Technological Innovation and Economic Growth: A Policy Perspective

Karin Hoisl [a, b, c] & Leo Schmallenbach [a] [1]

a University of Mannheim, Mannheim School of Management
b Copenhagen Business School, Department of Strategy & Innovation
c Max Planck Institute for Innovation & Competition

"Empires of the future are the empires of the mind."
(Winston Churchill, 1943 at Harvard University[a])

1. Introduction

The importance of knowledge for a nation's economic prosperity and economic growth has long been recognized by academics and policymakers. Seminal works by Romer (1986), Lucas (1988), and Grossman and Helpman (1994) underscore the importance of knowledge in driving technological advancement (invention) and innovation (invention and exploitation), laying the foundation for endogenous growth models. These models posit that economic growth is primarily driven by factors within the economy, ascribing governments an active role in fostering growth via policies that stimulate knowledge creation and innovation.

The discussion on the most effective policy instruments to encourage technological innovation and especially how intellectual property rights (IPR) can best support technological innovation is still very controversial. We contribute to this discussion by answering the two overarching questions:

1) *What policy instruments can help foster economic growth via technological innovation? and*
2) *How can Europe remain or become competitive with the U.S. and China in the race for technological leadership in key technologies over the long term?*

To address these questions, we first provide a systematic review of recent theoretical and empirical research on the relationship between technological innovation and economic growth, with a special emphasis on IPR. In a second step, we explore common policy instruments that promote R&D and IPR investments, limiting our review to the most common instruments without claiming to be exhaustive. Finally, we critically examine the direction of causality in the relationship between technological innovation and economic growth.

Our theoretical discussion is complemented by an empirical analysis examining the link between technological innovation and economic growth across 36 OECD countries and China from 2000 to 2021. We extend our analysis to include a descriptive analysis of patenting activities within the technology areas of sustainable technology and artificial intelligence—two rapidly evolving technology areas with increasing importance for future competitiveness and addressing major societal challenges in health and climate, for example.

Although our literature review spans various types of IPR, our analysis, particularly in the review of policy instruments and our empirical study, concentrates on patents. Geographically, our focus initially is on OECD countries and China, subsequently narrowing down to an in-depth look at three European countries—Germany, France, and the Netherlands—alongside the U.S. and China when focusing on sustainable technology and artificial intelligence.

2. Impact of technological leadership and IPR-intensive companies on countries

2.1 Scientific literature

In economics, a lot has been written about the relationship between innovation and growth. Early work can be traced back to Schumpeter, who, already back in the 1930s wrote about the relationship between

[1] The order of the authors is alphabetical, both authors contributed equally to this report.

industrial innovation and economic growth (Schumpeter 1932). In the mid-1980s, this relationship was primarily researched by theorists who, based on work by Arrow (1962) amongst others, coined the endogenous growth theory. This theory was a reaction to their dissatisfaction with the previously prevailing opinion that growth was only determined by exogenous technological change (Romer 1994). Romer (1986), Lucas (1988) and their colleagues replaced exogenous technological change by endogenous knowledge and R&D. Aghion and Howitt (1992), for instance, developed a model in which internally developed innovations make existing products obsolete and become a source of growth by increasing demand for the improved product. Innovation was further shown to spur economic growth by creating externalities, i.e., spillovers, which enable follow-up innovation (Griliches 1992) and new business formation, which, amongst others, creates new jobs (Kirchhoff 1994).

According to innovation system theory, innovation and technological advancement are the outcome of a complex set of relationships among actors in a system. Actors include private companies, universities, and research institutes (Freeman 1995, Nelson 1993). These so-called national innovation systems also deal with how intellectual property is protected.

Although a lot of studies have been published in the last two decades on the importance of IPR for companies, e.g., to protect intellectual property from imitation, we still do not know enough about how the use of IPR influences economic growth. In particular, we still know too little about causal relationships. Therefore, in what follows, we first summarize recent empirical findings for Europe, the U.S., and China that have analyzed the relationship between IPRs and economic growth. In a second step, we will take a closer look at possible mechanisms underlying this relationship, which will bring us closer to understanding the underlying causality.

2.2 Empirical studies investigating the relationship between IPR and economic growth

A joint study by the European Patent Office (EPO) and the European Union Intellectual Property Office[2] (EUIPO) has analyzed the importance of IPR[3] for the European Union (EU) economy between 2017 and 2019 (EPO/EUIPO 2022). The study identified 357 IPR-intensive industries at the NACE 4-digit level, which are defined as industries having an above-average ownership of IPRs per employee, as compared with other IPR-using industries. To give examples, manufacturing of communication equipment, manufacturing of engines, and research in biotechnology were amongst the top 20 most patent-intensive industries.

Results show that IPR-intensive industries generate 47% of the GDP in the EU (17.4% of GDP is accounted for by patent-intensive industries alone), are responsible for 29.7% of all jobs (almost 39.4% if the sectors that supply to these industries are included). What makes IPR-intensive industries attractive is that the companies in these industries pay higher wages than companies in non-IPR-intensive industries. The wage premium in IPR-intensive industries amounts, on average, to 40.7% (65.0% in patent-intensive industries). Finally, IPR-intensive industries account for 75.9% of EU's trade in goods and services with other regions of the world.

In 2022, the USPTO released the third edition of "Intellectual Property and the U.S. Economy"[4] (USPTO 2022a, 2022b), which assesses the use of IPR across U.S. industries through 2019. Comparable to the EPO/EUIPO-report, IPR-intensive industries are defined as industries in which the intensity of IPR, i.e., the number of IPR obtained during the five-year period ending in 2016 per 1,000 employees, exceeds the IPR intensity for the whole economy. The study identified 127 IPR-intensive industries at the NACE 4-digit level. Computer equipment, semiconductors, software, and pharmaceuticals are amongst the top ten IPR-intensive industries.

Results show that IPR-intensive industries accounted for 41% of domestic economic activity (output) in 2019 and for 44% of the jobs in IPR-intensive industries (33%) and other industries that supply goods and services (11%) to these industries. Workers in IPR-intensive industries earn higher wages than workers in non-IPR-

[2] The EUIPO, which was founded in 1994, is the European Union Agency responsible for the registration of the European Union trademark and the registered Community design.

[3] In this report, IPR include patents, trademarks, designs, copyrights, geographical indications, and plant variety rights.

[4] In this report, IPR include utility patents, design patents, trademarks, and copyrights.

intensive industries. Average weekly earnings for workers in IPR-intensive industries were 60% higher than those for works in other industries (in utility patent-intensive industries, average weekly earnings were almost twice as high (+97%) than for workers in other industries). In addition, IPR-intensive industries accounted for 79% of all U.S. commodity exports in 2019.

A study by Chang et al. (2022) provides figures for China for 2012-2015. The authors focus on patents and follow the EUIPO definition of patent-intensive industries, classifying industries with an above-average use of patents per employee as patent-intensive (i.e., the patent quantity per capita in the selected industry should be larger than the mean across all industries). In total, 42 patent-intensive manufacturing industries were identified. Computer manufacturing, telecommunication manufacturing, and electronic device manufacturing were amongst the top five patent-intensive industries.

The authors find only a weak positive relationship between patent-intensity and the gross industrial output value in China. Their explanation for this finding is that China's patent incentive policy pursued quantitative expansion rather than quality improvement, leading to an inflation of patent filings, many of which were for low-quality inventions, which did not necessarily spur economic growth. A second reason is that many industries benefit indirectly from China's growth, not necessarily through (their own) innovations, but rather through increased sales of products that are either complementary to (innovative) products of others, i.e., are purchased at the same time, such as hardware and software, or are used as inputs in them. This dynamic reduces the propensity of companies in these growing industries to take the risk of investing in own R&D.

A very recent report[5] of the Intellectual Property Department of the Government of Hong Kong (IPD-HK 2023) looks at the impact of IPR-intensive industries on the economy in Hong Kong. IPR-intensive industries were identified based on the use of IPR between 2015 and 2019. The methodology used follows that of the EPO/EUIPO and the USPTO described above. As an industry classification, the study uses the Hong Kong Standard Industrial Classification (HSIC)[b]. Of the 483 industries in total, 339 industries were identified to have filed IPR and 196 were classified as IPR-intensive. These IPR-intensive industries contributed to 32.7% of the GDP, created 29.1% of the jobs, and paid a wage premium amounting to 11% (13% in patent-intensive industries), on average.

In summary, the results of the reports on Europe, the U.S., and Hong Kong agree that the above-average use of IPR in industries is positively correlated with economic indicators. However, we cannot derive any causal relationships from their results. In other words, we do not know whether IPR indeed contributes to higher economic performance or whether more IPR is filed in industries with higher economic performance because these industries are more attractive.

In the next section, we discuss potential reverse causality and possible mechanisms through which patents may affect economic growth and how economic growth may affect firms' patenting activity. We focus on patents and technological innovation because patents are one of the most important IPRs for protecting inventions against imitation and because the effects summarized in the above reports are highest for patent-intensive industries.

2.3 Patents and technological innovation - A discussion of causality

<u>Patents can induce technological innovation, which fosters economic growth</u>

First, patents provide incentives for companies to invest in R&D, since patents grant a temporary exclusion right, which can prevent imitation (Hall and Harhoff 2012). Thereby, patents attract investment from both domestic and foreign sources. However, some industries profit more from patents than others. Whereas patents, for instance, play a major role in chemicals, pharmaceuticals, biotechnology, and medical instruments, since, in these technological areas, patents are an appropriate means to prevent imitation, patents are of less importance to protect processes or inventions in very fast-moving industries, such as

[5] In this report, IPR include utility patents, design patents, trademarks, and copyrights.

information and communication technologies. In the latter, being first on the market may be a more valuable appropriation mechanism (Mansfield 1986, Levin et al. 1987, Cohen et al. 2000).

