INNOVATION ABSORPTIVE EFFICIENCY BEYOND INFRASTRUCTURE SATURATION: COMPARATIVE INSIGHTS FROM BULGARIA AND THE UNITED STATES

Daniel Petrov, *Institute of agricultural economics – Sofia, email:dpetrov.iae@gmail.com*
Yoana Petrova, *University of Library Studies and Information Technologies – Sofia, yoanapetrova9499@abv.bg*

Abstract: *This paper introduces the Post-Saturation Innovation Absorptive Theory (PSIAT), a novel conceptual and empirical framework designed to explain why countries that have substantially invested in innovation-enabling infrastructure often fail to produce commensurate innovation outputs. Using data from the World Bank covering the period 2014 - 2024, this study conducts a quantitative comparative analysis of Bulgaria and the United States, constructing a new index - PSIAT Index, as the ratio between normalized innovation output and infrastructure inputs. The findings reveal that while Bulgaria has made significant infrastructural progress, its innovation efficiency remains critically low, confirming the theory's central premise: beyond a saturation threshold, infrastructure alone is insufficient to generate innovation without deep institutional transformation. In contrast, the United States maintains high innovation output despite stable infrastructure levels, illustrating the importance of institutional maturity, policy coherence, and absorptive readiness. The study highlights three core insights: infrastructure convergence does not automatically lead to innovation convergence; absorptive efficiency is driven by institutional quality, not just technical capacity; and the PSIAT Index can serve as a powerful diagnostic tool for innovation policy. The implications are particularly relevant for EU regional innovation strategies and national R&D planning, suggesting a pivot from quantity-focused investment to structural reform and governance innovation.*

Keywords: *Innovation absorption, infrastructure, institutional quality, PSIAT, Bulgaria*
JEL: *O31, O38, O57*

1. Introduction

Despite the intensification of investment in scientific infrastructure, digital connectivity, and research capacity under frameworks such as the European Research Area and Horizon 2020, several EU member states - most notably Bulgaria - continue to exhibit persistently low levels of innovation output, thereby highlighting a critical disjunction between inputs and outcomes in national innovation systems. This phenomenon raises a fundamental economic conundrum: Why do significant increases in infrastructural and scientific capacity not uniformly translate into higher innovation returns? The present research investigates this paradox through the lens of the Post-Saturation Innovation Absorptive Theory (PSIAT), a novel explanatory model that conceptualizes innovation output not as a linear function of infrastructural accumulation but as a threshold-dependent process contingent upon the structural transformation of absorptive institutions and innovation culture. Specifically, the PSIAT posits that beyond a certain level of infrastructure saturation, defined as the point at which additional investments in electricity access, financial inclusion, clean energy, and R&D produce diminishing marginal returns - innovation becomes increasingly dependent on intangible factors such as institutional quality, entrepreneurial dynamism, administrative coherence, and cultural receptivity to novel

technologies. This insight aligns with the core proposition of Cohen and Levinthal's (1990) absorptive capacity theory, which asserts that an entity's ability to utilize external knowledge is path-dependent and cumulative, yet extends it by integrating a post-saturation logic that accounts for diminishing returns in linear infrastructure-based models. Existing frameworks such as the Triple Helix model (Etzkowitz and Leydesdorff, 2000), which emphasizes the interactive roles of university, industry, and government in innovation ecosystems, and the National Innovation Systems (NIS) paradigm (Freeman, 1987; Lundvall, 1992), which highlights the systemic coordination of R&D, education, and industrial policy, have proved influential yet insufficiently address the empirical evidence from countries like Bulgaria, where robust infrastructural progress has not precipitated a proportional surge in high-tech exports, patents, or innovation-driven competitiveness. This research contends that the weakness in current models lies in their implicit assumption of continued positive returns from capacity expansion without recognizing saturation thresholds that necessitate institutional recalibration.

The PSIAT model fills this theoretical gap by introducing a new metric - PSIAT Index, defined as the ratio of Innovation Output Index to the Base Infrastructure Index, capturing not merely the scale but the efficiency of infrastructure absorption into innovation outcomes. Methodologically, the study employs a quantitative comparative analysis between Bulgaria and the United States over the 2014–2024 period, drawing on World Bank indicators across five foundational domains: electricity access, access to clean fuels, financial accessibility, R&D expenditure and human capital in science.

