

VAR Analysis of the Transformation of Energy Systems and the Use of Mineral Resources in the Context of Sustainable Development

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Abstract

The article investigates the transformation of energy systems in the context of mineral resource use and sustainable development, focusing on Ukraine, France, and Germany as representative cases of diverse energy policies. The research aims to identify long-term trends in the transition from fossil fuels to renewable sources and to assess the consequences of these changes for the mining industry. For this purpose, a vector autoregression (VAR) model with scenario corrections was applied to historical data from 2000 to 2020, enabling the construction of baseline and accelerated development scenarios up to 2030. Compared with traditional econometric and machine learning methods, the VAR approach ensures interpretability of interdependencies among variables and allows the analysis of causal relationships through impulse response functions and forecast error variance decomposition. The results reveal significant national differences in the trajectories of energy transformation. Ukraine demonstrates accelerated structural changes due to war-related disruptions, while maintaining nuclear power as the backbone of electricity generation and gradually increasing renewables. France continues to rely heavily on nuclear power, complemented by a moderate growth of renewable energy sources, which is consistent with its strategic energy plans. Germany illustrates the most dynamic transition, with a rapid decline in coal and nuclear generation and a strong expansion of renewables, aiming to reach over 78% of electricity production by 2030. The findings confirm that energy transformation directly affects the demand for mineral resources: a decrease in coal and gas, stable demand for uranium, and a rising need for critical raw materials such as lithium, cobalt, and rare earths. The study contributes to the development of adaptive strategies for mineral resource policy and highlights the importance of scenario-based forecasting for energy security and sustainable development.

Keywords

energy transition, VAR model, electricity generation, mineral resources, sustainable development



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Introduction

The contemporary development of the energy sector is inextricably linked with the mining industry, as the structure of electricity generation is determined by the volumes of extraction and use of fossil resources – coal, oil, natural gas, uranium ores, etc. The transition to renewable energy sources is leading to a gradual decline in demand for traditional mineral resources while simultaneously creating new challenges for the mining industry, associated with the need to extract rare-earth elements, such as lithium, cobalt, and other materials required for "green" energy technologies and energy storage.

In this context, forecasting transformational changes in the structure of electricity generation and assessing their impact on the mineral resource base becomes particularly relevant. A study using the examples of Ukraine, France, and Germany makes it possible to trace different trajectories of the energy transition and to identify their consequences for the mining industry. Ukraine remains dependent on coal- and gas-fired generation, which is directly linked to the operation of mines and extraction enterprises; France is characterised by the dominance of nuclear power, based on the use of uranium ores; Germany is demonstrating a rapid phase-out of coal-fired power generation, with the simultaneous closure of mines and large-scale growth in renewable sources.

Thus, research into the transformation of energy systems in the context of the mining industry is important for strategic planning, optimising the use of mineral resources, and forming a sustainable development model.

The scientific novelty of this study lies in the application of a VAR model with scenario-based adjustments to forecast structural changes in electricity production, taking into account technological, economic, political, and military factors and their impact on the mineral resource base. Unlike existing approaches, this research conducts comparative modelling for the first time, using the examples of Ukraine, France, and Germany within a unified methodological framework. It draws on data from 2000 to 2020 and constructs forecast scenarios up to 2030. This makes it possible not only to reproduce long-term trends in energy development but also to assess the demand for both traditional and emerging mineral resources.

The relevance of this research is determined by the need to forecast long-term trends in energy transformation, to assess the impact of the shift from fossil resources to renewable sources on the mining industry, and to develop scientifically grounded scenarios for strategic planning in mineral resource policy. The application of a VAR model with scenario-based adjustments makes it possible to account for complex factors and enhances the reliability of forecast estimates in an international context.

The task is to develop a model that forecasts the transformation of the electricity generation structure and assesses its impact on mineral resource utilization. The main objective is to identify key trends in the development of energy systems and their connection with the mining industry, assess the role of renewable energy sources, and forecast changes in demand for various types of raw materials. An additional task is scenario analysis – baseline and accelerated development – to identify risks and opportunities associated with the restructuring of the mining industry, the decline in fossil fuel production, and the growing demand for critical minerals.

The scientific hypothesis of the study is that the application of a VAR model with scenario-based adjustments will not only reliably reproduce long-term trends in the transformation of energy systems, but also allow an assessment of their impact on the development of the mineral resource base – particularly in terms of declining demand for traditional fossil resources and the growing need for critical elements required for renewable energy.

Analysis of recent research and publications

In the study by Zaichenko S. V. et al. (2024), a comprehensive approach was proposed for assessing the strategic development of renewable energy sources in Ukraine, based on integrated indicators and taking into account the national energy strategy.

Syasev & Makarenkov (2025) investigated innovative algorithms for managing renewable energy in Ukraine, with a focus on forecasting, optimisation, and enhancing the stability of energy networks.

Doumèche et al. (2023) analysed the impact of population spatial mobility on the accuracy of electricity demand forecasting in France during the 2022 energy crisis, revealing a dependence of consumption on socio-economic changes.

Şahin (2021) applied an optimised fractional nonlinear Bernoulli grey model to forecast renewable energy consumption up to 2030 in six European countries and Turkey, demonstrating the method's high adaptability to different national profiles.

Walczewski & Wöhrle (2024) proposed a model for forecasting electricity generation from wind and solar installations in Germany, demonstrating its effectiveness for operational energy system planning.

Aksan et al. (2023) compared CNN-LSTM and LSTM-CNN architectures for forecasting power flow directions in the high-voltage network of northeastern Germany, identifying the advantages of hybrid models.

Similarly, Gavurova and Polishchuk (2025) develop a decision-making support system for inclusive travel planning based on fuzzy set theory, demonstrating the applicability of advanced mathematical models in managing uncertainty – an approach directly relevant to forecasting and optimization in energy transitions.

Wahdany et al. (2023) presented an end-to-end method for forecasting wind energy generation, focused not only on accuracy but also on optimising the overall operation of the energy system.

Potrč et al. (2025) investigate the optimisation of renewable energy supply networks in the European Union, emphasising the need for a gradual transition to carbon neutrality by 2050 in accordance with the Paris Agreement. The study uses a multi-period mixed integer programming model aimed at maximising the net present value of sustainable development, taking into account various resources – biomass, waste, and renewable electricity. The main results show that wind energy is currently the most promising solution for rapid expansion of generation, while the role of solar photovoltaics will gradually increase, reaching 43% of electricity production from renewable energy sources (RES) in 2050. An important conclusion is that the transition does not threaten food security, ensuring a balance between energy and food production. In addition to environmental results, the authors highlight socio-economic benefits, forecasting the creation of more than 1.5 million jobs, which demonstrates the interdependence of energy policy, sustainability, and economic growth. This study offers a methodological approach to reconciling technological development, policy objectives, and sustainability criteria, contributing to the debate on the integration of renewable energy at the European level.

Simoes et al. (2025) investigate the impact of climate variability on the deployment of renewable electricity in Europe, focusing on the relationship between climate change, weather conditions, and electricity demand and generation. The study uses the TIMES energy system model (eTIMES-EU) for the entire European energy sector until 2050, taking into account six climate scenarios for each Member State, which generate future capacity utilisation factors for wind, solar, and hydro power, as well as the impact of temperature on heating and cooling demand. The modelling results show that there are no significant changes at the EU level, but at the national level, there are significant differences in the deployment of renewable energy (especially wind and solar) and in electricity trading. This work highlights the importance of integrating climate variability into the planning of large energy systems, demonstrating the heterogeneity of climate impacts across countries and the need for adaptive energy policies to achieve RES and emissions targets.

Hainsch et al. (2025) explore energy transition scenarios in the context of the EU Green Deal, focusing on the interaction of technology, policy, and public attitudes to achieve a 100% reduction in greenhouse gas emissions by 2050. The authors propose an original set of future scenarios for 2050 to help modellers, policymakers, industry experts, and the public assess: the extent to which public commitment or enhanced cooperation within the EU can be relied upon without significant technological progress, and which technological innovations may be key to an effective energy transition. Analysis of the four scenarios shows that a high level of electrification is necessary for rapid decarbonisation, highlighting the importance of simultaneous technological development and strengthened policy control in the short term. In addition, the results are compared with other European energy transition scenarios, allowing similarities between development paths to be identified and key conclusions relevant to the strategic planning of the EU Green Deal to be summarised.

