, близкие к 1, означают более высокую точность, и для текущих моделей (Dossumbekov et al., 2024) значения R^2 , превышающие 0,95, считаются приемлемыми.

$$R^2 = 1 - \frac{\sum_{i=1}^n (y_{i,actual} - y_{i,modeled})^2}{\sum_{i=1}^n (y_{i,actual} - \bar{y}_{actual})^2} \quad (15)$$

4. Результаты и обсуждение

В данном исследовании для моделирования выбросов CO₂ использовались два интеллектуальных метода: GMDH и MLP ANN. Для разработки модели GMDH использовалось программное обеспечение GMDH Shell. Входные данные предложенных моделей включают общий объем энергоснабжения из различных источников: 1) уголь, 2) природный газ, 3) нефть, 4) гидроэнергия, 5) биотопливо и отходы, 6) другие возобновляемые источники энергии (ветер, солнце и т. д.) и 7) ВВП. Поставки различных источников энергии используются в качестве входных данных, так как они являются важными факторами, характеризующими энергосистемы, а ВВП применяется как экономический индекс, влияющий на выбросы парниковых газов. Данные собраны за период с 1990 по 2021 г. Общее количество наборов данных составляет 96, что не является слишком большим для анализа. Кроме того, за рассматриваемый период отсутствуют пропуски в данных. Также предполагается, что все полученные данные корректны. По этим причинам предварительная обработка для настоящего анализа и моделирования не проводилась (García et al., 2015, 2016). Следует отметить, что все исходные данные использовались без нормализации. Данные, относящиеся к поставкам различных источников энергии, получены с сайта IEA (Energy Statistics Data Browser, n.d.-c; Energy Statistics Data Browser, n.d.-a; Energy Statistics Data Browser, n.d.-b), а данные о ВВП собраны с сайта Всемирного банка (GDP (Current US\$) - Kazakhstan, n.d.; GDP (Current US\$) - Turkmenistan, n.d.; GDP (Current US\$) - Uzbekistan, n.d.). Для обучения и тестирования предложенных моделей использовалось соответственно 70 % и 30 % наборов данных. Следует указать, что проверочный набор данных в настоящем исследовании не рассматривался. На Рисунке 6 представлено сравнение между смоделированными и фактическими значениями выбросов CO₂. Большинство данных очень близки к линии $Y = X$, что означает, что прогноз точный и достоверный. Значение R^2 данной модели для всех данных составляет 0,9936. Это значение R^2 очень близко к 1, что говорит об удовлетворительной точности модели.

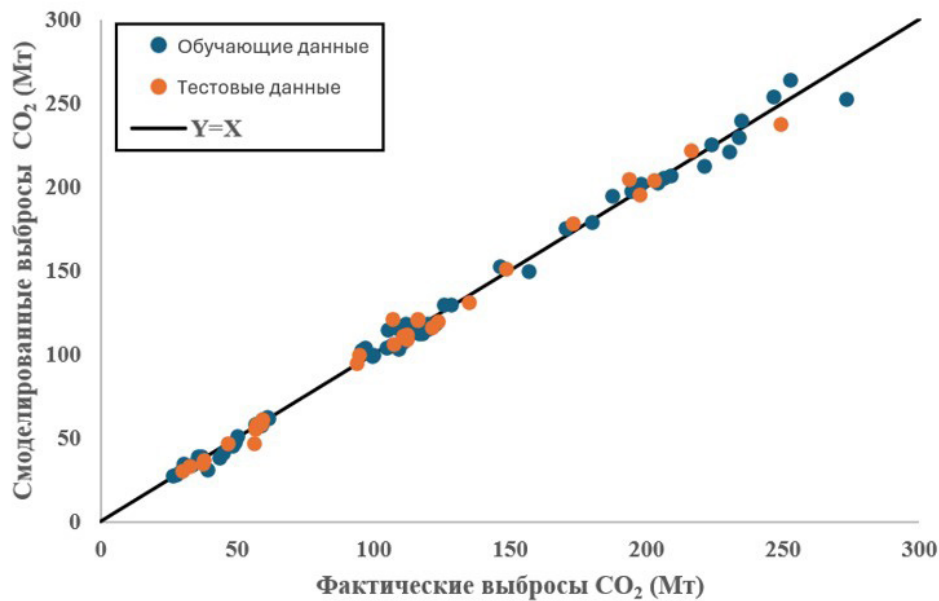


Рисунок 6. Сравнение смоделированных и фактических значений выбросов CO₂ для модели GMDH

