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ENERGY INFRASTRUCTURE ECONOMICS: MIND MAP FOR NATIONAL, REGIONAL AND WORLDWIDE SCALES

Oleksii Havrylenko
PhD in Technical Sciences, Director, Energy Machinery Advanced, Sumy, Ukraine;
ORCID: 0000-0002-7276-550X

Artem Artyukhov
D.Sc. in Economics, Associate Professor of the Research Institute of Trade and Sustainable Business, University of Economics in Bratislava, Bratislava, Slovakia; Associate Professor of the Department of Marketing, Sumy State University, Sumy, Ukraine;
ORCID: 0000-0003-1112-6891

Oleksandr Dluhopolskyi
D.Sc. in Economics, Professor of the Faculty of Management and Social Sciences, Lubelska Akademia WSEI, Lublin, Poland; Professor of the Department of Economics, West Ukrainian National University, Ternopil, Ukraine
e-mail: dlugopolsky77@gmail.com
ORCID: 0000-0002-2040-8762
(Corresponding author)

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ABSTRACT

This study aims to develop a comprehensive analytical framework for investigating energy infrastructure economics across country, regional, and worldwide scales, establishing methodological foundations and empirical evidence necessary for coordinated decision-making in the face of climate change, technological transformation, and geopolitical disruption. The research addresses the inadequacy of traditional single-scale approaches by examining complex interconnections and cascading effects of infrastructure decisions across multiple geographical levels. The investigation develops distinct analytical structures at the country, regional, and worldwide levels. The analysis reveals that energy infrastructure economics operates within complex webs of interconnections across geographical scales, each presenting distinct analytical challenges and methodological requirements. Country-level investigations provide granular precision but are constrained by limited scope in addressing cross-border spillovers. Regional investigations emerge as critical intermediate scales that balance national specificity with broader coordination perspectives, achieving economies of scale through cooperation while facing significant coordination challenges. Worldwide investigations provide essential insights into global trends but operate with high abstraction levels and uncertainty that may limit direct policy applicability. The study identifies significant governance gaps in current cross-scale coordination approaches, particularly in policy harmonization, benefit-sharing mechanisms, and risk management. Traditional single-scale approaches to energy infrastructure economics are insufficient for addressing the multifaceted challenges of energy system transformation. The research establishes that effective energy infrastructure economics must account for complex interconnections between local, regional, and global considerations while addressing unique analytical challenges at each scale. Success in achieving sustainable and secure energy systems requires technological innovation and institutional innovation in analytical approaches, financing mechanisms, and coordination frameworks. The framework provides foundations for integrated approaches to energy infrastructure economics. However, substantial additional work is required to translate conceptual insights into practical decision-making tools for the unprecedented scale and urgency of required infrastructure transformation.

Keywords: energy infrastructure economics, methodological foundations, regional-level, worldwide-level, mind map

JEL Classification: O13, O31, Q40

INTRODUCTION

Energy infrastructure represents one of the most capital-intensive and economically significant components of modern economies, with global investment requirements estimated at over USD 4 trillion annually through 2030 to meet growing energy demand and climate objectives (IEA, 2023). The economic complexities surrounding energy infrastructure development, financing, and operation have become increasingly critical as nations navigate the dual challenges of ensuring energy security while transitioning toward sustainable energy systems. Traditional economic models for infrastructure investment, primarily developed for conventional fossil fuel systems, are being challenged by the unique characteristics of renewable energy technologies, smart grid systems, and distributed energy resources that exhibit different cost structures, risk profiles, and operational dynamics (Stern, 2007; IRENA, 2019).

Energy infrastructure's economic analysis encompasses multiple dimensions beyond simple cost-benefit calculations. Energy sector infrastructure assets are characterized by high upfront capital costs, long operational lifespans spanning decades, and significant economies of scale that create natural monopoly conditions in many segments (Viscusi et al., 2018). These characteristics generate complex financing challenges, particularly in developing economies where capital scarcity and institutional weaknesses can impede necessary investments (Eberhard et al., 2016). Moreover, the regulatory environment plays a crucial role in shaping investment incentives, with rate-of-return regulation, price caps, and performance-based mechanisms creating different economic outcomes for investors and consumers (Joskow, 2008).

The ongoing energy transition has fundamentally altered the economic landscape of infrastructure investment by introducing new sources of uncertainty and risk. Unlike conventional power plants that provide predictable, dispatchable generation, renewable energy sources exhibit variable output patterns that require complementary investments in grid flexibility, storage systems, and demand response capabilities (Ueckerdt et al., 2013; Borysiak et al., 2024). This technological shift has created new categories of stranded asset risk, where existing infrastructure may become economically obsolete before the end of its technical lifetime due to policy changes or technological disruption (Caldecott et al., 2016). Simultaneously, the decentralized nature of many renewable technology’s challenges traditional utility business models and creates opportunities for new market participants and financing mechanisms (Richter, 2012).

