

# ЭМПИРИЧЕСКИЕ ИССЛЕДОВАНИЯ

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## **R&D and Innovation Mechanisms: A Data-Driven Study of Knowledge and Technology Creation in Europe**

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This study examines the key drivers of knowledge and technology creation output, as well as its subsequent application, across 22 European countries between 2013 and 2020. Utilizing artificial intelligence tools, the analysis incorporates a comprehensive range of variables, including the business environment, creative goods and services, government effectiveness, human capital and research, ICT access, ICT services exports, patent applications by origin, knowledge creation, political and operational stability, and university-industry research collaboration. The research explores the interconnections among these factors and their impact on the critical outcome — Knowledge and Technology Outputs. By applying both multiple regression analysis and machine learning techniques, various models were assessed to identify the most effective approach. The findings reveal that different drivers influence countries with varying levels of Gross Expenditure on R&D (GERD), highlighting significant variation in innovation drivers across countries. Each GERD level exhibits a distinct innovation mechanism, demanding tailored policy approaches. These results underscore the need for the implementation of focused policy measures aimed at boosting innovation and accelerating technological advancement throughout Europe.

**Keywords:** knowledge and technology outputs, innovation, research and development, key drivers, knowledge creation, human capital, university-industry collaboration.

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## Introduction

Innovation is a cornerstone of economic growth and competitiveness in the modern global economy. A critical measure of a nation's commitment to fostering innovation is its Gross Expenditure on Research and Development (GERD), which represents the total domestic spending on R&D across all sectors, including business enterprises, government, higher education institutions, and non-profit organizations. GERD is typically expressed as a percentage of GDP, allowing for meaningful international comparisons. Data for GERD is primarily sourced from reputable institutions such as the UNESCO Institute for Statistics (UIS), the OECD, and the World Bank. This indicator captures both current R&D expenditures (e. g., salaries and operational costs) and capital investments in research infrastructure, providing a comprehensive view of a country's investment in scientific and technological advancement. Higher GERD values are often associated with greater innovation capacity, economic competitiveness, and long-term growth.

This research investigates the relationship between GERD levels and key drivers of innovation, specifically focusing on how different predictors — such as Human Capital & Research, PCT (Patent Cooperation Treaty) Applications, University-Industry Collaboration, and Knowledge Creation — influence Knowledge & Technology Outputs.

Using GERD (Gross Expenditure on Research and Development) as the primary criterion, EU countries are classified into distinct categories based on their R&D investment levels as a percentage of GDP. This categorization provides a clear framework for understanding the varying degrees of commitment to innovation and technological advancement across the region. *Category 1*, defined by a GERD index ranging from 7 to 23, includes

countries such as Bulgaria, Central and Eastern European (CEE) nations<sup>1</sup>, Greece, Poland, and Romania. *Category 2*, with a GERD index between 23 and 39, encompasses the Baltic states, Hungary, Ireland, Italy, Luxembourg, other EU member states, Portugal, and Spain. *Category 3*, characterized by a GERD index of 39 to 55, comprises Belgium, France, the Czech Republic, and the Netherlands. *Category 4*, with a GERD index ranging from 55 to 71, includes Austria, Denmark, and Germany. Finally, *Category 5*, representing the highest GERD index of 71 to 87, features Finland and Sweden, as the leading innovators in the EU.

This GERD-based classification not only highlights the disparities in R&D investment across EU countries, but also underscores the critical role of GERD as a key indicator for assessing innovation capacity and economic competitiveness. By grouping countries according to their GERD levels, the analysis provides a structured approach to understanding how varying degrees of R&D expenditure influence innovation outcomes and technological progress.

The *Knowledge and Technology Outputs* index is a measure used in the context of the Global Innovation Index (GII) to assess a country's ability to transform innovation into tangible results in the field of knowledge and technology, including patents, scientific publications, and the export of high-tech goods and services. It also examines the impact of the knowledge produced, and its contribution to the economy through innovation, as the results of investments in research and development (Leogrande, 2024a). According to world ranking of more than 150 countries, Serbia takes 55<sup>th</sup> place in regard to Innovation Index by Country, 52<sup>th</sup> place in regard to Human Capital and Research Innovation by Country, and 42<sup>nd</sup> place in regard to Knowledge and Technology Outputs Innovation by Country [*World Intellectual...*, 2022].

## Theoretical base

### Knowledge creation as a driver of innovation and competitiveness

A number of studies have shown that innovation and knowledge creation are important drivers of economic growth [Moyo, Phiri, 2024]. Knowledge emerged as an important factor of production function that outweighs the traditional ones of land, labor, and financial capital [Vo, 2012; Khadir-Poggi, Keating, 2013]. In some papers, it is referred to as explicit scientific and technical knowledge, i. e. knowledge that has been formulated, usually presented in written form [Dewantoro et al., 2022]. It is considered the main distinguishing factor for competitiveness in the context of the innovation capacity [Nonaka, 1994].

Innovation is viewed as an intellectual agility driven primarily by competition, an ability to use knowledge and skills, and an ability to build on prior knowledge and generate new knowledge [Khadir-Poggi, Keating, 2015]. The process of innovation consists of the generation of new knowledge and / or the recombination of the existing knowledge in a new way, and its application, in order to create a sustainable and value-adding solutions [Tekic et al., 2013]. Successful innovation requires linking knowledge to operating processes in an effective and efficient way [Schumpeter, 1934]. Innovative knowledge, therefore, is considered to be the applied knowledge which satisfies needs through a radically novel approach

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<sup>1</sup> Central and Eastern European Countries (CEECs) here is a term referring to the group of countries comprising Albania, Croatia, the Czech Republic, the Slovak Republic, Slovenia, and the three Baltic States: Estonia, Latvia and Lithuania.

[Philipson, 2020]. In order for innovation to add value through knowledge, new knowledge must be useful in practice [Kosturiak, 2010; Azizi et al., 2023].