Naegler et al. (2025) examine the environmental consequences of Germany's energy system transformation, focusing on the interaction between climate and environmental goals. The authors emphasise that environmental protection goes beyond climate policy, and underestimating this aspect can lead to strategies that reduce CO₂ emissions but increase other environmental risks. The study evaluated ten structurally different scenarios for the transformation of the energy system, five of which envisage an 80% reduction in direct energy-related CO₂ emissions, and the other five a 95% reduction. The assessment utilized life cycle data for energy and transport technologies, enabling the evaluation of impacts across multiple categories, including mineral resource consumption, land use, and human health. The results indicate that transitioning to a climate-friendly system generally reduces environmental impacts, although some exceptions may occur where certain indicators increase due to reduced CO₂ emissions. A comparison of moderate (80%) and very ambitious (95%) strategies shows that strengthening climate policy is not always accompanied by greater environmental risks, and the optimal combination includes moderate electrification of heat and transport, a balanced technology mix for electricity generation, and a reduction in the number and impact of passenger cars. This study highlights the need for a systematic approach to achieve climate and environmental goals simultaneously.

Hassan et al. (2025) conduct a comprehensive analysis of the global transition to renewable energy, highlighting significant differences in implementation rates and technological achievements between countries, and demonstrating the potential for large-scale transformation of energy paradigms. Using data from the renewable energy map scenario, the authors show that RES could provide up to two-thirds of global primary energy supply by 2050, compared to a modest 24% in the baseline scenario. EU countries, especially Denmark and Germany, stand out for their high integration of wind energy and overall contribution of RES, while in Asia, China and India are showing rapid annual growth of over 30% in the solar and wind energy sectors. The American continent, represented by the United States, Canada, and Brazil, shows varying integration of renewable sources, while Middle Eastern countries are gradually diversifying their energy portfolios. Africa has potential, but the transition is limited by infrastructure barriers. The authors emphasise that the global momentum of RES is palpable, but disparities remain due to geopolitical, technological, and economic factors. The results of the study highlight the

current status and trajectory of RES deployment worldwide and emphasise the need for targeted policies, investment, and international cooperation to accelerate the global transition to renewable energy.

Kuzemko et al. (2025) examine the implications of Russia's 2022 invasion of Ukraine for European energy policy and sustainable transformations. The authors note that the crisis has exacerbated Europe's dependence on Russian fossil fuels, accelerated the deployment of clean energy in the region, but at the same time created difficulties in moving away from fossil fuels, negatively affected sustainable transitions in countries of the Global South, and raised new questions about energy justice and the role of the state as a participant in the energy market. The study emphasises that global geopolitical crises can shift energy policy priorities, making it difficult to achieve long-term, sustainable, and just transitions.

Genovese et al. (2025) explore the role of Power-to-Hydrogen (PtH) and Hydrogen-to-X (H2X) hydrogen energy systems in the future industrial sector of Europe, with a particular focus on forecasting energy needs and technology integration by 2050. The authors emphasise that the EU considers hydrogen to be a key energy carrier capable of covering up to 20% of energy consumption, 20-50% of transport needs, and 5-20% of industrial needs. The article discusses the main sectors where hydrogen can play a significant role: transport, power generation, industrial production, oil refining, and agriculture, with an emphasis on potential technological integration and synergies between sectors.

The forecasts include short-term and long-term roadmaps for the implementation of technologies that enable industrial players to plan investments and adapt to changes in the energy sector structure. The authors emphasise that electrolysis and the conversion of renewable electricity into hydrogen provide flexible energy storage and transport, making PtH and H2X critical to the stability and efficiency of future energy systems. The study demonstrates that synchronous forecasting of technological development, energy demand, and the integration of hydrogen solutions is key to achieving the EU's climate goals and ensuring the long-term sustainability of the industrial sector.

Redko et al. (2025) conduct a comparative analysis of the development strategies of the fuel and energy complexes of Ukraine and EU countries, drawing attention to international experience and the principles of the European Green Deal. The authors emphasise that Ukraine is developing its own energy strategies in line with economic, social, and climatic conditions, integrating European approaches. An analysis of the strategies of France, Austria, and Poland shows that decarbonisation should take place gradually, as sudden changes can lead to negative economic and social consequences. The results of the study can serve as a useful guideline for energy reforms in Ukraine.

Sturm (2025) analyses European energy policy in the context of Russia's war against Ukraine, focusing on the challenges of restoring energy sovereignty. The author emphasises that most European economies had not strengthened their energy security prior to the invasion and that the war has significantly complicated the situation. A comparative study of the vulnerabilities of Germany and Lithuania reveals different approaches to energy security and crisis response. The study shows that trade cannot resolve all political differences, and that the accelerated introduction of RES requires technological breakthroughs in energy storage and significant investment in infrastructure, as political will alone is not enough to overcome obstacles.

Lima et al. (2025) analyse the non-renewable and renewable exergy costs of green ammonia production in small-scale plants using various combinations of electrolyzers (AWE, PEM, SOEC, AEM) and electricity sources (hydropower, wind, solar, grid). The study takes into account both energy conversion efficiency and resource costs for RES infrastructure and electrolyzers. The forecast indicates that exergy costs will range from 12.5 to 32.5 MWh/t NH₃ in 2025, decreasing to 11.5-19.1 MWh/t NH₃ by 2050, depending on the scenario (the most efficient being the Solid Oxide Electrolyser Cell combined with hydropower). The authors emphasise that infrastructure accounts for a significant share of costs, and the future integration of by-products (Ar, H₂, O₂) could reduce the burden. The research methodology enables a thorough assessment of the origin and impact of the natural resources used, and the results obtained are crucial for predicting the role of green ammonia as a key energy vector by 2050.

Bahini et al. (2023) examine the role of cobalt and lithium in the global transition to renewable energy, using panel data from 69 countries for 2007-2022. The authors show that cobalt plays a key role in the growth of renewable electricity, while lithium has no significant impact. The results indicate that China, the largest importer of cobalt, particularly contributed to the development of renewable energy during the global financial crisis. Importantly, cobalt has a positive impact in both low- and high-CO₂ emitting countries, while the impact of lithium has been found to be controversial. The study highlights the importance of cobalt for energy storage, technology development, and innovation, making it a critical mineral in global energy transition strategies.

Chisale et al. (2023) analyse the prospects for full electrification of Malawi by 2063 using modern forecasting methods – ECEEMDAN (enhanced complete ensemble empirical mode decomposition with adaptive noise) in combination with the BiGRU (bidirectional gated recurrent units) neural network. The study models three scenarios: business as usual (BAU), low and high demand, which take into account different rates of industrialisation and policy effectiveness. Forecasts show that by 2060, electricity demand will range from 8,219.47 MW (low demand) to 9,492.14 MW (high demand), while the BAU scenario predicts around 8,544.64

MW. To achieve 100% electrification, the country needs to add between 193.31 MW (low demand) and 224.69 MW annually.

The authors emphasise that rapid urbanisation, population growth, and transport development pose serious challenges for Malawi's energy system. The study focuses on strategic forecasting, the need for large-scale infrastructure investments, and comprehensive planning to implement Agenda 2063. Thus, the work offers scientifically sound guidelines for the government and investors to ensure the sustainable development of the country's energy sector and economy.

Hu & Nontero (2023) examine how indicators of the extended energy transition, as well as the supply and demand of key minerals for green energy, affect CO₂ emissions from electricity and heat production in developing countries in Asia between 1998 and 2022. The authors found that the growth of expanded transition indicators (related to the abandonment of fossil fuels and the development of renewable energy sources) contributes to a significant reduction in CO₂ emissions. On the other hand, increased demand for critical minerals (lithium, cobalt) may have a negative environmental impact, as their extraction and processing generate additional emissions.