Moreover, innovation is a cumulative process, which means that inventions are typically the outcome of a recombination of existing knowledge (Scotchmer 1991). Patent documents contain a wealth of technical knowledge which, once disclosed (all major patent systems worldwide require the publication of the patent specification after 18 months), becomes available for subsequent inventions. Without the publication requirement to obtain patent protection, firms would (try to) keep their knowledge secret. Thus, patents not only promote innovation by preventing imitation, but also provide an important source of knowledge. Third parties can learn from the published knowledge (spillover effects) or benefit from the legal use of a protected invention, e.g., by licensing or purchasing the patented technology. In this way, subsequent inventions may be produced more quickly and/or at lower costs.

Third, patents allow trading of technology-related knowledge, i.e., they create so-called "markets for technology" (Arora et al. 2004). Technology markets attract venture capital and investors seeking high-growth opportunities. The availability of funding, in turn, allows start-ups to enter existing markets (Arora et al. 2004, Hall and Ziedonis 2001, Arora and Merges 2004). Start-ups play an important role in growth, often contributing to radical innovation. Large and established companies, on the other hand, often tend to avoid risk and cannibalization of existing technology and therefore often invest in incremental innovation. However, it should be mentioned that markets for technologies, especially in complex or fragmented technologies, where one product is protected by several patents, also lead to transaction costs (e.g., costs for contracts, monitoring, litigation), which may disadvantage firms that lack resources or do not have internal IP departments, such as small and medium sized firms (Heller and Eisenberg 1998, Shapiro 2001, Gallini and Scotchmer 2002).

<u>A growing economy can encourage technological innovation and the creation of patents</u>

Causality can also go in the opposite direction. In particular, growing economies may attract investment in R&D, and patents are filed to protect the resulting inventions. In this case, an extensive patenting behavior would not be the cause of but the consequence of innovation.

Moreover, in growing economies, competition increases. Competitive environments may induce companies to invest in R&D to differentiate themselves from their competitors through innovation. In such environments, patents are often used strategically. One example are so-called "patent wars" in the information and communication (ICT) industry, in which technological complexity combined with the broadening of the patent claims led to a sharp increase in litigation worldwide (Comino et al. 2015). The costs of legal disputes absorb resources. This can slow down future technological progress, and the losers of such patent wars may be driven out of the market. Economic growth may therefore lead to more patents in the short-term, but this is not necessarily a sign of long-term innovation and may even delay or prevent future innovation. Another example are standards. Even though standards play an important role in promoting innovation, particularly in high-tech areas such as telecommunications, e.g., by enabling the interoperability of products, they also could create room for strategic or even anti-competitive behavior if the holders of so-called standard essential patents (SEPs) would not license their patents either directly or via have-made rights (Martinez 2019)[c]. A voluntary commitment of the holders of SEPs to license their patents under fair, reasonable and non-discriminatory terms – known under the acronym "FRAND" – can help to balance the interests of licensor and licensee.[d]

Growing economies also have more resources to invest in education, and well-educated workers (knowledge workers) in turn are needed in research and development to make inventions that can then be patented. Empirical evidence for this is provided by the USPTO, which reports that employees in patent-intensive industries are characterized by a higher level of education compared to industries which are not patent-intensive. For example, the proportion of bachelor's degrees in patent-intensive industries is 32.4%, compared to non-patent-intensive industries, where this proportion is only 14.4%. The proportion of graduate degrees is 23.9% in patent-intensive industries and 14.4% in non-IPR-intensive industries (USPTO 2022a).

Finally, growing economies attract foreign direct investment (FDI). This investment can contribute to technological progress and once more increase patenting activity.

Unfortunately, empirical evidence on the direction of causality between IPR and economic growth is scarce. One exception is the work of Hassan and Tucci (2010). The authors use data on 58 countries for the period 1980-2003, divided into high- and upper-middle-income countries and lower-middle and low-income countries. A standard per capita growth equation shows that R&D and patents are positively related to economic growth in both groups of countries. Although the causality between patents and growth appears to be bidirectional (see Figure 1), the direction from patents to growth is shown to be much stronger than the direction from growth to patents. These findings suggest that patented inventions may contribute to per capita economic growth at the national level.

Figure 1. Bidirectional causality between patented inventions and economic growth

Overall, we can assume that the causality between IPR and economic growth is two-sided. Patents can promote economic growth, but high-growth environments also have a strong attraction for (R&D) investment. Based on the results summarized above, to make a country competitive, the IPR system needs to be functional and attractive on the one hand, and R&D funding is required on the other. As outlined above, one of the overarching questions of this study is *what policy instruments can help foster economic growth via technological innovation*. In the following chapter, we therefore summarize the most used policy instruments related to IPR protection and R&D support. In a second step, we critically discuss the effectiveness of the instruments described.

3. Policy instruments governments employ to foster R&D investment and IPR

Should governments support innovation? In the absence of market failures, economic theory suggests that investment decisions for innovation should be left to the private sector (Bloom et al. 2019). However, market failures, such as underinvestment in R&D and IPR, often justify policy interventions, especially due to the public good nature of knowledge (i.e., knowledge is non-rival and characterized by partial excludability). Arrow (1962) highlights the societal benefits of innovation and the role of public policy in mitigating innovation underinvestment.

One example of market failures are externalities, such as knowledge spillovers. Knowledge spillovers can, for example, encourage follow-on inventions but simultaneously diminish the incentive to develop original inventions. The risk associated with spillovers may lead firms to opt for secrecy over patenting their inventions, as the latter requires public disclosure. In the absence of policy interventions, spillovers will induce firms to underinvest in R&D or not disclose their knowledge.

Governments have a wide range of policy tools at their disposal to incentivize firms to invest in R&D and IPR. Within this report, we broadly group these instruments along two categories, direct incentives and indirect incentives, targeted towards R&D investment or IPR. Direct incentives include immediate financial and non-financial benefits for investing in R&D and IPR, while indirect incentives encompass long-term instruments to foster innovation, such as regulatory and economic reforms. Our primary focus will be on policies implemented in the U.S., China, France, Germany, and the Netherlands.

3.1 Direct incentives

3.1.1 Direct incentives: Policy instruments fostering investments in R&D

Tax incentives

Tax incentives for R&D come in various forms, such as R&D tax credits, allowances, and deductions. These incentives effectively reduce the after-tax cost of R&D spending, making investment in innovation more attractive for firms. The R&D tax credit, which allows firms to deduct a percentage of their R&D expenditures from their tax liability, is one of the most widely used mechanisms. Empirical studies have shown positive relationships between tax incentives and R&D investment. Bloom et al. (2002) investigated nine OECD countries (AU, CA, JP, ES, US, DE, FR, IT, UK) and found that R&D tax credits are effective in increasing R&D expenditure, especially in high-tech sectors. Similarly, Czarnitzki et al. (2011) provided evidence from Canada that R&D tax incentives are associated with higher R&D spending by firms.[e]

Several countries have implemented R&D tax incentive policies. For instance, in the **U.S.,** the United States' Research & Experimentation Tax Credit, commonly known as the R&D Tax Credit, has been a critical policy tool for promoting R&D investments since its introduction in 1981. Another notable example is Canada's Scientific Research and Experimental Development (SR&ED) tax incentive program, which is one of the most generous tax incentive programs for R&D in the world. The SR&ED program provides refundable and non-refundable tax credits to eligible firms for their expenditures on eligible R&D activities, including wages, materials, machinery, equipment, some overheads, and third-party payments related to R&D activities. The program is administered by the Canada Revenue Agency (CRA), and the tax credits can cover up to 35% of eligible expenditures for Canadian-controlled private corporations (Parsons and Phillips 2007).

In **China**, most incentives offered by local governments are based on negotiations on a case-by-case basis. Incentives typically include tax rebates and tax credits. Moreover, in recent years, certain special economic zones, such as Greater Bay Area, Lingang Area in Shanghai, Hainan Free Trade Port have been established. These special zones offer preferential policies for domestic and foreign companies to foster economic growth.[f] In addition, the R&D Super Deduction Program allows a Chinese resident company to deduct 200% of eligible R&D expenses (i.e., an additional 100% deduction on top of the normal expense deduction) in calculating its tax liability if the expenses do not result in the creation of an intangible asset. If intangible assets are created, the capitalized eligible R&D expenditures can be amortized based on 200% of the actual R&D costs, without any restrictions on the timing of the asset creation or depreciation.[g]

Tax incentives for R&D also have a long history in EU countries. In **France**, tax incentives, introduced for the first time in 1983, were reformed in 2008 with the introduction of the “Crédit Impôt Recherche” program. Companies applying for research funding for the first time within five years receive a tax credit of 50% of expenditure instead of the usual 30% (before 2008: 10%). Since January 1, 2013, France has also granted an innovation tax credit (Crédit d’ Impôt Innovation – CII) (Deutscher Bundestag 2017). Tax incentives were introduced in the **Netherlands** in 1994. Today, the Promotion of Research and Development Act (WBSO) promotes R&D through a wage tax credit of 40% (50% for start-ups) on the first EUR 350,000 of certain R&D costs per calendar year and 16% on any amount above that (Spengel et al. 2017). In addition, the Innovation Box offers a tax reduction on profits derived from innovation of 7% (9% from 2021) instead of the standard corporate income tax rate of 25%.[h] **Germany** was one of the few OECD countries that did not offer R&D tax incentives until a few years ago. In 2019, The Law on Tax Incentives for R&D (Forschungszulagengesetz) was passed by the Bundestag and Bundesrat and came into force at the beginning of 2020. The basis of assessment for funding corresponds to the eligible expenses of up to a maximum of EUR 2 million. The tax-based R&D funding amounts to 25%, i.e., up to a maximum of EUR 500,000 per financial year (EFI 2020).

