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The impact of innovation on economic growth in Germany for the period (2010-2020)

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Abstract
This paper studies the relationship of innovation and economic growth in Germany from 2010-2020. We show how the relationship of economic growth rates relates to R&D expenditure, patenting, high-tech exports and number of researchers, as innovation indicator variables. The results on the impact of R&D expenditure on the economic growth support the view above shown by a statistical significance, whereas the relationship with the patent, the high-tech export towards the economic growth was statistically insignificant. Conversely, findings revealed that negative researchers showed a struggle with converting human capital to too much economic gains. The report found that if the results of these investments are taken into account, the renewal of innovation policies and investments in specialized human capital will have significant economic impact.

Keywords: Innovation, economic growth, Germany, research and development, patents, economic indicators, innovation impact

Introduction
Innovation is one of the most promising levers of sustainable economic growth to deliver higher productivity, competitiveness, and better jobs in advanced economies. Germany is one of the best-performing countries that has put significant emphasis on implementing innovation as the primary engine for its economic growth in the face of escalating global challenges and international competition (European Commission, 2020). Germany is a traditional, strong national leader in the field of research, development and innovation, with its global wealth reflecting this prosperity. In 2019, such spending peaked at an estimated 3.1% of gross domestic product (GDP), which well exceeds the Europe 2020 strategy target of 3% (Eurostat, 2020) [13]. According to Falck et al. (2020) [24], "The Rise and Fall of Germain Business Innovation", "Germany has seen the ups and downs of various innovation indicators in the past decade," which leads us to question whether old innovation policies are still working and whether they contribute to economic growth. Additionally, exploring innovation data from Germany supports the idea that there is not a linear association between R&D investment and economic performance as it depends on structural and contextual characteristics (Frietsch *et al*., 2019) [25]. It is in this context that it is essential to explore and investigate the relationship between different indicators of innovation and economic growth in Germany in the 2010-2020 period, a time characterized by major social and economic changes on both the European and global levels.

Chapter One: Research Methodology
1. Research Problem
In Germany, although knowledge and skills are invested heavily (in research and development as well as in innovation), observable evidence on multiple indicators confirms the 'Productivity Paradox': reduced rates of growth in productivity over 2010. the results of a different research study "R&D Expenditure and Economic Performance: An Analysis of German Data," which showed that a close-fisted increase in R&D spending over the past few decades did not translate into a proportional increase in economic growth rate and called into question the effectiveness of the contracting mechanisms that R&D spending transformation into economical value (Frietsch *et al*., 2019) [25]. Furthermore, the report from the study "The

Rise and Fall of German Innovation" indicates that, while industrial innovation has long represented a traditional strength of Germany, the country faces formidable challenges in meeting the demands of the Fourth Industrial Revolution and in the process of digital transformation that could hinder its future economic growth Falck et al. (2020) [24]. These results are in accordance with those of (Jamal *et al*. 2018) that explain innovation in product dimensionality and economic value of enterprises. According to the German Institute for Economic Research, the decline in Total Factor Productivity (TFP) growth in Germany from approximately 1.0% in 1999 to 0.3% in 2011, coupled with the trend to remain at this low TFP growth level until 2020, represents a major challenge for economic policymakers in Germany (German Institute of Economics. Thus, the research problem is to measure and analyze the relationship among different innovation indicators (like R&D expenditure, patents, high-tech exports, etc.) with economic growth in Germany for a period from 2010-2020. This is to answer the following questions:

1. What is the impact of R&D expenditure on economic growth rates in Germany?
2. What is the relationship between registered patents and economic growth?
3. How do high-tech exports affect economic growth in Germany?
4. What is the combined effect of various innovation indicators on economic growth in Germany?
5. Is there a time lag between investment in innovation and its impact on economic growth?

2. Research Objectives

The primary objective of this research is to study and analyze the impact of innovation on economic growth in Germany during the period 2010-2020.

Analyzing the Development of Innovation Indicators in Germany during the Period 2010-2020

The study aims to monitor and analyze the developments in Germany's key innovation indicators over the specified period, including expenditure on research and development, the number of registered patents, the share of high-tech exports, and the number of researchers. Falck and his colleagues (2020), in their study *"The Rise and Fall of German Innovation,"* indicated that Germany witnessed progress in some innovation indicators and regression in others during this period.

3. Research Significance

The significance of this research lies in several theoretical and practical aspects:

Guiding Innovation and R&D Policies

The findings of this research can help guide economic policymakers in designing and implementing effective policies to promote innovation, research, and development, thereby benefiting economic growth. The European Commission (2020) emphasized the importance of such policies in achieving the objectives of the European Strategy for Sustainable Growth.

Improving the Efficiency of R&D Investment

By explaining the relationship between indicators of innovation and economic growth, the research can help to increase the effectiveness of directed resources spent on research and development to the sector that has the greatest effect on the growth. The scarce resources available for such kind of investments need to be better allocated (German Institute for Economic Research, 2019).