This is the first comprehensive study that combines an analysis of extended energy transition indicators with mineral supply and demand indicators, using Asian countries as an example. The work holds practical importance for forming sustainable natural resource management policies and can serve as additional comparative experience for developing strategies in other world regions.

Despite a substantial body of research dedicated to forecasting energy sector development, the scientific literature reveals differences in methodological choices depending on national characteristics. For example, in Ukraine, most studies focus on econometric approaches (ARIMA, VAR, integrated indicators), which can be explained by the availability of statistical data and the need for macroeconomic justification of state policy. In France, where the energy system is characterised by a high share of nuclear generation, research predominantly employs models for optimising supply and demand, taking into account socio-economic factors such as population mobility and consumer behaviour scenarios. In Germany, emphasis is placed on machine learning and hybrid approaches (neural networks, CNN-LSTM, grey models), which allow for consideration of the rapid growth of renewable energy and the complexity of network balancing. Thus, differences in methodological choices reflect the specificity of national energy strategies: in Ukraine, the focus is on macroeconomic stability and political challenges; in France, on ensuring the stability of nuclear generation; and in Germany, on the rapid integration of renewable sources and the development of flexible digital forecasting tools.

Methodology

For this study, three countries – Ukraine, Germany, and France – were selected as examples of different approaches to energy policy and generation structure. The data range was determined based on the availability of indicators within the chosen dataset. A complete list of features was used to form a set of variables, for which constraints were established to prevent values from exceeding permissible limits during calculations. Missing values were imputed using interpolation, after which the data were scaled (VAR standardisation). The modelling approach employed automatic lag selection based on the Akaike Information Criterion (AIC), with results subsequently subjected to inverse scaling. For visualisation, indicators representing electricity production from nuclear power plants, renewable sources, and fossil fuels were selected.

The selection of the optimal lag order is carried out using information criteria (AIC), which ensures a balance between model accuracy and the number of parameters. Once the model is constructed, it becomes possible to generate forecasts for multiple variables simultaneously, as well as to analyse the dynamics of their mutual interactions using Impulse Response Functions (IRF) and Forecast Error Variance Decomposition (FEVD).

Therefore, the application of the VAR model in this study enables not only the construction of forecasts for energy and economic indicators but also the assessment of complex interrelationships between them, which is particularly important for a comprehensive analysis of the sustainable development of the energy sector.

At the initial stage of the study, a sample of countries was selected to ensure data representativeness and to account for varying levels of energy infrastructure development. The main selection criteria were the availability of complete historical data, diversity of geographic regions, and differing levels of economic development. This approach allows for a comprehensive coverage of the global energy landscape and facilitates the identification of both general and regional trends in sustainable energy development.

Ukraine was selected as a subject of study due to the intensive development of renewable energy under conditions of martial law, its active integration into the European energy market, and the implementation of energy efficiency projects that hold strategic significance for the country's energy security.

France was included in the sample due to the high share of nuclear energy in its national energy balance, the implementation of renewable energy development programmes, and the integration of conventional and "green" technologies to ensure the stability of energy supply.

Germany was selected as an example of a country with a comprehensive "Energiewende" strategy, aimed at the gradual phase-out of nuclear power and the active expansion of solar and wind generation capacities.

Overall, the selection of these countries is motivated by the need to study different models of energy development in the context of ensuring sustainable energy supply and enhancing energy security. Together, these countries represent diverse energy development models, allowing for a comparative analysis of their approaches to sustainable energy provision.

This study forecasts energy consumption volumes for Ukraine, France, and Germany until 2030 based on historical data from 2000 to 2020 using vector autoregression (VAR). The analysis includes an assessment of current trends, the impact of economic, technological, and political factors on the structure of energy consumption, and the construction of possible scenarios for changes in the energy balance. Particular attention is given to the role of renewable energy sources in shaping forecast indicators and the influence of energy policy on achieving sustainable development targets.

In this study, a vector autoregression (VAR) model was selected to forecast electricity generation volumes and structure. Unlike classical univariate methods, such as ARIMA, VAR allows for the simultaneous consideration of the dynamics of multiple endogenous variables and the examination of their mutual interactions. This is particularly important in the energy sector, where changes in electricity generation from one source (e.g., nuclear power) directly affect the balance of others (renewable or fossil).

Machine learning methods demonstrate high accuracy in short-term forecasting, but their use in long-term scenarios (up to 2030) is limited due to the 'black box' in interpreting results and the complexity of political and economic factors. The VAR model, on the other hand, provides transparency, interpretability, and the possibility of econometric analysis of cause-and-effect relationships thanks to impulse response functions (IRF) and forecast error variance decomposition (FEVD) tools.

Thus, the choice of VAR is motivated by the need to construct long-term scenarios that are based not only on statistical relationships but also on the economic and political logic of energy sector development. This makes the method more suitable for strategic planning and scenario analysis compared with ARIMA or artificial intelligence approaches, which are primarily oriented towards short-term forecasts.

For this study, indicators from the global dataset on sustainable energy development, Global Data on Sustainable Energy (2000-2020), were used, reflecting the structural characteristics of electricity generation and the macroeconomic parameters of the energy sector (Tanwar, 2023).

The main variables include electricity generation from fossil fuels (TWh), nuclear power plants (TWh), and renewable sources (TWh). Auxiliary indicators comprise GDP per capita, CO₂ emissions per capita, primary energy consumption per capita, and other macroeconomic parameters that indirectly influence energy dynamics.

Missing values were restored using linear interpolation, followed by forward fill and backward fill methods. Data adjustment was performed by clipping values according to substantively justified limits (for example, the share of renewable energy in electricity generation $\in [0; 100]$).

The stationarity of the time series was tested using the Augmented Dickey-Fuller (ADF) test (Smeeke & Wilms, 2023). This test is based on the estimation of the following equation:

$$\Delta y_t = \alpha + \beta t + \gamma y_{t-1} + \sum_{i=1}^{p-1} \delta_i \Delta y_{t-i} + \varepsilon_t \quad (1)$$

where

Δy_t	is the first difference of the series,
α	is a constant,
β	is the trend component,
t	is the time trend,
p	is the lag order,
ε_t	is the random error.

H₀: $\gamma = 0$ indicates the presence of a unit root, i.e., the non-stationarity of the time series.

In cases where the obtained p-value exceeded 0.05, the null hypothesis was not rejected, indicating the non-stationarity of the series. To achieve stationarity in such cases, a transformation was applied by computing the first differences:

$$\Delta y_t = y_t - y_{t-1} \quad (2)$$

To ensure the correctness and accuracy of the study results, the data from the Global Data on Sustainable Energy dataset underwent thorough pre-processing. The first step involved the elimination of missing values using linear interpolation:

$$x_t = x_{t_a} + \frac{x_{t_b} + x_{t_a}}{t_b - t_a} (t - t_a) \quad (3)$$

where

x_t is the restored value,
 t_b, t_a are the indices of known points before and after the skip.

$$z_t = \frac{x_t - \mu}{\sigma} \quad (4)$$

where

x_t is the initial value,
 μ is the sample mean,
 σ is the standard deviation.

Reverse scaling is performed using the formula:

$$x_t = z_t \cdot \sigma + \mu \quad (5)$$

This approach brings the variables onto a common scale, improving the numerical stability of models (e.g., VAR) and enabling a proper comparison of indicators across different countries and years.

For further analysis and time series forecasting, the Vector Autoregression (VAR) model was applied. This approach generalises classical autoregressive models for cases where a system of multiple variables is being modelled. VAR allows the simultaneous consideration of the dynamics of the entire system, as each variable can depend both on its own lags and on the lags of other variables.

If a variable exhibits no variation, it is excluded from the VAR model and carried forward into the forecast as a constant, since only time series demonstrating dynamic behaviour are suitable for model construction.

Let $y_t \in R^k$ – be a vector of k endogenous variables at time t . The VAR(p) model can then be expressed as:

$$y_t = A_1 y_{t-1} + A_2 y_{t-2} + \dots + A_p y_{t-p} + u_t \quad (6)$$

where

A is a coefficient matrix of dimension $k \times k$,
 p is the model order,
 u_t is the vector of random errors.