Direct Funding and Grants

There are several different forms through which governments can provide direct financial support for R&D, the most common ones are grants and loans. Grants are non-repayable funds provided to firms, often targeted at specific research areas or themes deemed as priorities for national or regional development. Loans represent financial support with the expectation of repayment, which can be offered at favorable terms, such as low-interest rates or flexible repayment schedules, to make them more attractive for R&D projects. But there are also other financial support mechanisms such as equity investments, subsidies, or innovation vouchers that firms can use to purchase expert services or access facilities to support their R&D activities.

Numerous studies have examined the effectiveness of direct financial support in boosting R&D investment. David et al. (2000) survey 35 years of econometric evidence on the impact of public R&D funding on private R&D expenditure. Five-sixths of the studies based on data other than the U.S. and four-seventh of the studies based on U.S. data found complementarity of the two sources of funding. However, one third of the studies they sampled found that public R&D founding can also be a substitute for private R&D funding.

The **European** Union's Horizon 2020 program, known for its funding towards research and innovation, is a prime example of a policy that provides direct financial support to stimulate R&D activities across member states. With a budget of nearly €80 billion, it was one of the largest publicly funded international research programs. Structured around societal challenges, such as climate change, energy and food security, and aging populations, Horizon 2020 placed a strong emphasis on innovation. From research to retail, the program covered a broad range of activities like basic research or market uptake, including innovation in SMEs and public sector innovation (Veugelers et al. 2015). Another example is the **United States'** Small Business Innovation Research (SBIR) program, which provides grants to small businesses to engage in federal R&D with the potential for commercialization (Lanahan and Feldman 2015). Established in 1982, the SBIR program is designed to support scientific excellence and technological innovation through the investment of federal research funds for proof-of-concept, demonstration and commercialization activities. In addition, there are grant funding programs for academia, above all funding from the U.S. National Institutes of Health (NIH). This funding also benefits companies, for example in the case of collaborations (Azoulay et al. 2019). One of the largest recent funding programs in the U.S. is the CHIPS and Science Act for Research, Development, and Workforce, announced by the Biden Administration in February 2024. The $5 billion program aims to strengthen the U.S. semiconductor industry by providing funding and support for R&D initiatives and workforce development. It encourages investment in R&D by providing financial incentives, fostering public-private partnerships, and ensuring a skilled workforce.

The **Chinese** government also offers several direct funding programs. To encourage foreign investment, for example, China allows local governments to support investment projects that make a significant contribution to local employment, economic development, and technological innovation.[i] The Chinese government is also channeling substantial financial resources into government-led guidance funds, blending public and private investments to support the nation's industrial innovation strategies. By the early months of 2020, there were 1,741 of these guidance funds in existence, with a collective size of 11 trillion RMB (approximately 1.55 trillion USD)[j]. Chinese government-led guidance funds target equity investments in startups and non-listed companies within strategically important sectors, including advanced manufacturing and emerging technologies. These investments aim to foster innovation and support the development of China's industrial capabilities, often aligning with the government's broader economic goals[k].

Looking back to Europe, **France** offers several R&D grants, including funding for innovation clusters. The grants are targeted to specific industries, such as medical research, big data, green technology, smart cities, or robotics.[l] **The Netherlands** provides companies with high-risk innovation projects with innovation loans amounting to between 25% and 50% of project costs. Moreover, cash grants are provided for research, pilot, and demonstration projects. These grants are limited to knowledge-intensive and export-oriented sectors, including agriculture and food, chemicals, energy, life sciences and health. The grants can comprise up to 80% of R&D and investment costs.[m] **Germany** provides technology-specific funding, such as for energy (7th Energy Research Program, Federal Funding for Energy Efficiency in Economy), civil aeronautics (Civil Aeronautical Research Program), or autonomous vehicles (New Vehicle Technologies). The programs typically fund R&D (25-50% of eligible costs).[n] Moreover, in December 2019, the Federal Agency for Disruptive Innovation (SPRIND GmbH) was founded in Leipzig, Germany. The agency is a flexible and fast state funding instrument with which the Federal Ministry of Education and Research (BMBF) and the Federal Ministry of Economics and Climate Protection (BMWK) support and accelerate the identification and development of innovative ideas.[o] In 2017, the BMWK has also launched the WIPANO program, which aims to improve patenting, protect innovation, and support standardization projects by providing financial and expert assistance to academia and SMEs in the management and use of intellectual property rights.[p] Also in Europe, funding programs for academia, such as those offered by the European Commission, can benefit companies through university-industry collaboration (Azoulay et al. 2019).

3.1.2 Direct incentives: Policy instruments fostering investments in IPR

Direct Financial Incentives

To motivate firms to invest in IPR, governments can provide several direct incentives designed to reduce the financial burdens associated with securing and maintaining IPR.

One of the most straightforward incentives is to reduce the fees associated with filing and maintaining IPR. By lowering the cost barriers, governments can make it more accessible for companies, especially small and medium-sized enterprises (SMEs), to use IPR to protect their innovations. This includes fees for patents and trademarks, which can sometimes be prohibitively expensive. At the EPO, for example, the procedural cost (filing and search fees) of obtaining a patent up to grant as of February 2024 is around € 6,300[q,6]. Lanjouw and Schankerman (2004) highlight the impact of fee structures on the propensity of firms, especially SMEs, to patent their innovations. Their research underscores the importance of cost considerations in the decision to seek IP protection.

A policy example aimed at reducing the procedural costs associated with obtaining and maintain IPR is the Unitary Patent system, which was introduced by the EPO in 2023. The unitary patent is valid in 17 EU member states which have ratified the agreements. It is amongst others designed to significantly reduce costs, particularly in terms of validation and maintenance, making it a more cost-effective option for patent protection. This is particularly attractive in the early years, with the total cost of maintaining a unitary patent for the first ten years estimated to be less than €5,000. This contrasts with the renewal fees for a European patent maintained in the 17 member states that ratified the agreements, which could total more than €35,000 over the same period.[r] However, this savings potential requires a large number of validated countries. If applicants are only interested in protection in up to four countries (e.g., DE, FR, UK, NL), a European patent would still result in lower renewal fees.

In the **U.S.**, the USPTO offers, for example, a "small entity" status that enables small businesses and independent inventors to pay reduced fees (60% discount) for patent filing, search, and examination. Moreover, an even lower fee schedule (80% discount) is available for "micro entities", which include small entities that meet certain criteria, such as having a low number of previous patent applications or meeting specific income thresholds[s]. Similarly, in **Europe**, the EPO has implemented fee reductions for specific applicants, including small and medium-sized enterprises (SMEs), non-profit organizations, universities, and natural persons. These reductions are intended to decrease the obstacles to patenting in Europe and apply to multiple stages of the patent application process, such as filing, examination, and grant.[t]

Another significant direct financial incentive comes in the form of IPR-related tax incentives, such as the "patent box" regimes. These regimes allow companies to apply a lower corporate tax rate to income derived from patented inventions and intellectual property. This typically includes royalties, license fees, and even profits from the sale of IPR, although the specific types of IPR and forms of income that qualify may vary depending on jurisdiction. Alstadsæter et al. (2018) conducted an empirical analysis of the impact of such tax incentives on innovation activities. They found evidence of the positive effects of patent box regimes on fostering IPR investments. As of 2022, 13 out of 27 EU member states have a patent box regime, and 5 non-EU European countries have implemented such a system. The tax reductions vary between 1.75% (Malta) and 11.5% (Turkey).[u] **France** introduced a patent box regime in 2000, which underwent amendments in 2005 and 2010[v], offering a reduced corporate income tax rate of 15% on license income and capital gains from the

[6] If one adds to this the validation fees, annual fees, and the costs for a patent attorney and patent monitoring, costs of over €50,000 per patent are not uncommon, depending on the number of countries in which protection is sought and the number of years that a patent is maintained.

transfer or sale of IPR[w]. Similarly, **China** has implemented a patent box regime for technology and software companies, providing tax relief for income from technology transfer. These regimes incentivize firms to invest in IPR creation and exploitation by directly linking the tax benefits to the income generated from IPR[x]. In the **Netherlands**, the patent box regime taxes profits earned by companies from their innovative activities, such as patents and certain types of R&D work, at 9% compared to the standard corporate income tax rate of 25.8%[y]. Currently, **Germany** does not offer such tax schemes.

Direct Non-financial Incentives

In addition to direct financial incentives, policymakers can provide guidance and non-financial support to help companies navigate the complexities of IPRs systems. This is often a hurdle for companies seeking to protect their inventions (Jaffe and Lerner 2011). Examples of such non-financial support include reforms that simplify the patent process and reduce legal hurdles, in line with the idea that streamlined processes can encourage investment in IPR. Creating more efficient patent examination processes, providing pre-filing assistance, and offering clear, accessible guidelines for IPR filings can also help firms to save time and other resources. Additionally, legal guidance and advice for preparing IPR filings can demystify the process for many firms, encouraging them to protect their innovations[z]. This support can be especially valuable in complex fields or for technologies, which were originally not patentable, where the path to protection is less clear, such as computer software[aa].