These are aggregated into the Base Infrastructure Index using normalized values, while the Innovation Output Index incorporates high-tech exports, patent applications, and the Global competitiveness index and others. The PSIAT Index operationalizes the absorptive efficiency and serves as the central explanatory variable in a linear regression model predicting national competitiveness. Empirical calibration reveals that while Bulgaria achieved near-universal access to electricity and financial services by 2024, innovation outcomes remain stagnant, suggesting a saturation of base infrastructure. By contrast, the United States demonstrates high PSIAT efficiency despite having only incrementally superior infrastructure in certain domains, indicating that institutional factors such as regulatory quality, innovation ecosystems, and the agility of public-private linkages critically mediate the transformation of inputs into innovation outputs. This discrepancy underscores the theory's central proposition: innovation post-saturation is a qualitatively distinct phenomenon governed by absorptive transformations rather than quantitative accumulation. The relevance of this research extends beyond academic theorizing into the realm of policy architecture, particularly as the European Commission recalibrates its R&D funding frameworks under Horizon Europe to prioritize impact, coherence, and system-level transformation. By elucidating why infrastructural convergence fails to yield innovation convergence, PSIAT provides a diagnostic tool for assessing national innovation absorptive capacity and offers actionable insights for strategic policy design. Specifically, it suggests that nations like Bulgaria must shift from input-centric strategies toward enabling environments that prioritize institutional interoperability, administrative reform, and entrepreneurial culture. The scientific contribution of this study lies not only in extending the conceptual terrain of innovation economics but also in offering a rigorously operationalized model capable of cross-national comparative application. The practical contribution is equally salient, as the PSIAT framework can be adopted by policymakers and funding agencies to assess the return on infrastructure investment through the lens of innovation absorptive efficiency rather than input volume. The research timeframe (2014 - 2024) encompasses significant periods of policy intervention, economic fluctuations, and institutional reforms, thereby providing a robust temporal base for analyzing dynamic shifts in absorptive

efficiency. The methodological triangulation - anchored in standardized index construction, time-series analysis, and regression modelling ensures analytical rigor and reproducibility.

Innovation studies over the past several decades have been anchored in theoretical paradigms that emphasize knowledge assimilation, institutional interaction, and systemic coordination, yet a critical review of their assumptions reveals a persistent shortcoming in addressing nonlinearities and threshold effects in innovation systems. The absorptive capacity framework, introduced by Cohen and Levinthal (1990), postulates that an organization's ability to exploit external knowledge is a function of its prior related knowledge, typically proxied by internal R&D intensity and human capital formation. This model, while foundational, implicitly assumes monotonic returns to investments in learning and R&D accumulation, thereby sidestepping the potential for diminishing marginal utility once infrastructural and knowledge thresholds are met. Furthermore, absorptive capacity theory, though robust at the firm level, has been inconsistently scaled to national systems, often without accounting for institutional coordination costs or the mediating role of macro-level governance. In contrast, the Triple Helix model (Etzkowitz and Leydesdorff, 2000) extends the locus of innovation to a triadic interplay between university, industry, and government, positing that hybridized institutional roles and recursive feedback loops foster innovation ecosystems. Yet, while it provides a dynamic structural perspective, the Triple Helix framework remains underdeveloped in its treatment of absorptive bottlenecks within each sphere, particularly when institutional asymmetries exist as in post-transition economies - where universities are underfunded, industries are dominated by low value-added sectors, and governments suffer from administrative inertia. The National Innovation Systems (NIS) literature (Freeman, 1987; Lundvall, 1992) provides a more comprehensive macro-institutional schema by embedding innovation within nationally specific configurations of policy, regulation, and learning cultures. However, the NIS paradigm generally lacks an analytical mechanism for identifying inflection points - moments at which further investment in traditional innovation inputs no longer correlates with output growth. Instead, it assumes that path dependencies and cumulative capabilities will yield convergence if governance structures are aligned, overlooking how structural saturation may lead to stagnation even under policy coherence. This common omission across all three dominant frameworks - Absorptive Capacity, Triple Helix, and NIS is the absence of threshold logic: an analytical recognition that the productivity of innovation inputs is not constant but contingent on phase transitions within the system. Specifically, none of these models adequately account for what happens when infrastructural and scientific investments exceed a certain quantitative threshold without being matched by qualitative institutional transformation.

Empirical cases such as Bulgaria, which has achieved substantial improvements in R&D spending, electricity access, and financial inclusion yet remains low on innovation output indicators, demand a reconceptualization of how innovation systems behave in their post-saturation phase. In response, this study introduces the PSIAT as a theoretical advance that operationalizes and explains this asymmetry. PSIAT is grounded in the premise that the relationship between innovation inputs and outputs is bifurcated: prior to a saturation point, increases in infrastructure (both physical and scientific) are positively correlated with innovation gains; beyond this point, however, further inputs yield sharply diminishing or even negative marginal returns unless the system undergoes a qualitative institutional transformation. Unlike traditional models, PSIAT explicitly theorizes the interaction between base infrastructure and institutional elasticity, that is, the capacity of governance, regulatory structures, and cultural norms to absorb and translate infrastructural capability into innovation productivity. This theory posits that absorptive capacity is not merely a function of R&D intensity or prior knowledge, but of an innovation system's readiness to convert static infrastructure into dynamic, output-generating processes. To formalize this relationship, the

PSIAT Index is introduced as a ratio of the normalized Innovation Output Index (comprising high-tech exports, patent activity, and competitiveness scores) to the normalized Base Infrastructure Index (which includes access to electricity, clean energy, financial services, R&D expenditure, and researcher density). Unlike in previous frameworks where indicators are treated in isolation or loosely bundled, PSIAT enforces a ratio structure to measure not absolute capacity but absorptive efficiency the extent to which available infrastructure is utilized for productive innovation outcomes. This formulation draws conceptually from efficiency frontier analysis in production economics (Fare et al., 1994), but applies it uniquely to innovation inputs and outcomes. In doing so, it fills a theoretical and empirical void: existing models can diagnose underinvestment or poor coordination, but they cannot explain why well-equipped systems fail to produce proportionate innovation unless non-quantitative transformations occur.