The estimation of the parameters of the vector autoregression (VAR) model is performed using the ordinary least squares (OLS) method, applied separately to each equation of the system. This approach is equivalent to the matrix representation of the model:

$$Y = XB + U \quad (7)$$

where

Y is a $(T - p) \times k$ dimensional matrix with observations of endogenous variables,
 X is a regressor matrix containing lagged values of variables,
 B is a block matrix of coefficients (A_1, \dots, A_p) ,
 U is a residual matrix.

The estimates of the parameters in matrix form are given by the expressions:

$$\hat{B} = (X^T X)^{-1} X^T Y, \quad \hat{\Sigma}_u = \frac{1}{T-p} \hat{U}^T \hat{U}, \quad \hat{U} = Y - X \hat{B} \quad (8)$$

where

\hat{B} is an estimate of the VAR coefficients,
 $\hat{\Sigma}_u$ estimate of the residual covariance matrix,
 \hat{U} residual matrix.

Forecasting represents a key stage in the application of VAR models, as it enables the assessment of not only short-term but also medium- and long-term system dynamics. Multi-step forecasts over the steps ahead are generated recursively, using previous forecasted values as inputs, which allows for tracing the trajectories of variable changes over time.

Impulse characteristics (Impulse Response Functions, IRF) play a particularly important role in the study of system dynamics. They describe how a one-time shock to one of the variables affects the entire system over subsequent periods. For a VAR model, this is expressed through the decomposition:

$$y_{t+h} = \sum_{i=0}^h \Phi_i u_{t+h-i} \quad (9)$$

where

Φ_i are obtained from the companion matrix of the model.

Another analytical tool is the Forecast Error Variance Decomposition (FEVD), which allows for the assessment of the proportion of variation in a forecasted variable that is explained by innovations in other variables. For a VAR(p) model, it can be rewritten in the form of an infinite Wold decomposition:

$$y_t = \sum_{i=0}^{\infty} \Phi_i u_{t-i} \Phi_0 = I_k \quad (10)$$

where

y_t is vector of variables (dimension $k \times 1$),
 Φ_i vector of innovations (forecast errors or shocks),
 u_t coefficient matrices (obtained from the companion matrix),
 I_k unit matrix of dimension.

$$\sigma_j^2(h) = \sum_{i=0}^{h-1} [e_j^T \Phi_i \Sigma_u e_h] \quad (11)$$

where

e_j is a unit vector with a unit at the j -th position,
 h step forecast error.

$$\theta_{jk}^2(h) = \frac{\sum_{i=0}^{h-1} [e_j^T \Phi_i \Sigma_u e_h]^2}{\sigma_j^2(h)} \quad (12)$$

where

e_j vector indicator with a unit at the position corresponding to variable j and zeros at other positions,
 Φ_i matrix of VAR model coefficients at step i , which determines the dynamic response of the system to shocks,
 Σ_u covariance matrix of innovations (shocks), reflecting the interdependence between errors,
 e_h a vector indicator for variable k , which selects the corresponding column from the covariance matrix,
 $\sigma_j^2(h)$ the variance of the forecast error of variable j at horizon h .

The obtained estimates $\theta_{jk}(h)$ allow for conclusions regarding the extent to which innovations in variable k influence the forecast error variance of variable j over a given forecast horizon. This renders IRF and FEVD

extremely important tools in applied research, where it is necessary to understand not only the overall system dynamics but also the internal structure of interdependencies.

Specifically, upper and lower bounds were established for electricity production and consumption, in line with historical data from the Global Data on Sustainable Energy dataset. For percentage-based variables, such as the share of renewable energy in the overall balance, a range of 0 to 100% was applied.

Such constraints ensure the practical relevance of forecasts and reduce the risk of inaccurate results, while also allowing for the consideration of scenarios of economic and technological development in the countries studied.

To maintain the integrity of the time series, all missing values in the dataset were addressed, which enhanced the accuracy and reliability of the forecasting model.

To enhance computational stability, numerical features were brought onto a common scale, preventing variables with larger magnitudes from dominating and promoting accurate forecasting.

Results

Ukraine. The forecast model, constructed based on historical data from 2000 to 2020, reproduces the key structural features of Ukraine's energy balance with considerable accuracy: the stable dominant role of nuclear power in electricity generation (over half of total generation) and the gradual decline in the share of fossil fuels, particularly coal and gas. The forecast also predicts a steady increase in the share of renewable energy sources (RES) within the generation mix.

However, actual statistical data for 2021-2023 show that the rate of change in Ukraine's energy balance has been significantly more dynamic than previously anticipated. The share of fossil fuels declined more rapidly due to the destruction and shutdown of a substantial number of thermal power plants, while renewable energy grew faster in certain periods owing to the large-scale development of solar and wind projects in preceding years. Despite the negative impact of military actions and investment constraints, in 2024 the Ukrainian government approved the National Energy and Climate Plan (NECP) for 2025-2030, which envisages increasing the share of renewable energy from the current ~10% to 27% of final consumption by 2030, the commissioning of approximately 10 GW of new capacity, and a 65% reduction in greenhouse gas emissions relative to 1990 levels. Achieving these targets is expected to require investments of USD 41.5-50 billion and the implementation of a distributed generation development strategy through 2035, aimed at enhancing the resilience of the energy system (Center for Strategic and International Studies, 2024).

Thus, military factors, targeted energy attacks, the loss of generation capacity, and changes in the electricity import-export structure have led to an accelerated transformation of the energy mix, which the model – based on conditions of relative stability – could not fully capture.

In view of the objectives set out in Ukraine's National Energy and Climate Plan for 2025-2030 – namely, increasing the share of renewable energy to 27% of final consumption, implementing small modular reactors (SMRs), commissioning approximately 10 GW of new RES capacity, and undertaking a large-scale modernisation of the electricity grid – it is advisable to complement the forecast with scenario analysis, considering both baseline and accelerated development scenarios (Ministry of Energy of Ukraine, 2023). This approach enables the assessment of the impact of external financial and technological support, the pace of recovery of damaged infrastructure, as well as potential risks related to the country's energy security and compliance with commitments under the European Green Deal.

The dynamics of electricity generation in Ukraine by source for 2000-2030 are presented in Figures 1 and 2. The first graph illustrates changes in the generation structure across the main sources – fossil fuels, nuclear power, and RES – incorporating the forecast up to 2030. The second graph depicts total electricity generation over the same period, allowing for an assessment of the impact of structural changes on overall generation volumes.

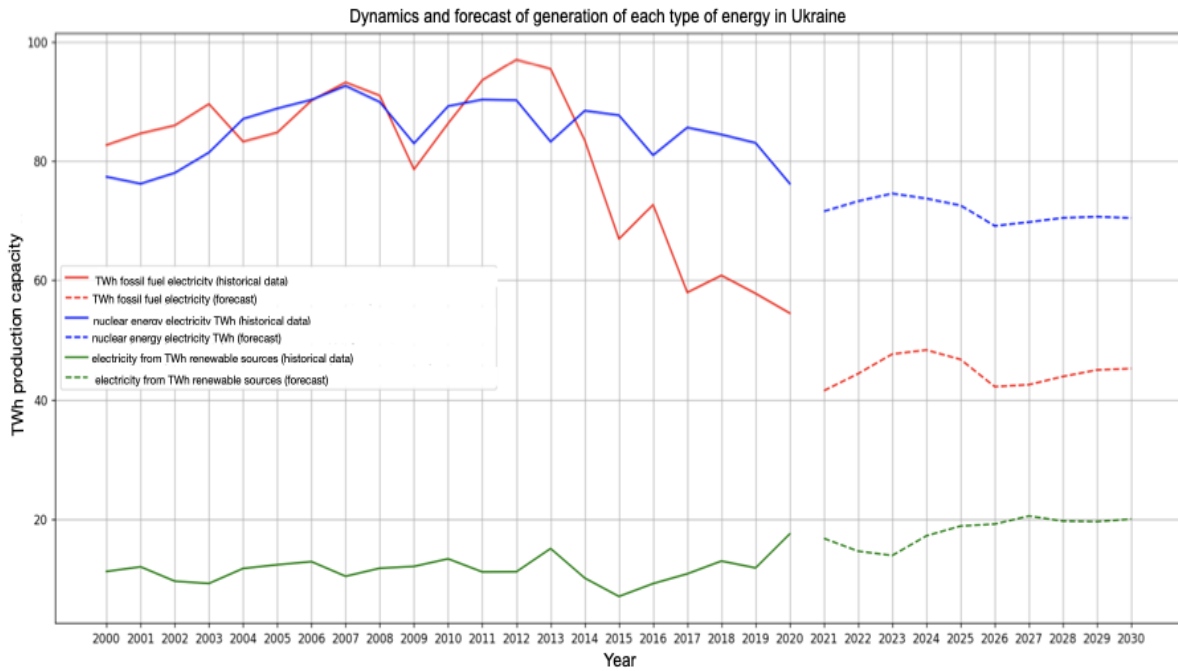


Fig. 1. Electricity generation in Ukraine by source for the period 2000-2030.