На Рисунке 7 показано относительное отклонение (RD) различных данных относительно соответствующего фактического значения выбросов CO₂. Можно наблюдать, что в большинстве случаев значение RD находится в диапазоне $\pm 5\%$, что указывает на высокую точность модели, а максимальное абсолютное значение составляет около 20,5%. Высокие значения RD в некоторых годах для моделей были также зафиксированы в других исследованиях аналогичных задач. Например, Ahmadi, Dehghani Madvar, et al. (2019) сообщили, что для их модели прогнозирования выбросов CO₂ в странах Латинской Америки с использованием метода PSO-LSSVM максимальное значение RD составляло около 22%. Полученные значения для разработанной модели в данном исследовании показывают, что модель является приемлемой для оценки выбросов CO₂ в большинстве случаев и может быть применена для этой цели.

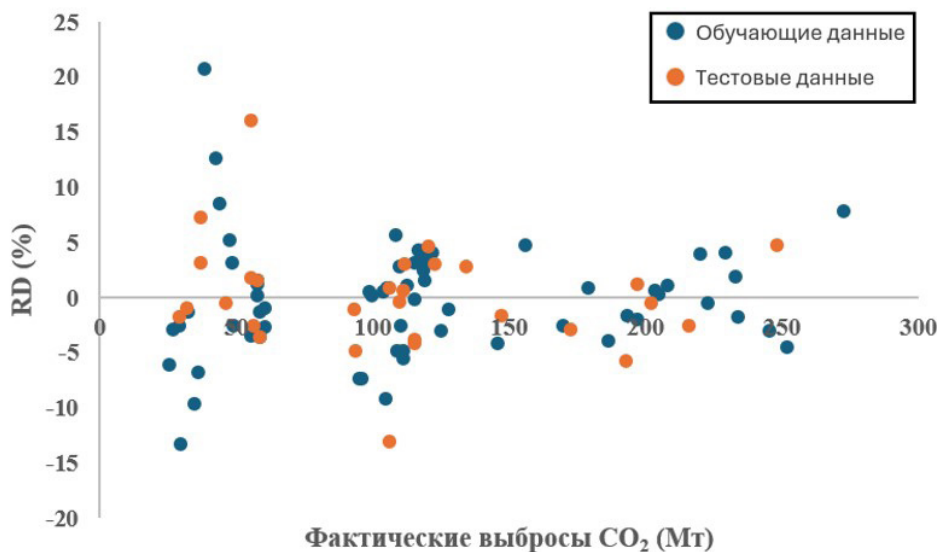


Рисунок 7. Значение RD по сравнению с фактическими значениями выбросов CO₂ для модели GMDH

Аналогичные данные использовались для моделирования выбросов CO₂ в упомянутых странах с использованием MLP ANN. В предложенной модели учитывается только один скрытый слой, а для достижения максимальной точности использовалось различное количество нейронов – от 4 до 15. В Таблице 1 представлены значения MSE для различных структур модели. Можно наблюдать, что использование 5 нейронов в сети обеспечивает максимальную точность среди протестированных моделей. В этом случае значение MSE составляет 29,55, а R² – 0,9929.

Таблица 1. Значения MSE для различных структур сети

Обучающее	Набор данных	Значение MSE
Тестовое	Обучающее	736.94
	Итоговое	459.23
	Итоговое	653.05
5	Обучающее	35.50
	Тестовое	22.74
	Итоговое	29.55
6	Обучающее	59.51
	Тестовое	30.58
	Итоговое	50.77
7	Обучающее	67.33
	Тестовое	15.18
	Итоговое	51.57

Таблица 1. продолж.