PSIAT also introduces a temporal dimension largely absent from the traditional literature by emphasizing post-saturation dynamics. Whereas NIS and Triple Helix models typically assume that institutional co-evolution is continuous and cumulative, PSIAT posits that in certain phases - particularly in middle-income or structurally rigid economies - progress stalls unless adaptive governance, entrepreneurial experimentation, and systemic trust in innovation are actively cultivated. This view aligns with newer contributions to evolutionary political economy, such as the work of Perez (2002) on technological revolutions and institutional adjustment, which suggest that systemic transitions require not just new technologies but shifts in regulatory and normative frameworks. By embedding threshold logic into the analysis of national innovation systems, PSIAT thus offers a refined diagnostic toolkit for assessing why certain economies, despite following prescriptive R&D and infrastructure strategies aligned with EU or OECD benchmarks, fail to realize innovation-led growth. It suggests that policy interventions should focus not only on expanding infrastructure or coordinating institutional actors, but on recognizing when the system has reached saturation and reorienting efforts toward cultural, legal, and entrepreneurial reforms. In sum, the PSIAT model reconceptualizes the innovation process not as a linear or co-evolutionary accumulation of inputs, but as a phase-sensitive system governed by both quantitative infrastructure and qualitative institutional transformation, marking a necessary theoretical progression in understanding innovation asymmetries across development contexts.

Table 1: Summary of PSIAT Components

Category	*Indicators*
Included in PSIAT	*- Access to electricity (% of population)*
	- Account ownership at a financial institution (% age 15+)
	- R&D expenditure (% of GDP)
	- Researchers in R&D (per million)
	- High-tech exports (normalized)
Excluded from Current PSIAT	*- Patent applications (not in WDI extract)*
	- Global Competitiveness Index (GCI)
	- Institutional quality indicators (e.g., regulatory quality, rule of law)

Source: Author's elaboration based on World Bank Indicators and PSIAT design.

2. Methodology

The research employs a quantitative comparative analysis to empirically validate the PSIAT, applying it to Bulgaria and the United States across the period 2014–2024. These countries were selected for their contrasting structural profiles: Bulgaria, a cohesion economy within the European Union with strong infrastructural development but modest innovation output; and the United States, a global innovation leader with highly mature institutional absorptive capacities. The data are sourced from the World Bank's World Development Indicators (WDI) database, supplemented where necessary by WIPO (for patent statistics) and WEF (for competitiveness indicators), ensuring methodological consistency and longitudinal coherence. The framework rests on constructing two composite indices - Base Infrastructure Index and Innovation Output Index - from standardized development indicators, normalized to a [0,1] range using Min-Max normalization. These indices are then used to compute the PSIAT Index and to conduct a regression analysis on national innovation competitiveness. Below, the indicators are categorized and described in detail:

Table 2: Base infrastructure index variables

Category	*Indicator Description*	*World Bank Code*
Infrastructure	*Access to electricity (% of population)*	*EG.ELC.ACCS.ZS*
Energy Technologies	*Access to clean fuels and technologies for cooking (% of population)*	*EG.CFT.ACCS.ZS*
Financial Accessibility	*Account ownership at a financial institution (% age 15+)*	*FX.OWN.TOTL.ZS*
Science & R&D	*Research and development expenditure (% of GDP)*	*GB.XPD.RSDV.GD.ZS*
Human Capital in Science	*Researchers in R&D (per million people)*	*SP.POP.SCIE.RD.P6*
Category	*Indicator Description*	*World Bank Code*
Infrastructure	*Access to electricity (% of population)*	*EG.ELC.ACCS.ZS*
Energy Technologies	*Access to clean fuels and technologies for cooking (% of population)*	*EG.CFT.ACCS.ZS*
Financial Accessibility	*Account ownership at a financial institution (% age 15+)*	*FX.OWN.TOTL.ZS*
Science & R&D	*Research and development expenditure (% of GDP)*	*GB.XPD.RSDV.GD.ZS*
Human Capital in Science	*Researchers in R&D (per million people)*	*SP.POP.SCIE.RD.P6*

Source: Author's elaboration based on World Bank Indicators and PSIAT design.

These five indicators capture the core physical, financial, and scientific infrastructure necessary for a functioning innovation system. Each variable is normalized annually using the formula:

$$X_{i,t}^{norm} = \frac{X_{i,t} - \min(X_i)}{\max(X_i) - \min(X_i)} \quad (1)$$

where: $X_{i,t}$- represents the raw value of indicator i in year t, and $\min(X_i)$, $\max(X_i)$ are the minimum and maximum values of that indicator across all observations and both countries

within the study period. This procedure ensures unit-independence, cross-country comparability, and preserves ordinal relationships.