Financial innovation has emerged as a critical factor in addressing the scale and complexity of modern energy infrastructure requirements. Traditional project finance structures are supplemented by green bonds, blended finance mechanisms, and risk-sharing instruments designed to attract private capital toward sustainable infrastructure projects (Dan & Tiron-Tudor, 2021). The development of standardized approaches to environmental, social, and governance considerations has further influenced investment decision-making, with sustainability criteria increasingly integrated into infrastructure economic evaluation frameworks (Tolliver et al., 2021). These evolving financial tools and assessment methodologies reflect the growing recognition that energy infrastructure economics must account for externalities, long-term resilience, and systemic risks that conventional economic analysis may overlook.

The economic efficiency of energy infrastructure is increasingly being evaluated through the lens of system-wide optimization rather than individual asset performance. This perspective recognizes that the value of infrastructure investments depends not only on their direct economic returns but also on their contribution to overall system reliability, flexibility, and resilience (Joskow, 2019). Integrating digital technologies and data analytics enables more sophisticated approaches to infrastructure planning and operation, creating opportunities to optimize asset utilization and reduce system costs while maintaining service quality (MIT Energy Initiative, 2016). Understanding these complex economic relationships is essential for developing effective policy frameworks and investment strategies to support the transition to a sustainable, secure energy future.

LITERATURE REVIEW

The national-level analysis of energy infrastructure economics has been dominated by empirical studies examining the relationship between infrastructure investment and economic development outcomes. Seminal work by Aschauer (1989) established the foundation for understanding infrastructure's role in economic growth, with subsequent energy-specific research building upon these theoretical frameworks. Contemporary research has increasingly focused on the efficiency of energy infrastructure investment and its regional economic impacts, with studies demonstrating significant variations in investment efficiency across different national contexts (Kuang et al., 2023).

Recent empirical research has highlighted the complex relationship between energy infrastructure investment and economic development at the national level. Kuang et al. (2023) constructed input-output and environmental indicator combination frameworks to evaluate the efficiency of energy infrastructure investment, finding that efficiency varies widely across regions and is highly correlated with regional economic development models, levels of economic development, and industrial importance. This research has revealed that the driving effect of energy infrastructure investment on economic growth exhibits considerable heterogeneity depending on national circumstances and policy frameworks.

The national energy infrastructure economics literature has also extensively examined the role of regulatory frameworks and market design in shaping investment outcomes. Joskow's (2008) influential work on electricity market restructuring has provided theoretical foundations for understanding how different regulatory approaches affect infrastructure investment incentives. Subsequent research has demonstrated that the choice between rate-of-return regulation, price caps, and performance-based mechanisms significantly influences both the level and efficiency of infrastructure investment (Viscusi et al., 2018). These studies have shown that regulatory uncertainty represents a significant barrier to optimal infrastructure investment, with implications for long-term energy security and economic competitiveness.

National-level research has increasingly incorporated technological change and innovation considerations into infrastructure economic analysis. Richter (2012) documented how the transition to renewable energy technologies creates new categories of investment risk and opportunity, with traditional infrastructure economic models requiring substantial modification to account for the intermittency, modularity, and declining cost characteristics of renewable technologies. Ueckerdt et al. (2013) developed system-level cost methodologies that account for the unique economic characteristics of variable renewable energy sources, showing that countries with supportive policy frameworks and strong institutional capabilities are better positioned to capture the economic benefits of energy infrastructure modernization.

The financing dimension of national energy infrastructure has received considerable attention in recent literature. Eberhard et al. (2016) examined independent power projects in Sub-Saharan Africa, revealing how domestic capital market development and regulatory frameworks significantly influence the cost and availability of infrastructure financing. Similarly, research on developed economies has shown that the evolution toward performance-based regulation and competitive markets has fundamentally altered the risk-return profiles of energy infrastructure investments, requiring new approaches to financial analysis and investment evaluation (MIT Energy Initiative, 2016; Pivnyak et al., 2024).

Regional analysis of energy infrastructure economics has gained prominence as countries increasingly recognize the benefits of cross-border energy cooperation and integration. The literature in this area has focused primarily on the economic implications of regional energy market integration, examining how shared infrastructure investments can generate economies of scale and improve overall system efficiency. Yang et al. (2020) found that "power-importing" and "power-balancing" regions benefit more from power grid infrastructure in the long term, while "power-exporting" regions may become trapped in resource curse dynamics.

The regional literature has extensively examined the role of cross-border infrastructure projects in promoting economic development and energy security. Studies of regional power pools in Africa, gas pipeline networks in Europe, and renewable energy resource sharing arrangements in Asia have demonstrated that regional cooperation can significantly reduce infrastructure costs while improving system reliability (OECD, 2015). However, the literature highlights substantial challenges in coordinating regional infrastructure investment, including differences in national regulatory frameworks, financing capabilities, and political priorities.

Economic analysis of regional energy infrastructure has increasingly incorporated spatial econometric methods to capture spillover effects and spatial dependencies in infrastructure investment outcomes. Research applying spatial panel data models has shown that economic growth from infrastructure investment exhibits characteristics of significant spatial dependence, with the degree and significance of spatial dependence gradually declining over time (Yang et al., 2020). These studies have revealed that the economic benefits of energy infrastructure investment extend beyond national borders, creating positive externalities that justify coordinated regional investment strategies.

