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A Scenario-Based Model of Energy Transition in Central and Eastern Europe: Implications for Energy Security and Decarbonization

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Abstract

This study examines energy transition pathways in Central and Eastern Europe by integrating decarbonization goals with energy security requirements. The transition is shaped by two major challenges: reducing greenhouse gas emissions and ensuring stable energy supply under geopolitical uncertainty. Transition strategies include the expansion of renewable energy sources, electrification, diversification of supply, and the development of system flexibility. Using a scenario-based modeling framework aligned with international energy outlooks, this study analyzes the implications of different transition pathways for 11 countries in Central and Eastern Europe. The results indicate that a high ambition scenario could increase the share of renewable energy sources to 60–80% of the energy mix by 2050, while maintaining 10–20% nuclear capacity to support system stability. At the same time, electricity demand could increase by approximately 120% due to transport and industrial electrification, despite decreasing total primary energy consumption. The study identifies three transition models—renewable-dominated, hybrid, and nuclear-oriented—and concludes that effective transition strategies in Central and Eastern Europe require differentiated policy approaches that account for infrastructure constraints, energy security, and regional heterogeneity.

Keywords: energy transition; challenges; Central and Eastern Europe; energy security; energy systems; strategies; scenario analysis

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1. Introduction

In 2015, in Paris, nearly 200 countries—which are responsible for the majority of global greenhouse gas emissions—committed to making every effort to keep the global temperature rise this century well below 2 °C and pursue efforts to limit the temperature increase to 1.5 °C [1]. The Paris Agreement is a milestone in raising awareness that climate change is one of the greatest threats to humanity [2]. Globally, decarbonization is progressing at varying rates. However, the European Union has been a leader in climate action for years [3]. The European Union has managed to maintain the growth of the gross domestic product (GDP) while reducing emissions, create the largest emissions trading system in the world, and implement innovative solutions such as offshore wind energy and electromobility [4,5]. Until February 2022, security and reliability, which are part of the energy trilemma, received less attention in the European Union than reduction of CO_2 emissions and energy costs [6]. The war in Ukraine has brought energy security into the spotlight. In the countries of Central and Eastern Europe (CEE), the process of

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implementing decarbonization technologies has progressed more slowly, partly due to the limited capacity to bear the higher costs of the transition [7]. Currently, a change is underway as the costs of renewable technologies decline; in many cases, renewable energy sources (RESs) are already cheaper than conventional energy sources [8,9]. At the same time, the total cost of ownership for electric vehicles is approaching that of internal combustion engine vehicles [10,11]. The increasing prosperity of transition economies further supports investments in energy transition [12]. Despite a slower pace of decarbonization, CEE has excelled in terms of diversifying energy supplies and reducing imports of raw materials from Russia [13]. The invasion of Ukraine in 2022 underscored the importance of investing in the resilience of the energy system [14]. Due to previous infrastructure investments, countries such as Poland, Lithuania, and Croatia were prepared for alternative supplies of raw materials [15]. The war in Ukraine has disrupted the energy market in Europe, forcing a shift in priorities towards energy security [16]. Its current state is the result of investment decisions made over decades [17]. Effective management of the energy transition is crucial for energy security and increased innovation in CEE [18,19]. In the long term, energy security is not in conflict with the energy transition but is an integral part of it [16]. The move away from fossil fuel imports improves national security [17]. The transformation process must be analyzed holistically, taking into account both sustainable development and energy security [20]. According to analyses of CEE, the energy system is undergoing a profound structural transformation. The share of renewable energy sources could increase significantly by 2050, accompanied by a decline in the importance of fossil fuels and an increase in the role of nuclear energy [21].

This study develops a scenario-based conceptual framework to analyze the energy transition in CEE, integrating the dimensions of energy security and decarbonization. Based on the above considerations, the study addresses the following research problem. The main research problem addressed in this study is to determine how the energy transition in CEE can be structured in a way that simultaneously achieves deep decarbonization and ensures energy security. In particular, this study seeks to answer the following research question. How do different energy transition pathways (based on current policies and higher climate ambitions) affect the structure, stability, and security of energy systems in CEE?

To operationalize this objective, the following research hypotheses are formulated.

H1. *The energy transition in CEE follows a hybrid model that combines the expansion of renewable energy with stabilization mechanisms, including nuclear energy and transitional fuels.*

H2. *Increasing electrification leads to a divergence between total energy consumption and electricity demand, resulting in a decline in overall energy use and a significant increase in electricity demand.*

H3. *Reduced dependence on fossil fuels contributes to improved energy security in the CEE through reduced import dependence and increased resilience of the system.*

H4. *Higher climate ambition scenarios, represented by the Announced Pledges Scenario (APS), accelerate structural changes in the energy system compared to current policy scenarios of the Stated Policies Scenario (STEPS), leading to faster decarbonization and greater system transformation.*

This study contributes to the literature in three main ways. First, it develops a regionally disaggregated modeling framework for CEE, addressing a gap in existing studies that predominantly analyze the European Union as a homogeneous system. Second, it integrates policy scenarios, National Energy and Climate Plans (NECP), global energy pathways, the International Energy Agency (IEA), and macroeconomic drivers into a unified analytical structure, allowing for a multidimensional assessment of the dynamics of energy transition.