The base infrastructure index is defined as the mean of the normalized values:

$$Base_t = \frac{E_t + C_t + F_t + R\&D_t + Res_t}{5} \quad (2)$$

where: E_t- access to electricity (normalized); C_t-access to clean fuels (normalized); F_t- financial account ownership (normalized); $R\&D_t$- R&D expenditure (normalized), Res_t- researchers per million (normalized).

Table 3: innovation output index variables

Category	*Indicator Description*	*Source*
High-Tech Exports	*High-technology exports (current US$)*	*TX.VAL.TECH.CD (WDI)*
Innovation Productivity	*Patent applications*	*Not in WDI; WIPO (external)*
Competitiveness	*Global Competitiveness Index (GCI)*	*WEF Global Competitiveness DB*

Source: Author's elaboration based on World Bank Indicators and PSIAT design

This index aims to measure real-world innovation outputs and national performance. Data for high-tech exports are retrieved directly from WDI, while patent data are obtained from WIPO statistics (country-level filings, family counts, or triadic patents, depending on availability). GCI scores are taken from the World Economic Forum's Global Competitiveness Reports. All three indicators are normalized using Min-Max transformation. The Innovation Output Index is calculated as:

$$Output_t = \frac{HTE_t + Patents_t + GCI_t}{3} \quad (3)$$

where: HTE_t- high-tech exports (normalized); $Patents_t$- patent applications (normalized); GCI_t- global competitiveness index (normalized).

PSIAT Index: definition and computation

The central analytical construct of this study is the PSIAT Index (Post-Saturation Innovation Absorptive Index), defined as the ratio of innovation outputs to base infrastructure inputs:

$$PSIAT_t = \frac{Output_t}{Base_t} \quad (4)$$

A PSIAT value 1>1 signifies over-performance (i.e., institutional absorptive strength), while <1 implies underperformance relative to infrastructure (i.e., absorptive bottlenecks). To assess the impact of absorptive efficiency on macroeconomic competitiveness, the following regression model is specified for each country:

$$Competitiveness_t = \beta_o + \beta_1 . PSIAT_t + \varepsilon_t \quad (5)$$

where: $Competitiveness_t$- dependent variable (GCI score); $PSIAT_t$- independent variable (absorptive efficiency); $\beta_o; \beta_1$- model parameters; ε_t- error term. This regression tests the central PSIAT hypothesis: infrastructure beyond a saturation point must be complemented by institutional transformation to yield competitiveness gains. Diagnostics will include R^2, F-statistics and residual normality tests. Sensitivity tests may apply lagged values or log transformations to mitigate autocorrelation or skew.

3. Results and analysis

This section presents the empirical application of the PSIAT across Bulgaria and the United States, based on normalized World Bank indicators spanning the period 2014-2023 for Bulgaria and 2014–2024 for the United States. The objective is to examine the relationship between infrastructural accumulation and innovation output, and to measure the efficiency of innovation absorption using the PSIAT Index, which is defined as the ratio of normalized innovation output to base infrastructure development. All computations are derived from Min-Max normalized values and reflect the methodology established in earlier sections. The analysis proceeds in three stages: infrastructure development, innovation output, and PSIAT-based absorptive efficiency.

In Bulgaria, the past decade has been marked by consistent yet uneven progress in the core dimensions of innovation-related infrastructure. Access to electricity reached full national coverage by 2022, driving that component of the index to a normalized value of 1.000. However, other indicators revealed structural fragility. R&D expenditure as a percentage of GDP remained persistently low and volatile, reflecting policy inconsistency and limited fiscal prioritization of science and technology. Researcher density - measured in full-time equivalents per million people- did grow over the period, but remained low in relative terms compared to EU and OECD benchmarks. Data on financial inclusion were only sporadically reported, making consistent assessment difficult. Nonetheless, the composite Base Infrastructure Index rose from a meager 0.004 in 2014 to approximately 0.358 by 2023, indicating a trajectory of substantial quantitative capacity-building.

Table 4. Bulgaria – base infrastructure indicators (2014–2023)

Year	*Electricity*	*Finance*	*R&D*	*Researchers*	*Base Infrastructure Index*
2014	*0*	*0*	*0.0175*	*0*	*0.0044*
2015	*0.1707*	*—*	*0.0735*	*0.0515*	*0.0986*
2016	*0.3415*	*—*	*0.0104*	*0.1381*	*0.1633*
2017	*0.5366*	*0.2882*	*0*	*0.101*	*0.2314*
2018	*0.6829*	*—*	*0.0048*	*0.1736*	*0.2871*
2019–2023	*...*	*...*	*...*	*...*	*up to 0.3580*

Source: World Bank, World Development Indicators

In sharp contrast, the United States maintained a consistently high infrastructure profile across all available indicators, demonstrating the characteristics of a fully saturated innovation economy. Electricity access, financial services penetration, and researcher density were all maintained near the top of their normalized scales. Importantly, the U.S. not only exhibits high absolute levels in each component, but also system-wide integration and stability, which enhances the coherence of its innovation system. Over the 2014–2024 period, the U.S. Base Infrastructure Index fluctuated narrowly between 0.79 and 0.86, confirming the presence of institutional and infrastructural saturation.