The **USPTO**, for example, has initiatives to aid under-resourced inventors and small businesses in filing patents. The USPTO's Pro Bono Program connects eligible inventors with volunteer patent attorneys to assist in patent application preparation and filing at no cost[bb]. Furthermore, the Pro Se Assistance Program provides resources and guidance for individuals who choose to file patents without attorney representation[cc]. Similarly, the **German** Patent and Trademark Office offers preliminary advice for inventors.[dd]

3.2 Indirect incentives

3.2.1 Indirect incentives: Policy instruments fostering investments in R&D

Indirect incentives are also important for promoting investments in R&D by creating an environment that supports innovation activities. These policy instruments, ranging from infrastructure development to market stimulation, not only facilitate R&D efforts but also enhance the overall innovation ecosystem.

Infrastructure and Resource Development

Investing in research infrastructure, such as state-of-the-art laboratories, technology parks, and advanced data networks, is foundational to promoting R&D. The **U.S.**, for instance, has a long history of supporting research infrastructure through initiatives like the National Science Foundation (NSF) and the establishment of renowned high-tech clusters like Silicon Valley. These investments provide the physical and technological backbone necessary for cutting-edge research and innovation.

Human capital development is equally important and should be supported by policies that focus on scholarships, training programs, and support for Science, Technology, Engineering, and Mathematics (STEM) education. In **China**, for instance, the "Thousand Talents Plan" aims to attract high-level global talent in science and technology to enhance the country's innovation capabilities (Wang 2011).

Collaboration, Networking, and Knowledge

Fostering international partnerships and engaging in multilateral trade deals are key strategies for enhancing global R&D collaboration. For instance, the Asia-Pacific Economic Cooperation (APEC) is an intergovernmental organization with 21 member countries in the Pacific that promotes free trade throughout the Asia-Pacific region. APEC has initiated a Science and Technology Innovation Cooperation[ee] to harness the collective expertise and resources of member economies to drive scientific advancements and technological innovation. This collaborative effort underscores the importance of regional alliances in promoting shared R&D goals and facilitating technological exchange.

The dissemination of scientific and technological knowledge is pivotal for spurring innovation across industries and countries. Digital repositories and open-access databases, such as the **United States'** PubMed Central, offer an invaluable resource for researchers, facilitating the free flow of scientific information and findings. In addition, patent offices provide free of charge access to patent databases, one example is Espacenet, which was developed by the EPO together with the member states of the **European** Patent Organization. Open access to research outputs supports the global scientific community's efforts to build upon existing knowledge and foster innovation in diverse fields (Suber 2012).

By leveraging international collaborations and ensuring the broad dissemination of knowledge, countries and organizations can accelerate the pace of innovation, benefiting from the synergies created through shared expertise and resources.

Market Creation and Stimulation

Governments also play a significant role in creating and supporting markets by utilizing procurement policies and setting standards to drive demand for innovative products and services. In the **U.S.**, the Small Business Innovation Research (SBIR) program mandates that federal agencies with large R&D budgets allocate a portion to contracts and grants to small businesses, stimulating innovation in specific areas (Lerner 2000).

In **France**, the "Investments for the Future" program (Programme d'Investissements d'Avenir) aims to stimulate investment in innovative sectors, including digital technology, renewable energy, and health, thereby creating markets for new technologies and supporting the development of innovative firms.[ff]

Germany's High-Tech Strategy[gg, hh] and the **Netherlands'** Top Sector Approach[ii] are examples of national strategies that align government, academia, and industry efforts towards innovation, creating conducive markets for new technologies and services. Germany's High-Tech Strategy, initiated by the Federal Government, aims to transform innovative ideas into marketable products and services, thereby securing the country's position as a leading technological powerhouse. A notable aspect of this approach is the emphasis on "Innovation Alliances" between businesses and research institutions, aimed at accelerating the development of key technologies. The Netherlands' Top Sector Approach also fosters public-private partnerships, known as "Innovation Contracts," where businesses, research institutions, and the government collaborate on R&D projects and innovation agendas. One distinctive feature of this approach is the "TKI (Top Consortium for Knowledge and Innovation) Allowance," which incentivizes private sector investment in joint R&D.[jj]

3.2.2 Indirect incentives: Policy instruments fostering investments in IPR

Moving to indirect incentives aimed at fostering investments in IPR, it is essential to explore how these strategies can create a conducive environment for investments in the legal protection of innovation. Beyond merely strengthening IPR laws and streamlining patent processes, additional legal frameworks and initiatives can significantly enhance the protection and management of IP, thereby encouraging investments in IPR.

Robust Enforcement Mechanisms

The establishment of specialized IPR courts is a critical step in ensuring that intellectual property laws are actively upheld. For instance, the Intellectual Property High Court in Japan, established in 2005, specializes in IPR disputes and has contributed to more consistent and expert rulings. This has reduced uncertainty for investors and innovators regarding the protection of their rights (Tilt 2021). However, there is also a downside to the strength of IPR protection (Mazzoleni and Nelson 1998). While strong protection is beneficial for basic research, as Park and Lippoldt (2005) found a strong correlation between robust IPR and R&D intensity, it can sometimes prevent follow-up inventions (Bessen and Meurer 2009). Overly strict IPRs or particularly broad patent scopes can hinder incremental innovation and access to knowledge. Recognizing this tradeoff, some policies aim to balance protection and stimulation of innovation. For instance, the American Inventors Protection Act (AIPA), which was enacted as Public Law in the **U.S.** on November 29, 1999, requires patent applications to be published after 18 months (previously only granted patents were published)[kk]. This law aims to stimulate follow-up innovation by making early-stage inventions public. Additionally, changes in legislation, such as the Leahy–Smith America Invents Act (AIA)[ll] signed into law on September 16, 2011, have revised and expanded post-grant opposition procedures in the U.S. patent system. Oppositions originally aimed to serve as a post-grant evaluation mechanism, can however also be used for anti-competitive reasons. Mainly large technology companies may, for instance, use the opposition system as a tool in the business practice of predatory infringement, i.e., companies use patented technology without first negotiating a license. If they are sued for patent infringement within the opposition period, they can file an opposition against the patent they are infringing. Consequently, the effectiveness of AIA in stimulating follow-on innovation is controversial.[mm]

Cross-Border IP Protection

International treaties, such as the Agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPS), ensure that IPR protection is not limited to national borders but extends globally. This global framework provides a secure environment for multinational investments, as evidenced by increased patent filings in member countries following the TRIPS agreement (Maskus 2000).

Alternative Dispute Resolution (ADR)

Encouraging the use of ADR mechanisms, such as arbitration and mediation, for resolving IP disputes can offer a more efficient, cost-effective, and less adversarial alternative to traditional litigation. The WIPO Arbitration and Mediation Center and the Board of Appeal at the EPO[nn] are excellent examples of this, providing services for the resolution of international commercial disputes between private parties and fostering a more business-friendly environment for IP rights (Christie 2020).

IP Licensing and Technology Transfer Frameworks

Developing transparent frameworks for IP licensing and technology transfer is crucial for the commercialization of innovations. The "Best Practices in Licensing: Frameworks for University Technology Transfer" by the Association of University Technology Managers (AUTM), a non-profit association of over 3,100 technology transfer agencies worldwide outlines guidelines to ensure that licensing agreements are fair and reasonable, encouraging both IP owners and users to engage in transactions.[oo]

Technology Transfer Offices (TTOs)

The establishment of Technology Transfer Offices (TTOs), particularly at universities and research institutions, can significantly foster investments in IPR by commercializing academic research through effective IP management, licensing, and spin-off creation (Thursby and Thursby 2002). The success of the Massachusetts Institute of Technology's (MIT) Technology Licensing Office serves as a benchmark, having facilitated numerous successful technology transfers and startup formations (Shane 2002). A recent study of the impact of outsourcing technology transfer functions to a more established TTO by four Australian universities found an immediate increase in invention disclosures and provisional patent applications following outsourcing. This highlights the benefits of accessing advanced commercialization expertise and fostering academic entrepreneurship, although no significant increase in standard essential patents, licensing deals, or start-ups was observed (Nugent and Chan, 2023).

Digital Intellectual Property Protections

With digital innovation's growing importance, laws must evolve to protect digital creations adequately. The European Union's Directive on Copyright in the Digital Single Market[pp] is an example of adapting copyright laws to protect software, digital content, and databases, addressing the challenges posed by digital duplication and distribution (European Commission 2021).

Combating Online Piracy and Counterfeiting

Implementing measures to combat (online) piracy and counterfeiting, including effective takedown procedures for infringing content and collaboration with online platforms to enforce IPR, is essential. The "Notice and Takedown" procedures under the Digital Millennium Copyright Act (DMCA)[qq] in the **U.S.** have been a first attempt to address these issues by offering a legal framework for addressing online IP infringements. However, online piracy and counterfeiting remain fundamental challenges for IP protection in the digital era and the DMCA could not stop that (Cobia 2009). Therefore, the **European** Union Agency for Law Enforcement Cooperation (EUROPOL) and the European Union Intellectual Property Office (EUIPO) have joined forces to launch the Intellectual Property Crime Coordinated Coalition (IPC3). The IPC3 provide operational and technical support to law enforcement agencies and other partners in the EU and beyond.[rr]

IP Education and Awareness

Educating inventors, creators, businesses, and the judiciary about the value of IPR and the details of IP law can significantly enhance respect for IP and encourage a more informed use of the IPR system, leading to a more vibrant culture of innovation and investment in IPR-intensive industries. Programs like the "IP Identifier"[ss] developed by the **USPTO** aim to enhance IPR awareness among entrepreneurs and innovators. The IP Identifier is a comprehensive tool designed to help individuals and businesses, including manufacturers, small businesses, entrepreneurs, and independent inventors, evaluate their understanding of intellectual property (USTPO 2023). The tool aims to increase users' awareness of IP issues relevant to their creative projects and business objectives by guiding them through a series of questions related to IPR. Upon completion of the assessment, users received customized training resources to address identified needs, enhancing their IPR knowledge in areas where it is most required. Another example is the **European** Patent Academy of the European Patent Office[tt], which serves as the educational and training institution of the European Patent Office. The mandate of the Academy is to improve education and training structures in the field of IPR in Europe and to raise awareness of IPR. Founded in 2004, the Academy collaborates with national and international institutions, including EUIPO.