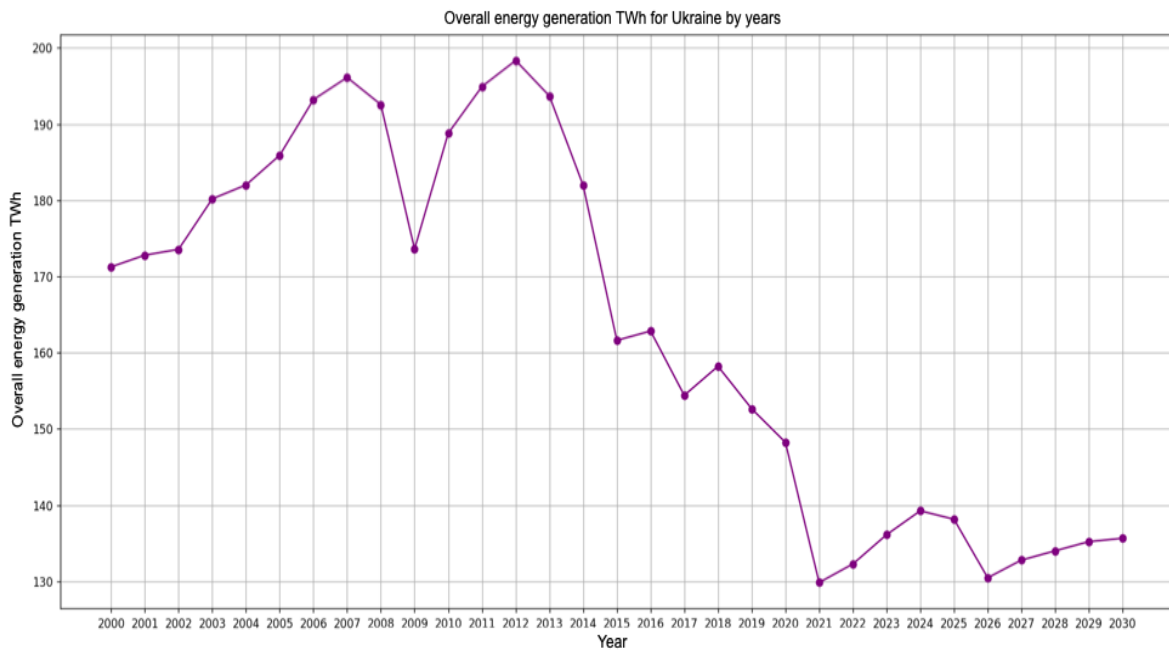


Fig. 2. Total electricity generation in Ukraine by source for the period 2000-2030.

The trends observed in Figures 1 and 2 clearly reflect the structural changes in electricity generation in Ukraine over the period 2000-2030. Different generation sources exhibit distinct dynamics: nuclear power maintains a stable share, fossil fuels gradually decline, and renewable energy sources show a steady increase, both in terms of percentage share and absolute volumes.

The following Table 1 provides a detailed breakdown of these data, allowing for a more precise assessment of annual changes in electricity generation by source and the overall generation dynamics.

Table 1 shows that over the period 2000-2030, Ukraine's energy balance undergoes significant changes: the share of fossil fuels gradually decreases, nuclear power remains stable, and renewable energy sources exhibit consistent growth. This distribution confirms the trends shown in the graphs and serves as the basis for further scenario-based forecasting of the country's energy development.

Table 1. Electricity generation in Ukraine by source for the period 2000-2030

Year	Fossil fuels TWh/year (%)	Atomic energy TWh/year (%)	Renewable energy TWh / year (%)	Fossil fuels TWh / year change %	Nuclear energy TWh / year change %	Renewable energy TWh / year change %	Total change % in generation
2000	48.26	45.16	6.59				
2001	48.95	44.08	6.97	2.35	-1.51	6.83	0.9
2002	49.51	44.93	5.56	1.58	2.39	-19.92	0.44
2003	49.68	45.18	5.14	4.18	4.39	-3.94	3.82
2004	45.72	47.81	6.47	-7.04	6.89	27.08	1.01
2005	45.59	47.74	6.67	1.84	2	5.26	2.14
2006	46.62	46.69	6.69	6.3	1.64	4.19	3.94
2007	47.48	47.18	5.34	3.37	2.57	-18.96	1.51
2008	47.21	46.65	6.14	-2.37	-2.92	12.89	-1.82
2009	45.26	47.76	6.98	-13.57	-7.7	2.54	-9.85
2010	45.69	47.21	7.09	9.8	7.51	10.48	8.75
2011	47.96	46.29	5.75	8.37	1.23	-16.36	3.25
2012	48.9	45.44	5.66	3.73	-0.12	0.27	1.75
2013	49.24	42.96	7.8	-1.65	-7.69	34.55	-2.34
2014	45.84	48.57	5.59	-12.55	6.23	-32.69	-6.06
2015	41.39	54.21	4.39	-19.79	-0.86	-30.19	-11.18
2016	44.62	49.71	5.68	8.59	-7.62	30.28	0.75
2017	37.53	55.42	7.05	-20.23	5.72	17.62	-5.18
2018	38.43	53.34	8.23	4.92	-1.38	19.67	2.47
2019	37.86	54.37	7.78	-4.97	-1.66	-8.83	-3.52
2020	36.76	51.4	11.84	-5.69	-8.19	47.94	-2.88
2021	31.97	55.09	12.94	-23.82	-6.11	-4.32	-12.41
2022	33.53	55.38	11.09	6.86	2.4	-12.68	1.87
2023	35	54.75	10.24	7.41	1.75	-4.93	2.91
2024	34.71	52.92	12.37	1.44	-1.13	23.57	2.3
2025	33.83	52.51	13.66	-3.3	-1.56	9.52	-0.79
2026	32.33	52.95	14.71	-9.75	-4.76	1.71	-5.56
2027	32.02	52.51	15.47	0.8	0.93	7.04	1.78
2028	32.75	52.55	14.7	3.21	1.01	-4.13	0.92
2029	33.27	52.23	14.5	2.5	0.28	-0.45	0.9
2030	33.33	51.9	14.77	0.51	-0.31	2.2	0.32

France. In France, the structure of electricity generation differs significantly from that of Ukraine, primarily due to the dominance of nuclear power. According to data from the International Energy Agency (IEA), in 2023, nuclear power accounted for approximately 64% of the country's total electricity generation (International Energy Agency, 2024). At the same time, renewable energy sources, such as solar and wind power, are gradually increasing, although their share in the overall balance has not yet reached substantial levels.

Over the period 2025-2030, a more noticeable reduction in the role of fossil fuels is forecasted – from the current approximately 10% to a level close to a "reserve" function, primarily for balancing peak loads. Renewable energy sources are expected to continue growing during this period, reaching roughly 39.9% of total electricity generation by 2030. This growth will be accompanied by the maintenance of a high share of nuclear generation, which will remain a key pillar of the country's energy stability.