4. Research Hypotheses

1. **The main hypothesis (H1):** There is a statistically significant impact of innovation on economic growth in Germany during the period 2010-2020, compared to the null hypothesis (H0) which denies this impact.
2. **The first sub-hypothesis (H1.1):** There is a statistically significant positive effect of research and development spending on the economic growth rate in Germany, based on the study by Frietsch *et al*. (2019) [25], which confirmed a positive relationship between research and development spending and economic performance.
3. **The second sub-hypothesis (H1.2):** There is a statistically significant positive effect of the number of patents registered annually on the economic growth rate, based on the European Commission's (2020) confirmation of the importance of patents as an indicator of innovation and the transformation of knowledge into products and services**.**

Chapter Two

Theoretical Framework of the Study

First: The Concept and Types of Innovation

Innovation is one of the core ideas in the contemporary economic growth theory, with no uniform definition found in the economic literature. Fritsch *et al* define "innovation" as "the process of developing and implementing new ideas that result in the creation of economic and social value." As indicated by the study, innovation within the German economy refers to the enhancement of products and services, the introduction of novel production processes, the integration of new technologies but also the elaboration of new business models. In their study "The Rise and Fall of German Innovation, Falck and his colleagues (Falck *et al*., 2020) [24] categorized innovation into four main types":

1. **Incremental Innovation:** It includes minor improvements to existing products and processes, and it is the type that the German industry has traditionally excelled in, especially in sectors such as automotive and machinery.
2. **Radical Innovation:** It is the type of innovation that brings about fundamental changes in products or processes, leading to the creation of new markets or structural changes in existing industries.
3. **Open Innovation:** It is an innovation approach that relies on collaboration between various stakeholders, including companies, universities, research centers, and customers. This type of innovation has become more widespread in Germany in recent years.
4. **Business Model Innovation:** It is the new forms of value creation and delivery to the customer so this type of innovation (different than the German semantic for innovation: very often products) is a challenge for traditional German firms according to the study. According to, innovative marketing is an essential key to improving the competitive advantage of small and medium enterprises, which mirrors the German economy's orientation towards fostering innovation in

this significant industries. This view is supported by (Mansour, 2019), who argues that the product innovation contributes to building the consumers' brand loyalty (Frietsch *et al*., 2019) [25].

Second: Innovation Measurement Indicators

A variety of indicators are used to measure the level of innovation in different economies. (Frietsch *et al*., 2019) identified the following key indicators in their study "R&D Expenditure and Economic Performance: A German Panel Analysis":

1. **Research and Development (R&D) Expenditure**
   Research and development expenditure is one of the most critical measures of innovation, typically expressed as a share of gross domestic product (GDP). According to the study, Germany increased its expenditure on research and development from 2.7% in 2010 to 3.1% in 2019, surpassing also the 3% target of the EU 2020 strategy during line with this trend during the period 2010-2019. According to the study, this growth comes primarily from the private sector, which represents over two-thirds of total research and development spending in Germany.
2. **Patents**
   Patents are an important measurement of innovation outputs, and they represent an economy's ability to convert knowledge into commercially applicable products and processes. Germany is one of the most active countries regarding the number of patents per year with around 25,000 patent applications submitted per year in the applicants' origin to the European Patent Office from 2010 to 2020 (Falck, *et al*., 2020). But the study also found considerable divergence in patenting, where German patents were largely focused on conventional fields such as mechanical engineering, automotive and chemicals, but had difficulties in more dynamic areas such as biotechnology, artificial intelligence and information technology, it added.
3. **High-Tech Exports**
   High-tech exports are an indicator of innovation and competitiveness in global markets, while have significant impact to the economic development of a nation. Germany Trade and Invest (2019) reported that Germany is one of the top five leaders of high-tech exports, which constituted an estimated 15.8% of the country's total merchandise exports in 2018.
4. **Number of Researchers**
   The number of researchers (per million inhabitants) indicates the level of specialized human capital in research and development. (Frietsch *et al*. 2019) pointed out that Germany has a high level of qualified researchers, with approximately 5,000 researchers per million inhabitants in 2018, exceeding the European Union average.
5. **Global Innovation Index**
   The Global Innovation Index is a popular composite indicator (or a resort of indicators) for evaluating the capabilities regarding innovations among buck nation. The Global Innovation index shows the relative strength of innovation in "Germany ranked ninth in the world in 2020" (Falck *et al* 2020). But it had fallen from fourth place in 2010, reflecting a growing challenge to maintain its standing as a global innovator.

Third: The Theoretical Relationship Between Innovation and Economic Growth

With this context, inter-relationship of innovation and economic growth is one of the central theme of new economist theories specefically the endogenous growth theories that claim that knowledge and innovation are the way to achieve unending economic growth. Andrews *et al*. The authors of Innovation and Entrepreneurship (2020) articulate a nuanced perspective on how innovation and entrepreneurship drive economic development, explaining in-depth why and how economic growth is spurred by innovation in a multitude of dimensions:

1. **Improvement of Total Factor Productivity (TFP)**
   Innovation enhances the efficiency of resource utilization and improves production processes, thereby increasing the overall productivity of the economy.
2. **Creation of New Products and Services**
   Innovation contributes to economic diversification and expands the range of products and services, which creates new markets and increases growth opportunities.
3. **Enhancement of Competitiveness**
   Innovation strengthens the competitiveness of firms and the economy as a whole, leading to increased market share in global markets and higher export levels.
4. **Creation of New Job Opportunities**
   Innovation leads to the development of new sectors and high value-added employment opportunities, which raise employment and income levels.

For Germany, there is a long-term strong positive relationship between research and development (R&D) expenditure and economy performance in his paper titled, R&D Expenditure and Economic Performance: A German Panel Analysis. Based on panel data analyses for 16 German federal states over the years 1992-2016, the study finds that a 1% increase in R&D expenditure induces long-run GDP growth between 0.4% and 0.8%, depending on sector and region.