3.3 Critical discussion of the effectiveness of these policy instruments

In the following, the effectiveness of selected policy instruments in promoting investments in R&D and IPR is critically discussed. The discussion will focus on direct incentives for R&D and IPR.

Studies evaluating tax incentives at both the country and the firm level find that tax incentives increase R&D spending. A 10% reduction in the tax price increases R&D by at least 10% (see Bloom et al. 2019 for an overview). Tax incentives could therefore be considered as an effective policy instrument. However, there are also negative voices, as firms might "relabel" non-R&D expenditures as R&D expenditures to obtain tax savings. Chen et al. (2021) find such behavior in China after a change in corporate tax rules. In addition, multinational firms may not increase their overall R&D spending but relocate R&D activities to countries with tax incentives. Wilson (2009) and Bloom and Griffith (2001), for example, report relocation behavior in the U.S. and UK. Examining output measures, such as the number of patents filed after the implementation of tax policies, may provide more reliable evidence of the effectiveness of tax incentives than R&D spending. Studies have shown an increase in patent filings in Europe, the U.S., and China following tax reforms (Lucking 2019, Akcigit et al. 2019, Chen et al. 2021; for additional research, see Bloom et al. 2019).

Evaluating the effectiveness of government R&D funding and research grants is particularly difficult because - if the allocation of funding procedures work - only the most promising proposals are funded. On the one hand, with this positive selection it is not surprising that promising results emerge; on the other hand, high quality projects would probably also have secured other external sources of funding (e.g., private foundations) or the companies responsible would have financed the projects themselves. In other words, public R&D funding should be complementary to private R&D or crowd in (not crowd out) R&D funding by private firms (Bloom et al. 2019). Moreover, public funds may support projects that otherwise would not have cleared the internal company hurdle for further pursuit. Looking at the relationship between public funding and innovation quality, Jacob and Lefgren (2011) find moderately positive effects of NIH funding on the number of citations received by publications resulting from publicly funded projects, compared to non-funded but qualitatively comparable projects. However, government-funded research has been found to have a positive effect on the patent activity of companies (Belenzon and Schankerman 2013).

Patent boxes, which reduce the tax rate to revenues from patents relative to other revenues, were designed to incentivize investment in R&D. Although this incentive was well-intentioned, the reality is that patent boxes are often used by companies to shift IP royalties to a country with patent box regimes to reduce their tax burden (Griffith et al. 2014, Gaessler et al. 2021). This is particularly true for multinational companies, which have many opportunities to shift royalties between countries. Due to their potential for tax avoidance, patent boxes are often viewed critically. The German government, for instance, introduced a so-called license barrier in 2019, which prevents tax avoidance made possible by patent boxes and Italy abolished their patent box system again in 2021.[uu]

Whether the reduction in patent fees leads to more innovation is also difficult to evaluate. Merely counting patents is an inadequate evaluation criterion. It is crucial to ensure that the average quality of patents does not decrease as their quantity increases. The possibility of a decrease in patent quality due to a reduction in fees appears to be a legitimate concern, as it has been shown that a fee increase can be an effective mechanism to discourage the filing of low-quality patent applications. A study investigated the impact of a fee increase on the quality of patents granted under the Patent Law Amendment Act of 1982, which resulted in a significant increase in patenting fees at the USPTO. It was found that after the fee increase, the number of patents with relatively low quality[7] decreased by 14% (de Rassenfosse and Jaffe 2018). Most direct financial incentives focus on the filing of IPR. However, it can be at least equally important to maintain, enlarge, or enforce IPR. Direct financial support for specific IPR-related activities, such as international patent filing or legal costs for defending IPR, can also be a powerful financial incentive, particularly for smaller firms that might otherwise be unable to afford these expenses.

Support is often offered to SMEs. In the UK, financial support of up to 5,000 GBP is granted to SMEs through an innovation voucher scheme. This support allows SMEs to engage the services of experts from universities, research institutes, or IPR advisors when pursuing innovation-related projects. The scheme has shown a positive effect on innovation. However, this is only short-term and fades out after only two years (Kleine et al. 2022). A general danger with all policy measures is also that they do not reach those they are intended to reach. A very recent example is the Inflation Reduction Act (IRA) of 2022. One of the purposes of the IRA, according to U.S. President Joe Biden and others, was to decrease reliance on China and encourage the growth of a domestic solar industry. However, Chinese solar companies are now constructing factories in the United States and receiving a significant portion of the $370 billion allocated for climate-friendly technologies. It is estimated that one-quarter of the planned solar panel capacity is being provided by Chinese companies[vv]. This brings us to the next point: What (almost) all policy instruments have in common is that, although they were created to strengthen the national innovation system, globalization means that firms from other countries can profit as well. Firms have subsidiaries abroad to gain access to attractive markets or they deliberately shift profits to countries with a lower tax burden. These are just two of many examples. It is therefore not possible or meaningful to just evaluate policy instruments at a national level.

Even if we do not consider indirect policy instruments further at this point, this does not mean that they are not important. The strengthening of patent systems should be mentioned here as an example. The introduction of the Unitary Patent[ww] in 25 EU member states in 2023 aims, among other things, to simplify access to the European patent system and reduce the cost of patent protection in Europe. It is not yet possible to assess whether this initiative will succeed at the start of 2024. The impact of the Leahy-Smith America Invents Act[xx], which was passed in the U.S. in 2011 and aims to harmonize the patent system, create an innovation-friendly patent system, and reduce uncertainty, for example by changing the post-grant review system, has also not yet been sufficiently evaluated and, as we have already mentioned above, is also viewed critically.

[7] In this study, quality was measured along four dimensions: number of citations received by the patent; number of independent claims at grant; size of the patent family; and number of times the patent was renewed.

Overall, incentives for R&D and IPR are important instruments for promoting innovation. Each policy instrument has advantages and disadvantages and can be strategically exploited by companies. It is therefore important that policy instruments (continue to) be evaluated on an ongoing basis. Furthermore, the instruments should not only be considered in isolation. Policy instruments are and should be combined if this leads to them reinforcing each other. In this context, the concept of "policy mix" has gained traction in innovation policy, emphasizing the importance of understanding the interactions between different policies to achieve desired outcomes (Flanagan et al. 2011). However, the reinforcing dynamics between simultaneously introduced policies make it difficult to assess their isolated or combined effects and to causally attribute changes in outcomes to individual interventions (Magro and Wilson 2013). This challenge becomes even more relevant with the increasing number of innovation policies that have been introduced in recent decades, for example, at the regional, federal, and international level.

Even if this goes beyond the scope of this study, it should further be noted that the promotion of R&D and IPR alone is not enough to foster innovation. In Europe, for instance, there are currently increasing calls for less regulation, a reduction in bureaucracy, and cheaper energy. Bureaucracy including extensive reporting obligations for sustainability and data security, can become an obstacle to innovation and costs companies millions every year. While regulation is necessary, some countries - positive examples in Europe are the Nordic countries - show that less bureaucracy and regulation is also possible. In addition, companies must develop internal capabilities for innovation management, create a culture of innovation that also allows for failure, and hire creative employees. Finally, there are policies and regulations that can encourage technological innovation, that are directed at individuals rather than firms, such as inventor compensation (Harhoff and Hoisl 2007). In Germany, for example, the German Employees' Inventions Act requires employers to compensate inventors if they claim the right to an invention. In other countries inventor compensation is governed by country-specific laws, sectoral norms and regulations, and employment contracts (Hoisl and Mariani 2024).

4. Analysis of the Economic Relevance of Patent Quantity and Patent Quality

We complement the theoretical discussion of the relationship between technological innovation and economic growth and the role of policies, with an empirical analysis. As the evaluation of individual policies is complicated by the omnipresence and pervasiveness of policy mixes (see above), especially at the macro level of our analyses, we use a backward induction approach. We first identify how the quantity and quality of technological innovation are related to economic growth in 36 OECD countries and China for the period 2000 to 2021[8]. In a second step, we narrow our focus to sustainable technologies and AI, two key technology areas for the future and analyze the level of technological innovation in these areas across a subset of countries and indicators. In a final step, we use the insights from these analyses to consider of how appropriate policies could be designed to achieve technological leadership and economic prosperity in the future.

4.1 Data Sources

The dataset we use for our analysis is constructed from two sources. First, we use PATSTAT[yy] (version 10/2023), a database provided by the EPO that contains bibliographic and legal event patent data from nearly 100 countries worldwide. Second, we use the World Development Index (WDI)[zz] database provided by the World Bank to extract macroeconomic GDP data.