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Third, it provides a comparative scenario analysis that highlights structural differences between countries, offering insights into the feasibility and limitations of achieving EU climate targets at the regional level.

2. Literature Review

2.1. State of the Research

Efforts related to the energy transition focus largely on the energy sector, as it accounts for one of the largest shares of global greenhouse gas emissions [22]. In light of current changes, it is clear that conventional fossil fuel-based energy sources will not be environmentally or economically viable in the future [9,23]. With the total energy supply, a decline in coal use is observed, which has historically dominated the energy mixes of many countries, including Poland and the Czech Republic [24]. The planned dates for the phasing out of coal in Europe fall within a wide time frame that varies by country [25]. The widespread adoption of more efficient technologies helps reduce total energy supply and consumption [26]. This is due to the higher efficiency of renewable energy sources and electrical appliances [27]. The analyses indicate that electrification is a key direction for the transformation of many sectors [14,28]. It will be enabled by the development of renewable energy sources, and, in the European Union, additional impetus comes from emission costs under the European Union Emissions Trading System (EU ETS) and commitments under the Paris Agreement [1,25]. A significant increase in renewable energy capacity will be particularly evident in CEE, where there is still substantial untapped potential [21]. Wind and solar power plants provide cheap and low-emission energy, but their output is variable and depends on weather conditions [29,30]. Therefore, the energy system requires flexible sources. Currently, this role is often fulfilled by natural gas, which allows for rapid adjustment of energy production [31,32]. At the same time, as a fossil fuel, it generates CO_2 emissions, which means that it must gradually be replaced or supplemented with CO_2 capture technologies [33,34]. Nuclear power is an alternative to stable, low-emission energy supplies [35,36]. Due to high investment costs and low operating costs, nuclear power plants typically operate as the base load of the system [35,37]. Short-term stabilization of the system can be provided by energy storage, particularly batteries, which allow energy to evolve over time [38]. Long-term storage remains a greater challenge, where solutions such as pumped hydro storage are used [39]. New solutions include biomethane and green hydrogen, which can be stored and used in the energy sector [8,40]. At the same time, the advancement of digitalization enables the use of demand-side response (DSR) mechanisms, covering both industry and households [41]. More than half of the countries in CEE plan to develop nuclear energy, including large power units and small modular reactors (SMRs) [35]. SMRs are being considered not only in the power sector but also in industry and district heating, which is a distinctive feature of the region [35,42].

2.2. Theoretical Framework

Despite extensive research on energy transition, relatively little attention has been paid to integrated models combining energy security and decarbonization in the CEE context. Two key forces driving change in the energy sector are at work in CEE: the green transition and the transition toward energy security [43]. The green transition focuses on decarbonization and combating climate change, while the second dimension concerns supply diversification and the resilience of the energy system [14]. Each of these dimensions presents different challenges and opportunities that shape the future energy landscape [20]. The green transition is a response to the urgent need to reduce greenhouse gas emissions [34]. In the energy sector, this means a fundamental shift from fossil fuels to renewable energy sources and other low-emission technologies [16]. Fossil fuel-based technologies will be phased out or supported by solutions such as carbon capture and storage [34]. Investments in wind, solar, and hydroelectric power are of key importance [9]. In the transportation sector, the transition is reflected in the growing role of electric vehicles, both battery-powered and fuel-cell-based [14]. In segments that are difficult to electrify, such as aviation, biofuels and synthetic fuels are gaining importance [16]. In industry, the transition involves electrification of processes, increased recycling rates, and the use of materials with a lower environmental footprint. These measures lead to reduced emissions and increased resource efficiency in the economy [27].

Recent studies also emphasize that the dynamics of energy transitions are increasingly influenced by behavioral responses and demand-side effects, which can alter system-level outcomes and introduce additional uncertainty [43].

Energy security has long been a significant challenge for CEE due to its geopolitical conditions [43]. The importance of this issue rose sharply after the invasion of Ukraine in 2022, leading to unprecedented changes in Europe's energy policy [16]. The war in Ukraine has significantly increased the importance of energy security, forcing a reassessment of supply routes and strategic relationships [44]. These changes have included, among other things, the diversification of energy resource imports and the development of new supply routes [45,46]. The shift toward security also involves the development of regional cooperation and energy infrastructure. The interconnections and transmission infrastructure for gas, electricity, and crude oil are of particular importance [31]. Expanding this infrastructure increases the resilience of energy systems and reduces the risk of supply disruptions [47]. Another key element of energy security is the storage of raw materials and energy, which allows for increased system flexibility and resilience to external shocks [14]. Effective transition management requires an integrated approach that combines climate and energy security objectives [48]. How the CEE responds to these challenges will be crucial not only for its energy future but also for its geopolitical position [18].