8	Обучающее	26.55
	Тестовое	176.54
	Итоговое	71.86
9	Обучающее	144.71
	Тестовое	121.40
	Итоговое	137.67
10	Обучающее	152.78
	Тестовое	139.91
	Итоговое	148.89
11	Обучающее	57.44
	Тестовое	4109
	Итоговое	52.51
12	Обучающее	71.70
	Тестовое	25.99
	Итоговое	57.89
13	Обучающее	116.54
	Тестовое	7.32
	Итоговое	83.55
14	Обучающее	43.67
	Тестовое	8.06
	Итоговое	32.92
15	Обучающее	696.00
	Тестовое	569.56
	Итоговое	657.80

На Рисунке 8 представлено сравнение между фактическими и смоделированными значениями для модели MLP. Можно видеть, что большинство прогнозов близки к линии $Y=XY = XY=X$, что указывает на высокую точность модели. Аналогично предыдущей модели, значения RD по сравнению с фактическими выбросами изображены на Рисунке 9. Можно заметить, что максимальное абсолютное значение RD выше, чем у модели GMDH; однако большинство значений RD находятся в диапазоне $\pm 5\%$. Для лучшего понимания обеих моделей значения AARD сравниваются на Рисунке 10. Согласно полученным значениям AARD, которые составляют приблизительно 4,28 % и 3,69 % для моделей MLP и GMDH соответственно, последняя модель оказывается немного точнее.

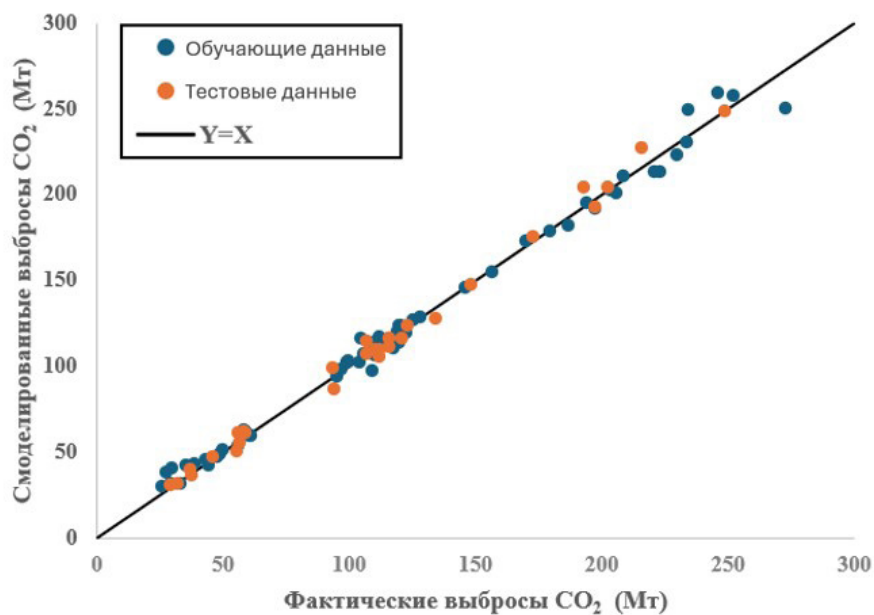


Рисунок 8. Сравнение смоделированных и фактических значений выбросов CO₂ для модели MLP

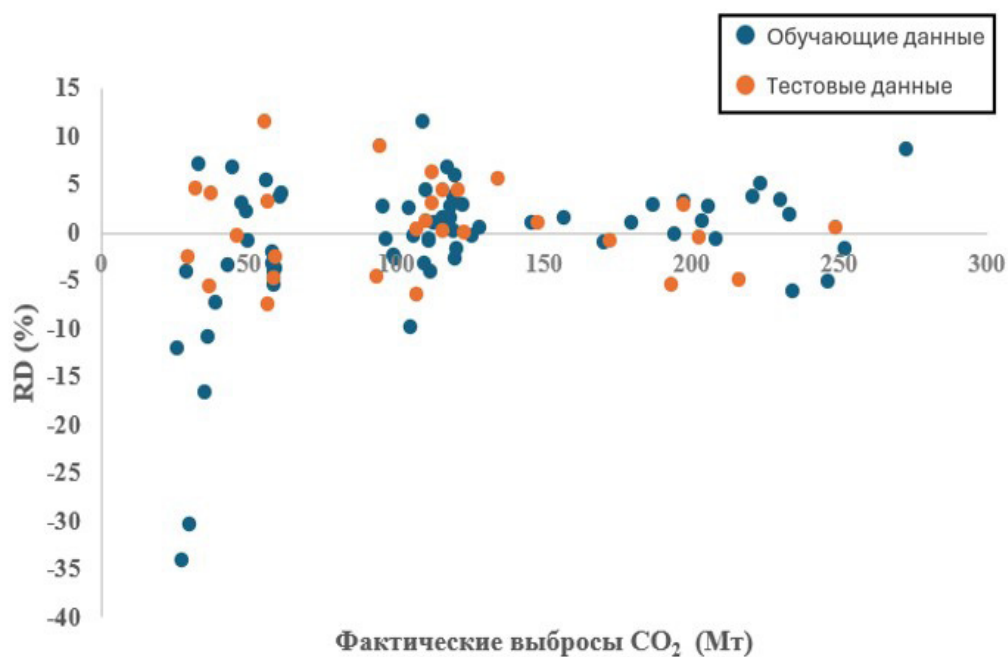


Рисунок 9. Значение RD по сравнению с фактическими значениями выбросов CO₂ для модели MLP