France's strategic plans for 2030 (PPE, SNBC) envisage approximately 55-60% nuclear generation and around 40% renewable energy, which aligns with the current projections (IEA, 2021). However, positive trends in recent years suggest that the potential for reducing fossil fuels and increasing renewable energy may be even higher than assumed in the baseline scenarios.

Figure 3 illustrates the change in the structure of electricity generation in France by main energy sources between 2000 and 2030. This graph enables us to evaluate the dynamics of nuclear energy and renewable energy development in relation to total electricity production.

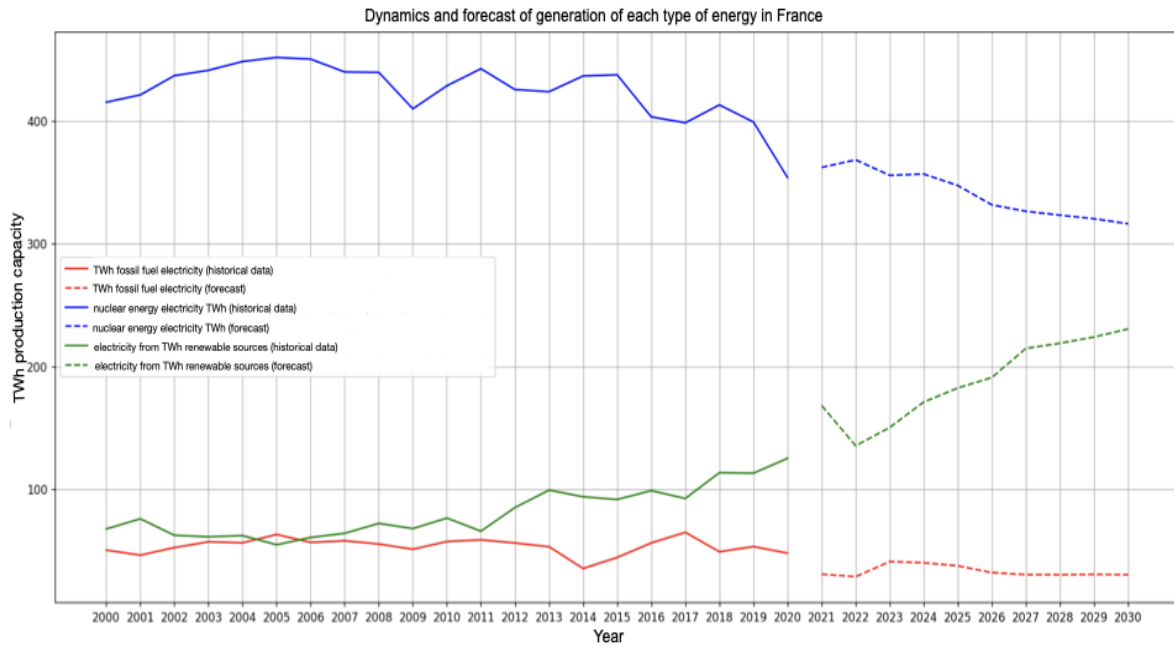


Fig. 3. Electricity production in France by source in the period 2000-2030.

Figure 4 shows the total electricity production in France for the period 2000-2030, taking into account the projected changes in the energy mix. This graph helps to understand how changes in the energy balance affect the total electricity production in the country.

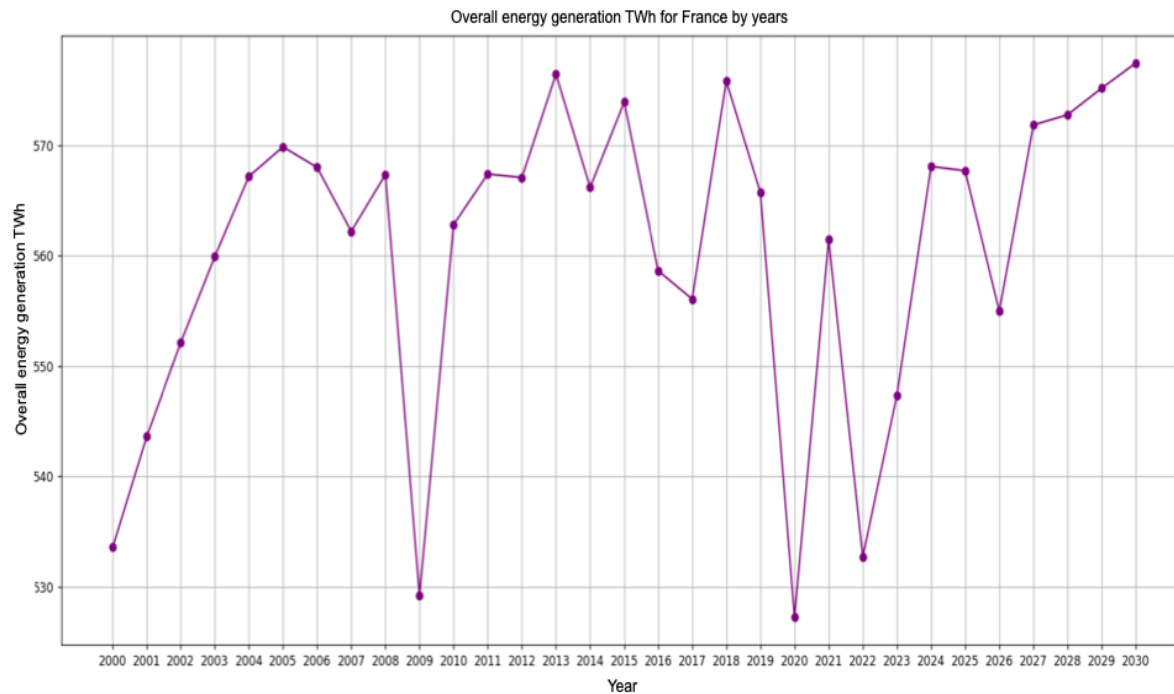


Fig. 4. Total electricity production in France by source in the period 2000-2030.

Table 2 provides detailed data on electricity production in France by energy source for the period from 2000 to 2030. These data include production volumes for each energy source, allowing for a detailed analysis of trends and forecasts in the development of the country's energy sector.

Table 2 Electricity production in France by source in the period 2000-2030

Year	Fossil fuel TWh/year (%)	Nuclear energy TWh/year (%)	Renewable energy TWh / year (%)	Fossil fuels TWh / year change %	Nuclear energy TWh / year change %	Renewable energy TWh / year change %
2000	9.48	77.8	12.71			
2001	8.55	77.45	14	-8.16	1.43	12.18
2002	9.54	79.11	11.35	13.32	3.72	-17.61
2003	10.25	78.77	10.98	8.94	0.99	-1.95
2004	9.97	79.03	11.01	-1.48	1.63	1.55
2005	11.12	79.24	9.65	12.06	0.73	-11.92
2006	10.02	79.26	10.72	-10.18	-0.3	10.79
2007	10.35	78.21	11.44	2.25	-2.32	5.57
2008	9.79	77.46	12.75	-4.49	-0.06	12.49
2009	9.7	77.42	12.88	-7.65	-6.76	-5.78
2010	10.24	76.14	13.62	12.3	4.58	12.52
2011	10.4	77.97	11.64	2.36	3.24	-13.9
2012	9.95	75.02	15.03	-4.36	-3.84	29.13
2013	9.25	73.5	17.25	-5.44	-0.41	16.62
2014	6.3	77.09	16.61	-33.12	3.02	-5.42
2015	7.78	76.22	16	25.14	0.22	-2.33
2016	10.1	72.17	17.72	26.43	-7.83	7.8
2017	11.71	71.64	16.66	15.31	-1.2	-6.43
2018	8.56	71.71	19.73	-24.3	3.66	22.66
2019	9.46	70.53	20.01	8.59	-3.37	-0.36
2020	9.13	67.11	23.76	-10.02	-11.32	10.66
2021	5.53	64.49	29.98	-35.45	2.33	34.36
2022	5.44	69.12	25.44	-6.82	1.7	-19.48
2023	7.55	64.97	27.48	42.72	-3.42	10.97
2024	7.1	62.79	30.11	-2.42	0.29	13.75
2025	6.67	61.18	32.15	-6.17	-2.62	6.69
2026	5.82	59.75	34.43	-14.66	-4.53	4.69
2027	5.37	57.08	37.56	-4.93	-1.57	12.39
2028	5.35	56.43	38.22	-0.28	-0.97	1.94
2029	5.37	55.68	38.95	0.82	-0.91	2.33
2030	5.3	54.76	39.93	-0.77	-1.26	2.92

The subsection substantiates the feasibility of developing a system based on an analysis of the relevance of the problem and identification of the limitations of existing solutions. It defines technical, functional, and operational requirements and outlines key tasks to ensure the efficiency, reliability, and scalability of the future system.