Recent research highlights that energy transition pathways are increasingly shaped by systemic uncertainty, external shocks, and the need for robust and adaptive policy design [49]. In particular, the interaction between decarbonization and energy security has become a central analytical dimension, especially in regions exposed to geopolitical risks. At the same time, electrification and sector coupling are identified as key structural mechanisms that allow deep decarbonization across energy systems, linking electricity, transport, and industry [50]. Emerging modeling approaches also emphasize the importance of integrating climate dynamics into energy system analysis, highlighting the sensitivity of transition pathways to external environmental and economic conditions [51].

In the context of CEE, recent studies underscore the importance of region-specific policy frameworks and structural constraints, including legacy infrastructure, the composition of the energy mix, and institutional capacity [52,53]. These factors significantly influence the feasibility and pace of transition strategies and reinforce the need for differentiated and context-sensitive approaches to the design of energy policy [54].

Existing energy transition assessment frameworks, including the Energy Transition Index and multidimensional transition indicators, typically incorporate additional dimensions such as institutional readiness, affordability, innovation capability and environmental performance. While these broader frameworks provide comprehensive assessments, the present study intentionally focuses on the interaction between decarbonization, electrification, and energy security. These dimensions were selected because they represent the most critical challenges currently shaping transition pathways in CEE.

Based on the identified research gaps, four hypotheses were formulated. First, previous studies have highlighted the growing role of renewable energy, but have not reached a consensus on whether renewable-dominated systems can ensure long-term stability without complementary technologies. Therefore, H1 examines whether energy transition in CEE follows a hybrid model combining RES expansion with stabilizing technologies. Second, while electrification is widely recognized as a key transition mechanism, its implications for the relationship between total energy consumption and electricity demand remain insufficiently explored in the regional context, motivating H2. Third, the existing literature suggests a potential link between decarbonization and energy security, but empirical evidence for CEE remains fragmented; thus, H3 investigates whether reduced fossil fuel dependence contributes to improved energy security. Finally, H4 evaluates whether higher policy ambition accelerates structural transformation compared with current policy trajectories.

3. Research Methodology

This study develops an integrated analytical framework to assess energy transition pathways in CEE, combining multiple data sources and scenario-based modeling approaches. Although the model builds upon established international scenario frameworks, including those proposed by the IEA [16] and publicly available regional analyses [55], it introduces an original structure for country-level disaggregation and cross-scenario comparison.

The novelty of the approach lies in the integration of three analytical layers: (i) historical statistical reconstruction based on Eurostat data [4], (ii) policy-driven projections derived from NECPs [56], and (iii) scenario harmonization based on global pathways (STEPS and APS). Unlike existing studies, which typically analyze the European Union as a single system, this model explicitly disaggregates projections to the level of CEE.

The model applies a bottom-up allocation mechanism in which EU-level trajectories are adjusted using country-specific parameters, such as initial energy mix, sectoral structure, and policy commitments. This enables a more accurate representation of regional heterogeneity and transition dynamics. The model incorporates macroeconomic drivers, including GDP growth and demographic trends, to capture the interaction between economic development and energy demand. This integrated approach allows a more realistic simulation of long-term transformation pathways compared to models purely based on policies or technologies [9,14,49]. The empirical analysis covers 11 CEE countries: Poland, Czechia, Slovakia, Hungary, Romania, Bulgaria, Slovenia, Croatia, Lithuania, Latvia, and Estonia.

3.1. Research Design

This study adopts a hybrid qualitative–quantitative approach, combining conceptual modeling with scenario analysis. The objective is to develop a structured model of the energy transition in CEE that integrates both the decarbonization and the energy security dimensions.

The model is conceptual in nature and does not rely on econometric estimation. Instead, it is based on a systematic synthesis of existing research, policy frameworks, and scenario projections.

3.2. Data Sources

The analysis is based on three main categories of data:

1. Historical data—energy statistics from Eurostat covering the period 2010–2021;
2. Policy documents—National Energy and Climate Plans (NECPs) adopted by EU member states in 2019 [56];
3. Scenario data—projections from the International Energy Agency, including:

- Stated Policies Scenario (STEPS);
- Announced Pledge Scenario (APS).

These sources provide a consistent empirical and policy framework for analyzing both current conditions and future transition pathways.

3.3. Scenario Framework

The model applies a scenario-based approach aligned with the methodology of the International Energy Agency.

- The STEPS scenario reflects current policy frameworks and officially announced measures, providing a baseline trajectory for the energy system.
- The APS scenario assumes full implementation of declared climate commitments, including long-term net zero targets.

To enhance analytical clarity, these scenarios are mapped onto two model variants.

- Scenario "Current Plans"—consistent with existing national policies and regulatory frameworks;
- "High Ambition" scenario, assuming full achievement of the objectives of EU climate neutrality by 2050.

Modeling assumptions are consistent with recent European transition perspectives, which highlight the scale and structural complexity of decarbonization pathways across member states of the European Union [57].

Scenario values presented in the Results section were derived through proportional allocation of IEA STEPS and APS trajectories to CEE countries using historical Eurostat energy balances, NECP targets, and country-specific energy mix structures. The resulting values should be interpreted as indicative scenario-based estimates rather than precise forecasts.