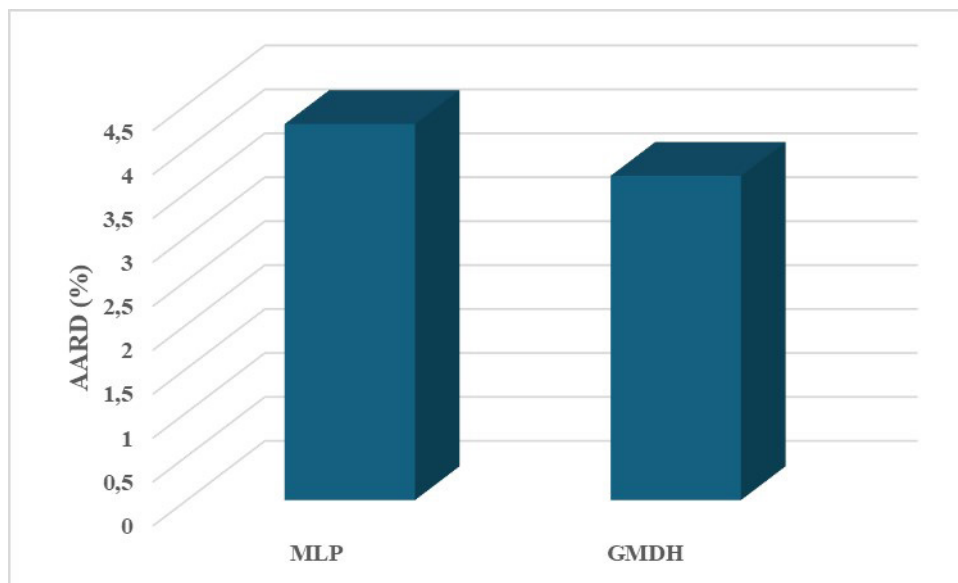


Рисунок 10. Значение AARD предложенных моделей

Согласно полученным значениям R^2 , AARD и RD, можно отметить, что предложенные модели демонстрируют приемлемую точность в оценке выбросов. Следует отметить, что в настоящей модели предполагается, что выбросы зависят от поставок различных источников энергии и ВВП, в то время как другие факторы, такие как погодные условия и социальные параметры, также могут оказывать влияние на выбросы. Это предположение сделано из-за доступности данных и для упрощения предложенной модели. Ограниченность доступных данных, влияющих на выбросы CO_2 , и сложности количественной оценки характеристик энергосистемы являются одними из наиболее значимых ограничений для разработки более точных и детализированных моделей. Использование таких моделей может быть полезным для политиков и ученых для оценки выбросов в ближайшие годы и анализа различных сценариев. С помощью этих моделей можно оценивать и сравнивать разные сценарии с точки зрения выбросов CO_2 .

Среди основных преимуществ искусственных нейронных сетей (ANNs) – способность синтеза алгоритмов через процесс обучения, решение нелинейных задач и высокая устойчивость моделей. Однако необходимость обучения для каждой задачи, проведение множества тестов для поиска оптимальной структуры и потребность в больших объемах данных для обучения сети являются основными недостатками этих методов (Alhuyi Nazari et al., 2021; Navarro, 2013). В этой связи могут быть рассмотрены другие методы. В будущих исследованиях можно протестировать и сравнить с настоящей моделью другие интеллектуальные методы, включая ANFIS и LSSVM. В некоторых случаях, в зависимости от задачи и ее характеристик, использование других моделей может обеспечить более

высокую точность и более точные прогнозы. Основными преимуществами ANFIS являются его надежность в моделировании нелинейных процессов и быстрая обучаемость. Кроме того, эта техника объединяет числовые и лингвистические знания (Şahin & Erol, 2017). Способность к решению нелинейных задач является одним из важнейших преимуществ методов, основанных на SVM; однако основная проблема этого подхода заключается в необходимости знаний, связанных с функцией ядра (Alhuyi Nazari et al., 2021). Помимо использования других методов, целесообразным предложением может быть применение различных функций активации в модели MLP для проверки их влияния на точность. Кроме того, предлагается рассмотреть больше стран региона для повышения комплексности моделей.