The regional literature has also examined the distributional implications of cross-border energy infrastructure investment. Strand et al. (2011) showed that while regional integration can generate substantial aggregate benefits, the distribution of costs and benefits across countries is often uneven, creating political economy challenges for regional cooperation. Studies have identified the need for compensation mechanisms and burden-sharing agreements to ensure regional infrastructure projects generate broad-based support and sustainable financing.

Recent research has highlighted the role of regional development banks and multilateral institutions in facilitating cross-border energy infrastructure investment. These institutions have developed specialized financing instruments and risk-sharing mechanisms that address the unique challenges of regional energy projects, including political risk, currency risk, and coordination failures (Dan & Tiron-Tudor, 2021). The literature suggests that effective regional infrastructure development requires technical and economic coordination and institutional innovation in financing and governance structures.

The global perspective on energy infrastructure economics has been shaped by recognition that energy system transformation requires unprecedented international cooperation and investment coordination. The International Energy Agency (IEA, 2024) analysis indicates that clean energy investments are set to approach USD 320 billion in 2024, representing more than 50% growth since 2020, with similar growth patterns observed in advanced economies while trailing behind China's 75% growth rate. This research has highlighted the critical role of international financial institutions and development banks in mobilizing capital for global energy infrastructure transformation.

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The global literature has extensively examined technology transfer and innovation diffusion in energy infrastructure development. Studies have shown that technology spillovers from leading countries can significantly reduce infrastructure costs in developing nations, but that effective technology transfer requires supportive institutional frameworks and adequate absorptive capacity (IRENA, 2019). Research has documented how learning curve effects and international technology cooperation can accelerate the global deployment of clean energy infrastructure while reducing costs through economies of scale.

Global energy infrastructure economics research has increasingly focused on the role of international climate finance in supporting infrastructure transformation. Bhuiyan et al. (2022) documented that public-private partnership investments serve as incentives to enhance renewable energy projects in several countries, with a detailed analysis highlighting that sustainable energy and clean energy sources have encouraged multiple countries to promote renewable energy and technology development. Tolliver et al. (2021) showed that international climate finance mechanisms, including green bonds and blended finance instruments, are essential for bridging the global energy infrastructure transformation financing gap. The global literature has also examined supply chain considerations in energy infrastructure development, recognizing that energy infrastructure components are increasingly manufactured and traded globally. Research has shown that supply chain disruptions can significantly affect infrastructure costs and deployment timelines, with implications for energy security and economic development (Song et al., 2022). Studies have highlighted the need for diversified and resilient global supply chains to support sustainable energy infrastructure deployment at scale.

Climate change considerations have become increasingly prominent in global energy infrastructure economics research. Caldecott et al. (2016) examined stranded asset risks in fossil fuel infrastructure, showing how climate policies create systematic risks for existing energy infrastructure investments. This research has highlighted the need for new approaches to infrastructure valuation that account for climate policy risk and the transition to low-carbon energy systems.

The energy infrastructure economics literature has contributed substantially to understanding the complex relationships between infrastructure investment, technological change, and economic development across different geographical scales. Research has demonstrated that effective energy infrastructure economics requires consideration of diverse factors, including regulatory frameworks, financing mechanisms, technological characteristics, and institutional capabilities (Joskow, 2019; Stern, 2007). While significant progress has been made in developing theoretical frameworks and empirical methodologies, essential research gaps remain, particularly regarding the economic implications of emerging technologies and the distributional consequences of infrastructure investment. Future research should prioritize integrated analytical approaches that can inform policy decisions in an increasingly complex and rapidly evolving energy system landscape.

AIMS AND OBJECTIVES

Energy infrastructure economics investigation at multiple geographical scales has become essential due to the unprecedented transformation in global energy systems. The traditional approach of analyzing energy infrastructure in isolation at single geographical levels is insufficient to address modern energy systems' complex, interconnected challenges. The economic implications of energy infrastructure decisions made at one scale inevitably cascade across other levels, creating ripple effects requiring a comprehensive understanding and coordinated analysis.

This article aims to develop a comprehensive analytical framework for investigating energy infrastructure economics across country, regional, and worldwide scales, establishing the methodological foundations and empirical evidence base necessary for coordinated decision-making in the face of climate change, technological transformation, and geopolitical disruption.

METHODS

The research employs a multi-methodological approach using three interconnected methods to describe the dynamic "Energy infrastructure economics" system across national, regional, and worldwide scales. These methods work together to create a comprehensive analytical framework that addresses modern energy systems' complex, interconnected nature.

Within the framework of the work, the following methods were used to describe the dynamic system of "Energy infrastructure economics": abstract-logical method, method of analogies, method of induction-deduction.

The abstract-logical method identifies and analyzes the fundamental relationships and structural patterns within energy infrastructure economics across different geographical scales. The analogical method draws parallels and comparisons between different scales, systems, and contexts to understand complex relationships and transfer insights across varying levels of analysis. The method of induction-deduction combines bottom-up empirical observation (induction) with top-down theoretical reasoning (deduction) to build a comprehensive understanding and validate theoretical frameworks.