To link patent applications to countries, we use the country of the first applicant listed on the earliest patent application (first priority application). If information on the country of the applicant is not available, we follow the approach of de Rassenfosse et al. (2013) and use the country of the first inventor listed on the patent or,

[8] Our analysis includes the following countries: AT, AU, BE, CA, CH, CL, CN, CO, CR, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IL, IS, IT, JP, KR, LT, LU, LV, MX, NL, NO, NZ, PT, SE, SI, SK, US

if not available, the country of the patent authority where the first priority was filed. To avoid double counting, we follow Dechezleprêtre et al. (2017) and calculate our variables at the level of the DOCDB patent family. The latter is defined as all patent documents covering the same technical invention and sharing the same priority (i.e., first filing date).[aaa]

4.2 Description of the variables

In the following, we outline the variables used in our analysis. As proxy for economic growth and our dependent variable, we use the annual growth in real GDP per capita, measured as the percentage year-by-year change in the GDP per capita in constant 2015 USD (Hassan and Tucci 2010). We use several macroeconomic GDP indicators as explanatory variables, such as variables capturing government consumption, export, foreign direct investment, and the usage of Information and Communication Technology (ICT). The latter are intended to measure a country's level of technological advancement. Finally, to avoid spurious correlations, we add controls for technological areas, and country and time fixed effects.

As the main explanatory variables in our economic growth models, we use measures that capture both the quantity and the value of patent applications. It is important to note that measuring patent value is challenging, despite the existence of a large literature on proxies for patent value (e.g., Harhoff et al. 2003, Squicciarini et al. 2013, Tapia 2016). One reason for this is that it is difficult to separate the value of an invention from the quality of its associated IPRs, such as patents. Even valuable inventions can have imprecisely formulated, low-quality patents. Inventions with a high inventive step, so-called radical inventions, are often associated with a broad scope of protection and are typically of high value (Arts and Veugelers 2015, Rizzo et al. 2020). This, in turn, can increase the patent quality. It is also important to note that the definition of patent value is subjective, i.e., lies in the eye of the beholder. While a lawyer may consider patents valuable if they can withstand a dispute, the patent holders may have different criteria. The owner of a high-tech firm, for instance, would argue that a valuable patent protects an invention from imitation or has a high strategic value in cross-license negotiations.

In this report, we do not distinguish between the value of the invention, i.e., the value of the technology underlying the invention, and the quality of the patent, i.e., the extent to which a patent protects an invention against imitation. Rather, we assume that the two are inextricably linked to the value of a patent, i.e., its commercial value. Following the literature, we use more than one proxy for patent quality/invention value and refer to these proxies as patent value proxies. As a first proxy for patent value, we consider whether a patent has been granted; second, the size of the patent family (i.e., the number of jurisdictions in which patent protection was sought); third, the number of forward citations a patent received from subsequent patents within five years of filing[9]; and fourth, we categorize the inventions underlying the patents as radical versus non-radical (Verhoeven et al. 2016). While the grant of a patent and the radicalness of the invention are mainly proxies for the value of the invention, the size of a patent family is a proxy for the market value of an invention. Citation counts have been shown to be a proxy for both technology and market value (Reitzig 2002, Squicciarini et al. 2013). The detailed variables descriptions and the data sources are provided in Table 1.

Table 1: Description of the variables

Variables	Description	Data Source
Annual growth in real GDP per capita	Growth rate of real annual per capita GDP in a country. The real per capita GDP is defined as per capita GDP deflated to the base year 2000.	World Bank

[9] We only consider citations at the DOCDB family level to account for different citation behaviors across jurisdictions.

Patent applications	Number of patent applications per year and per country. In the regression we use the natural logarithm of this variable to account for its skewed distribution.	PATSTAT
Granted patents	Number of patents that were granted by 10/2023. In the regression we use the natural logarithm of this variable to account for its skewed distribution.	PATSTAT
Granted patents with at least two family members	Number of patents that were granted by 10/2023 and that have at least two patent family members. We use the definition of the DOCDB patent family, i.e. the number of all patent documents in different jurisdictions that cover a single invention, with identical technical content, and share the same priority date. In the regression we use the natural logarithm of this variable to account for its skewed distribution.	PATSTAT
Patent applications with at least one forward citation in 5 years	The number of patents that received at least one forward citation within 5 years from the filing date. In the regression we use the natural logarithm of this variable to account for its skewed distribution.	PATSTAT
Radical inventions	The number of patents that protect radical inventions, which are defined as containing at least one pair of IPC that had previously not been combined (Verhoeven et al. 2016). In the regression we use the natural logarithm of this variable to account for its skewed distribution.	PATSTAT
Real GDP per capita (t-1)	GDP per capita from the previous year in constant 2015 USD. In the regression we use the natural logarithm of this variable to account for its skewed distribution.	World Bank
Gross capital formation (% of GDP)	Expenditures on additions to the fixed assets of the economy plus net changes in the level of inventories relative to GDP.	World Bank
Government final consumption expenditure (% of GDP)	Share of national GDP that is spent by the government on final goods and services.	World Bank
Exports of goods and services (% of GDP)	Total value of all exported goods and services relative to GDP.	World Bank
Foreign direct investment, net inflows (% of GDP)	Net inflows to foreign investments relative to GDP.	World Bank
Individuals using the Internet (% of population)	Percentage of the population that has used the Internet (from any location) at least once over a period of three months.	World Bank
Fixed telephone subscriptions (per person)	Active number of analogue fixed telephone lines and fixed public phones per person.	World Bank
Mobile cellular subscriptions (per person)	Subscriptions to a public mobile phone service that provide access to the PSTN using cellular technology per person.	World Bank
Share of patent applications by non-residents	Share of patent applications filed by non-residents relative to all patent applications.	World Bank
Technology class controls	Share of patents per country that fall into the five technical main areas electrical engineering, instruments, chemistry/ pharmaceuticals, mechanical engineering, and other fields (e.g., construction and civil engineering). The classification was developed by the German Fraunhofer Institute for Systems and Innovation Research (FhG-ISI) and the French Intellectual Property Institute (INPI) (OECD 1994).	PATSTAT
Year fixed effects	Year of economic indicator / year of earliest patent filing within the DOCDB patent family.	PATSTAT/ World Bank
Country fixed effects	Application country of the patent.	PATSTAT

4.3 Descriptive Statistics

Table 2 summarizes the descriptive statistics of the variables included in the regression analyses. The level of analysis is the country-year level, and all variables are reported accordingly. The average annual growth rate of real GDP per capita across the 37 countries in our sample is 1.9% (min = -14.5%; max = 23.3%). Looking at the different patent measures, we see the expected gradient in the means of our logged patent counts. On average, applicants from a given country filed 21,301 patent applications per year, of which 9,738 were granted. Of these granted patents, 3,396 patents have at least two family members, i.e., they were filed in at least two jurisdictions. On average, 12,512 patent applications are cited at least once within the first five years after filing, and on average, 731 patent applications are related to radical inventions according to the IPC-based measure proposed by Verhoeven et al. (2016). These numbers already show that there is significant heterogeneity in patent value across countries. Along various quality measures, we find that far from all patent applications meet the proposed quality thresholds (e.g., are granted or cited at least once).

Turning to macroeconomic indicators, the countries in our sample have an average real GDP per capita of 26,768 constant 2015 USD. The maximum real GDP per capita is 112,417.88 constant 2015 USD (Luxembourg in 2007) and the minimum real GDP per capita is 2,038.21 constant 2015 USD (China in 2000). Other macroeconomic indicators such as gross capital formation (mean = 0.24), government final consumption (mean = 0.19), exports of goods and services (mean = 0.48), and net inflows of foreign direct investment (mean = 0.05) - all expressed as a percentage of total GDP - show values that are similar to related research on economic growth (e.g., Hasan and Tucci 2010).

The countries in our sample, on average, are technologically advanced, with 66% of the countries' population using the Internet at least once every three months and people having, on average, at least one mobile phone subscription. The countries in our sample also appear, on average, to have open markets that are attractive to international firms, as indicated by the relatively high share of patent applications filed by non-residents (mean = 0.38). Looking at the main technological fields in which most patent applications are filed, we see a rather even distribution among electrical engineering, instruments and chemistry, above-average filing rates in mechanical engineering and relatively low filing rates in other fields.

Table 2: Descriptive Statistics (N= 814 observations at the country-year-level)

variable name	mean	sd	min	max
annual growth in real GDP per capita	1.93	3.62	-14.464	23.305
patent applications	21300.81	108962.91	2	1393950
granted patents	9738.10	37700.56	0	437407
granted patents with at least two family members	3395.97	8815.16	0	51820
patent applications with at least one forward citation within 5 years	12511.76	58944.72	0	792677
radical inventions	730.91	2247.63	0	29066
real GDP per capita (t-1)	34073.03	21976.72	2038.21	112418
gross capital formation (% of GDP)	0.24	0.05	0.119	0.548
government final consumption expenditure (% of GDP)	0.19	0.04	0.09	0.282
exports of goods and services (% of GDP)	0.48	0.30	0.09	2.132
foreign direct investment, net inflows (% of GDP)	0.052	0.143	-1.174	2.342
individuals using the Internet (% of population)	0.66	0.25	0.018	0.997
fixed telephone subscriptions (per 100 people)	0.39	0.16	0.037	0.745
mobile cellular subscriptions (per 100 people)	1.04	0.31	0.053	1.77
share of patent application by non-residents	0.38	0.32	0.007	0.987
technology main area: electrical engineering	0.30	0.14	0	1
technology main area: instruments	0.23	0.09	0	1
technology main area: chemistry	0.28	0.12	0	0.688
technology main area: mechanical engineering	0.36	0.11	0	0.938
technology main area: other fields	0.17	0.08	0	1
year	2010	-	2000	2021

Looking at the bivariate correlations (Table 3), it is noteworthy that all variables related to the number and value of patents show a negative correlation with the annual growth rate of real GDP per capita, but a positive correlation with total GDP per capita. The inverse relationship observed between the annual growth rate and total GDP per capita highlights the need for a multivariate analytical approach. Such an approach would allow us to assess the influence of patent metrics on economic expansion while controlling for aggregate GDP. Moreover, the patent variables exhibit a high degree of intercorrelation, as indicated by Pearson correlation coefficients above 0.96 at a significance level below 0.01. Due to multicollinearity concerns, we therefore include these patent metrics in separate models rather than a single model.