5. Заключение

В заключительной части данного исследования подчеркиваются сложные взаимосвязи между выбросами CO₂, которые в значительной степени зависят от моделей энергопотребления, состава источников энергии и экономических показателей. Выбросы CO₂ зависят от множества факторов и параметров, однако энергопотребление и доли различных источников оказывают наибольшее влияние. Кроме того, ВВП может быть значимым фактором, который следует учитывать при оценке и прогнозировании выбросов. Основной вклад данной работы заключается в применении методов, основанных на данных и искусственном интеллекте, для разработки прогнозных моделей выбросов CO₂. В исследовании рассматривались три страны: Казахстан, Узбекистан и Туркменистан. Для сбора данных использовались источники, такие как IEA, Всемирный банк и USAID. Также были предоставлены ценные сведения об энергетических системах этих стран и их политике, направленной на повышение энергоэффективности и снижение выбросов. Страны Центральной Азии все больше признают ключевую роль экономической политики и энергетических стратегий в формировании траекторий выбросов. Политика, интегрирующая экономический рост с практиками устойчивого развития энергетики, крайне важна. Меры, такие как стимулирование инвестиций в возобновляемую энергию, продвижение энергоэффективности в промышленности и домашних хозяйствах, а также внедрение более чистых технологий, могут значительно снизить выбросы CO₂, способствуя при этом экономическому развитию. Применение метода группового учета аргументов (GMDH) и модели многослойного перцептрона (MLP) продемонстрировало высокую эффективность в оценке выбросов, при этом GMDH показал незначительное преимущество в точности по сравнению с MLP. Сравнительный анализ показал, что обе модели имеют приемлемую точность,

однако использование GMDH предпочтительнее с точки зрения точности. Высокие коэффициенты детерминации (R^2) и низкие средние абсолютные относительные отклонения (AARD) для обеих моделей – 0,9936 и 3,69 % для GMDH, и 0,9929 и 4,28 % для MLP – подтверждают их надежность. Предложенные модели могут служить ценными инструментами для прогнозирования будущих выбросов, предоставляя данные, которые могут помочь политикам при разработке эффективных стратегий для устойчивого развития и охраны окружающей среды. Политики могут рассматривать эти модели для оценки различных сценариев прогнозирования выбросов и их сравнения. В будущих исследованиях могут быть использованы другие структуры сетей и функции для разработки более точных моделей. Кроме того, для моделирования выбросов CO₂ могут быть рассмотрены другие методы, основанные на данных, такие как LSSVM и ANFIS, чтобы достичь более точных прогнозов.

Благодарности

Исследование выполнено при поддержке Комитета науки Министерства науки и высшего образования Республики Казахстан (грант № AP23490690, BR21882258).

Список литературы

- Ahmadi, M. H., Dehghani Madvar, M., Sadeghzadeh, M., Rezaei, M. H., Herrera, M., & Shamshirband, S. (2019). Current Status Investigation and Predicting Carbon Dioxide Emission in Latin American Countries by Connectionist Models. *Energies*, 12(10), 1916. <https://doi.org/10.3390/en12101916>
- Ahmadi, M. H., Jashnani, H., Chau, K. W., Kumar, R., & Rosen, M. A. (2019). Carbon dioxide emissions prediction of five Middle Eastern countries using artificial neural networks. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*. <https://doi.org/10.1080/15567036.2019.1679914>
- Alhuyi Nazari, M., Mukhtar, A., Yasir, A. S. H. M., Rashidi, M. M., Ahmadi, M. H., Blazek, V., Prokop, L., & Misak, S. (2023). Applications of intelligent methods in solar heaters: an updated review. *In Engineering Applications of Computational Fluid Mechanics* (Vol. 17, Issue 1). Taylor and Francis Ltd. <https://doi.org/10.1080/19942060.2023.2229882>
- Alhuyi Nazari, M., Salem, M., Mahariq, I., Younes, K., & Maqableh, B. B. (2021). Utilization of Data-Driven Methods in Solar Desalination Systems: A Comprehensive Review. *Frontiers in Energy Research*, 0, 541. <https://doi.org/10.3389/FENRG.2021.742615>
- Altikat, S. (2021). Prediction of CO₂ emission from greenhouse to atmosphere with artificial neural networks and deep learning neural networks. *International Journal of Environmental Science and Technology*, 18(10), 3169-3178. <https://doi.org/10.1007/s13762-020-03079-z>
- Betting Big on Renewables. (n.d.). USAID. <https://www.usaid.gov/stories/betting-big-on-renewables#:~:text=From 2018 to 2020%2C USAID, the road for a year.>
- Carbon Capture, Utilisation and Storage. (n.d.). IEA. <https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage>
- CO₂ Emissions in 2023 A new record high, but is there light at the end of the tunnel? (2024).