Germany. The forecast model, based on data from 2000-2020, reflects a trend characteristic of Germany – a gradual decline in the share of fossil fuels and steady growth in renewable energy sources (RES). While fossil fuels accounted for more than 64% of electricity generation in the early 2000s, this figure had fallen to 44.3% by 2020, with RES exceeding 44% for the first time.

Actual data for 2021-2023 show the rapid development of renewable energy – in 2023, its share exceeded 60%, which is significantly higher than in the medium-term forecasts of previous years (Kappner et al., 2023). At the same time, the share of fossil fuels fell to around 38%, while nuclear generation, in line with the Energiewende policy, almost disappeared from the energy balance.

Between 2025 and 2030, the role of fossil fuels is expected to decline particularly rapidly, from 28.3% in 2025 to around 18.5% in 2030 (Schmid et al., 2013). This will be accompanied by an increase in RES to over 78%, indicating the country's actual transition to an energy system based almost entirely on clean sources. Fossil fuels

will mainly perform balancing functions and provide reserves during peak periods, while solar, wind, and other renewable technologies will provide the bulk of generation.

The current growth rates of renewable energy exceed some ambitious Energiewende scenarios, opening up opportunities to achieve climate neutrality even faster. The period from 2025 to 2030 will be decisive for completing the structural transition from an energy system where fossil fuels played a leading role to a model where they serve only as a supporting element in a flexible, high-tech, and sustainable energy complex.

The German government aims to achieve 80% of generation from renewable sources by 2030, and the Renewable Energy Sources Act (EEG) and Energiewende policy provide for an increase in solar capacity to 215 GW and wind capacity to 145 GW (Cheung et al., 2019). Germany stopped using nuclear power plants in 2023, and plans to phase out coal-fired power generation by 2038 (and possibly earlier).

Two visual materials were used to illustrate these trends. The first (Fig. 5) illustrates the annual dynamics of electricity production by three main source groups – fossil fuels, nuclear energy, and RES – in 2000-2030, combining actual data and forecast calculations, which allows us to clearly trace the intersection of trends in the decline of fossil resources and the growth of renewables.

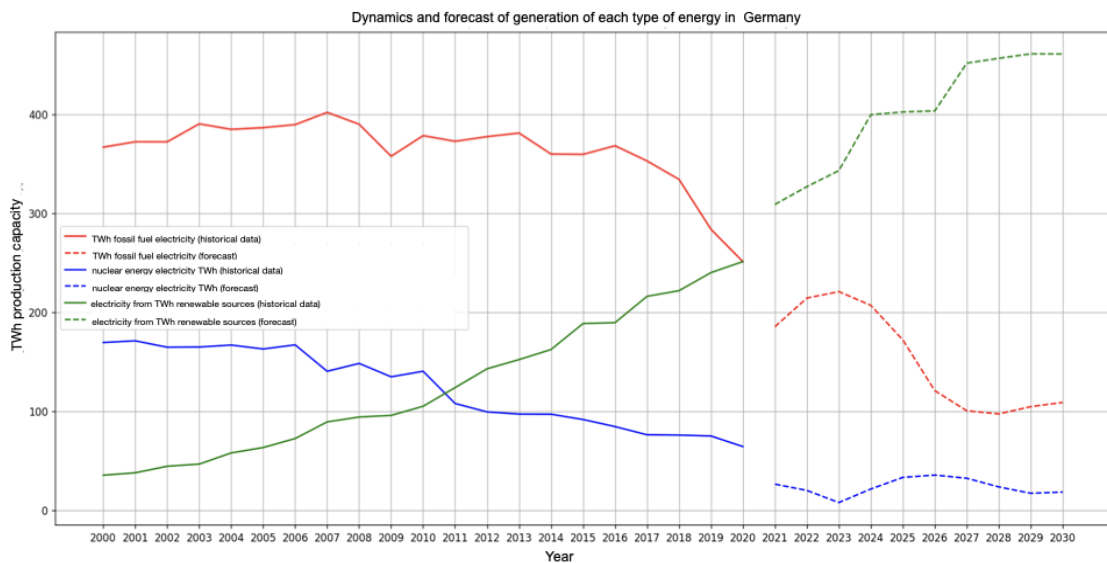


Fig. 5. Electricity production in Germany by source in the period 2000-2030.

The second (Fig. 6) shows the total electricity production volumes for the same period, which makes it possible to correlate structural changes with the dynamics of total generation and determine the balancing role of traditional capacities in the process of scaling up RES.

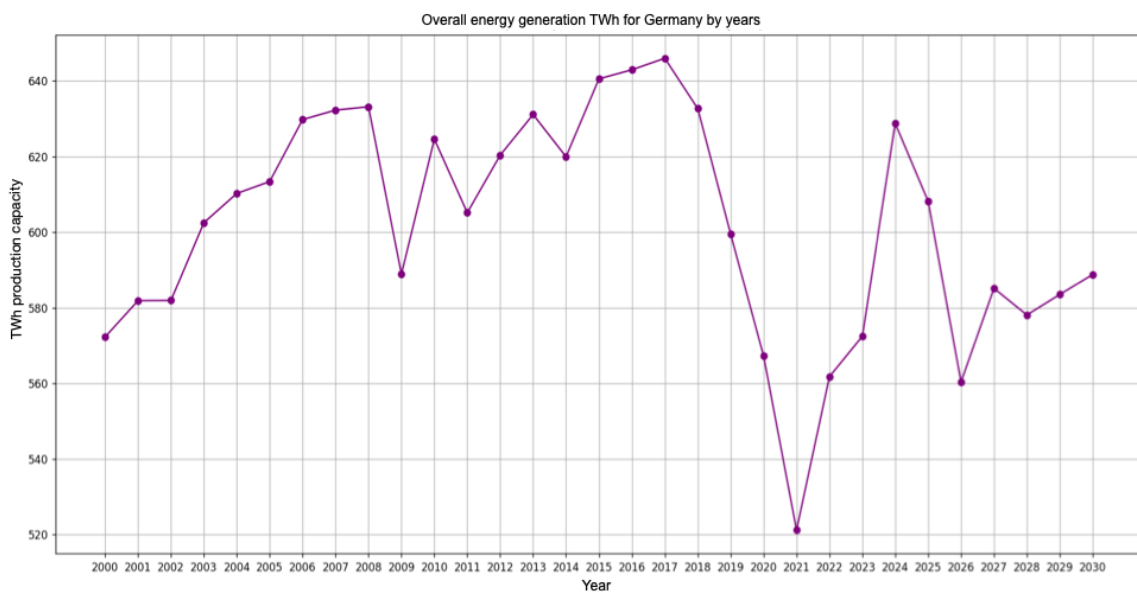


Fig. 6. Total electricity production in Germany by source in the period 2000-2030.

In order to ensure the reproducibility of calculations and the possibility of verifying the results, a summary table with key indicators (Table 3) is provided, containing production volumes by individual sources and annual changes.