Table 3: Correlation matrix

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
(1) annual growth in real GDP per capita	1																				
(2) ln patent applications	-0.10	1																			
(3) ln granted patents	-0.09	0.98	1																		
(4) ln granted patents with at least two family members	-0.11	0.96	0.99	1																	
(5) ln patent applications with at least one forward citation within 5 years	-0.11	0.97	0.97	0.97	1																
(6) ln radical inventions	-0.12	0.98	0.96	0.96	0.97	1															
(7) real GDP per capita (t-1)	-0.31	0.40	0.41	0.46	0.41	0.43	1														
(8) gross capital formation (% of GDP)	0.43	0.19	0.20	0.16	0.18	0.15	-0.24	1													
(9) government final consumption expenditure (% of GDP)	-0.23	0.03	0.06	0.10	0.01	0.02	0.32	-0.23	1												
(10) exports of goods and services (% of GDP)	0.09	-0.27	-0.25	-0.22	-0.27	-0.30	0.25	-0.05	-0.01	1											
(11) foreign direct investment, net inflows (% of GDP)	0.08	-0.08	-0.08	-0.07	-0.07	-0.08	0.06	-0.01	-0.01	0.31	1										
(12) individuals using the Internet (% of population)	-0.24	0.23	0.21	0.23	0.17	0.22	0.61	-0.16	0.33	0.24	0.01	1									
(13) fixed telephone subscriptions (per 100 people)	-0.14	0.44	0.46	0.49	0.48	0.45	0.56	-0.17	0.17	-0.01	0.04	0.07	1								
(14) mobile cellular subscriptions (per 100 people)	-0.21	0.02	-0.02	-0.01	-0.03	0.00	0.34	-0.18	0.24	0.26	0.02	0.68	-0.13	1							
(15) share of patent application by non-residents	0.07	-0.28	-0.30	-0.31	-0.23	-0.22	-0.19	-0.04	-0.34	-0.18	0.01	-0.26	-0.17	-0.35	1						
(16) technology main area: electrical engineering	0.03	0.46	0.48	0.49	0.47	0.44	0.31	0.13	0.05	0.01	0.02	0.32	0.16	0.11	-0.04	1					
(17) technology main area: instruments	-0.09	-0.08	-0.08	-0.05	-0.05	-0.06	0.25	-0.15	0.09	0.04	0.01	0.28	0.12	0.23	0.11	0.18	1				
(18) technology main area: chemistry	0.06	-0.38	-0.41	-0.41	-0.35	-0.36	-0.47	0.11	-0.25	0.03	0.06	-0.37	-0.23	-0.17	0.16	-0.54	-0.18	1			
(19) technology main area: mechanical engineering	-0.12	-0.01	-0.01	0.00	-0.03	0.03	0.07	-0.16	0.14	0.07	-0.04	0.06	-0.04	0.16	-0.20	-0.43	-0.27	-0.04	1		
(20) technology main area: other fields	-0.21	-0.11	-0.12	-0.12	-0.13	-0.08	0.11	-0.23	0.05	-0.09	-0.04	0.06	-0.05	0.07	0.08	-0.38	-0.15	-0.10	0.12	1	
(21) year	-0.14	0.06	0.00	-0.02	-0.07	0.01	0.14	-0.10	0.11	0.14	-0.05	0.73	-0.39	0.66	-0.14	0.17	0.17	-0.24	0.07	0.08	1
Observations	814																				

4.4 Methodology and Results

We investigate the relationship between technological innovation and economic growth in a series of linear panel regressions that include both country and year fixed effects as shown in Table 4. All models include a comprehensive set of control variables as well as various patent-based proxies for technological innovation. We cluster the standard errors at the country level. Model 1 shows the baseline model with all controls. The model confirms that smaller economies grew faster, on average, over the sample period. In addition, government consumption expenditure, exports of goods and services, the number of mobile phone subscriptions, and the share of patent applications filed by non-residents appear to be statistically significant predictors of economic growth, while government consumption expenditure is a strong predictor of economic contraction.

Model 2 adds the natural logarithm of the number of patent applications filed by applicants from a given country. In this model, we find no statistically significant relationship between the number of patent applications and economic growth. In Models 3 to 6, we adjust the number of patent applications for value along several dimensions and find persistent positive effects of the quality-adjusted volume of technological innovation on economic growth. Model 3 shows that, on average, a 1% increase in the number of patents granted is associated with a 0.35 percentage point increase in a country's economic growth rate. Model 4 shows that, on average, a 1% increase in the number of patents with at least two family members is associated with a 0.43 percent point increase in a country's economic growth rate and Model 5 finds that for patents with at least one forward citations within 5 years the effect is even 0.52 percentage points. Finally, for patents protecting radical inventions, we find that a 1% increase is associated with an increase in economic growth of up to 0.55 percentage points (Model 6). Compared to an average growth rate of 1.93% in our sample, these effect sizes imply a relative increase in economic growth of 18% and 28% for a 1 percentage point increase in the number of patents that are granted or protecting radical inventions, respectively. These results underscore the importance of distinguishing between the sheer quantity of patents and their value. In other words, not all patent applications contribute equally to economic growth.

We conclude our multivariate analysis by testing for reverse causality. In Model 7, we regress the number of patent applications on the previous year's economic growth rate and our control vector. While we do not find a statistically significant effect of the growth rate on patent applications, we do find that the total volume of GPD per capita is a strong predictor of patent applications. In fact, it is the only statistically significant predictor in the entire model. The estimate suggests that a 1% increase in real GDP per capita is associated with a 2.8% increase in patent applications[10].

Table 4: Regression analyses

dependent variable	annual growth in real GDP per capita						ln patent applications
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
ln patent applications		0.245 (0.235)					
ln granted patents			0.353** (0.174)				
ln granted patents with at least two family members				0.431** (0.204)			
ln patent applications with at least one forward citation within 5 years					0.521** (0.217)		
ln radical inventions						0.553** (0.244)	
annual growth in real GDP per capita (t-1)							-0.0123 (0.009)
real GDP per capita (t-1)	-6.780*** (1.734)	-7.471*** (1.520)	-7.896*** (1.469)	-7.887*** (1.434)	-8.640*** (1.511)	-8.173*** (1.442)	2.810*** (1.029)
gross capital formation (% of GDP)	25.07*** (7.145)	25.20*** (7.151)	25.18*** (7.200)	24.90*** (7.105)	25.73*** (7.275)	25.51*** (7.160)	-0.220 (1.139)
government final consumption expenditure (% of GDP)	-64.78*** (14.028)	-64.73*** (14.188)	-65.18*** (14.155)	-64.75*** (14.035)	-64.75*** (14.203)	-66.50*** (13.974)	-0.953 (3.560)
exports of goods and services (% of GDP)	3.543* (1.982)	3.520* (2.066)	3.298 (2.065)	3.062 (2.029)	3.542 (2.150)	3.427 (2.138)	0.104 (0.656)
foreign direct investment, net inflows (% of GDP)	1.073 (1.136)	1.078 (1.139)	1.089 (1.144)	1.109 (1.152)	1.106 (1.151)	1.113 (1.155)	-0.0173 (0.069)
individuals using the Internet (% of population)	-0.867 (1.307)	-0.987 (1.397)	-0.888 (1.339)	-0.768 (1.269)	-1.219 (1.429)	-0.859 (1.304)	0.449 (0.556)
fixed telephone subscriptions (per 100 people)	1.316 (1.335)	1.076 (1.353)	1.246 (1.339)	1.310 (1.340)	1.081 (1.339)	0.763 (1.291)	0.994* (0.567)
mobile cellular subscriptions (per 100 people)	1.504** (0.706)	1.591** (0.711)	1.814** (0.683)	1.833** (0.707)	1.720** (0.748)	1.609** (0.748)	-0.344 (0.342)
share of patent applications by non-residents	1.221* (0.691)	1.209* (0.703)	1.090 (0.696)	0.997 (0.687)	1.090 (0.697)	1.326* (0.715)	0.0635 (0.414)
technology class controls	included	included	included	included	included	included	included
year dummies	included	included	included	included	included	included	included
country fixed effects	included	included	included	included	included	included	included
constant	74.21*** (16.680)	79.54*** (14.361)	83.18*** (13.563)	83.09*** (13.357)	89.27*** (13.584)	87.04*** (13.360)	-21.57** (10.059)
observations	814	814	814	814	814	814	814
adjusted R-squared	0.694	0.695	0.696	0.697	0.698	0.698	0.472

*note: standard errors clustered at the country level in parentheses; * p < 0.1, ** p < 0.05, *** p < 0.01*

[10] We find very similar results, both in terms of effect size and statistical significance, when using value-adjusted patent counts as the dependent variable.

5. A closer look at two key technologies of the future: Sustainable Technologies and Artificial Intelligence

In the last section, we will take a closer look at patenting activity related to two technologies that have been identified as particularly relevant for future economic growth and welfare: AI and Sustainable Technologies (World Economic Forum 2023[bbb]). To give two examples: AI is expected to impact nearly 40% of jobs worldwide[ccc], reshaping the nature of work and total factor productivity (Wang et al. 2023). Sustainable technologies—those that mitigate and alleviate the adverse effects of climate change—will contribute significantly to the transformation of industries by increasing resource efficiency and reducing carbon emissions. By 2030, the global green technology and sustainability market is expected to grow to nearly 62 billion U.S. dollars, representing a compound annual growth rate of 20.8% from 2023 to 2030[ddd].