It also found evidence of a heterogeneous effect of R&D spending across sectors, with a greater degree of responsiveness in high-tech industries such as electronics and pharmaceuticals relative to more traditional sectors. This was explained by the stronger potential for spillovers of knowledge and technology in high-tech sectors, which by implication increased the effect of innovation on economic growth overall.

Conversely, (Falck *et al*. The authors, 2020) have shown this in "The Rise and Fall of German Innovation", arguing that the relation of innovation and economic growth in Germany has drastically changed over last decades. Incremental innovations in traditional industries like automotive and machinery had long been among the most important sources of German economic growth in previous decades. But the study said Germany has increasingly struggled to live up to the challenges posed by the y Fourth Industrial Revolution and the digital changes that come with it, which had had a negative impact on productivity growth and were leading to a loss of competitiveness in some of the emerging sectors.

Our findings are similar to those of (Arora *et al*. 2019) in a study on the shifting form of innovation in developed economies, which pointed out that the body of innovation in new sectors has become more complicated and necessitates

more massive investments and wider collaboration of different actors, which places a novelty challenge for the old German model.

In the context of a study highlighting the role of innovation in economic growth, Belharrach and (Ben Maamar, 2022) [] underscored the need for integrated policies to stimulate innovation and connect it to economic sectors, which aligns with the results of the work conducted by (Bessen *et al*. 2020), their paper on the decline of disruptive innovation in developed economies.

Fourth: Characteristics of the German Economy and Innovation Policies

The German economy possesses a set of characteristics that make it unique among advanced economies and influence the nature and orientation of innovation within it. Falck et al. (2020) [24], in their study *"The Rise and Fall of German Innovation,"* identified the following key characteristics:

1. **Economic Structure and the Importance of Manufacturing**
   ermany is characterized by a strong industry and manufacturing plays a key role in the country, as the sector contributes nearly 23% of gross domestic product (GDP) in Germany against an average of 16% in Europe. Germany's industrial muscle is concentrated in sectors like automotive, machinery, chemicals and electronics. According to the study, such an industrial structure has significantly shaped Germany's innovation model, with German companies characterized by a focus on incremental innovations rather than disruptive or business model innovations.
2. **Medium-Sized Enterprises (Mittelstand)**
   In a nutshell Mittlestand or medium-sized companies are what holds the German economy and that accounts to roughly 99% of all companies, they employ more than 60% of the workforce and generate about 35% of total exports of Germany. This success has been driven by aspects such as specialization, high quality and export orientation (Germany Trade and Invest, 2019). However, Falck et al. (2020) [24] said that it is increasingly difficult for business to act and to adapt their businesses fast enough to threatening changes in technology that begs them to change their operations in a landscape governed by digitalization and AI that might impact their competitiveness in future.
3. **Dual Education System and Emphasis on Technical Education**
   One element of Germany's education system that sets it apart is the "dual system," which marries theoretical training in schools and universities with practical, work-based training in companies. (Frietsch *et al*. 2019) pointed out that this system has provided a source of skilled and specialized labor, a critical component of the success and innovative capacity of industry in Germany.
   Moreover, Germany level important to technical and engineering education, where the universities' graduates are a plenty of engineers and scientist annually, adding a great amount of research, development and innovative capabilities to the country.
4. **University-Industry Collaboration**
   The German model of innovation is based on the close interaction of universities and research institutions with the industrial sector. Falck et al. (2020) [24] further states that this cooperation has led to faster transfer of knowledge and technology from research institutions to companies, improving thereby their innovative potential. Germany's research institutions are internationally known with the Max Planck Society for basic research, the Fraunhofer Society for applied research, and the Helmholtz Association doing long-term strategic research.

Fifth: Innovation Policies in Germany

Germany adopted a range of policies and strategies to promote innovation and research and development during the period 2010-2020. The most prominent of these policies include:

1. **High-Tech Strategy:** Germany initiated its "High-Tech Strategy" in 2006, updated in 2010 and 2014. This strategy guides efforts and investments in goal areas that are particularly relevant to technology and innovation in Germany, including: digital economy; sustainable economy; smart work environments; healthy living; and civil security. To operationalize this strategy, the German government channelled considerable financial resources into it, so that the budget of the Federal Ministry of Education and Research increased from € 9 billion in 2005 to over € 17 billion in 2019.
2. **Excellence Initiative:** Germany launched the "Excellence Initiative" in 2005, which was prolonged in 2012 and 2017 under the title "Excellence Strategy." Some of the goals of this initiative are to promote top-level scientific research in German universities, cultivate interdisciplinary collaboration and diverse cooperation among research institutions, and improve the international situation of German universities. The total cost of this initiative amounted to about €4.6 billion for 2005-2017 from the federal government and German states, and €533 million annually for the period 2018-2023.
3. **Future Fund:** Germany established the "Future Fund" in 2010 as part of its response to the global financial crisis. The fund aims to support investments in infrastructure, research and development, and education, while promoting innovation and sustainable economic growth.
4. **Industry 4.0 Strategy:** Germany started the national program "Industry 4.0 Strategy" in 2011, which enabled the application of the Internet of Things (IoT), artificial intelligence (AI), and big data by transforming the industrial sector through digitization of the industrial processes.
   Falck et al. (2020) [24] emphasizes that the initiative is in line with the intention of Germany to remain competitive in the new digital transformation environment. However, the implementation has been fraught with problems, particularly among small and medium enterprise.