Since innovation is based on the development and application of new knowledge [Leber et al., 2015], knowledge creation and knowledge transfer have significant role in fostering innovation [Khadir-Poggi, Keating, 2015]. Although different knowledge processes have a positive impact on innovation, it has been shown that knowledge creation impacts innovation the most, and fully mediates the impact of other knowledge processes (knowledge sharing etc.) [Andreeva, Kianto, 2011]. According to knowledge-based view theory, knowledge creation and innovation are strongly related [Estate, 2018], and competitive advantage is achieved by organizing, aggregating, and integrating specialized knowledge [Mustapha, 2023].

Knowledge creation implies the creation of new knowledge in general. In terms of scientific and technical knowledge, it is considered an organization's ability to create new knowledge that is useful in continuous organizational processes [Kusumawijaya, Astuti, 2024], in the form of its outputs, which represent a source of competitive advantage [Khadir-Poggi et al., 2017]. Knowledge creation capability includes combining information and knowledge into new knowledge, and perceiving value from the exchange and combination process, which is crucial for improving competitiveness [Zámborský et al., 2023].

As the articulator of knowledge creation and knowledge transfer, knowledge management is posited as the fundamental prerequisite for innovation, and a positive relationship has been demonstrated between the knowledge cycle and innovation performance [Khadir-Poggi, Keating, 2015; Azizi et al., 2023]. It implies generation, dissemination and utilization of knowledge, in the processes of knowledge creation, knowledge storage and retrieval, knowledge transfer and knowledge application [Nonaka, 1995]. From the knowledge management perspective, innovation comes from knowledge creation, whereas commercialization is accomplished by knowledge application, which leads to value creation or performance improvement [Leber et al., 2015]. This is especially important for emerging markets, since significant differences in knowledge transfer and innovation have been noticed between emerging-economies and advanced-economies [Zámborský et al., 2023].

Globalization, competitiveness and knowledge-based economy are considered to be the three powerful economic narratives that have prevailed globally since the 1970s [Eriksson, Van Langenhove, 2021]. Globalization and the interconnectedness of global markets have intensified competition, driving greater emphasis on innovation [Abdi, Senin, 2015]. Innovation, however, exhibits a particular regional diversification. In attempting to deconstruct the "spatial" dimension of innovation, several authors have postulated that different types of "space" produce different sources of knowledge as their competitive advantage [Kogler, 2018]. The estimation of company-level knowledge production function shows that innovation varies across businesses the most due to the country-specific factors [Meriküll et al., 2012]. The Global Innovation Index (GII) shows significant variation between countries, reflecting their ability to distribute the benefits of innovation and the degree of connection with the global economy. It is based on the estimation of knowledge diffusion, in terms of process through which innovation and technological knowledge spread among individuals, companies, and countries, and it is considered to be a crucial component of global competitiveness. According to 2022 data, Serbia scored 35.8, compared to the highest ranked Ireland with a score of 73.3 [Leogrande, 2024b]. In order to drive knowledge creation, government, academic institutions, and industry have been placed in leading roles [Moyo, Phiri, 2024].

### Drivers of knowledge and technology outputs

As one of the key elements of knowledge-based economies, innovation encompasses inputs such as research and development (R&D) investments, and outputs such as patents [Moyo, Phiri, 2024]. The studies have shown that **R&D** and human capital are clearly essential for innovative activity, with the latter being much more effective in driving the creation of knowledge [Marrocu *et al.*, 2013]. R&D facilitate experimentation and improvisation with new knowledge not yet available in the market [Audretsch *et al.*, 2024]. While research implies production of new knowledge by using scientific and technical methods, the term development refers to the adaptation of new knowledge in the context of its use. Knowledge creation and R&D activities are essential for innovation, since they provide continuous development and application of new ideas and technologies. R&D activities generate new scientific and technical knowledge, as the foundation for developing new products, processes, and technologies, transforming knowledge into practical applications and solutions. Investments in R&D are vital for providing environment for knowledge creation, which in turn drives innovation and economic growth [Borrás, Edquist, 2014]. Investments in R&D activities support development of patents, as critical drivers of knowledge creation, fostering scientific advancements, human capital development, innovation, and the overall economy [Florio, 2021].

The shift toward knowledge-based economies, incorporating intangible assets, emphasizes the importance of intellectual property as a critical factor of value creation [Brodzicki, 2024]. **Intellectual property rights** are essential when it comes to the translation of ideas and knowledge into innovations. They contribute to the development of a market system where the generation of economically valuable knowledge is rewarded, as well as to technological change that enhances economic growth, with knowledge creation being a critical factor in competitiveness [Kogler, 2015]. Intellectual property rights are part of intellectual capital that have capability of strengthening the organization's performance [Khadir-Poggi, Keating, 2015]. Patents have been indicators of the character of invention, the concentration of knowledge creation, and the correlation between invention and economic advancement. As the resource of public knowledge [Hermans, Castiaux, 2007], patents track flows of knowledge between inventors, organizations and regions [Kogler *et al.*, 2013]. In regard to this, it has been shown that the channels of inventors' and researchers' professional relationships appear to be very effective conduit of knowledge creation to positively affect patenting activity [Favaro, Ninka, 2019]. The protection of intellectual property rights is fundamental to economic growth, since it provides an incentive for investment in technological innovation R&D [Carayanni, Sipp, 2005].

Intellectual capital is considered to be the core of knowledge-based economies, since it is involved in a dynamic of continuous improvement [Khadir-Poggi, Keating, 2013]. According to one study, people can enhance innovation if being mediated by knowledge management, and **human capital** and knowledge management need to be integrated, because both have been proven to be able to upgrade the value of an organization [Linda *et al.*, 2020]. The value-creation of knowledge depends on the level of sharing knowledge and skills among people across the organization [Azizi *et al.*, 2023]. Knowledge management capacities have a positive influence on organization's intellectual capital, which in turn has a positive influence on its innovative capabilities [Khadir-Poggi, Keating, 2015]. In the person-centric approach to human capital, human capital contains the crucial knowledge in organization, and people are at the origin of its competitive advantage [Khadir-Poggi, Keating, 2013; Leber

*et al.*, 2015]. Human resources can enable the conversion of data into relevant information, which can be transformed into new knowledge, creating new value, which, in turn, can be transformed into innovation through technology transfer [Grimaldi *et al.*, 2025]. It includes the competence and knowledge of individuals, which generate economic value, and plays an important role in fostering innovation, since knowledge creation effectively mediates the impact of human capital on competitive advantages. Human resources management is required to collect and share knowledge, arising from the internal acquisition and diffusion [Linda *et al.*, 2020; Nonaka *et al.*, 2006], which is then used in collaborative processes for creating new knowledge [Kusumawijaya, Astuti, 2024].