3.4. Model Structure

The proposed model integrates three key dimensions of the energy transition:

1. Energy supply transformation
    - share of renewable energy sources (RES);
    - fossil fuel dependence;
    - role of nuclear energy and transitional fuels.
2. Demand-side transformation
    - electricity demand growth;
    - electrification rate across sectors (transport, industry, buildings).
3. Energy security dimension
    - import dependency;
    - diversification of supply sources;
    - energy storage capacity;
    - development of interconnections and infrastructure.

This structure reflects the multidimensional nature of energy transition processes in CEE (Figure 1).

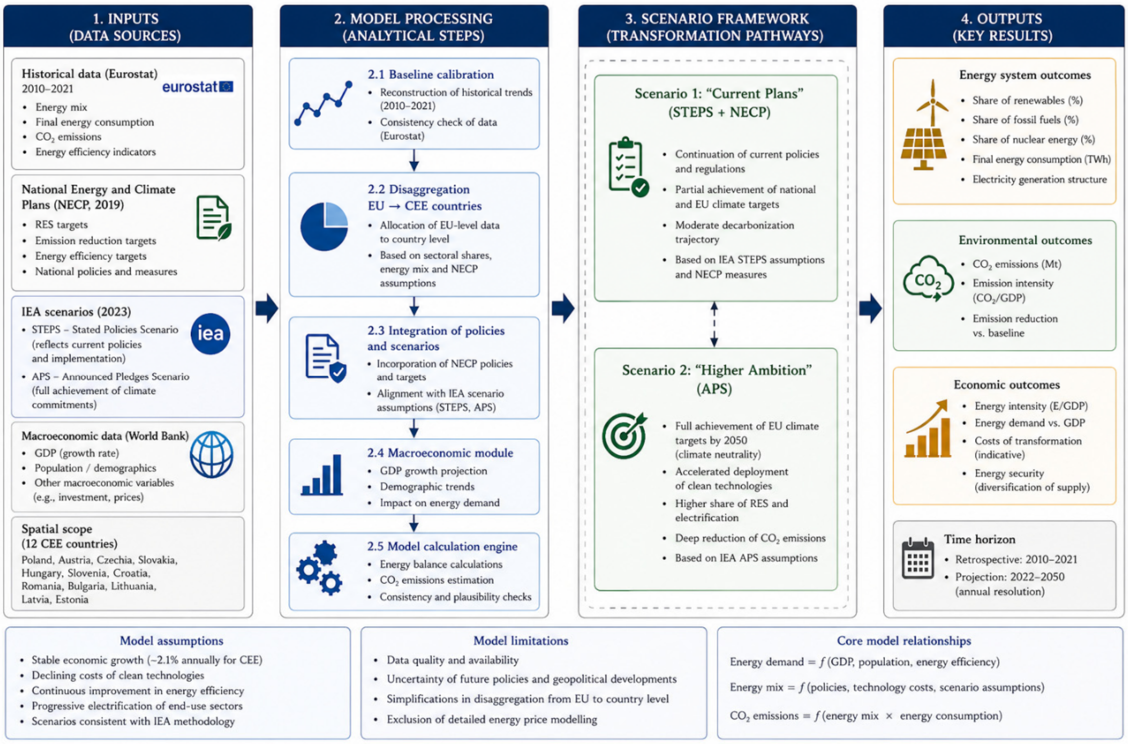

Figure 1. Conceptual model of the energy transition in CEE integrating the transformation, electrification, and energy security dimensions.

Figure 1 was developed with the assistance of ChatGPT (OpenAI) to support the visualization of the conceptual framework proposed in this study. The author designed the conceptual model, defined its analytical structure, specified all model components, relationships, and methodological assumptions, and prepared the prompts used for figure generation. ChatGPT was used exclusively to generate the initial graphical representation of the author's original concept. The resulting figure was critically reviewed, verified, and manually refined by the author to ensure consistency with the study methodology, scientific accuracy, and the final content of the manuscript.

The selection of variables was guided by three criteria: (1) relevance in the energy transition literature, (2) consistency with IEA and NECP analytical frameworks, and (3) their direct influence on decarbonization and energy security outcomes. Together, these variables capture both supply-side and demand-side transformation processes as well as system resilience characteristics. The operational indicators corresponding to each conceptual dimension of the proposed model are summarized in Table 1.

Table 1. The operational indicators used for each conceptual dimension.

Concept	Indicator
Decarbonization	Share of RES (%), reduction of fossil fuels (%)
Electrification	Growth of electricity demand (%), electrification rate (%)
Energy security	Import dependency (%), diversification index, storage capacity
System stability	Nuclear share (%), storage capacity, interconnection level
Transition speed	Rate of change between STEPS and APS scenarios

These indicators were used as analytical proxies for evaluating the research hypotheses and comparing alternative transition pathways. To ensure consistency between the conceptual framework and the empirical assessment, the relationships between the research hypotheses, analytical indicators, and expected outcomes are summarized in Table 2.