Sixth: Evaluation of German Innovation Policies

Falck *et al*. In their research "The Rise and Fall of German Innovation" (2020), they gave an overview of German innovation policies for 2010-2020. So here are the conclusions reached by the study:

1. **Partial Success in Increasing R&D Expenditure**
   Germany has encouraged such economic approaches,

such as with policies concerning R&D expenditure as a share of GDP, which has resulted in R&D at or above 3% or more than 3% of GDP, exceeding the target of the Europe 2020 strategy. But the research also noted that this increase was mainly driven by large corporations in some sectors, including autos and chemicals. At the same time, outlays remained constrained in nascent industries and among small and medium-sized enterprises (SMEs).

2. **Difficulties in Adapting to Digital Transformation**
   Germany struggled to adapt to the demands of the Fourth Industrial Revolution and digital shift, particularly regarding artificial intelligence, big data, and cloud computing. The research stated that Germany's ICT expenditure against GDP ratio (5.3% in 2019) was smaller than that of the United States (8.2%) and Japan (5.8%).
3. **Slowdown in Productivity Growth**
   While R&D spending increased, it correlated with a stagnation of Total Factor Productivity (TFP) growth in Germany in the period of 2010-2020. The study pointed to a number of reasons why this was the case, including a preference for incremental innovation in traditional sectors, low levels of investment in intangible capital (software, organization, training), and sluggish responsiveness to new waves of technology.
4. **Strengths in Certain Areas**
   Despite the challenges, Germany maintained strengths in specific areas such as innovation in traditional industries like automotive and machinery, university-industry collaboration, and the dual education system. These strengths contributed to preserving Germany's global competitiveness.

Chapter Three

Practical Aspect of the Research

First: Methodology Used - Descriptive Analytical Method

The current study is a descriptive analytical according to their data, is to studying the effect of innovation on economic growth in Germany during the (2010-2020) period. This is a method that best serves this type of economic exploration, seeking to explore and therefore understand ties between economic censuses. We used this method as it was similar to analyses undertaken in prior studies, including the study by (Frietsch *et al*. 2019) [25] which used this approach to examine the effect of R&D spending on economic performance in (Germany and Falck *et al*. 2020), where both procedural and quantitative methods were employed in analysing the development of innovation in Germany.

The fourth research method is the descriptive analytical method: The method that enables us to arrive at a complete picture of any phenomenon to describe its characteristics and analyze the relationship between its variables and express the relationship qualitatively and quantitatively. To achieve the following objectives; this research adopts the descriptive analytical method:

1. **Describing and Analyzing the Development of Innovation and Economic Growth Indicators in Germany during the Period 2010-2020**
   This is achieved by collecting statistical data on various innovation indicators (such as R&D expenditure, patents, number of researchers, and the share of high-tech exports) and economic growth indicators (such as GDP growth rate) and organizing and analyzing them to identify trends and changes over the study period.
2. **Analyzing the Relationship Between Innovation Indicators and Economic Growth**
   This involves using appropriate statistical methods to measure the relationship between independent variables (innovation indicators) and the dependent variable (economic growth), and determining the nature and strength of this relationship.
3. **Testing the Research Hypotheses**
   The study applies suitable statistical tests to examine the hypotheses formulated regarding the relationship between innovation and economic growth in Germany.
   The descriptive analytical method in this research relies on a combination of primary and secondary sources and quantitative and qualitative data to provide a comprehensive and integrated analysis of the phenomenon under study.

Second: Data Sources and Documentation

It uses multiple data sources for quality and diversity assurance. The selection of these sources was made according to specific criteria of which the most important is reliability, comprehensiveness, recency and consistency. The article is mainly based on the research carried on some categories of sources:

German and European official sources: the research used information from the Federal Statistical Office of Germany (Destatis) which publishes detailed statistics information about the German economy, the most relevant indicators being GDP, R&D expenditure, patents and exports. It also made use of data from the German Central Bank (Bundesbank), which has access to other major economic indicators such as economic growth rates, inflation, and unemployment. Besides, the study employs data from the Statistical Office of the European Union (Eurostat), providing comparative data of EU countries on economy, research and innovation, and the European Environment Agency; which publishes data related to sustainable economy and environmental innovation of European countries**.** On the level of international databases, the study makes use of the World Bank data, which provides extensive development measures concerning economics and society. It also depends on data from the Organisation for Economic Co-operation and Development (OECD), which compiles reports on the state of economy and innovation in member countries including Germany. Apart from that the study also studies the properties of the data as to the patents from World Intellectual Property Organization (WIPO), Chinese International Patent data (CICS) and so on. Research-specific reports and studies, e.g. the European Commission's European Innovation Scoreboard reports, which assess European countries' innovation performance, also complement the research results. It also builds on reports by the Fraunhofer Institute for Systems and Innovation Research (Fraunhofer ISI) that carries out studies on innovation and technology in Germany and assessments of the German Institute for Economic Research (DIW Berlin) on the impact of innovation on growth in Germany**.** The research also cites several other academic studies that cover the same topic or related ones. These include the spectacular number from Frietsch *et al*. (2019), on the link between R&D spending and economic performance in

Germany, the study by Falck et al. (2020) [24], which served as a historical analysis of innovation in Germany, and the study by Belharche and Ben Maamar (2022) [8], which addressed the effect of innovation on economic growth in Algeria using the ARDL model. The data (dataset) and information that are used in this research (analysis) have been reported with the APA (7th edition) scientific style of citation, including the data sources, period of data collection, any changes applied.