How the three methods work together:

- Complementary strengths: abstract-logical provides theoretical rigor and structural clarity; analogical reasoning enables knowledge transfer and pattern recognition; induction-deduction ensures empirical grounding and practical relevance.
- Addressing complexity: each method addresses different aspects of the complex energy infrastructure system; the combined approach captures both theoretical relationships and practical realities; integration enables comprehensive analysis across multiple scales simultaneously.
- Quality assurance: triangulation of methods increases the reliability of findings; different methodological perspectives validate conclusions; a comprehensive approach reduces the risk of methodological bias.
- Limitations and considerations: a predominantly descriptive approach limits quantitative precision; a high level of abstraction may obscure important local variations; coordination challenges between different analytical scales.
- Practical applications: the framework provides a foundation for policy development at multiple scales; methodology can be adapted for specific regional or national contexts; the approach enables better coordination between different levels of analysis.

Integrating abstract-logical methods, analogical reasoning, and induction-deduction creates a robust methodological framework for analyzing energy infrastructure economics as a dynamic system. This approach successfully addresses the complexity and interconnectedness of modern energy systems while providing practical guidance for decision-makers across national, regional, and worldwide scales.

RESULTS

We propose investigating energy infrastructure economics analysis on three levels (Figure 1): national, regional, and worldwide.

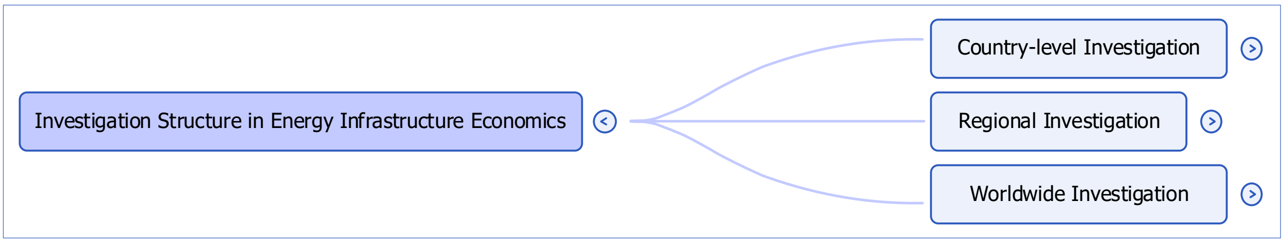

Figure 1. Investigating energy infrastructure economics on different scales.

The country-level investigation structure includes (Table 1):

1. National energy infrastructure assessment. The country-level analysis begins with a comprehensive evaluation of existing energy infrastructure assets, including generation capacity, transmission networks, distribution systems, and storage facilities. This assessment involves detailed technical and economic audits of infrastructure conditions, remaining useful life, and replacement costs. The investigation examines the relationship between infrastructure age, maintenance expenditures, and system reliability to establish baseline economic performance metrics.

2. Regulatory and policy framework analysis. A critical component involves analyzing the domestic regulatory environment, including electricity market structures, pricing mechanisms, investment incentives, and environmental regulations. This analysis evaluates how national policies influence infrastructure investment decisions, examining the effectiveness of different regulatory approaches such as rate-of-return regulation, price caps, or performance-based mechanisms in promoting efficient infrastructure development.

3. National energy security economics. The investigation assesses the economic value of energy security at the national level, examining supply diversification benefits, strategic reserve requirements, and the costs of supply disruptions. This part includes modelling the economic impact of potential infrastructure failures and evaluating the optimal level of redundancy and resilience investments from a national perspective.

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4. Domestic financing and investment analysis. Country-level analysis focuses on domestic capital markets, government financing capabilities, and the role of national development banks in infrastructure funding. The investigation examines sovereign debt capacity, fiscal constraints, and the potential for public-private partnerships in addressing infrastructure financing gaps.

5. Macroeconomic impact assessment. This component evaluates how energy infrastructure investments affect broader economic indicators such as GDP growth, employment, industrial competitiveness, and inflation. The analysis includes input-output modelling to capture indirect economic effects and multiplier impacts across different sectors of the national economy.

Table 1. Elements of scales for energy infrastructure economics.

Scales	Elements
Country-level Investigation	Nacional Energy Infrastructure Assessment
	Regulatory & Policy Framework Analysis
	National Energy Security Economics
	Domestic Financing & Investment Analysis
	Macroeconomic Impact Assessment
Regional Investigation	Cross-border Infrastructure Integration
	Regional Market Development
	Geopolitical Risk Assessment
	Regional Development Banks & Financing
	Climate & Environmental Coordination
Worldwide Investigation	Global Infrastructure Investment Flows
	Technology Transfer & Innovation Economics
	Global Supply Chain Analysis
	International Climate Finance
	Comparative Economic Analysis

The regional investigation structure includes (Table 1):

1. Cross-border infrastructure integration. Regional analysis emphasizes interconnection projects, shared transmission systems, and coordinated infrastructure planning across multiple countries. This part includes economic evaluation of regional power pools, gas pipeline networks, and renewable energy resource sharing arrangements. The investigation examines economies of scale achievable through regional cooperation and the distribution of costs and benefits among participating nations.