- Decree of the President of the Republic of Uzbekistan “On measures to radically improve the management system of the fuel and energy industry of the Republic of Uzbekistan” dated 01.02.2019 №UP-5646. (2022). IEA. <https://www.iea.org/policies/13314-decree-of-the-president-of-the-republic-of-uzbekistan-on-measures-to-radically-improve-the-management-system-of-the-fuel-and-energy-industry-of-the-republic-of-uzbekistan-dated-01022019-up-5646>
- Dossumbekov, Y. K., Zhakiyev, N., Nazari, M. A., Salem, M., & Abdikadyr, B. (2024). Sensitivity analysis and performance prediction of a micro plate heat exchanger by use of intelligent approaches. *International Journal of Thermofluids*, 22(February), 100601. <https://doi.org/10.1016/j.ijft.2024.100601>
- Elbaz, K., Shen, S., Zhou, A., Yin, Z., & Lyu, H. (2021). Prediction of Disc Cutter Life During Shield Tunneling with AI via the Incorporation of a Genetic Algorithm into a GMDH-Type Neural Network. *Engineering*, 7(2), 238-251. <https://doi.org/10.1016/j.eng.2020.02.016>
- Electric Vehicles. (2023). IEA. <https://www.iea.org/energy-system/transport/electric-vehicles>
- Energy. (2023). CAREC. [https://www.carecprogram.org/?page_id=16#:~:text=Key Projects,support growth in ongoing trade.](https://www.carecprogram.org/?page_id=16#:~:text=Key%20Projects,support%20growth%20in%20ongoing%20trade.)
- Energy efficiency classes of buildings. (2022). IEA. <https://www.iea.org/policies/7040-energy-efficiency-classes-of-buildings>
- Energy Statistics Data Browser. (n.d.-a). IEA. <https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?country=KAZ>
- Energy Statistics Data Browser. (n.d.-b). IEA. <https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?country=UZB>
- Energy Statistics Data Browser. (n.d.-c). IEA. <https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?country=TKM>
- Executive summary. (n.d.). IEA. <https://www.iea.org/reports/kazakhstan-2022/executive-summary>
- Farlow, S. J. (2020). *Self-Organizing Methods in Modeling: GMDH Type Algorithms*. CRC Press, Boca Raton.
- Filik, Ü. B., & Filik, T. (2017). Wind Speed Prediction Using Artificial Neural Networks Based on Multiple Local Measurements in Eskisehir. *Energy Procedia*, 107, 264-269. <https://doi.org/10.1016/J.EGYPRO.2016.12.147>
- Filipović, S., Orlov, A., & Panić, A. A. (2024). Key forecasts and prospects for green transition in the region of Central Asia beyond 2022. *Energy, Sustainability and Society*, 14(1), 25. <https://doi.org/10.1186/s13705-024-00457-0>
- García, S., Luengo, J., & Herrera, F. (2015). *Data Preprocessing in Data Mining (Vol. 72)*. Springer International Publishing. <https://doi.org/10.1007/978-3-319-10247-4>
- García, S., Ramírez-Gallego, S., Luengo, J., Benítez, J. M., & Herrera, F. (2016). Big data preprocessing: methods and prospects. *Big Data Analytics*, 1(1), 9. <https://doi.org/10.1186/s41044-016-0014-0>
- GDP (current US\$) - Kazakhstan. (n.d.). *WorldBank*. <https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?locations=KZ>
- GDP (current US\$) - Turkmenistan. (n.d.). *WorldBank*. <https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?locations=TM>
- GDP (current US\$) - Uzbekistan. (n.d.). *WorldBank*. <https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?locations=uz>
- Ghalandari, M., Forootan Fard, H., Komeili Birjandi, A., & Mahariq, I. (2020). Energy-related carbon dioxide emission forecasting of four European countries by employing data-driven methods. *Journal of Thermal Analysis and Calorimetry*, 1-10. <https://doi.org/10.1007/s10973-020-10400-y>
- Heat Pumps. (n.d.). IEA. <https://www.iea.org/energy-system/buildings/heat-pumps>
- KAZAKHSTAN: Law No. 541-IV of 2012 on Energy Saving and Energy Efficiency (2019 Ed.). (2019). *Asia-Pacific Energy*. <https://policy.asiapacificenergy.org/node/135>