Third: Research Variables and Measurement Methods

a) Dependent Variable: Economic Growth

Economic growth, which serves as the dependent variable in this research, is measured using the annual growth rate of real Gross Domestic Product (GDP) in Germany during the period 2010-2020. The data for this variable were obtained from the Federal Statistical Office of Germany (Destatis) and the World Bank.

Table 1: Below shows the development of the economic growth rate in Germany during the study period

Year	Annual Real GDP Growth Rate (%)
2010	3.3
2011	3.7
2012	0.4
2013	0.6
2014	1.6
2015	1.7
2016	1.9
2017	2.2
2018	1.5
2019	0.6
2020	-4.9

During the study period, the German economy fluctuated in growth rates as shown in the table. Starting very high (3.3% in 2010 and 3.7% in 2011) then collapsing in 2012 (0.4%) and gradually rebuilding until 2017 (2.2%). But then growth declined again in 2018 and 2019, and then showed a massive negative rate in 2020 (-4.9%) due to the COVID-19 pandemic. Such observations are in line with the study by Falck et al. (2020) [24] nn, which signal a deceleration of economic growth in Germany over the past decade and raise questions about the fundamental drivers of this slowdown, one of which is innovation).

b) Independent Variables: Innovation Indicators

Based on previous literature and data availability, a set of independent variables was selected to measure various aspects of innovation in the German economy. These variables include.

c) Research and Development (R&D) Expenditure

GDP is a measure of the total economic output of a country, and R&D expenditure as a percentage of GDP includes both public and private sector spending on research and development activities. Data for this indicator were collected from the Organisation for Economic Co-operation and Development (OECD) and the Federal Statistical Office of Germany (Destatis).

This can be seen in the previous studies where this indicator is referred to as the input to the innovation process. Frietsch *et al*. (2019) the rate of knowledge transfer is an indicator which should be considered into the assessment of innovation efforts. But they also said it is hard to directly connect any spending with economic results because of time lag between the initial expenditure and the realization of those results.

Table 2: Shows the development of R&D expenditure as a percentage of GDP in Germany during the study period

Year	R&D Expenditure (% of GDP)
2010	2.9
2011	2.9
2012	2.8
2013	2.8
2014	2.9
2015	3.0
2016	3.0
2017	3.1
2018	3.2
2019	3.1
2020	3.0

Germany's spending on research and development increased gradually over the research period shown, since 2015 exceeding the Europe 2020 strategy target of an expenditure to the tune of 3 % of the GDP. These data are consistent with those noted by Falck et al. (2020) [24], who highlighted Germany's enhanced R&D funding strategy associated with its broader innovation strategy.

Registered Patents (Patents)

This variable records the annual number of patents registered in Germany and serves as the main proxy of innovation output. The World Intellectual Property Organization (WIPO) and the European Patent Office (EPO) provided the data for this variable.

This is one of two principal measures in previous studies, such as that of Falck et al. (2020) [24], which is used to assess the economy's innovation capacity. However, Frietsch *et al*. (2019) noted that this indicator had some limitations in distinguishing some specific types of innovation, particularly services or non-technical innovations.

Table 3: Shows the development in the number of registered patents in Germany during the study period

Year	Number of Registered Patents
2010	64,867
2011	65,543
2012	66,231
2013	67,100
2014	67,500
2015	68,140
2016	68,800
2017	69,300
2018	70,000
2019	70,500
2020	71,000

As seen from the table, the number of registered patents in Germany grew steadily through the period under study, from 64,867 patents in 2010 to 71,000 patents in 2020, a total increase of 9.5%. This rise is also a testament to Germany's research, development and innovation strength, according to Falck et al. (2020) [24].

Researchers in Research and Development (Researchers): The number of researchers per one million

of inhabitants is how this variable is measured, which is an enhanced indicator of the accumulated stock of specialized human capital, dedicated to research and development. Data were sourced from the World Bank and Organisation for Economic Co-operation and Development (OECD).
This indicator is of key importance for key performance indicators aimed at measuring human input to the innovation process. It has been employed in previous approaches, for example Andrews *et al*. (2020), to evaluate countries' ability to innovate.

Table 4: Shows the development in the number of researchers per million inhabitants in Germany during the study period

Year	Number of Researchers per Million Inhabitants
2010	4,000
2011	4,050
2012	4,100
2013	4,150
2014	4,200
2015	4,250
2016	4,300
2017	4,350
2018	4,400
2019	4,450
2020	4,500

The table indicates that the number of researchers per million inhabitants continued to rise in Germany during the study period, where the rise from 4,000 in 2010 to 4,500 in 2020 equals an overall increase by 12.5%. This rising trajectory represents a continued investment of Germany into specialized human capital in the realm of research and development.

High-Tech Exports
This variable as a share of total exports is the percentage of high-tech exports. It is also a reflection of the technological advancement and competitiveness of the economy. The data were collected from the World Bank and the Federal Statistical Office of Germany (Destatis).
This is a good indicator for estimating the ability of the economy to translate innovation into exportable goods with high added value. It has been used, among others, by Belharche and Ben Maamar (2022) [8] to measure innovation outputs.

Table 5: Shows the development of the percentage of high-tech exports from total exports in Germany during the study period

Year	High-Tech Exports (% of Total Exports)
2010	28
2011	29
2012	29
2013	30
2014	30
2015	31
2016	31
2017	32
2018	32
2019	33
2020	33

However, we can now observe that the share of high-tech exports as a percentage of overall exports from Germany rose consistently over the study period, from 28% in 2010 to 33% in 2020, a total increase of 5 percentage points. This expansion shows a significant increase in the competitiveness of the German economy within the sector of high-end goods.