2. Regional market development. The structure focuses on regional electricity markets, harmonized regulatory frameworks, and cross-border trade mechanisms. This part involves analyzing price convergence, market coupling effects, and the economic efficiency of regional market integration. The investigation evaluates how regional cooperation can reduce infrastructure costs and improve system reliability.

3. Geopolitical risk assessment. Regional analysis incorporates geopolitical considerations, including energy security implications of regional interdependence, political stability risks, and the economic impact of regional conflicts on infrastructure investments. This component examines the balance between regional integration benefits and energy security concerns.

4. Regional development banks and financing. The investigation analyzes the role of regional financial institutions, multilateral development banks, and regional investment funds in infrastructure financing. This part includes evaluating blended finance mechanisms, risk-sharing instruments, and coordinated investment strategies across the region.

5. Climate and environmental coordination. Regional analysis examines coordinated climate policies, carbon pricing mechanisms, and environmental standards influencing infrastructure investment decisions. This part includes assessing the economic implications of regional renewable energy targets and emission reduction commitments.

The worldwide investigation structure includes (Table 1):

1. Global infrastructure investment flows. The worldwide analysis focuses on global capital flows, international financing mechanisms, and cross-border investment patterns in energy infrastructure. This part includes examination of foreign direct investment trends, sovereign wealth fund activities, and the role of international development finance institutions in global infrastructure development.

2. Technology transfer and innovation economics. Global analysis emphasizes technology diffusion patterns, intellectual property considerations, and the economics of technology transfer in energy infrastructure. This part evaluates how innovation in leading countries affects infrastructure costs and capabilities worldwide, including the role of learning curves and technology spillovers.

3. Global supply chain analysis. The investigation examines global supply chains for energy infrastructure components, including manufacturing capacity, logistics networks, and supply security considerations. This part includes an analysis of commodity price volatility impacts, trade policy effects, and the economic implications of supply chain disruptions on global infrastructure development.

4. International climate finance. Worldwide analysis focuses on international climate finance mechanisms, carbon markets, and global climate policy coordination effects on infrastructure investment. This part includes the evaluation of international climate funds, carbon credit mechanisms, and the economic impact of global climate agreements on infrastructure development patterns.

5. Comparative economic analysis. The global investigation involves comparative analysis of infrastructure economics across different regions, examining best practices, policy effectiveness, and economic outcomes under various institutional frameworks. This part includes benchmarking studies and cross-country econometric analysis to identify factors driving successful infrastructure development. Country-level investigations focus on detailed, specific analysis using granular domestic data and engineering-economic models. They directly inform national policy decisions and involve primarily domestic stakeholders. Regional investigations emphasize integration and cooperation effects, requiring harmonizing multi-country data and game-theoretic approaches. They face coordination challenges but can achieve economies of scale through regional cooperation. Worldwide investigations operate at the highest level of abstraction, focusing on global trends and patterns using macro-econometric models and international data sources. They deal with the most significant uncertainty but inform global policy coordination.

Each level requires different analytical methodologies, data sources, and stakeholder engagement approaches, reflecting the increasing complexity and uncertainty as the scope expands from national to global analysis.

DISCUSSION

The analysis presented in this study reveals that energy infrastructure economics operates within a complex web of interconnections across country, regional, and worldwide scales, each presenting distinct analytical challenges and methodological requirements. While offering the advantage of granular data and direct policy relevance, the country-level investigations are constrained by their limited scope in addressing cross-border spillovers and global market dynamics. The

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detailed engineering-economic models employed at the national level provide precision in technical and economic assessment but may fail to capture the broader systemic implications of infrastructure decisions that extend beyond national boundaries.

Regional investigations emerge as a critical intermediate scale that balances the specificity of national analysis with the broader perspective required for effective coordination. The economies of scale achievable through regional cooperation, as demonstrated in the study of cross-border infrastructure integration, present significant opportunities for cost reduction and improved system reliability. However, the coordination challenges inherent in regional approaches, including harmonizing regulatory frameworks, equitable benefit-sharing mechanisms, and managing geopolitical risks, require sophisticated game-theoretic approaches and institutional innovations that extend beyond traditional economic analysis.

While operating at the highest level of abstraction, the worldwide investigation structure provides essential insights into global trends and patterns that influence infrastructure economics at all scales. Analyzing global supply chains, technology transfer mechanisms, and international climate finance reveals how global forces increasingly shape local infrastructure decisions. However, the macro-econometric models employed at this scale face significant uncertainty and may obscure important regional variations and country-specific conditions crucial for effective policy design.

The methodological approach employed in this study, utilizing abstract-logical methods, analogies, and induction-deduction, provides a solid foundation for understanding the structural relationships within energy infrastructure economics across multiple scales. However, several methodological limitations warrant discussion. While valuable for establishing conceptual frameworks, the reliance on descriptive analysis limits the quantitative insights that could inform specific policy recommendations. Future research would benefit from incorporating econometric analysis, system dynamics modelling, and optimization techniques to provide more precise guidance for decision-makers.

Integrating findings across different geographical scales presents both opportunities and challenges for policy coordination. The cascading effects identified in the analysis suggest that optimal infrastructure investment strategies require consideration of cross-scale interactions that traditional single-level analyses may overlook. However, the varying data availability, institutional frameworks, and analytical methodologies across scales create significant challenges for developing truly integrated analytical approaches.