It has been shown that **government** involvement can enhance the process of knowledge creation [Zhang *et al.*, 2021]. Governments are considered to be the crucial factors of fostering knowledge creation, providing funding to support R&D activities, establishing policies to encourage research and innovation, developing research infrastructures, facilitating collaboration, addressing market failures, promoting open science, and investing in human capital. These actions collectively enhance the capacity for scientific advancements and innovation [Florio, 2021]. **Political stability** plays an important role in creating an atmosphere favorable for R&D investments, which in turn drives innovation, as well as in facilitating international collaboration and attracting foreign direct investments, which in turn facilitate the introduction of innovative technology and financial resources [Wang *et al.*, 2024].

Information and communication technology (ICT) has a major role in the process of fostering innovation, achieving competitive advantage, and driving economic advancement [Singh, 2022]. From a spatial perspective, the importance of **ICT access** for knowledge transfer and globalization is significant, since local variations in the availability of knowledge still exist [Van Egeraat, Kogler, 2013]. Countries with a developed ICT infrastructure are more likely to see significant growth in technological innovation, and investments in ICT have a considerable influence on innovation performance [Wang *et al.*, 2024]. Although some studies showed that ICT access lack the direct impact on innovation through knowledge creation, the significant indirect contribution was evident, in the form of knowledge transfer and networking. The use of ICT can foster knowledge management processes by acquiring, generating, combining and recombining external knowledge resources. ICT facilitate knowledge creation, providing the exploitation of the analysis of huge amount of data, and knowledge exchange [Grimaldi *et al.*, 2025]. A study showed that information technology infrastructure is essential for effective knowledge management, enabling efficient communication, easy knowledge transfer, faster knowledge creation and organizational memory building [Ko *et al.*, 2019]. ICT have a significant impact on knowledge-based activities, because of the potential capability of ICTs to create a virtual dimension through which individuals can share and create new knowledge [Vaccaro *et al.*, 2009]. By using digital technologies such as artificial intelligence, organizations can revolutionize their approach to knowledge acquisition, storage, and dissemination [Chandratreya, 2025]. The use of ICT is important factor for improving cooperation, knowledge sharing, and access to global markets, as well as for promoting technological innovation and increasing competitiveness [Wang *et al.*, 2024].

Holding a prominent place in knowledge creation and fostering innovation through research and education [Moyo, Phiri, 2024], universities are recognized as engines for regional and national economic growth [Umar, 2024; Zhang *et al.*, 2021]. In order to contribute to innovation, universities must collaborate with other sectors, such as industry, in the knowledge creation processes [Azizi *et al.*, 2023]. **Industry-university research collaboration** gen-

erates new knowledge by bridging research and practical expertise, through publications and patents, with technology transfer as the final product [Zhang *et al.*, 2021]. On the other hand, the feedback and investment from the other parties involved in collaboration contribute to the knowledge creation process [Hermans, Castiaux, 2007]. University-industry collaboration is a vital component of the regional innovation, the successful exploitation of R&D results, and it is fundamental for improving regional competitiveness [Ćudić *et al.*, 2022]. The four main groups of factors that impact university-industry collaboration performance have been identified: institutional factors, which refer to the business environment and government effectiveness and investments in R&D; human factors, which refer to human capital and research; linkage factor, which refers to relationships between universities and industry, and framework factors, which refer to the business infrastructure [Ibid., 2022].

It has been shown that knowledge creation directly depends on a company's problem-solving approach [Ginsberg, 1994], and indirectly on the company's propensity to extract knowledge from its internal and external environments [Soo *et al.*, 2002]. Its significance was confirmed by different studies [Liebeskind *et al.*, 1996]. In knowledge-based view, a good **business environment** is considered to be the one that enables the human capital development, which contributes not only to knowledge production and transfer, but to the overall advancement of business environment [Bratianu, Orzea, 2010], where the employees would operate in a dynamic way, through the profusion of data, information, the circulation of knowledge, and competence [Ferreira da Silva Neto, Lopes La Falce, 2024].

## Methodology

The dataset employed in this study serves as the foundation for our analysis. It comprises data collected over an eight-year period (2013–2020) from the Global Innovation Index (GII) database, which provides comprehensive insights into various dimensions of innovation, including business environment, creative goods and services, government effectiveness, human capital and research, ICT access, ICT services exports, patent applications by origin, knowledge creation, political and operational stability, university-industry research collaboration, and knowledge and technology outputs. By applying both multiple regression analysis and machine learning techniques, various models were assessed to identify the most effective approach. In order to compare and validate the multiple regression analysis models, the Multilayer Perceptron (MLP) neural network method was applied using IBM SPSS. This method facilitates the identification of complex, non-linear relationships among variables, providing a more comprehensive and robust evaluation of the key drivers influencing Knowledge and Technology Outputs (KTO).

## Variables

The GII database constructs its variable indices by aggregating and normalizing data from multiple sources. Each index represents a composite measure derived from sub-indicators, which are weighted and combined into broader categories. The methodology ensures cross-country comparability and a robust assessment of innovation-related factors.

The Business Environment index is derived from the World Bank's Doing Business Report and the World Economic Forum's (WEF) Global Competitiveness Index. It includes sub-indicators such as the ease of starting a business, ease of resolving insolvency, and regulatory quality and burden. The Creative Goods and Services index is based on data from

UNESCO, UN Comtrade, and WIPO, measuring creative goods exports such as design, media, and software, as well as creative services exports in areas like advertising, R&D, and architecture. It also includes national feature film production and other cultural outputs.