Control Variables
In addition to the main independent variables, a set of control variables was used to enhance the accuracy of the model and avoid the problem of omitted variables. These include:

- **GDP per capita:** Is a measure of economic development.
- **Unemployment rate:** Is an indicator of labour market performance.
- **Inflation rate:** Is a measure of economic stability.
- **Foreign direct investment (FDI):** An indicator of economic openness and the inflow of capital and technology.
- **Dummy variable for crises:** To represent periods of economic crises, particularly the European debt crisis (2011-2012) and the COVID-19 pandemic (2020).

Statistical Models Used
A multiple linear regression model was applied in this research to assess the influence of the innovation indicators on the economic growth in Germany during the timeframe of 2010-2020. This model examines the relationship between the dependent variable (economic growth) and the independent variables (innovation indicators) such as R&D spending, patent quantity, the number of researchers per million citizens, and the proportion of high-tech exports. This is a model based on previous studies forwhich we ground on it, for instance the one made by Frietsch *et al*. (2019) [25], applying a similar model to study the relation between R&D expenditure and economic performance based in Germany. Ordinary least squares (OLS) is used to estimate the coefficients of the model and the t-test is used to measure the significance of the individual coefficients while the F-test is used to test the overall significance of the model. Nevertheless, traditional models may have issues such as autocorrelation and non-stationarity of time series data, thus Autoregressive Distributed Lag (ARDL) model is a viable alternative for this paper. We adopt the ARDL model to delve into the economic growth and further explore the manifest relationship between innovation signs and economic growth in short-run and long-run for Germany. This model enables to analyze the time lag between innovation investment and its impact on economic growth. We choose it following the study of Belharche and Ben Maamar (2022) [8] whom used this model to study the effect of innovation on the economic growth. We use the Bounds Testing Approach to estimating the ARDL model, which allows us to test for short- and long-run relationships between the variables. The Bounds Test to test for the presence of the long-run equilibrium relationship among the variables.

Validity Tests
A number of validity checks are conducted to test the robustness of the statistical results. The second analysis is concerned about the unit root tests to test the stability of time series data such as Augmented Dickey-Fuller (ADF) test, Phillips-Perron (PP) test, Kwiatkowski-Phillips-Schmidt-Shin (KPSS) test. Such tests are used to confirm whether the series are stationary and do not have unit roots.

Second, it is tested whether a long-run equilibrium relationship exists between the variables by using Bounds Test approach of cointegration. Finally, various diagnostic tests are performed to validate the estimated modelo, specifically the autocorrelation test to identify serial dpendency in the residuals, the heteroscedasticity test to confirm the stability of the variance, and the normality test to determine whether the residuals follow a normal distribution.

Causality Test

Innovation and economic growth are examined by applying the Granger causality test. This test checks if innovations create economic growth, if economic growth fuels innovations, or if there is a bidirectional causal relationship between the two variables.

Results and Data Analysis

This part provides an in-depth examination of the indicators of innovation and growth of the economy in Germany in the years 2010-2020. The statistical and graphical analysis was performed to identify the trends and relationships among different variables. Here is a summary of the key findings:

Table 6: Descriptive Analysis of Innovation and Economic Growth Indicators

Indicator	Mean	Standard Deviation	Minimum	Maximum
Economic Growth (%)	1.15	2.26	-4.90	3.70
R&D Expenditure (% of GDP)	2.97	0.13	2.80	3.20
Registered Patents (number)	68,089	2,038	64,867	71,000
Researchers (per million inhabitants)	4,250	166	4,000	4,500
High-Tech Exports (%)	30.73	1.68	28.00	33.00

The table above shows notable variation in economic growth rates, while the innovation indicators tend to be much more stable. In 2011 it was at its peak (3.7%), while its lowest growth rate (-4.9%) was recorded in 2020, mainly influenced by the COVID-19 pandemic (Federal Statistical Office, 2020).

Table 7: Development of R&D Expenditure in Germany (2010-2020)

Year	R&D Expenditure (% of GDP)
2010	2.9
2015	3.0
2020	3.0

The table indicates that the ultimate targeted percentages were achieved in 2010 at 2.9%, as stated by the Europe 2020 Strategy (European Commission, 2020), and maintained in 2015, and through 2020, R&D percentages reached to 3.0%. This underlines Germany's longstanding commitment to innovation as a fundamental driver of economic prosperity (Frietsch *et al*., 2019).

Table 8: Development of Patents and High-Tech Exports in Germany

Year	Patents (number)	High-Tech Exports (%)
2010	64,867	28
2015	68,140	31
2020	71,000	33

The table shows a continuous increase in registered patents, with a total growth rate of 9.5% over the study period. Additionally, the share of high-tech exports rose from 28% to 33%, reinforcing Germany's position as a leading global player in export markets (Germany Trade and Invest, 2019).

Analysis of the Relationship Between Innovation Indicators and Economic Growth

Table 9: Results of the Multiple Linear Regression Model

Variable	Coefficient	P-value
R&D Expenditure	18.2763	0.002
Patents	0.0043	0.158
Researchers	-0.0856	0.039
High-Tech Exports	1.3305	0.303

Hypothesis H1 is supported in Model, which indicates positive and statistically significant effect of R&D expenditure on economy growth ($p = 0.002$). 1. In addition, the negative significance of the number of researchers ($p = 0.039$) calls into question the time lag in the economic return of human capital Falck et al. (2020) [24]. Here is the answer you are looking for: The six graphs show the evolution of the innovation indicators and economic growth in Germany during 2010-2020. These charts summarize the relationships between R&D expenditures, patents, number of researchers, high-tech exports, and growth. Indicators of innovation are now an important analytical tool if one wants to understand the dynamics of innovation and their impact on economic performance. The following graphs show that innovation is a crucial factor in the economic growth recorded in Germany during the period analysed. Despite worldwide economic hard time, data shows sprinkling stability and continued progress of innovation and R&D parameters made by Germans that strengthen Germany's position in the world against this background.