The analysis reveals critical governance gaps in current approaches to energy infrastructure economics. While each geographical scale has developed specialized analytical methodologies and institutional frameworks, the coordination mechanisms between scales remain underdeveloped. Regional analysis highlights the tension between national sovereignty concerns and the efficiency gains from regional cooperation. This tension is exacerbated by the uneven distribution of costs and benefits from regional infrastructure projects, necessitating innovative compensation mechanisms and burden-sharing agreements.

On a global scale, the analysis underscores the critical role of international financial institutions and development banks in facilitating infrastructure investment. However, the current institutional framework may be inadequate for addressing the unprecedented scale and urgency of the required infrastructure transformation. The analysis suggests that new international cooperation and coordination forms are needed to address global infrastructure investment gaps and ensure equitable access to clean energy technologies.

The ongoing energy transition has fundamentally altered the infrastructure investment's economic landscape, creating opportunities and risks that require new analytical approaches. The analysis reveals how the unique characteristics of renewable energy technologies, including intermittency, modularity, and declining costs, challenge traditional infrastructure economic models. The stranded asset risks associated with existing fossil fuel infrastructure create additional complexity for investment decision-making, particularly in developing countries where infrastructure replacement costs may be prohibitive.

The role of digitalization and smart grid technologies in enabling system optimization presents significant opportunities for improving infrastructure economics across all scales. However, the analysis suggests that capturing these benefits requires substantial coordination efforts and institutional innovations that extend beyond traditional utility business models. The emergence of distributed energy resources and prosumer markets further complicates traditional infrastructure valuation and investment planning approaches.

Integrating climate considerations into infrastructure economics has emerged as a critical challenge across all geographical scales. The analysis reveals how climate policy uncertainty creates systematic risks for infrastructure investments, while climate change impacts threaten the physical resilience of existing infrastructure systems. The development of climate-resilient infrastructure requires new risk assessment and valuation approaches that account for long-term climate projections and adaptation costs.

The international climate finance mechanisms examined in the analysis represent essential innovations in addressing global infrastructure financing gaps. However, these mechanisms' current scale and effectiveness appear insufficient for meeting the requirements of global energy system transformation. The analysis suggests substantial expansion and innovation in climate finance mechanisms will be required to achieve global climate objectives while ensuring equitable access to clean energy infrastructure.

CONCLUSIONS

This study has developed a comprehensive analytical framework for investigating energy infrastructure economics across country, regional, and worldwide scales, revealing the complex interconnections and coordination challenges that characterize modern energy systems. The analysis demonstrates that traditional approaches focusing on single geographical scales are insufficient for addressing the multifaceted challenges of energy system transformation in the context of climate change, technological disruption, and geopolitical instability.

The investigation has established that energy infrastructure economics exhibits distinct characteristics and requirements at each geographical scale, necessitating different analytical methodologies, data sources, and stakeholder engagement approaches. Country-level investigations provide the detailed technical and economic analysis necessary for national policy decisions but require integration with regional and global perspectives to address cross-border spillovers and coordination opportunities. Regional investigations offer critical opportunities for achieving economies of scale and improving system efficiency through cooperation, but face significant coordination challenges that require innovative institutional and financing mechanisms. Worldwide investigations provide essential insights into global trends and patterns but operate with high levels of uncertainty and abstraction that may limit their direct policy applicability.

The analysis has revealed significant gaps in current approaches to cross-scale coordination, particularly in policy harmonization, benefit-sharing mechanisms, and risk management. The cascading effects of infrastructure decisions across geographical scales create complex interdependencies that require new forms of analytical integration and institutional coordination. The study has identified the need for new methodological approaches to capture these cross-scale interactions while maintaining the analytical precision required for effective decision-making.

The findings have important implications for policymakers, investors, and other stakeholders involved in energy infrastructure development. At the country level, the analysis suggests that national infrastructure strategies must account for regional and global contexts to optimize investment decisions and avoid suboptimal outcomes. The importance of regulatory frameworks and institutional capabilities in shaping infrastructure economics underscores the need for continued attention to governance and policy design.

Regional cooperation emerges as a critical strategy for improving infrastructure economics, but success requires addressing coordination challenges through innovative institutional arrangements and financing mechanisms. The analysis suggests that regional development banks and multilateral institutions play crucial roles in facilitating cooperation but may require enhanced mandates and capabilities to address current coordination gaps.

At the global level, the analysis highlights the urgent need for scaled-up international coordination and financing to address infrastructure investment requirements. The current institutional framework appears inadequate for the unprecedented scale and urgency of required infrastructure transformation, necessitating new forms of international cooperation and innovative financing mechanisms.

This study has several limitations that suggest important directions for future research. While valuable for establishing analytical frameworks, the predominantly descriptive and conceptual approach limits the quantitative insights available for specific policy guidance. Future research should incorporate econometric analysis, optimization modelling, and case study approaches to provide more precise guidance for decision-makers. The methodological challenges of integrating analysis across different geographical scales represent an important area for continued research. Developing analytical approaches that capture cross-scale interactions while maintaining methodological rigour represents a significant opportunity for advancing the field. Incorporating system dynamics modelling, network analysis, and multi-level optimization techniques could provide valuable tools for addressing these challenges.