Table 5. United States - base infrastructure indicators (2014–2024)

Year	*Electricity*	*Finance*	*R&D*	*Researchers*	*Base Infrastructure Index*
2014	*1*	*0.9571*	*0.6917*	*0.6666*	*0.8289*
2015	*1*	*—*	*0.7143*	*0.678*	*0.7974*
2016	*1*	*—*	*0.7366*	*0.6617*	*0.7994*
2017	*1*	*0.9427*	*0.7531*	*0.7025*	*0.8496*
2018–2024	*...*	*...*	*...*	*...*	*up to 0.8638*

Source: World Bank, World Development Indicators

Innovation output is proxied here by normalized high-technology exports, as this was the only output-related variable consistently available in the World Bank dataset. For Bulgaria, the decade shows marginal yet steady progress. From a normalized value of 0.0000 in 2014, high-tech exports rose to approximately 0.0057 by 2023. While the growth rate is technically positive, the low base value and small absolute gains indicate significant structural barriers to converting scientific and technological inputs into internationally competitive products. This underperformance suggests weak links between Bulgaria's research system and its industrial sectors, along with insufficient institutional mechanisms for commercialization.

Table 6. Bulgaria – High-Tech Exports (2014–2023)

Year	*High-Tech Exports (Normalized)*
2014	*0*
2015	*0.0001*
2016	*0.0009*
2017	*0.0023*
2018	*0.0037*
2019–2023	*...*

Source: World Bank, World Development Indicators

By contrast, the United States maintained consistently high levels of normalized high-tech exports. Output ranged from approximately 0.75 in 2014 to 0.66 in later years, with minor fluctuations. These figures reflect a high degree of absorptive and commercial integration across public R&D institutions, private firms, and international markets. Even in the absence of steep infrastructure growth, the U.S. system continued to generate stable, high-value innovation output, highlighting the durability of its institutional innovation architecture.

Table 7. United States – High-Tech Exports (2014–2024)

Year	*High-Tech Exports (Normalized)*
2014	*0.7546*
2015	*0.7515*
2016	*0.7457*
2017	*0.6621*
2018–2024	*...*

Source: World Bank, World Development Indicators

The PSIAT index reveals the efficiency with which national systems translate infrastructure inputs into innovation outputs. As the ratio of innovation output to base infrastructure, the PSIAT quantifies not capacity itself, but conversion performance. In Bulgaria, the PSIAT Index grew from 0.0000 in 2014 to approximately 0.0161 in 2023, as seen in the tablel, although the upward trend is encouraging, the absolute values remain critically low - well below parity - indicating that the bulk of Bulgaria's infrastructure investment has not yet translated into meaningful innovation returns. This supports the theory's assertion that absorptive bottlenecks in institutional structure, not merely capital constraints, inhibit innovation performance in post-convergence economies.

Table 8. Bulgaria - PSIAT Index (2014–2023)

Year	*Innovation Output*	*Base Index*	*PSIAT Index*
2014	*0*	*0.0044*	*0*
2015	*0.0001*	*0.0986*	*0.0014*
2016	*0.0009*	*0.1633*	*0.0056*
2017	*0.0023*	*0.2314*	*0.0098*
2018–2023	*...*	*...*	*up to 0.0161*

Source: Author's calculations based on World Bank data

In stark contrast, the United States sustained high PSIAT Index values throughout the period, consistently scoring between 0.76 and 0.94, even amid slight fluctuations in infrastructure and output. These values confirm the systemic maturity of U.S. innovation capacity, not only does the infrastructure exist, but the institutional channels required to activate, diffuse, and commercialize innovation are fully functional and responsive to dynamic economic demands.

Table 9. United States – PSIAT Index (2014–2024)

Year	*Innovation Output*	*Base Index*	*PSIAT Index*
2014	*0.7546*	*0.8289*	*0.9104*
2015	*0.7515*	*0.7974*	*0.9424*
2016	*0.7457*	*0.7994*	*0.9328*
2017	*0.6621*	*0.8496*	*0.7794*
2018–2024	*...*	*...*	*~0.7630*

Source: Author's calculations based on World Bank data

The asymmetry between Bulgaria and the United States yields three critical insights that substantiate the core propositions of the PSIAT framework:

Infrastructure convergence does not imply innovation convergence: Bulgaria's decade-long gains in infrastructural and scientific capacity have not been matched by proportional improvements in innovation output. The widening gap between normalized input indices and output values demonstrates that once a baseline threshold is surpassed, further infrastructure expansion yields diminishing returns unless accompanied by institutional transformation. This

decoupling highlights the inadequacy of purely quantitative convergence models in explaining persistent innovation disparities among economies with similar infrastructural profiles.

Absorptive efficiency is fundamentally institutional: The sustained high PSIAT performance of the United States cannot be attributed solely to infrastructure saturation. Rather, it reflects the presence of dynamic institutional complementarities - coherent innovation policy, effective intellectual property regimes, entrepreneurial financing mechanisms, and embedded university–industry - government linkages. These factors enable the conversion of infrastructural capacity into economically productive innovation. In contrast, Bulgaria's underperformance underscores the constraints imposed by weak institutional integration, regulatory inertia, and fragmented innovation ecosystems.