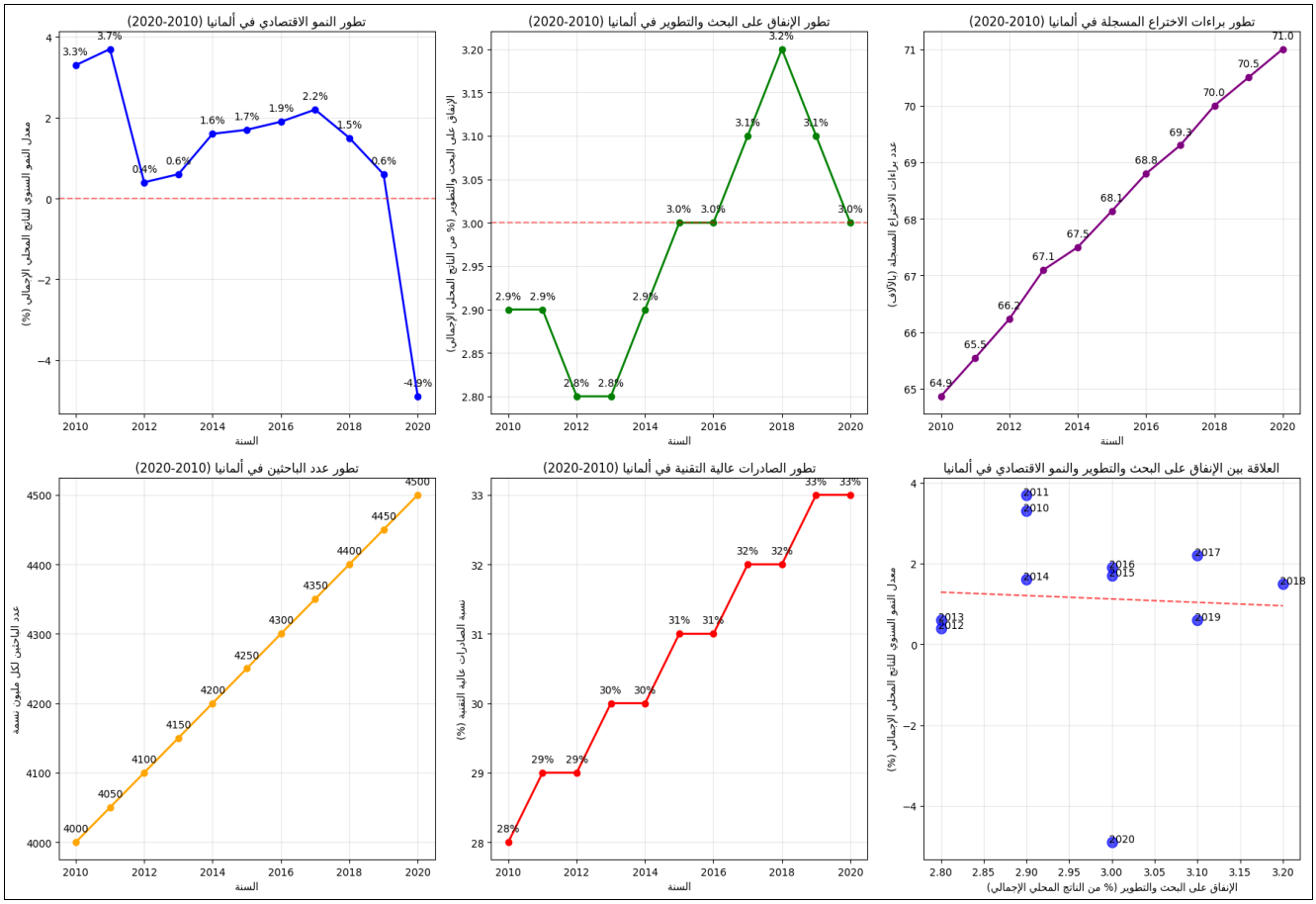

Fig 1: Analysis of Innovation Indicators and Economic Growth in Germany During the Period 2010-2020: Trends and Relationships

The first chart shows how Germany's annual economic growth rate has bounced all over the place. The German economy started the decade very positively, growing by 3.3% in 2010 and 3.7% in 2011. But with the downhill impact of the COVID-19 pandemic, growth indexes dropped dramatically in 2020 to -4.9%. The performance of the German economy is clearly strongly influenced by economic events in the rest of the world. The second chart illustrates the relatively constant level of R&D expenditure in Germany as a proportion of GDP, from around 2.9% to 3.2% during the period of study. Germany achieved the Europe 2020 strategy target of 3% starting in 2015, indicating the German government's commitment to supporting innovation and technology as a strategic economic priority. The third chart highlights a steady increase in the number of patents registered in Germany, rising from approximately 64,867 in 2010 to 71,000 in 2020. This provides evidence of the efficiency in the German innovation system, which can bring research ideas to applications in practice and thus to the economy. The fifth graph shows an increase from 4,000 researchers per million inhabitants in 2010, to an increasing number of researchers per million inhabitants, ending with 4,500 in 2020. This growth is a result of continuous investment in human capital, which is generating a sustainable scientific landscape and strengthening Germany's innovation potential.