Table 2. Mapping of hypotheses, indicators, and expected outcomes.

Hypothesis	Indicator	Expected Direction
H1	RES share, nuclear share	Hybrid structure
H2	Electricity demand growth	Positive
H3	Import dependency	Negative
H4	APS vs. STEPS gap	Positive

3.5. Analytical Approach

The analysis combines the following.

- Comparative scenario analysis (STEPS vs. APS);
- Trend extrapolation based on historical data;
- Interpretation based on the literature on structural changes.

Additionally, the study applies regional disaggregation, translating EU-level projections into country-level implications for CEE through integration of Eurostat data and NECP assumptions.

3.6. Macroeconomic and Demographic Assumptions

The model incorporates key exogenous variables influencing energy demand:

- economic growth (GDP dynamics);
- demographic trends;
- structural changes in energy consumption patterns.

These variables are included to ensure a more realistic representation of future energy demand trajectories, consistent with standard practices in energy system modeling.

3.7. Model Limitations

The model is subject to several limitations:

- It is based on scenario assumptions that may not fully materialize.
- It does not explicitly include cost optimization or price dynamics.
- It relies on aggregated regional data, which may obscure country-level heterogeneity.

4. Results

Results should not be interpreted solely as a projection of predefined policy scenarios but rather as an outcome of an integrated modeling framework that combines structural, policy, and macroeconomic drivers. In contrast to existing scenario-based reports, the presented results highlight differentiated transition trajectories across the CEE, reflecting structural heterogeneity, varying policy ambition, and distinct starting conditions of national energy systems. The results are presented in relation to the research hypotheses formulated in the Introduction, allowing for a structured assessment of energy transition pathways in CEE. An overview of the hypothesis testing results is presented in Table 3.

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Table 3. Summary of hypothesis testing.

Hypothesis	Indicator	Main Result	Status
H1	RES share, nuclear share	Hybrid transition structure observed	Supported
H2	Electricity demand growth	+56% STEPS, +120% APS	Supported
H3	Import dependency	Declining fossil fuel dependence improves security	Supported
H4	Difference between APS and STEPS	Faster transformation under APS	Supported

4.1. Hybrid Structure of Energy Transition (H1)

The results confirm that the energy transition in the CEE follows a hybrid model that combines the expansion of renewable energy with system stabilization mechanisms.

As shown in Table 4 and Figure 2, the share of renewable energy sources (RESs) increases significantly, reaching 45% in the "Current Plans" scenario and up to 60–80% in the "High Ambition" scenario by 2050. At the same time, nuclear energy maintains or moderately increases its role, while natural gas remains an important transition fuel that supports the flexibility of the system.

Table 4. Energy production projections in CEE.

Category	Current State	2030 (STEPS)	2050 (STEPS)	2050 (APS)
Renewables (RESs)	~15%	≈30–40%	≈45%	≈60–80%
Nuclear Energy	~7%	≈7–10%	≈7–12%	≈10–20%
Natural Gas	~20–25%	≈20–25%	≈10–15%	≈3–10%
Coal & Oil	~74%	≈50–60%	≈20–35%	≈0–10%

Note: STEPS—Stated Policies Scenario; APS—Announced Pledges Scenario. Electrification is a key trend in all scenarios, with an increasing dependence on renewable energy and complementary nuclear generation in selected countries of CEE.