Government Effectiveness is derived from the World Bank Governance Indicators and assesses the quality of public services, policy formulation and implementation, and government credibility, including corruption levels. Human Capital and Research is constructed using data from UNESCO, OECD, and the World Bank, incorporating tertiary education enrollment, expenditure on education and R&D as a percentage of GDP, and researcher density per million inhabitants. ICT Access relies on data from the International Telecommunication Union (ITU), with indicators such as internet penetration rate, broadband subscriptions, and mobile phone subscriptions.

The ICT Services Exports index is based on UN Comtrade and ITU statistics, measuring the percentage of ICT services in total exports. Patent Applications by Origin is derived from the World Intellectual Property Organization (WIPO) and quantifies patent filings per country of origin. Knowledge Creation includes patent applications, scientific and technical articles published, and university and research institution output.

Political and Operational Stability is based on World Bank Governance Indicators and the Economist Intelligence Unit (EIU) Risk Ratings, covering political stability, security risks, and business continuity factors. University-Industry Research Collaboration is derived from WEF surveys and measures industry funding for university research as well as the strength of partnerships between academia and businesses.

The Knowledge and Technology Outputs (KTO) index aggregates several dimensions, including knowledge creation through patents and publications, knowledge impact through high-tech manufacturing and innovation diffusion, and knowledge diffusion through high-tech exports, software spending, and trademarks. This structured approach to index construction ensures a comprehensive evaluation of innovation performance, supporting robust comparative analysis across countries.

Each of these indices is normalized (0–100 scale) to allow for cross-country comparisons. Weighting strategies vary, but they typically use principal component analysis (PCA) or expert-determined weights to combine sub-indicators.

In the Global Innovation Index (GII) database, Gross Expenditure on Research and Development (GERD) represents the total domestic R&D spending across all sectors, including business enterprises, government, higher education institutions, and non-profit organizations. It is typically expressed as a percentage of GDP to facilitate international comparisons. GERD data is primarily sourced from UNESCO Institute for Statistics (UIS), OECD, and the World Bank. The indicator captures total intramural R&D expenditures within a country, covering both current costs (such as salaries and operational expenses) and capital expenditures on research infrastructure. Higher GERD values typically indicate greater investment in scientific and technological advancements, fostering economic competitiveness and innovation-driven growth.

*The fundamental hypothesis is that different drivers influence Knowledge and Technology Outputs (KTO) depending on the magnitude of Gross Expenditure on Research and Development (GERD).*

The primary objective of the modeling process, which employs multiple regression analysis, is to identify the most significant drivers influencing Knowledge and Technology Outputs (KTO), with a focus on how these drivers vary across different levels of Gross Expenditure on Research and Development (GERD). By systematically evaluating a wide

range of variable combinations, the study aims to develop a robust and relevant model capable of accurately describing the dynamics of KTO. This approach ensures that the model not only captures the key factors driving innovation, but also provides actionable insights tailored to different stages of R&D investment, from low to high GERD levels. Ultimately, the goal is to offer a comprehensive framework that enhances understanding of how innovation outputs are shaped by varying levels of R&D expenditure and associated drivers.

## Results

### Modeling the drivers influencing KTO in relation to GERD by applying multiple regression analysis

Table 1. Model Summary<sup>b</sup>

Gross expenditure on R&D (GERD)	R	R Square	Adjusted R Square	Std. Error of the Estimate
7–23	,664a	.441	.375	4.83690
23–39	,600a	.360	.316	6.15232
39–55	,718a	.516	.431	5.60345
55–71	,933a	.871	.850	2.58763
71–87	,941a	.885	.843	3.39590

<sup>a</sup> Predictors: (Constant), Knowledge creation, Human capital and research, University / industry research collaboration, PCT international applications by origin

<sup>b</sup> Dependent Variable: Knowledge and technology outputs

In regions with low GERD (7–23), the model has **moderate explanatory power**, meaning R&D investments have some impact on knowledge and technology outputs, but other factors likely play a significant role.  $R = 0.664$ ,  $R^2 = 0.441$ , the model explains 44.1% of the variance in knowledge and technology outputs. After adjusting for the number of predictors, the model still accounts for 37.5% of the variance. (Adjusted  $R^2 = 0.375$ ) F-statistic = 6.707 ( $p < 0.001$ ), so the model is statistically significant.

In this range with GERD (23–39), the model's explanatory power decreases slightly compared to the previous range, possibly because additional external factors (e. g., policies, industry dynamics) influence knowledge and technology outputs.  $R = 0.600$ ,  $R^2 = 0.360$ , which means that the model explains 36% of the variance. Adjusted  $R^2 = 0.316$ , suggesting the predictors explain only 31.6% of the variance. F-statistic = 8.146 ( $p < 0.001$ ), which means that the model is statistically significant.

As GERD increases (39–55), the model's explanatory power improves significantly.  $R = 0.718$ ,  $R^2 = 0.516$ . The model explains 51.6% of the variance. Adjusted  $R^2 = 0.431$ . Still strong explanatory power (43.1%), suggests that predictors are relevant. F-statistic = 6.122 ( $p = 0.002$ ), which means that result is statistically significant. This suggests that R&D investment plays a more direct role in driving knowledge and technology outputs in this range.

For higher GERD values (55–71), the relationship between R&D investment and knowledge / technology outputs becomes extremely strong. This suggests that at this level of R&D investment, the impact is highly efficient and directly contributes to innovation

outputs.  $R = 0.933$ ,  $R^2 = 0.871$ , the model explains 87.1% of the variance, indicating a very strong relationship. Adjusted  $R^2 = 0.850$ , so even after adjustment, 85% of the variance is explained. F-statistic = 42.148 ( $p < 0.001$ ), and it means very strong statistical significance.

At very high GERD levels (71–87), R&D investment almost fully explains knowledge and technology outputs.  $R = 0.941$ ,  $R^2 = 0.885$ , the model explains 88.5% of the variance, showing an even stronger relationship. Adjusted  $R^2 = 0.843$ , so it is still very high at 84.3%. F-statistic = 21.072 ( $p < 0.001$ ), meaning it is statistically significant.