The rapidly evolving technological and policy landscape surrounding energy infrastructure requires continuous updating and refinement of analytical frameworks. Future research should develop adaptive analytical approaches to accommodate

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technological uncertainty and policy evolution while providing stable guidance for long-term infrastructure investment decisions.

The transformation of global energy systems represents one of the most significant economic and technical challenges of the 21st century, requiring unprecedented levels of coordination and cooperation across multiple geographical scales. This study has demonstrated that effective energy infrastructure economics must account for the complex interconnections between local, regional, and global considerations while addressing the unique analytical challenges present at each scale.

The framework developed in this study provides a foundation for more integrated approaches to energy infrastructure economics. Still, substantial additional work is required to translate these conceptual insights into practical tools for decision-making. The urgent need for accelerated infrastructure transformation in response to climate change creates an imperative for continued research and innovation in this critical area.

Success in achieving sustainable and secure energy systems will require technological innovation and institutional innovation in analytical approaches, financing mechanisms, and coordination frameworks. The multi-scale perspective developed in this study suggests that such innovation must co-occur across all geographical levels, with particular attention to the coordination mechanisms that can ensure coherent and effective action across scales. The economic stakes in energy infrastructure transformation demand nothing less than our most sophisticated analytical capabilities and most effective coordination mechanisms.

ADDITIONAL INFORMATION

AUTHOR CONTRIBUTIONS

All authors have contributed equally.

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CONFLICT OF INTEREST

The Authors declare that there is no conflict of interest.

REFERENCES

1. Aschauer, D.A. (1989). Is public expenditure productive? *Journal of Monetary Economics*, *23*(2), 177-200. https://doi.org/10.1016/0304-3932(89)90047-0
2. Bhuiyan, M.A., Zhang, Q., Khare, V., Mikhaylov, A., Pinter, G., & Huang, X. (2022). Renewable Energy Consumption and Economic Growth Nexus: a Systematic Literature Review. *Frontiers in Environmental Science*, *10.* https://doi.org/10.3389/fenvs.2022.878394
3. Borysiak, O., Brych, V., Dluhopolskyi, O., Popovych, P., & Bondarchuk, M. (2024). Low-carbon management in selecting resources for energy production of enterprises. *Energy Policy Journal*, *27*(4), 81-98. https://doi.org/10.33223/epj/195622
4. Caldecott, B., Kruitwagen, L., Dericks, G., Tulloch, D.J., Kok, I., & Mitchell, J. (2016). Stranded Assets and Thermal Coal: an Analysis of Environment-Related Risk Exposure. Stranded Assets Programme, SSEE, University of Oxford, http://dx.doi.org/10.2139/ssrn.2724550
5. Dan, A., & Tiron-Tudor, A. (2021). The Determinants of Green Bond Issuance in the European Union. *Journal of Risk and Financial Management*, *14*(9), 446. https://doi.org/10.3390/jrfm14090446
6. Eberhard, A., Gratwick, K., Morella, E., & Antmann, P. (2016). Independent Power Projects in Sub-Saharan Africa: Lessons from Five Key Countries*. Directions in Development: Energy and Mining*. World Bank. http://hdl.handle.net/10986/23970
7. IEA (2023, May). *World Energy Investment 2023 Datafile*. IEA: Paris. https://www.iea.org/data-and-statistics/data-product/world-energy-investment-2023-datafile-2
8. IEA (2024, June). *World Energy Investment 2024 Datafile*. IEA: Paris. https://www.iea.org/data-and-statistics/data-product/world-energy-investment-2024-datafile
9. IRENA (2019). Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables. Summary for policy makers. International Renewable Energy Agency, Abu Dhabi. https://efficiencyforaccess.org/wp-content/uploads/IRENA-Innovation-Landscape-Report-2019P.pdf
10. Joskow, Paul L. (2008). Incentive Regulation and Its Application to Electricity Networks. *Review of Network Economics*, *7*(4). https://doi.org/10.2202/1446-9022.1161
11. Joskow, Paul L. (2019). Challenges for wholesale electricity markets with intermittent renewable generation at scale:

the US experience. *Oxford Review of Economic Policy, 35*(2), 291–331. https://doi.org/10.1093/oxrep/grz001