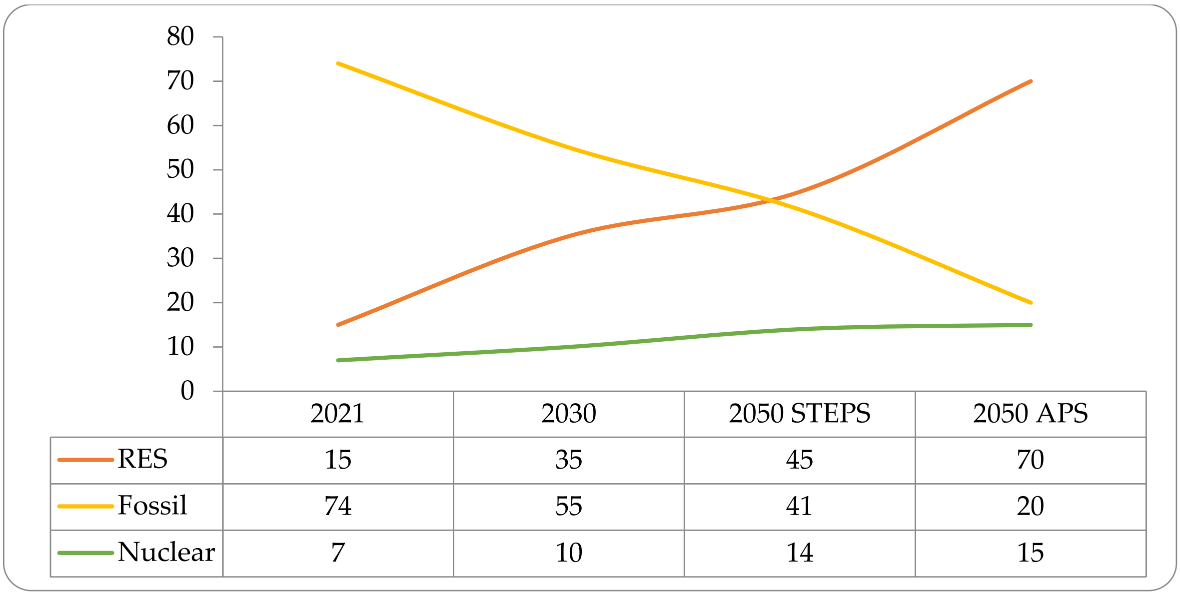

Figure 2. Energy mix transformation in CEE under STEPS and APS scenarios.

This configuration indicates that renewable energy alone is insufficient to ensure system stability, and, therefore, complementary technologies, such as nuclear energy and flexible gas-based generation, remain essential. H1 is confirmed.

4.2. Electrification and Demand Divergence (H2)

The results provide strong evidence supporting the hypothesis that electrification leads to a divergence between total energy consumption and electricity demand.

Total energy consumption decreases by approximately 23–35% by 2050 due to improvements in energy efficiency and structural changes in energy use (Table 1). In contrast, electricity demand increases substantially, by approximately 56% in the "Current Plans" scenario and up to 120% in the "High Ambition" scenario (Figure 3).

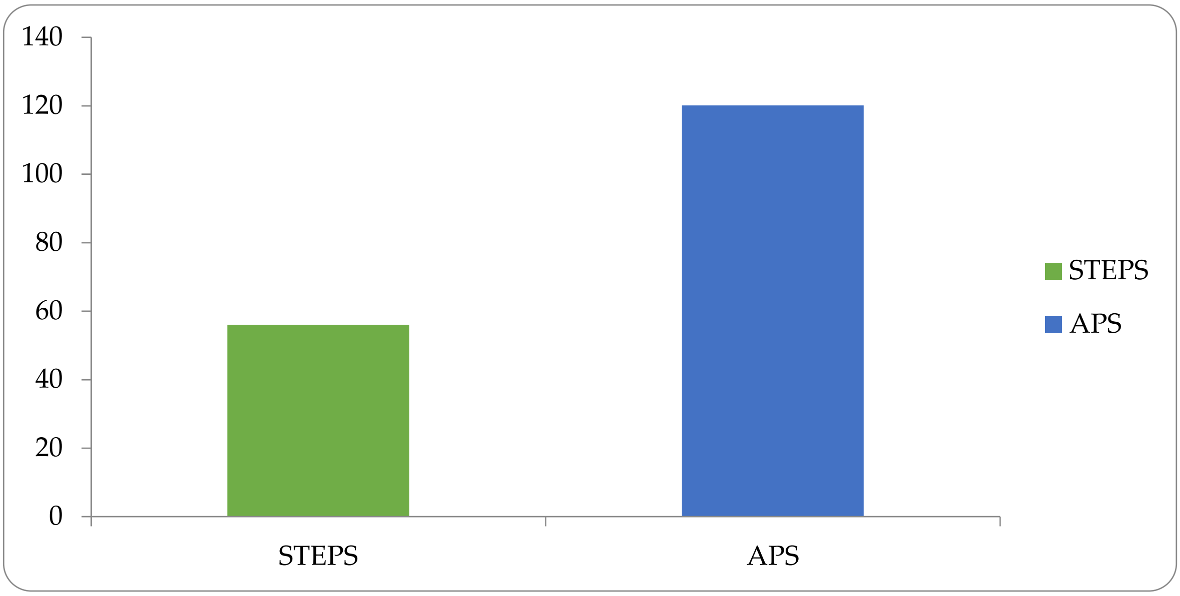

Figure 3. Growth of electricity demand in CEE under different scenarios.

This divergence reflects the increasing role of electricity as the dominant energy carrier, particularly in transport, industry, and buildings. H2 is confirmed.

4.3. Fossil Fuel Reduction and Energy Security (H3)

The results support the hypothesis that reducing fossil fuel dependence improves energy security in CEE.

As indicated in Table 1, the share of fossil fuels declines significantly across all scenarios, leading to a reduced dependence on imported hydrocarbons. This structural change contributes to improved energy independence and resilience of the system.

At the same time, diversification of energy sources and expansion of infrastructure further strengthen system robustness. However, the increasing share of variable renewable energy introduces new challenges related to system stability, as illustrated in Figure 2. H3 is confirmed.

4.4. Impact of Scenario Ambition Levels (H4)

The comparison between STEPS and APS scenarios confirms that a higher climate ambition accelerates the structural transformation of the energy system. Under the APS scenario, the increase in RES share is significantly higher, fossil fuel phaseout is faster, and electrification progresses more rapidly compared to the STEPS scenario (Table 1; Figure 3). These differences demonstrate that the ambition of policy is a key determinant of the speed of transition and system transformation. H4 is confirmed.