Interpretation of the obtained Coefficients for Different GERD Levels examines how different predictors (Human Capital & Research, PCT Applications, University-Industry Collaboration, and Knowledge Creation) influence Knowledge & Technology Outputs across different levels of Gross Expenditure on R&D (GERD).

The general multiple linear regression equation is:

$$Y = \beta_0 + \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \beta_4X_4 + \varepsilon$$

where:

Y = Knowledge and Technology Outputs

X1 = Human Capital & Research

X2 = PCT International Applications

X3 = University-Industry Research Collaboration

X4 = Knowledge Creation

$\beta_0$  = Constant (Intercept)

$\beta_1, \beta_2, \beta_3, \beta_4$  = Coefficients of predictors

$\varepsilon$  = Error term

At low R&D investment, GERD (7–23), as seen in Bulgaria, Central and Eastern European (CEE) nations, Greece, Poland, and Romania, collaboration between universities and industries is the key driver of knowledge and technology outputs. Other factors are less influential. University-Industry Research Collaboration ( $B = 0.488$ ,  $p = 0.002$ ) is the strongest predictor, with each unit increase leading to a 0.488 increase in outputs. It is highly significant ( $p = 0.002$ ), showing that collaboration is critical at low R&D levels. Knowledge Creation ( $B = 0.236$ ,  $p = 0.225$ ) has positive impact but not statistically significant. Human Capital & Research ( $B = -0.231$ ,  $p = 0.075$ ) has negative coefficient, suggesting an inefficient use of human capital in early-stage R&D. PCT Applications ( $B = -0.034$ ,  $p = 0.846$ ) has no significant impact at low GERD levels.

$$Y = 15.743 + 0.488X_3$$

For the next GERD level (23–39), as seen in the Baltic states, Hungary, Ireland, Italy, Luxembourg, other EU member states, Portugal, and Spain, collaboration between universities and industries remains the primary driver in this range, but knowledge creation starts gaining relevance. University-Industry Research Collaboration ( $B = 0.355$ ,  $p = 0.000$ ) is still the strongest factor, meaning collaboration continues to be crucial. Knowledge Creation ( $B = 0.303$ ,  $p = 0.074$ ) becoming more relevant, but not yet statistically significant. Human Capital & Research ( $B = 0.054$ ,  $p = 0.753$ ) has weak impact. PCT Applications ( $B = -0.029$ ,  $p = 0.622$ ) is still insignificant.

$$Y = 9.681 + 0.355X_3$$

For GERD (39–55), as seen in Belgium, France, the Czech Republic, and the Netherlands, University-Industry Research Collaboration ( $B = 0.384$ ,  $p = 0.029$ ), is still statistically significant and impactful. Knowledge Creation ( $B = 0.196$ ,  $p = 0.243$ ) has positive impact, but not yet significant. Human Capital & Research ( $B = -0.118$ ,  $p = 0.782$ ) has no significant effect. PCT Applications ( $B = -0.006$ ,  $p = 0.964$ ) is still not relevant.

$$Y = 21.266 + 0.384X3$$

For GERD (55–71), as seen in Austria, Denmark, and Germany, knowledge creation and patenting become the key drivers of technology and knowledge outputs, while collaboration loses significance. Knowledge Creation ( $B = 0.361$ ,  $p = 0.000$ ) is the most significant factor. Each unit increase leads to a 0.361 increase in outputs. Strong significance ( $p < 0.001$ ) is showing that at this GERD level, knowledge creation is crucial. Patent activity now plays a major role, PCT Applications ( $B = 0.170$ ,  $p = 0.003$ ). University-Industry Collaboration ( $B = -0.003$ ,  $p = 0.981$ ) is no longer significant, and it suggests that collaboration alone is no longer enough at high R&D investment levels. Human Capital & Research ( $B = -0.270$ ,  $p = 0.247$ ) is still not impactful.

$$Y = 32.383 + 0.361X4 + 0.170X2$$

At very high R&D investment levels (GERD 71–87), as seen in Finland and Sweden, knowledge creation emerges as the primary driver of technology and knowledge outputs. In this range, Knowledge Creation ( $B = 0.517$ ,  $p = 0.004$ ) is the strongest predictor, highlighting its dominant role. Innovation and research outputs become directly dependent on knowledge creation. PCT Applications ( $B = 0.093$ ,  $p = 0.380$ ) is still positive, but no longer significant. University-Industry Collaboration ( $B = 0.104$ ,  $p = 0.583$ ) is now irrelevant. Human Capital & Research ( $B = -0.063$ ,  $p = 0.894$ ) is not significant.

$$Y = 10.208 + 0.517X4$$

*Table 2. Summary Table of Key Factors by GERD Level*

GERD Level	Key Driver
7–23	University-Industry Collaboration
23–39	University-Industry Collaboration (Knowledge Creation emerging)
39–55	University-Industry Collaboration (Knowledge Creation increasing)
55–71	Knowledge Creation & PCT Applications
71–87	Knowledge Creation

For Low GERD (7–55), University-Industry Collaboration is the key driver. At Medium GERD (55–71), PCT Applications and Knowledge Creation start having an impact. At High GERD (71–87), Knowledge Creation dominates. University-Industry Collaboration is the key factor at lower GERD levels (7–55). Knowledge Creation becomes dominant at GERD > 55 and fully takes over at GERD > 71. PCT Applications (Patents) only become significant at GERD (55–71). Human Capital & Research does not play a significant role across any GERD range, suggesting that having researchers alone is not enough — they need funding and structured innovation support.

### Neural network method

In order to compare and validate the model, the Multilayer Perceptron (MLP) neural network method using IBM SPSS was applied. This method facilitates the identification of complex, non-linear relationships among variables, providing a more comprehensive and robust evaluation of the key drivers influencing Knowledge and Technology Outputs (KTO).