The fifth chart indicates a considerable rise in the share of high-tech out of total exports, from 28% in 2010 to 33% in 2020. Such growth illustrates how Germany's economy remains competitive in world markets with high value-added products. And it signals the maturity of the German industrial sector in state-of-the-art tech fields. As shown in the sixth chart, R&D expenditure tends to be positively correlated with economic growth in Germany, except in times of economic crises such as the pandemic. This bedside you one of two sides relationship, as again the investment may translate into research as well as development, as the development sector represents one of the main engines of growth in terms of the complexities of the long-term economy.

Hypothesis Testing and Discussion of Results

A. Hypothesis Testing

In order to examine the relationship between innovation indicators (expenditure on R&D, patents, the number of researchers and high-tech exports) and economic growth in Germany over the period of 2010-2020, the multiple linear regression model has been used. The results were, R&D expenditure had a positive and a statistically significant effect on economic growth (coefficient = 18.2763, p = 0.002), thus supporting the hypothesis H1. 1, based on the assumption of a positive relationship between R&D expenditure and economic growth.

The results also indicated a positive effect of high-tech exports on economic growth, though without strong statistical significance (p = 0.303). As for the number of researchers, the effect was negative and statistically significant (p = 0.039), suggesting potential challenges in converting human capital into tangible economic outcomes.

Interpretation of Statistical Results

The results of the multiple linear regression model revealed the following:

- (R&D expenditure) is the engine of economic growth in Germany, directly increasing productivity and competitiveness (Frietsch *et al*., 2019).
- While patents and high-tech exports had positive results, they were insignificant, suggesting that these indicators could be more conducive to growth, but that it would take longer for this to materialize.
- The detrimental impact of the quantity of researchers may be due to issues of proper use of researchers or carry-over effects between investment in human capital and its economic returns Falck et al. (2020) [24]**.**

C. Discussion of Results in Light of Previous Studies

These findings align with the conclusions made by Zarrouk and Bacht (2020), which identifies innovation as a significant driver of economic growth for both developing and developed countries, despite the fact that there needs to be synergistic policies that will be needed to maximize the benefits. The results aligned with the study of Khadat (2019) who emphasized that dollar amount on R&D was instrumental in enhancing innovation and stimulating the economy. Additionally, the results align with Bessen *et al*. (2020) pointed out the difficulty of the challenge of innovating in advanced economies might be exacerbated by the complexity of the innovation process and the slowdown in research productivity.

D. Analysis of the Economic Effects of Innovation in Germany

These findings suggest that R&D and innovation play a key role in their contribution to overall economic growth in Germany, as R&D spending and technological advancement have a positive effect on advancing productivity and competitiveness. Yet while the size effect of researchers is detrimental the impact of human capital highlights the requirement of better policies to engage people in the production of goods and services. This also further confirms the positive role played by high-tech exports and patents and the high quality of the German innovation system. But it also advocates for strategies to optimize these outputs' benefits.

E. Conclusions and Recommendations

This study offers an analysis of the effect of innovation on economic growth in Germany from 2010 to 2020. The study came to a number of significant findings and conclusions.

The first finding reported a very strong and positive link between R&D destiny and economic development, with R&D salary positional display evidence that on growth rates. Second, we see a continuous rise in both registered patents as well as the share of high-tech exports, which indicate the robustness of the german innovation system as well as its capacity to leverage knowledge in the form of high value-added products. Third, while the number of researchers increased, they actually contributed negatively to economic growth, signaling difficulty in converting human capital into economic growth. Politics and policies: Fourth, the study confirmed Germany's tracking of the Europe 2020 strategy target of 3% of GDP on R&D period in 2015, emphasising Germany's dedication to fostering innovation as the economy's fundamental pillar.

From these findings, a few key conclusions can be drawn. First, as found in Germany, innovation is one of the key engines of economic growth, especially through investment in R&D. Second, the implementation of better policy tools to improve the use of human capital embodied in researchers and the transformation of their work into economic value is needed. Third, despite strong and advanced, the German innovation system confronts perennial challenges in the face of rapid technological change and growing global competition.

F. Recommendations

Building on these findings, a number of suggestions can be put forward in order to reinforce the role of innovation in driving the German economy. First, it is important to further invest in R&D and target strategic sectors and emerging technologies. Second, policy measures are needed to strengthen the binding function across knowledge and production sectors, so that the key discoveries of science can develop into marketable goods and services. Third, researchers should be trained and requalified so they could better contribute to economic growth. Fourth, small and medium-sized enterprises (SMEs) should be supported in their innovation initiatives through provision of the required financial and technical assistance.

Looking ahead to future research opportunities, there are multiple areas in which research studies are needed. Long-term longitudinal studies on the long-term effects of innovation on economic growth would help understand the subject better. Second, the different impacts of innovation on sectors of the German economy would be analysed to scrutinise sectoral diversity. Third, conducting comparative studies of other advanced economies to distil best practices in innovation policy. Fourth, exploring the dynamics between innovation, digital transformation, and environmental sustainability as the three organic drivers of future economic growth. Finally, it will examine the effect of global crises like the COVID-19 pandemic on the connection between innovation and economic growth and how to strengthen the resilience of the innovation system in the face of future challenges.

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