4.5. Differentiated Transition Pathways

In addition to hypothesis testing, the analysis reveals heterogeneity between CEE, resulting in three distinct transition pathways (Table 5):

- RES-dominated systems;
- hybrid systems (RES + nuclear);
- nuclear-oriented systems.

Table 5. Energy transition models in CEE.

Model	Description	Countries
RES-dominated	High share of renewables	Lithuania, Latvia, Estonia, Croatia
Hybrid	RESs + nuclear	Poland, Romania, Slovenia
Nuclear-oriented	Strong nuclear reliance	Czechia, Slovakia, Hungary, Bulgaria

These pathways reflect differences in resource availability, policy priorities, and existing energy system structures. As shown in Table 5, three different energy transition models can be identified in CEE.

Countries were classified according to their projected 2050 energy mix. Renewable-dominated systems were defined as those where RESs accounted for more than 65% of electricity generation and nuclear energy remained below 10%. Hybrid systems were characterized by RES shares between 40% and 65%, combined with nuclear generation between 10% and 30%. Nuclear-oriented systems were defined as those where nuclear energy exceeded 30% of generation capacity or represented the primary low-carbon stabilization technology.

The allocation of individual CEE countries to the identified transition models, together with their principal characteristics, is presented in Table 6.

Table 6. Country-specific energy transition pathways in Central and Eastern Europe.

Country	Transition Model	Key Characteristic
Poland	Hybrid	RESs + nuclear expansion
Czechia	Nuclear-oriented	Strong nuclear development
Slovakia	Nuclear-oriented	Existing nuclear base
Hungary	Nuclear-oriented	Nuclear-led decarbonization
Romania	Hybrid	Balanced RESs and nuclear
Bulgaria	Nuclear-oriented	Nuclear modernization
Croatia	RES-dominated	High RES potential
Lithuania	RES-dominated	Wind and interconnections
Latvia	RES-dominated	Hydro-based system
Estonia	RES-dominated	RESs replacing oil shale
Slovenia	Hybrid	Mixed pathway

The projected country-level energy transition pathways, expressed through indicative ranges of renewable energy and nuclear shares in 2050, are presented in Table 7.

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Table 7. Country-level scenario results for energy transition pathways.

Country	RES Share 2050	Nuclear Share 2050	Transition Model
Poland	50–60%	20–30%	Hybrid
Czechia	35–45%	40–50%	Nuclear-oriented
Slovakia	30–40%	45–55%	Nuclear-oriented
Hungary	30–40%	45–55%	Nuclear-oriented
Romania	45–55%	20–30%	Hybrid
Bulgaria	35–45%	35–45%	Nuclear-oriented
Croatia	70–80%	0–5%	RES-dominated
Lithuania	75–85%	0–5%	RES-dominated
Latvia	70–80%	0–5%	RES-dominated
Estonia	65–75%	0–5%	RES-dominated
Slovenia	45–55%	15–25%	Hybrid

Note: Values represent indicative scenario ranges derived from STEPS and APS assumptions combined with national energy policy priorities.

The analysis indicates that despite the convergence toward decarbonization targets, CEE is likely to follow structurally diverse transition pathways. This divergence is mainly driven by differences in legacy energy systems, the availability of domestic resources, and the institutional capacity to implement energy policies. Compared to Western European countries, the transition in CEE is more constrained by infrastructure lock-in and capital intensity, which may slow the pace of decarbonization despite increasing policy ambition.

These findings suggest that a uniform policy approach at the EU level may not fully capture the specific needs of CEE, highlighting the importance of differentiated policy instruments and region-specific transition strategies [7,58].

5. Discussion

Unlike industry reports, which typically present scenario outcomes without methodological transparency, this study provides a replicable and analytically structured modeling framework, allowing further academic validation and extension. The results provide strong support for all four research hypotheses and provide important information on the structure and dynamics of the energy transition in CEE. The results are consistent with recent scenario-based analyses of European energy systems, confirming the robustness of the proposed modeling approach.

First, the confirmation of H1 highlights that the energy transition in CEE follows a hybrid configuration, rather than a purely renewable-based pathway. This finding is consistent with previous studies emphasizing the need for system stability mechanisms in high-renewable-energy systems. The continued role of nuclear energy and transition fuels reflects structural constraints and the need to balance decarbonization with reliability.

Second, the confirmation of H2 demonstrates a fundamental structural shift in energy systems, where electrification leads to a divergence between total energy consumption and electricity demand. This finding aligns with the existing literature on sector coupling and confirms that electricity becomes the dominant energy carrier in advanced transition scenarios.

Third, the results supporting H3 indicate that decarbonization contributes positively to energy security, particularly through reduced import dependency and increased diversification of energy sources. This finding is particularly relevant in the context of recent geopolitical disruptions, which have highlighted the vulnerability of fossil fuel-dependent systems.