In the presented model, the impact of the variables Human Capital & Research, PCT International Applications, University-Industry Research Collaboration, and Knowledge Creation on KTO was analyzed for different levels of investment in R&D (GERD). The training samples are generally larger, which is typical for training predictive models. The testing samples tend to be smaller, especially for the higher GERD levels, which is common in cases with fewer observations. Exclusions are minimal but do exist in the higher GERD levels (55–71 and 71–87).

Table 3. Case Processing Summary

7–23	Training	Sum of Squares Error	5,204
		Percent Incorrect Predictions	28,6%
		Stopping Rule Used	no decrease in error <sup>a</sup>
		Training Time	00:00.0
Testing	Sum of Squares Error	2,500	
	Percent Incorrect Predictions	45,5%	
23–39	Training	Sum of Squares Error	11,917
		Percent Incorrect Predictions	44,7%
		Stopping Rule Used	no decrease in error <sup>a</sup>
		Training Time	00:00.0
Testing	Sum of Squares Error	8,158	
	Percent Incorrect Predictions	52,0%	
39–55	Training	Sum of Squares Error	3,096
		Percent Incorrect Predictions	20,0%
		Stopping Rule Used	no decrease in error <sup>a</sup>
		Training Time	00:00.0
Testing	Sum of Squares Error	,800	
	Percent Incorrect Predictions	12,5%	
55–71	Training	Sum of Squares Error	2,132
		Percent Incorrect Predictions	15,0%
		Stopping Rule Used	no decrease in error <sup>a</sup>
		Training Time	00:00.0
Testing	Sum of Squares Error	2,432	
	Percent Incorrect Predictions	44,4%	
71-87	Training	Sum of Squares Error	2,801
		Percent Incorrect Predictions	21,4%
		Stopping Rule Used	no decrease in error <sup>a</sup>
		Training Time	00:00.0
Testing	Sum of Squares Error	,022	
	Percent Incorrect Predictions	0,0%	

Dependent Variable: Knowledge and technology outputs,

<sup>a</sup> Error computations are based on the testing sample. Stopping Rule Used: 1 consecutive step(s) with no decrease in error

Here is presented a breakdown of the normalized importance scores of each variable across the GERD levels, Figure 1.

**GERD 7–23** (Bulgaria, Central and Eastern European (CEE) nations, Greece, Poland, and Romania):

Knowledge Creation is the dominant factor, followed closely by Human Capital and Research and PCT International Applications. University / Industry Research Collaboration has a much smaller impact, indicating a weaker innovation ecosystem.

**GERD 23–39** (the Baltic States, Hungary, Ireland, Italy, Luxembourg, other EU member states, Portugal, and Spain): In these economies, Human Capital and Research is the most critical factor, suggesting that investment in education and research infrastructure significantly impacts knowledge and technology outputs. Knowledge Creation remains important, while University / Industry Collaboration gains importance compared to lower GERD countries, though PCT International Applications decline in influence.

**GERD 39–55** (Belgium, France, the Czech Republic, and the Netherlands): In mid-GERD economies, University / Industry Research Collaboration emerges as the most influential factor, indicating that innovation ecosystems rely heavily on strong academic-industry partnerships. The reduced importance of Human Capital and Research and Knowledge Creation suggests that these economies may already have a solid knowledge base and benefit more from applied collaboration.

**GERD 55–71** (Austria, Denmark, and Germany): At this level, Knowledge Creation is once again the primary driver, reflecting these nations' mature research environments. University / Industry Collaboration and PCT International Applications are moderately important, while Human Capital and Research becomes less critical, indicating a shift towards applied R&D and innovation commercialization.

**GERD 71–87** (Finland and Sweden): In the highest GERD economies, University/ Industry Research Collaboration takes precedence, suggesting that well-established knowledge infrastructures depend on strong links between academia and industry for technological advancements. Knowledge Creation plays a secondary role, while PCT International Applications are of low importance, possibly due to a shift towards domestic commercialization over international patenting.

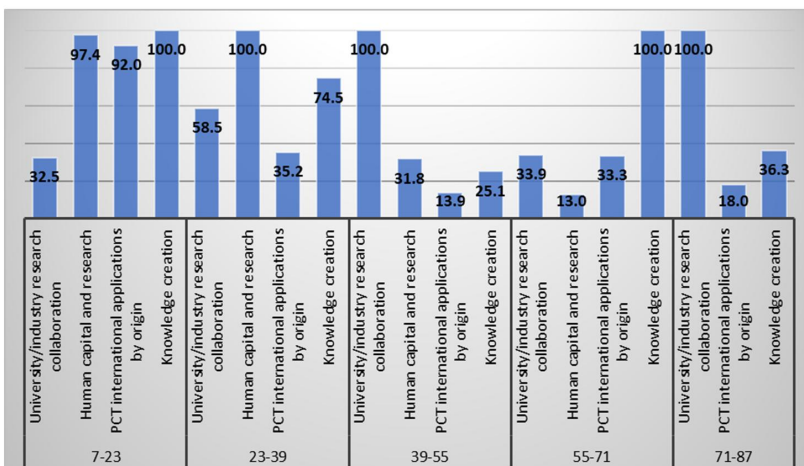


Fig. 1. Normalized importance of each variable across the GERD levels

Knowledge Creation is important across several GERD ranges, with its normalized importance reaching 100% in GERD 55–71 and GERD 7–23. It is a dominant factor in driving knowledge and technology outputs, particularly in medium and high GERD levels.

University / Industry Research Collaboration is crucial at GERD 39–55 and GERD 71–87. It plays a significant role in fostering innovation.

Human Capital and Research is a critical factor in Low GERD (7–23) and Medium GERD (23–39) but its importance diminishes at higher GERD levels.

PCT International Applications by Origin is the most influential in Low GERD (7–23), but it has less impact in higher GERD ranges.

## Conclusion

The findings of this research reveal that different drivers influence countries with varying levels of Gross Expenditure on R&D (GERD), highlighting significant variation in innovation drivers across countries. Each GERD level exhibits a distinct innovation mechanism, demanding tailored policy approaches.