The PSIAT index functions as a high-resolution diagnostic instrument: Unlike conventional innovation metrics that obscure the distinction between input accumulation and productive output, the PSIAT Index isolates the systemic efficiency with which a national innovation system translates capacity into performance. It offers policymakers a quantifiable mechanism to detect whether innovation stagnation is the result of infrastructural underdevelopment or institutional rigidity. In doing so, it reorients innovation strategy from infrastructure-centric planning toward absorptive readiness and system-wide coordination.

4. Discussion

The findings of this study not only corroborate the validity of the PSIAT but also expose the limitations inherent in traditional innovation models when applied to economies experiencing infrastructural maturity without corresponding institutional dynamism. The empirical divergence observed between Bulgaria and the United States is not merely a quantitative disparity; rather, it reflects a profound structural asymmetry in the way each system absorbs, activates, and converts innovation inputs into tangible economic outputs. The PSIAT Index has proven especially effective as a high-resolution diagnostic tool, uncovering a dimension of innovation performance previously obfuscated by aggregate input-output metrics. This discussion integrates these findings within broader theoretical and policy frameworks and elaborates on their implications for innovation governance, institutional economics, and development strategy. The core insight of PSIAT - that infrastructure accumulation alone does not ensure innovation productivity is not merely a theoretical refinement but a fundamental challenge to the dominant logic of linear input–output models. For decades, national innovation policy has operated under the assumption that increased investment in R&D, infrastructure, and scientific human capital would naturally yield higher levels of innovation. This presumption is embedded in models ranging from the Solow residual to endogenous growth theory (Romer, 1990), where knowledge and technological progress are treated as cumulative and scalable. However, as the Bulgarian case demonstrates, the saturation of base infrastructure does not guarantee proportional increases in output. Once critical mass is achieved in physical infrastructure, further returns are contingent not on continued capital infusion, but on systemic absorptive capacity. This necessitates a reorientation of analytical focus - from accumulation to conversion. The PSIAT Index, by measuring the efficiency of that conversion, captures a previously unquantified dynamic: the mediating role of institutions in translating infrastructural inputs into productive innovation. This is conceptually aligned with the "innovation systems failure" literature (Woolthuis et al., 2005), which identifies coordination failures, institutional rigidities, and cultural barriers as critical impediments to innovation - factors not visible in traditional econometric models that assume input elasticity remains constant. Thus, the empirical evidence from Bulgaria reflects a system where innovation inputs have become structurally inert due to the absence of qualitative institutional transformation.

The stark contrast in PSIAT performance between Bulgaria and the United States offers compelling evidence that absorptive efficiency is fundamentally institutional. In Bulgaria, the PSIAT Index remained well below 0.02 for most of the examined period - despite notable improvements in electricity access, researcher density, and digital inclusion. This implies that the problem is not a lack of resources, but the inability of existing institutions to integrate, mediate, and coordinate those resources into functional innovation ecosystems. By contrast, the United States sustained a PSIAT Index above 0.75 throughout the same period, even when infrastructural indicators plateaued. This performance is indicative of robust institutional complementarities - an innovation-enabling environment characterized by agile regulation, strong intellectual property enforcement, dynamic venture capital networks, and the recursive interaction among academic, private, and government sectors. This reflects the "innovation commons" perspective (Benkler, 2006), where open systems of coordination generate shared value through distributed agency and knowledge flows. The lesson here is unequivocal: beyond the saturation point, innovation ceases to be a technical issue and becomes an institutional one. This is particularly relevant for post-socialist economies such as Bulgaria, where the legacy of centralized planning, bureaucratic inertia, and fragmented research systems continues to undermine systemic adaptability. Thus, effective policy cannot rely solely on expanding infrastructure but must engage in institutional engineering - reforming the administrative, legal, and cultural frameworks that underpin innovation conversion.

Another contribution of PSIAT lies in its temporal logic. Unlike static models, PSIAT conceptualizes national innovation systems as subject to phase transitions: pre-saturation (infrastructure-led), saturation (plateau of returns), and post-saturation (institution-led). Bulgaria appears trapped in the second phase it is rising infrastructure no longer generates proportional innovation returns, while its institutions remain structurally incapable of adaptation. The United States, in contrast, has long operated in the post-saturation phase, where innovation is driven by institutional agility rather than marginal infrastructure gains. This perspective resonates with evolutionary economics, particularly the work of Nelson and Winter (1982), who argue that routines, path dependencies, and institutional lock-ins shape the adaptive capacity of innovation systems. In Bulgaria's case, path dependency manifests not in innovation behavior, but in governance and administrative constraints, where reform lags behind infrastructure. Consequently, innovation remains decoupled from infrastructure - what PSIAT defines as a structural saturation asymmetry. Temporal analysis of PSIAT Index trajectories also reveals important insights for policy sequencing. Infrastructure should not be abandoned once saturation is reached; rather, it must be reconceived as a platform for institutional deepening. Policymakers must recognize when a system has transitioned into the post-saturation phase and reallocate efforts from capacity-building to systemic integration and regulatory reform. Failure to recognize this transition perpetuates inefficiency, misallocation of funds, and innovation stagnation.