The analysis indicates the existence of both synergies and trade-offs between decarbonization and energy security. Reduced fossil fuel dependence decreases import vulnerability and strengthens energy autonomy. However, higher shares of variable renewable generation increase requirements for storage, backup capacity, and grid flexibility. Therefore, successful transition strategies depend on balancing climate objectives with system resilience investments. The interaction between decarbonization and energy security under the analyzed transition scenarios is summarized in Table 8.

Table 8. Interaction between decarbonization and energy security.

Dimension	Current State	STEPS 2050	APS 2050
Fossil fuel dependence	High	Moderate	Low
Import dependency	High	Moderate	Low
RES share	Low	Medium	High
Storage requirement	Low	Medium	High
Grid flexibility requirement	Low	Medium	High

The results indicate that decarbonization and energy security are generally complementary objectives; however, increasing renewable penetration requires additional investments in storage and system flexibility.

Fourth, the confirmation of H4 underscores the importance of policy ambition as a key driver of energy system transformation. Comparison between scenarios shows that higher climate ambition significantly accelerates structural change, suggesting that policy design plays a critical role in shaping transition pathways.

At the same time, the results reveal that the energy transition is not uniform across the region. The emergence of different transition pathways reflects national conditions, including resource availability, infrastructure, and policy frameworks. This heterogeneity suggests that a one-size-fits-all approach to energy transition is unlikely to be effective in the CEE context.

In general, the findings emphasize that the energy transition must be understood as a multidimensional and path-dependent process that requires integrated approaches that simultaneously address decarbonization, electrification, and energy security.

These findings are consistent with previous studies on the energy transition in CEE, which emphasize the role of structural constraints and policy heterogeneity. These results confirm the validity of the proposed model and its applicability to analyzing energy transitions in CEE.

The findings are broadly consistent with multidimensional energy transition frameworks, which emphasize that successful transitions depend not only on technological change but also on system resilience and policy coherence. Recent studies have also developed composite indicators and analytical frameworks for assessing the progress of energy transitions and the phase-out of fossil fuels, highlighting the multidimensional character of transition processes [59,60].

Furthermore, evidence from emerging economies suggests that energy transition pathways are closely associated with environmental performance and require complementary technological innovation to achieve long-term sustainability outcomes [61]. This supports the recent literature emphasizing the growing integration of climate and security objectives within energy policy design.

6. Theoretical and Policy Contributions

This study contributes to the literature on the energy transition in several ways.

First, it proposes an integrated conceptual model that combines three key dimensions of energy transition: decarbonization, electrification, and energy security. Although previous studies have often analyzed these dimensions separately, this study demonstrates their interdependence in the context of CEE.

Second, the study applies a scenario-based framework to link the goal of policy with structural changes in the energy system. By comparing STEPS and APS scenarios, it provides a structured approach to analyzing how different policy pathways influence transition outcomes.

Third, the study contributes to the growing body of research on the heterogeneity of energy transitions by identifying distinct transition models within CEE. This highlights the importance of the national context and supports the argument that energy transition pathways are not uniform across countries.

From a policy perspective, the results suggest that effective energy transition strategies should:

- Balance renewable energy expansion with system stability mechanisms;
- support electrification across sectors;
- reduce dependency on fossil fuel imports;
- and invest in infrastructure that allows for system flexibility.

These findings are particularly relevant for policymakers in CEE, where the energy transition must address both climate goals and energy security concerns. The study also contributes methodologically by demonstrating how scenario-based conceptual modeling can be applied to regional energy systems.

7. Conclusions

This study examined energy transition pathways in CEE using a scenario-based conceptual model that integrates decarbonization, electrification, and energy security.

The results indicate that the transition in CEE follows a hybrid model that combines renewable energy expansion with system stabilization mechanisms, including nuclear energy and transitional fuels. At the same time, increasing electrification leads to a divergence between declining total energy consumption and rapidly growing electricity demand. The findings also show that reducing fossil fuel dependence contributes to improved energy security, while greater policy ambition significantly accelerates the structural transformation of the energy system.

These results highlight the importance of integrated transition strategies that balance climate objectives with system reliability and security considerations.

This study is subject to several limitations, including reliance on scenario assumptions and the use of aggregated regional data. Future research should focus on country-level analyses and the incorporation of economic and technological uncertainties.

In general, this study contributes to a better understanding of the multidimensional nature of the energy transition in the CEE and its implications for policy and system design. The results further demonstrate that transition pathways differ substantially between CEE countries, confirming the importance of region-specific and country-specific energy strategies.

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Abbreviations

The following abbreviations are used in this manuscript:

APS	Announced Pledges Scenario
CCS	Carbon Capture and Storage
CEE	Central and Eastern Europe
CO_2	Carbon Dioxide
DSR	Demand-Side Response
EU	European Union
EU ETS	European Union Emissions Trading System
GDP	Gross Domestic Product
GHGs	Greenhouse Gas Emissions
GW	Gigawatts
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
LNG	Liquefied Natural Gas
NECPs	National Energy and Climate Plans
RESs	Renewable Energy Sources
SMR	Small Modular Reactor
STEPS	Stated Policies Scenario
TWh	Terawatt-hours
UNFCCC	United Nations Framework Convention on Climate Change

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