It has been shown that **knowledge creation** has a significant effect on innovation and competitive advantages [Kusumawijaya, Astuti, 2024], and that it is positively associated with economic growth [Moyo, Phiri, 2024]. In this sense, increased investments in research, in order to promote knowledge creation, are recommended in developing and emerging economies, particularly in science, technology, and engineering.

The results of a previous study showed that there were clearly differentiated patterns in the knowledge creation function of the European regions. The less developed regions are, the more important the role of universities in their innovation systems is [Baumert, 2021]. It was mentioned above that four main groups of factors impacting **university-industry collaboration** there had been identified: institutional, human, linkage and framework factors. According to institutional factors, the ranking of countries demonstrates a dominance of North and Western European economies and those “catch-up” economies from Central Europe. Economies of Southeastern Europe occupy the lower ranks. Serbia belongs to the group of economies with a medium level of institutional factors development. Considering human factors, countries with weak indicators knowledge, and a small percentage of spending on R&D sectors (Cyprus, Serbia, Montenegro, North Macedonia, Romania, Bosnia and Herzegovina, Albania) are ranked at the bottom. Serbia shows a medium level of developed linkage factors, and low levels of developed framework factors. In order to improve university-industry collaboration, Serbia should invest more in knowledge, networking, and R&D [Čudić et al., 2022]. In regard to the proportion of R&D investment in universities, cooperative patents, academic entrepreneurship, and the intensity of university-industry research cooperation of enterprises, there are different degrees of gaps compared with major developed countries [Zhang et al., 2021]. It has been demonstrated that for Central European countries partnerships between universities and industry are of great importance for overcoming the skills gap, particularly in technical and digital domains critical to knowledge-intensive businesses. Governments of these countries should create incentives for businesses to invest in R&D and advanced technologies, in order to align with national strategies for innovation [Brodzicki, 2024].

The results of this research align with the findings of previous studies which showed that **human capital** had an effect on knowledge creation, and, as an instrument of innovation,

it directly affected competitive advantages [Kusumawijaya, Astuti, 2024; Shih et al., 2010]. Another study confirmed the importance of investment in **R&D**, and revealed that human capital plays an even greater role in fostering innovative activity and generating inflows of knowledge relevant to region's existing knowledge base, and that the ability of a region to absorb and generate new knowledge depends on human capital and R&D investments [Marrocu et al., 2013].

The previous studies showed, as well, that **IPR** management is one of the key factors for enhancing innovation, together with the R&D activities [Wang et al., 2024], as well as that technological knowledge in the form of patents is a determinant of economic growth [Moyo, Phiri, 2024].

**Political stability** has been considered another important factor of the promotion of innovation, with a robust regulatory and political framework being correlated with a heightened innovation propensity [Wang et al., 2024].

Using multiple regression analysis, it was found that University-Industry Collaboration remains a consistently significant driver at lower GERD levels (7–55). In economies with low GERD (7–39), the model demonstrates moderate explanatory power, accounting for 31–44% of the variance, suggesting that other economic, social, or structural factors also influence knowledge and technology outputs. As GERD increases (39–55), the model's explanatory power improves significantly, highlighting R&D as a stronger driver of innovation. At high GERD levels (55–87), the relationship becomes extremely strong, with  $R^2$  reaching 85–88%, indicating that R&D investment is the dominant factor in knowledge and technology outputs. As this research has shown that the model is insufficiently precise for lower levels (7–55) of investment in R&D activities (GERD), it confirms that other factors make a more significant contribution to innovation (KTO). PCT Applications gain importance at GERD levels of 55–71, suggesting that patent activity becomes more relevant with higher R&D spending. Knowledge Creation emerges as the dominant factor beyond GERD 55, reinforcing the increasing role of research output in driving innovation.

The analysis reveals that the drivers of innovation vary significantly across different levels of Gross Expenditure on Research and Development (GERD), but there are consistent patterns that emerge when combining both methodologies. In low GERD Economies (7–55) University-Industry Collaboration is the key driver of innovation, as highlighted by both methodologies. This suggests that in less research-intensive economies, fostering partnerships between academia and industry is critical for translating research into practical applications and driving innovation. Human Capital and Research does not play a significant role, indicating that merely having a pool of researchers is insufficient without adequate funding, infrastructure, and structured support for innovation. In Medium GERD Economies (55–71) Knowledge Creation and PCT International Applications (Patents) begin to play a significant role, as identified by the multiregression model. This reflects a transition phase where economies begin to focus on generating new knowledge and protecting intellectual property through patents. University-Industry Collaboration remains important, but less dominant compared to low-GERD economies, as the focus shifts towards creating and commercializing new knowledge. In High GERD Economies (71–87) Knowledge Creation becomes the dominant driver of innovation, as confirmed by both methodologies. This indicates that in highly research-intensive economies, the primary focus is on advancing scientific knowledge and leveraging it for technological and economic growth. University-Industry Collaboration continues to play a role, but is secondary to knowledge creation, suggesting that these economies have already established strong innovation ecosystems and

now prioritize pushing the boundaries of research. PCT International Applications lose significance, possibly due to a shift towards domestic commercialization and a reduced emphasis on international patenting.

It can be concluded that University-Industry Collaboration is critical in low- to mid-GERD economies, where the focus is on building innovation ecosystems and translating research into practical applications. Knowledge Creation becomes increasingly important as economies advance in GERD levels, eventually dominating in high-GERD economies where the emphasis is on cutting-edge research and scientific advancement. PCT International Applications are significant only in mid-GERD economies, reflecting a transitional phase where intellectual property protection becomes relevant but is later overshadowed by domestic commercialization and knowledge creation in high-GERD economies. Human Capital and Research alone is insufficient across all GERD levels, underscoring the need for complementary factors such as funding, infrastructure, and structured innovation support to drive meaningful innovation.

Both methodologies highlight the evolving nature of innovation drivers across different stages of research and development investment. While the specific importance of factors like University-Industry Collaboration, Knowledge Creation, and PCT Applications may vary, the overarching trend is clear: as economies advance in GERD levels, the focus shifts from building collaborative innovation ecosystems to creating and commercializing new knowledge. Policymakers and stakeholders should tailor their strategies to align with these evolving priorities to maximize innovation outcomes.