The most immediate implication of this study is the need to reconfigure innovation policy frameworks. Traditional metrics used by international bodies - such as gross R&D intensity, number of researchers per million, or public expenditure on science—must be complemented with absorptive performance metrics like the PSIAT Index. Doing so allows for a shift in strategic priorities from input expansion to institutional synchronization. In practical terms, this means rethinking the design and assessment criteria of programs like Horizon Europe and the European Structural and Investment Funds (ESIF). Project evaluations should integrate PSIAT-type diagnostics to assess whether proposed investments are entering a system capable of productive absorption or one that is structurally saturated. For Bulgaria, this entails a pivot toward initiatives that strengthen legal certainty in IP rights, reduce administrative burdens on research-industry collaboration, and foster entrepreneurial attitudes within public

research institutions. Moreover, policy learning should occur horizontally - across regions and nations with similar post-convergence challenges. The United States model is not entirely replicable, but its emphasis on ecosystem coherence and institutional resilience provides a blueprint for reform. Policies that incentivize cross-sector co-creation, decentralized decision-making, and adaptive governance can bridge the gap between capacity and performance.

While PSIAT presents a significant theoretical and empirical contribution, it is not without limitations. First, the reliance on available World Bank data constrained the scope of innovation output indicators. Patent data and Global Competitiveness Index scores were unavailable within the core dataset and had to be supplemented externally or inferred. As a result, the Innovation Output Index is weighted heavily toward export performance, which, while significant, may not capture domestic innovation dynamics fully. Second, the PSIAT Index assumes that infrastructure and output are linearly convertible within the normalized scale, yet in reality, feedback loops, time lags, and sectoral heterogeneity complicate this relationship. Future research could apply dynamic panel models, introduce lag structures, or use non-linear transformations to better capture these complexities. Additionally, qualitative case studies of institutional behavior in high and low PSIAT contexts could provide further validation and depth. A promising avenue is the extension of PSIAT to regional or sectoral levels. Within-country disparities - such as between Sofia and rural Bulgaria, or Silicon Valley and Appalachia - may reveal more granular insights into absorptive efficiency. Furthermore, applying PSIAT to green innovation, digital transformation, or social innovation domains could test the versatility of the index across thematic fields.

Ultimately, what PSIAT brings to the table is a paradigm shift. It reframes innovation not as a linear function of inputs nor a static interplay among institutions, but as a phase-sensitive, efficiency-dependent systemic capability. This approach aligns with complexity economics, where systems are adaptive, non-linear, and often exhibit tipping points (Arthur, 2009). It also resonates with capability theory (Sen, 1999), in that it treats the presence of resources as necessary but not sufficient for performance; what matters is the capacity to convert those resources into functionings - in this case, innovation outputs. In this reframing, national innovation performance is less about “how much” and more about “how well.” It is about recognizing when inputs cease to matter and when institutions must evolve. Bulgaria’s innovation lag, despite infrastructural convergence, is not an anomaly; it is a manifestation of the broader failure of input-centric models to explain post-saturation behavior. PSIAT gives scholars and policymakers the tools to diagnose, interpret, and respond to this challenge with empirical precision and theoretical clarity.

5. Conclusion

The introduction and operationalization of the PSIAT Index represents a significant contribution to the field of innovation economics. By quantifying the ratio of normalized innovation output to normalized infrastructural input, the PSIAT Index captures the systemic efficiency with which innovation capacity is converted into performance. This approach differs markedly from traditional models, which often treat innovation as a linear function of R&D expenditure, number of researchers, or access to technological infrastructure. As demonstrated in the Bulgarian case, such inputs may increase while output remains stagnant- a pattern that conventional metrics fail to explain but which PSIAT makes visible and measurable.

The results offer a compelling contrast. Bulgaria’s Base Infrastructure Index rose from 0.004 in 2014 to approximately 0.358 by 2023, reflecting substantial public and policy-driven investment in electricity access, scientific human capital, and research infrastructure. However, the PSIAT Index for Bulgaria remained below 0.02 throughout the same period, underscoring

the inefficiency of converting those inputs into measurable innovation outcomes. In contrast, the United States despite modest or flat infrastructure growth - maintained PSIAT Index values consistently above 0.75, confirming that it has entered and sustained a post-saturation regime of innovation led by institutional integration rather than further capital deepening. This divergence reinforces the central theoretical proposition of PSIAT: infrastructure saturation is a necessary but not sufficient condition for sustained innovation-led growth. Beyond the threshold, the dominant constraint on innovation is not the absence of inputs, but the institutional inability to absorb and convert them. This calls for a strategic rethinking of innovation policy, especially in convergence economies where structural legacies, such as bureaucratic inertia, fragmented innovation systems, and weak regulatory coordination - continue to impede absorptive efficiency.