Table 3. Electricity production in Germany by source in the period 2000-2030

Year	Fossil fuel TWh/year (%)	Nuclear energy TWh/year (%)	Renewable energy TWh / year (%)	Fossil fuels TWh / year change %	Nuclear energy TWh / year change %	Renewable energy TWh / year change %	Fossil fuel TWh/year (%)
2000	64.17	29.64	6.2				
2001	64.05	29.44	6.51	1.49	1	6.85	1.68
2002	64.03	28.32	7.64	-0.01	-3.77	17.36	0.01
2003	64.86	27.39	7.75	4.88	0.13	4.92	3.54
2004	63.13	27.38	9.5	-1.43	1.22	24.21	1.28
2005	63.08	26.58	10.34	0.45	-2.41	9.37	0.51
2006	61.93	26.56	11.51	0.79	2.59	14.37	2.67
2007	63.64	22.22	14.14	3.17	-15.99	23.27	0.4
2008	61.66	23.45	14.89	-2.97	5.66	5.48	0.14
2009	60.8	22.91	16.29	-8.29	-9.13	1.76	-6.99
2010	60.66	22.5	16.84	5.82	4.17	9.63	6.06
2011	61.66	17.84	20.5	-1.51	-23.19	17.93	-3.12
2012	60.91	16.03	23.06	1.27	-7.88	15.32	2.51
2013	60.45	15.41	24.14	0.96	-2.18	6.5	1.73
2014	58.11	15.67	26.22	-5.57	-0.16	6.7	-1.77
2015	56.2	14.33	29.47	-0.08	-5.5	16.15	3.33
2016	57.34	13.16	29.5	2.41	-7.8	0.47	0.37
2017	54.7	11.81	33.49	-4.15	-9.82	14.05	0.47
2018	52.89	12.01	35.1	-5.3	-0.42	2.66	-2.06
2019	47.39	12.52	40.09	-15.11	-1.22	8.22	-5.25
2020	44.32	11.35	44.33	-11.51	-14.24	4.64	-5.38
2021	35.6	5.07	59.33	-26.2	-58.97	22.96	-8.12
2022	38.19	3.57	58.24	15.66	-24.13	5.81	7.8
2023	38.62	1.36	60.02	3.05	-61.11	5.01	1.9
2024	32.95	3.42	63.63	-6.3	176.02	16.45	9.84
2025	28.31	5.46	66.23	-16.89	54.39	0.67	-3.27
2026	21.58	6.35	72.08	-29.78	7.1	0.27	-7.87
2027	17.19	5.53	77.28	-16.81	-9.06	11.97	4.42
2028	16.85	4.08	79.06	-3.13	-27.02	1.07	-1.2
2029	17.96	2.95	79.09	7.56	-27.19	0.98	0.94
2030	18.51	3.12	78.37	3.99	7.04	-0.02	0.91

Analysis of the data shows that the structural shift in favour of RES is stable and even accelerating in the post-2020 period; nuclear generation has been permanently discontinued, and fossil fuel capacities retain mainly balancing functions. The forecast for 2025-2030 indicates the dominance of solar and wind generation amid growing demand for flexible solutions – manoeuvrable stations, storage systems, and network modernisation, confirming the realism of achieving a target of around 80% of RES in 2030, provided that infrastructure investments are accelerated and mechanisms to ensure reliability during peak periods are introduced.

Analysis of the data obtained shows that the energy transition process in the three countries demonstrates certain common trends and specific differences. Ukraine is characterised by a stable share of nuclear energy and accelerated growth of renewable sources in the post-2020 period, which is due to a combination of thermal power plant decommissioning, large-scale development of RES, and targeted measures at the state policy level. France is highly dependent on nuclear generation, while RES are showing gradual but steady growth, in line with the projected development scenarios for 2030. Germany, in turn, is demonstrating rapid development of renewable energy sources, active reduction of fossil fuels, and complete cessation of nuclear power generation, confirming the effectiveness of the Energiewende policy and legislative incentives.

The summary shows that in order to achieve the set goals of increasing the share of RES and reducing greenhouse gas emissions, a comprehensive combination of technological development, government investment, and incentive mechanisms for energy market participants is necessary. At the same time, scenario forecasting that takes into account baseline and accelerated development scenarios allows for the assessment of potential risks related to energy security and the identification of optimal ways to integrate new technologies into national energy

systems. This approach ensures the reliability, sustainability, and scalability of energy transformations in the long term.

An analysis of energy data for Ukraine, France, and Germany has revealed key trends in the structure of their energy balance. The data showed that France demonstrates stable dominance of nuclear energy, while Germany is gradually reducing the share of fossil fuels and actively investing in renewable technologies. Ukraine, for its part, is characterised by high dependence on fossil resources, but at the same time retains significant potential for the development of wind and solar generation.

The methods of preliminary data processing used, including interpolation of gaps, scaling, and optimal selection of lag according to the AIC criterion, ensured the reliability of the forecast calculations. Setting restrictions for variables made it possible to avoid extreme values that could lead to false conclusions.

The results obtained indicate the need for further diversification of energy sources for all three countries, with a particular focus on increasing the share of renewable energy. The study confirms that the effective use of statistical methods and machine learning tools can significantly improve the quality of strategic planning in the energy sector.

Discussion

The results of the study confirmed the hypothesis: the use of a VAR model with scenario adjustments allows for reliable forecasting of long-term trends in the transformation of the electricity generation structure. This model revealed differences in national trajectories: the stable dominance of nuclear energy in France, the consistent phase-out of nuclear generation, and the rapid growth of renewable sources in Germany, as well as accelerated structural changes in Ukraine caused by war damage and changes in the balance of power.

Despite confirming the hypothesis, the results have a number of limitations.

1. Time limits of the data. The model is based on statistics for 2000-2020, whereas the most dramatic changes in the Ukrainian energy sector occurred between 2021 and 2023 and are only partially accounted for due to scenario adjustments.
2. Lack of spatial dimension. The study does not include regional differences in generation development and uneven levels of infrastructure damage, which are critical for Ukraine.
3. Failure to take extreme events into account. Short-term shocks – targeted attacks on energy facilities, sharp fluctuations in import and export flows, or the emergency introduction of backup technologies – were not taken into account in the model.

Despite these limitations, the results are important for strategic energy planning. For Ukraine, the study highlights the need to integrate climate goals with energy security and system stability objectives in the context of military threats. For France and Germany, the forecasts confirm the advisability of investing in renewable energy and developing balancing mechanisms. Overall, the VAR model with scenario adjustments has proven its usefulness as a tool for developing adaptive energy policy and assessing potential development scenarios in the context of external shocks.

Conclusion

The study confirmed that the use of VAR modelling with scenario adjustments is an effective tool for forecasting the transformation of the electricity generation structure in different countries and assessing its impact on the mineral resource base. Preliminary data processing, including the restoration of missing values, standardisation of variables, and verification of the stationarity of time series, ensured the reliability of the results and made it possible to identify patterns in the energy transition. The use of a scenario approach made it possible to take into account technological, economic, and political factors, as well as to assess the risks and opportunities for the mining industry in the context of the transition to renewable energy.

The results of the analysis showed significant differences in the development trajectories of energy systems and their impact on the use of natural resources. Ukraine is demonstrating the growing role of renewable sources while maintaining the share of nuclear energy, which is leading to a gradual reduction in demand for coal and natural gas. France remains highly dependent on nuclear generation, which supports a stable demand for uranium resources while increasing the need for materials for renewable technologies. In Germany, the abandonment of coal and nuclear power generation is accompanied by the closure of mines and an increase in demand for minerals that are critical for the development of renewable energy.

A summary of the results shows that the transformation of the energy sector directly affects the dynamics of demand for various types of raw materials, determines the need for restructuring mining enterprises, and shapes new directions for the development of mineral resource policy. The scenario approach to forecasting enables the assessment of both long-term trends in traditional resource extraction and the prospects for growth in extracting critical elements necessary for green energy.

Further research is expected to focus on extending the time series with data after 2020, which will allow for a more accurate assessment of the impact of military events on Ukraine's energy and mining sectors. Promising areas include taking into account the spatial aspects of energy system transformation, integrating machine learning methods to improve forecast accuracy, and analyzing scenarios for the development of flexible technologies such as energy storage systems, maneuvering stations, and decentralized generation. Special attention will be paid to assessing new needs for the extraction of rare earth and strategic minerals necessary to ensure the sustainable transformation of the energy sector and the formation of a balanced mineral resource policy.

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