12. Kuang, L., Han, X., & Liu, G. (2023). The efficiency of energy infrastructure investment and its regional economic impact. *International Journal of Environmental Research and Public Health*, *20*(3), 2125. https://doi.org/10.3390/ijerph20032125
13. MIT Energy Initiative (2016). *Utility of the future: An MIT Energy Initiative response to an industry in transition*. Massachusetts Institute of Technology, 382 p. https://energy.mit.edu/wp-content/uploads/2016/12/Utility-of-the-Future-Full-Report.pdf
14. OECD (2015). Policy Guidance for Investment in Clean Energy Infrastructure: Expanding Access to Clean Energy for Green Growth and Development. OECD Publishing, Paris. https://doi.org/10.1787/9789264212664-en.
15. Pivnyak, G., Papaika, Y., Aziukovskyi, O., Lysenko, O., & Dluhopolskyi, O. (2024). Ensuring sustainability of the power supply system of mining enterprises in the conditions of war risks. *E3S Web of Conferences, 567,* 01012. https://doi.org/10.1051/e3sconf/202456701012
16. Richter, M. (2012). Utilities' business models for renewable energy: a review. *Renewable and Sustainable Energy Reviews*, *16*(5), 2483-2493. https://doi.org/10.1016/j.rser.2012.01.072.
17. Song, Y., Shahzad, U., & Paramati, S.R. (2022). Impact of energy infrastructure investments on renewable electricity generation in major Asian developing economies. *Australian Economic Papers*, *62*(1), 1–23. https://doi.org/10.1111/1467-8454.12282
18. Stern, N. (2007). *The economics of climate change: The Stern review*. Cambridge University Press. http://mudancasclimaticas.cptec.inpe.br/~rmclima/pdfs/destaques/sternreview_report_complete.pdf
19. Strand, J., Miller, S., & Siddiqui, S. (2011). Infrastructure investments under uncertainty with the possibility of retrofit: theory and simulations. *Policy Research Working Paper*, 5516. Washington, DC: World Bank. http://documents.worldbank.org/curated/en/393331468333607245
20. Tolliver, C., Keeley, A.R., & Managi, S. (2019). Green bonds for the Paris Agreement and sustainable development goals. *Environmental Research Letters*, *14*(6), 064009. https://doi.org/10.1088/1748-9326/ab1118
21. Ueckerdt, F., Hirth, L., Luderer, G., & Edenhofer, O. (2013). System LCOE: What are the costs of variable renewables? *Energy*, *63,* 61-75. https://doi.org/10.1016/j.energy.2013.10.072
22. Viscusi, W.K., Harrington Jr, J.E., & Vernon, J.M. (2018). *Economics of regulation and antitrust*. MIT Press. https://mitpress.ublish.com/book/economics-of-regulation-and-antitrust
23. Yang, F., Zhang, S., & Sun, C. (2020). Energy infrastructure investment and regional inequality: Evidence from China's power grid. *Science of The Total Environment, 749,* 142384. https://doi.org/10.1016/j.scitotenv.2020.142384

Гавриленко О., Артюхов А., Длугопольський О.

ЕКОНОМІКА ЕНЕРГЕТИЧНОЇ ІНФРАСТРУКТУРИ: МЕНТАЛЬНА КАРТА ДЛЯ НАЦІОНАЛЬНОГО, РЕГІОНАЛЬНОГО ТА ГЛОБАЛЬНОГО РІВНІВ

Дослідження має на меті розробку комплексної аналітичної структури для вивчення економіки енергетичної інфраструктури на національному, регіональному та глобальному рівнях із закладанням методологічних основ та емпіричних фактів, необхідних для узгодженого ухвалення рішень в умовах кліматичних змін, технологічних трансформацій і геополітичних потрясінь. Дослідження відповідає на виклики недостатньої ефективності традиційних підходів, аналізуючи складні взаємозв'язки та каскадні наслідки інфраструктурних рішень на різних географічних рівнях. У межах дослідження створено окремі аналітичні структури для трьох рівнів аналізу: національного, регіонального, глобального. Аналіз демонструє, що економіка енергетичної інфраструктури функціонує в складному мережевому середовищі міжрівневих взаємозв'язків, кожний із яких має свої особливі аналітичні виклики та методологічні вимоги. Дослідження на національному рівні забезпечують високу деталізацію, але мають обмеження щодо врахування транскордонних ефектів. Регіональний рівень виступає як критично важлива проміжна ланка, що поєднує національну специфіку з ширшими координаційними перспективами, дозволяючи досягати ефекту масштабу через співпрацю попри труднощі координації. Глобальні дослідження дають цінне розуміння світових тенденцій, однак вони мають високий рівень абстракції та невизначеності, що обмежує безпосереднє застосування їх у політиці. Дослідження виявляє суттєві прогалини в управлінні міжрівневою координацією, зокрема в питаннях гармонізації політик, механізмах розподілу вигод та управлінні ризиками. Традиційні підходи, зосереджені лише на одному рівні, виявляються недостатніми для виконання багатовимірних завдань трансформації енергетичних систем. Установлено, що ефективна економіка енергетичної інфраструктури повинна враховувати складні міжрівневі взаємозв'язки – від локального до глобального — та відповідати унікальним викликам кожного рівня. Успішне досягнення цілей сталого та безпечного енергопостачання вимагає не лише технологічних інновацій, а й інституційних — у підходах до аналізу, механізмах фінансування та рамках координації. Запропонована аналітична структура формує основу для інтегрованого підходу до економіки енергетичної інфраструктури, однак потребує подальшого розвитку для

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перетворення концептуальних висновків на практичні інструменти ухвалення рішень, здатні відповідати масштабам і терміновості необхідних змін.

Ключові слова: економіка енергетичної інфраструктури; методологічні засади; регіональний рівень; глобальний рівень; ментальна карта

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