- Kim, M., & Okuyucu, O. (2022). Prediction of Undrained Shear Strength by the GMDH-Type Neural Network Using SPT-Value and Soil Physical Properties. *Materials*, 15, 6385. <https://doi.org/10.3390/ma15186385>
- Komeili Birjandi, A., Fahim Alavi, M., Salem, M., Assad, M. E. H., & Prabakaran, N. (2022a). Modeling carbon dioxide emission of countries in southeast of Asia by applying artificial neural network. *International Journal of Low-Carbon Technologies*, 17, 321-326. <https://doi.org/10.1093/ijlct/ctac002>
- Komeili Birjandi, A., Fahim Alavi, M., Salem, M., Assad, M. E. H., & Prabakaran, N. (2022b). Modeling carbon dioxide emission of countries in southeast of Asia by applying artificial neural network. *International Journal of Low-Carbon Technologies*, 17, 321-326. <https://doi.org/10.1093/ijlct/ctac002>
- Kuziboev, B., Saidmamatov, O., Khodjaniyozov, E., Ibragimov, J., Marty, P., Ruzmetov, D., Matyakubov, U., Lyulina, E., & Ibadullaev, D. (2024). CO2 Emissions, Remittances, Energy Intensity and Economic Development: The Evidence from Central Asia. *Economies*, 12(4), 95. <https://doi.org/10.3390/economies12040095>
- Law of the Republic of Uzbekistan “On the use of renewable energy sources” dated May 21, 2019 No. ZRU-539. (2022). IEA. <https://www.iea.org/policies/13310-law-of-the-republic-of-uzbekistan-on-the-use-of-renewable-energy-sources-dated-may-21-2019-no-zru-539>
- Luo, X. J., Oyedele, L. O., Ajayi, A. O., Akinade, O. O., Owolabi, H. A., & Ahmed, A. (2020). Feature extraction and genetic algorithm enhanced adaptive deep neural network for energy consumption prediction in buildings. *Renewable and Sustainable Energy Reviews*, 131, 109980. <https://doi.org/10.1016/J.RSER.2020.109980>
- M. K., A. N., & V., M. A. (2020). Role of energy use in the prediction of CO2 emissions and economic growth in India: evidence from artificial neural networks (ANN). *Environmental Science and Pollution Research*, 27(19), 23631-23642. <https://doi.org/10.1007/s11356-020-08675-7>
- Nationally Determined Contribution (NDC) to the Paris Agreement (2022 Update): Turkmenistan. (n.d.). IEA. <https://www.iea.org/policies/17050-nationally-determined-contribution-ndc-to-the-paris-agreement-2022-update-turkmenistan>
- Navarro, R. I. (2013). Study of a neural network-based system for stability augmentation of an airplane Annex 1 Introduction to Neural Networks and Adaptive Neuro-Fuzzy Inference Systems (ANFIS).
- Oh, S., & Pedrycz, W. (2002). The design of self-organizing Polynomial Neural Networks. 141, 237-258.
- On protection of the atmospheric air. (2022). IEA. <https://www.iea.org/policies/11440-on-protection-of-the-atmospheric-air>
- Pindoriya, N. M., Singh, S. N., & Singh, S. K. (2008). An adaptive wavelet neural network-based energy price forecasting in electricity markets. *IEEE Transactions on Power Systems*, 23(3), 1423-1432. <https://doi.org/10.1109/TPWRS.2008.922251>
- Population, total - Kazakhstan. (n.d.). *WorldBank*. <https://data.worldbank.org/indicator/SP.POP.TOTL?locations=KZ>
- Population, total - Turkmenistan. (n.d.). *WorldBank*. <https://data.worldbank.org/indicator/SP.POP.TOTL?locations=TM>
- Population, total - Uzbekistan. (n.d.). *WorldBank*. <https://data.worldbank.org/indicator/SP.POP.TOTL?locations=UZ>
- Radovanović, M., Filipović, S., & Andrejević Panić, A. (2021). Sustainable energy transition in Central Asia: status and challenges. *Energy, Sustainability and Society*, 11(1), 49. <https://doi.org/10.1186/s13705-021-00324-2>
- Renewables. (n.d.). IEA. <https://www.iea.org/energy-system/renewables>
- Rezaei, M. H., Sadeghzadeh, M., Alhuyi Nazari, M., Ahmadi, M. H., & Astaraei, F. R. (2018a). Applying GMDH artificial neural network in modeling CO2 emissions in four nordic countries. *International Journal of Low-Carbon Technologies*, 13(3), 266-271. <https://doi.org/10.1093/ijlct/cty026>