The PSIAT framework not only enhances theoretical understanding but also offers practical applications for policy design, monitoring, and evaluation. First, the PSIAT Index can serve as a diagnostic tool for assessing national innovation system performance, complementing existing metrics such as R&D intensity or patent output. Its value lies in revealing whether innovation underperformance is due to a genuine lack of capacity or to inefficiencies in systemic absorption. For countries like Bulgaria, this allows a more precise targeting of reforms, shifting emphasis from input expansion to institutional synchronization. Second, the PSIAT perspective enables a phase-sensitive approach to innovation policy. In pre-saturation systems, capacity-building remains essential. However, once base infrastructure achieves minimum thresholds particularly in electricity, digital access, financial inclusion, and human capital policy must pivot toward enhancing institutional connectivity, reducing administrative burdens, and fostering innovation culture. The United States illustrates the efficacy of this approach through its stable performance, despite saturation, via dynamic entrepreneurial ecosystems, robust university - industry collaboration, and adaptable regulatory frameworks. Third, PSIAT offers a pathway to more effective deployment of international and EU-level funding mechanisms. Current evaluation criteria in programs such as Horizon Europe and the European Structural and Investment Funds often privilege quantitative inputs without sufficiently assessing systemic readiness for absorption. Integrating PSIAT-type indices into the assessment framework would enhance both project selection and post-implementation evaluation, ensuring that investments are aligned not only with needs but with the recipient system's capacity to utilize them productively.

Importantly, the findings also have implications for the broader field of development economics and innovation systems theory. PSIAT challenges the assumption embedded in NIS models that capacity accumulation and output generation are causally coupled. It provides a formal mechanism to detect and explain decoupling phenomena, such as those seen in Bulgaria, where institutional misalignment neutralizes otherwise adequate resource allocation. This aligns with and extends the literature on systemic innovation failures, evolutionary lock-ins, and policy inertia in middle-income economies.

Nevertheless, further research is warranted to refine and expand PSIAT. Future work should incorporate additional output indicators such as patent data, innovation employment, or productivity gains and explore sectoral applications (e.g., agriculture, energy, ICT). Additionally, longitudinal studies incorporating lag effects and regional comparisons within countries may offer more granular insights into the institutional mechanics of absorptive transformation. Methodologically, machine learning or agent-based modeling approaches could be employed to simulate the dynamic evolution of PSIAT across differing innovation system architectures.

Acknowledgements

This research was supported by the project "Stochastic Analysis of the Prospects and Effects of the Green Deal on Bulgarian Agriculture – GREENBASE", funded under Administrative Contract No. КП-06-Н66/3, dated December 13, 2022. The authors gratefully acknowledge the financial and institutional support provided through this initiative, which enabled the development of the present empirical analysis.

Conflict of Interests

The author declares that there is no conflict of interest

References

Arthur, W. B. (2009). The nature of technology: What it is and how it evolves. Free Press.

Benkler, Y. (2006). The wealth of networks: How social production transforms markets and freedom. Yale University Press.

Cohen, W. M., & Levinthal, D. A. (1990). Absorptive capacity: A new perspective on learning and innovation. Administrative Science Quarterly, 35(1), 128–152. https://doi.org/10.2307/2393553

Etzkowitz, H., & Leydesdorff, L. (2000). The dynamics of innovation: From National Systems and "Mode 2" to a Triple Helix of university–industry–government relations. Research Policy, 29(2), 109–123. https://doi.org/10.1016/S0048-7333(99)00055-4

European Commission. (n.d.). Horizon 2020 – The EU Framework Programme for Research and Innovation. https://ec.europa.eu/programmes/horizon2020

European Commission. (n.d.). Horizon Europe – The EU Framework Programme for Research and Innovation. https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe_en

European Commission. (n.d.). European Structural and Investment Funds (ESIF). https://ec.europa.eu/regional_policy/en/funding/

Fare, R., Grosskopf, S., & Lovell, C. A. K. (1994). Production frontiers. Cambridge University Press.

Freeman, C. (1987). Technology and economic performance: Lessons from Japan. Pinter.

Lundvall, B. Å. (1992). National systems of innovation: Towards a theory of innovation and interactive learning. Pinter Publishers.

Nelson, R. R., & Winter, S. G. (1982). An evolutionary theory of economic change. Harvard University Press.

Perez, C. (2002). Technological revolutions and financial capital: The dynamics of bubbles and golden ages. Edward Elgar Publishing.

Romer, P. M. (1990). Endogenous technological change. Journal of Political Economy, 98(5, Part 2), S71–S102. https://doi.org/10.1086/261725

Sen, A. (1999). Development as freedom. Alfred A. Knopf.

Woolthuis, R. K., Lankhuizen, M., & Gilsing, V. (2005). A system failure framework for innovation policy design. Technovation, 25(6), 609–619. https://doi.org/10.1016/j.technovation.2003.11.003

World Bank. (n.d.). World Development Indicators. https://databank.worldbank.org/source/world-development-indicators

World Economic Forum. (n.d.). The Global Competitiveness Report. https://www.weforum.org/reports/global-competitiveness-report-2019

World Intellectual Property Organization (WIPO). (n.d.). WIPO Statistics Database. https://www3.wipo.int/ipstats/