### **Policy Recommendations Based on the Research**

For low GERD economies (7–55), it is essential to prioritize university-industry collaboration. This can be achieved by establishing targeted funding programs and fiscal incentives to foster partnerships between universities, research institutions, and private enterprises. Developing innovation hubs or clusters that integrate academia, industry, and government stakeholders can facilitate knowledge transfer and collaborative R&D projects. Investing in research infrastructure, such as laboratories, technology parks, and innovation centers, is crucial to support applied research and development. Providing grants or subsidies to small and medium-sized enterprises (SMEs) can encourage their participation in R&D activities. Enhancing funding mechanisms by increasing both public and private sector funding for R&D will address gaps in structured innovation support. Introducing tax incentives and competitive grant schemes can stimulate R&D investments by businesses and academic institutions. Additionally, focusing on skill development is vital; while human capital alone is insufficient, targeted training programs can equip researchers and professionals with industry-relevant skills. Aligning educational curricula with the evolving needs of the labor market will ensure a steady pipeline of skilled talent for innovation-driven sectors.

For medium GERD economies (55–71), strengthening knowledge creation should be a priority. Increasing funding for basic and applied research will advance scientific knowledge and drive technological breakthroughs. Supporting interdisciplinary research initiatives can foster innovation across diverse fields and address complex societal challenges. Promoting intellectual property (IP) protection is also critical; encouraging the filing of PCT International Applications through financial support and simplified administrative procedures will help. Offering training and resources on IP management, commercialization, and patent

strategies to researchers and businesses is equally important. Maintaining university-industry collaboration remains essential, with a shift in focus towards commercialization and scaling up innovations. Developing clear frameworks for co-ownership of intellectual property resulting from university-industry partnerships will incentivize collaboration. Fostering a culture of innovation through national campaigns, awards, and recognition programs can promote entrepreneurship. Encouraging risk-taking and experimentation in both public and private sectors by creating supportive regulatory and financial environments will further drive innovation.

For high GERD economies (71–87), doubling down on knowledge creation is crucial. Allocating significant resources to cutting-edge research in emerging fields such as artificial intelligence, biotechnology, and clean energy will maintain global competitiveness. Supporting long-term, high-risk research projects with transformative potential is equally important. Enhancing domestic commercialization by focusing on translating research outcomes into marketable products and services within the domestic economy will maximize economic impact. Providing funding and incubation support for startups and spin-offs originating from academic institutions will further this goal. Streamlining university-industry collaboration to ensure efficiency and focus on high-impact projects is essential. Encouraging industry to play a more active role in co-designing research agendas with academia will align R&D efforts with market needs. Reducing reliance on international patenting by shifting focus from PCT International Applications to domestic IP strategies that align with national economic priorities is advisable. Investing in building robust domestic markets for innovative products and services will ensure the economic impact of R&D investments is fully realized.

Cross-cutting recommendations for all GERD levels include investing in holistic innovation ecosystems that connect education, research, industry, and government stakeholders. Ensuring policies are tailored to the specific strengths and needs of the economy is vital. Improving access to funding through diversified mechanisms, including public grants, venture capital, and private-sector investments, will support R&D and innovation. Creating specialized innovation funds targeting high-potential sectors or technologies can further this goal. Enhancing policy coordination between government agencies, academia, and industry will avoid fragmentation of efforts and ensure alignment of objectives. Regularly evaluating and updating innovation policies based on performance metrics and global trends is essential. Promoting international collaboration by encouraging participation in global research initiatives and partnerships will provide access to new knowledge, technologies, and markets. Leveraging international networks to attract foreign investment, talent, and expertise will strengthen domestic innovation capabilities. Addressing structural barriers by simplifying regulatory frameworks and reducing bureaucratic hurdles for R&D and innovation activities is necessary. Aligning education and training programs with the evolving needs of innovation-driven industries will address skill gaps and ensure a skilled workforce.

In conclusion, the research underscores the importance of adopting stage-specific innovation policies that align with the level of R&D investment (GERD) in an economy. Policymakers should prioritize university-industry collaboration in low-GERD economies, strengthen knowledge creation and IP protection in medium-GERD economies, and focus on cutting-edge research and domestic commercialization in high-GERD economies. By implementing these tailored strategies, governments can maximize the impact of their innovation policies, drive sustainable economic growth, and enhance global competitiveness.

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## **Механизмы НИОКР и инноваций: эмпирическое исследование производства знаний и технологий в Европе**

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В работе исследуются ключевые факторы получения результатов в области знаний и технологий, а также их последующего применения в 22 европейских странах в период 2013–2020 гг. С использованием инструментов искусственного интеллекта анализ включает широкий диапазон переменных, в том числе бизнес-среду, креативные товары и услуги, эффективность действий правительств, человеческий капитал и исследования, доступ к ИКТ, экспорт связанных с ИКТ услуг, патентные заявки по стране происхождения, производство знания, политическую и оперативную стабильность, сотрудничество университетов и промышленности. В исследовании рассмотрены взаимосвязи между этими факторами и их вклад в важнейший итоговый результат в области знаний и технологий. Путем одновременного применения множественного регрессионного анализа и методов машинного обучения были оценены различные модели для выявления наиболее эффективного подхода. Результаты показывают, что на страны с разными уровнями валовых расходов на НИОКР оказывают влияние разные факторы; подчеркнуты значительные различия факторов инновационного развития в разных странах. Каждый уровень валовых расходов на НИОКР представляет собой отдельный механизм инноваций, требуя индивидуального стратегического подхода. Эти результаты акцентируют необходимость реализации адресных стратегических мер, направленных на стимулирование инноваций и ускорение технического прогресса во всей Европе.

**Ключевые слова:** результаты в области знаний и технологий, инновации, исследования и разработки, ключевые факторы, производство знания, человеческий капитал, сотрудничество университетов и промышленности.