- Rezaei, M. H., Sadeghzadeh, M., Alhuyi Nazari, M., Ahmadi, M. H., & Astaraei, F. R. (2018b). Applying GMDH artificial neural network in modeling CO₂ emissions in four nordic countries. *International Journal of Low-Carbon Technologies*, 13(3), 266-271. <https://doi.org/10.1093/ijlct/cty026>
- Şahin, M., & Erol, R. (2017). A Comparative Study of Neural Networks and ANFIS for Forecasting Attendance Rate of Soccer Games. *Mathematical and Computational Applications* 2017, Vol. 22, Page 43, 22(4), 43. <https://doi.org/10.3390/MCA22040043>
- The Law About Support the Use of Renewable Energy Sources (amended). (2022). IEA. <https://www.iea.org/policies/5407-the-law-about-support-the-use-of-renewable-energy-sources-amended>
- The Outlook for the Development of Renewable Energy in Uzbekistan. (2014).
- Transition to renewable energy sources: economic benefits for entrepreneurs in Kazakhstan. (2024). UNDP. <https://www.undp.org/kazakhstan/stories/transition-renewable-energy-sources-economic-benefits-entrepreneurs-kazakhstan>
- Turkmenistan. (n.d.). IEA. <https://www.iea.org/countries/turkmenistan>
- Turmunkh, B.-E. (2021). Renewable and Non-Renewable Energy Consumption, Carbon Dioxide Emissions, and Economic Growth: Empirical Evidence from Central Asian Countries. *Journal of Economics and Development Studies*, 9(1). <https://doi.org/10.15640/jeds.v9n1a7>
- UNDP continues to support Turkmenistan in improving energy efficiency and developing renewable energy sources. (n.d.). IEA. <https://www.undp.org/turkmenistan/press-releases/undp-continues-support-turkmenistan-improving-energy-efficiency-and-developing-renewable-energy-sources>
- USAID Energizes Uzbekistan's First Green Hydrogen Hub. (n.d.). USAID. <https://uz.usembassy.gov/usaid-energizes-uzbekistans-first-green-hydrogen-hub/>
- USAID Power Central Asia. (n.d.). IEA. <https://www.usaid.gov/central-asia-regional/fact-sheets/usaaid-power-central-asia>
- Uzbekistan. (n.d.). IEA. <https://www.iea.org/countries/uzbekistan>
- Uzbekistan (12/08). (n.d.). U.S. Department of State. <https://2009-2017.state.gov/outofdate/bgn/uzbekistan/113251.htm>
- Xiu, Z. Wei. (2022). Environmental implications of economic transition in Central Asia: A study of energy consumption and carbon emissions. *Top Academic Journal of Economics and Statistics*, 7(3), 19-39.
- Yuldoshboy, S., Karimov, M., & Kuralbaev, J. (2022). The association between CO₂ and economic growth in Central Asian countries: Panel data approach. *Journal of Positive School Psychology*, 5587-5601.
- Zhakiyev, N., Khamzina, A., Zhakiyeva, S., De Miglio, R., Bakdolotov, A., & Cosmi, C. (2023). Optimization Modelling of the Decarbonization Scenario of the Total Energy System of Kazakhstan until 2060. *Energies*, 16(13), 5142. <https://doi.org/10.3390/en16135142>