Having established that patent quantity and patent value have different implications for economic growth, we compare the evolution of technological innovation in these key technologies along different patent indicators. The implicit assumption is that countries that lead in both patent quantity and patent value are likely to experience the strongest economic growth from technological innovation in these technologies.

5.1 Identification of Patents Protecting Sustainable and AI-Related Technologies

To identify patents protecting sustainable technologies, we use a classification scheme developed in 2013 by the EPO in collaboration with the USPTO, the United Nations Framework Convention on Climate Change (UNFCC) and the Intergovernmental Panel on Climate Change (IPCC). The classification uses a tagging system (the Y section) that assigns relevant patent documents to climate change mitigation technologies (Y02), which help to control, reduce or even prevent greenhouse gas emissions, and smart grids (Y04). The tags have been added to the International Patent Classification (IPC) - about 70,000 alphanumeric codes that assign patents to technology sections - so that patents protecting sustainable technologies can be easily identified in PATSTAT. The classification scheme is summarized in Table 5.

Table 5: Technology tags used to classify patents protecting sustainable technology (Source: EPO)

Sub-group	Description	Comment
Y02B	Climate change mitigation technologies in buildings, including the residential sector	Lighting, heating, ventilation and aircon, Construction, ICT, integrated renewables, power management
Y02C	Greenhouse gases capture and storage	CO_2 capture and storage
Y02E	Climate change mitigation technologies in energy generation, transmission and distribution	Renewable energy, efficient combustion, biofuels efficient transmission and distribution, energy storage, hydrogen technology
Y02T	Climate change mitigation technologies in the transportation of goods and persons	e-mobility, hybrid cars, efficient internal combustion engines, efficient airplanes, ships and trains
Y045	Smart grid technologies	Remote network operation, smart metering, electric and hybrid vehicles interoperability, trading and marketing

To identify AI-related patents, we follow the approach of Baruffaldi et al. (2020). The search is based on patent classes from the IPC and the Cooperative Patent Classification (CPC) that have been identified as AI-relevant, as well as AI-related keywords in patent abstracts. In a first step, the authors identified potentially relevant keywords and technology classes (IPC and CPC). The list of relevant keywords (e.g. chatbot, kernel learning or data mining) and the list of relevant IPC and CPC classes (e.g. IPC: G06N3, CPC: A61B5/(7264, 7267)) can be found in the Appendix of Baruffaldi et al. (2020). In a second step, the technology classes and keywords were reviewed by patent examiners and experts who manually went through the complete lists of technology classes and keywords. In a third step, the authors, together with the experts, defined rules to identify AI-related patents. These rules are summarized in Table 6.

Table 6: Procedure to identify AI-related patents (Baruffaldi et al. 2020)

Patents in AI are those:
classified in one of the IPC codes identified or
classified in one of the IPC codes identified and featuring in their English abstract or claims at least one of the keywords identified or
classified in one of the CPC codes identified and featuring in their English abstract or claims at least one of the keywords identified or
featuring at least three of the keywords identified in their English abstract or claims, in the patent document

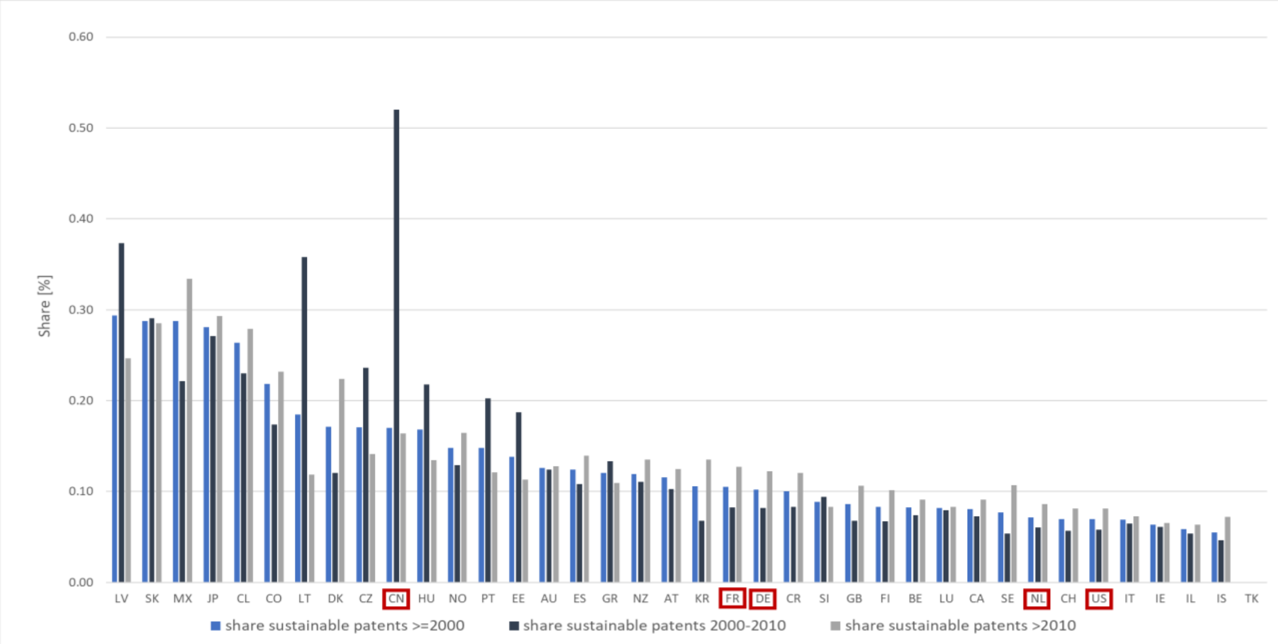
5.2 Patent and Inventive Activities in Sustainable and AI-Related Technologies

Due to the limited length of this report, we will focus on the period 2010-2023 and the countries Germany (DE), France (FR), the Netherlands (NL), the United States (US), and China (CN), unless otherwise noted. In addition, the following analyses are purely descriptive. Therefore, it is not possible to infer causal relationships from our findings. Causality must remain the subject of future research.

5.2.1 Sustainable Technologies

Figure 1 shows the share of patent applications for sustainable technologies from 2000 and for the time windows 2000-2010 and after 2010 separately. We see strong variation between countries, with Latvia, Slovakia, Mexico and Japan showing the highest shares. Some countries show higher shares of sustainable technology patent applications in the earlier period (e.g. Latvia, Lithuania, China, Hungary, Portugal), while others show higher shares in the later periods (e.g. Mexico, Denmark, Korea, Sweden). While China is in the first third of the distribution in terms of patents and France and the U.S. are in the middle, Germany and the Netherlands are at the end of the distribution.

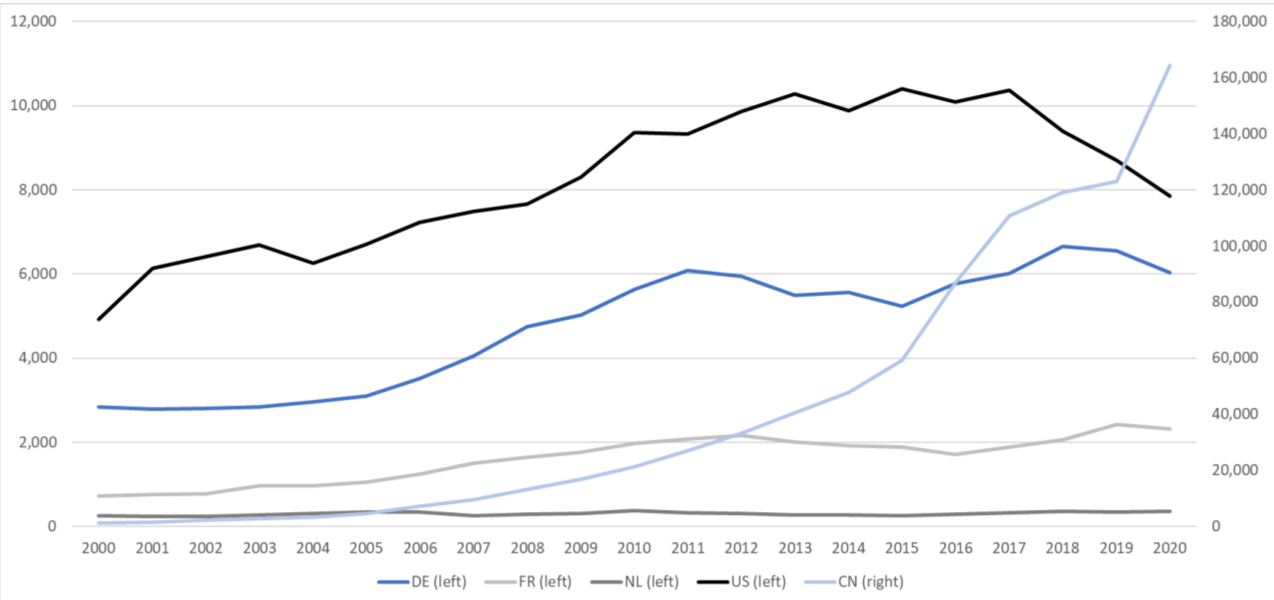
Figure 2: Share of patents protecting sustainable technologies



N>2000=18,737,156 / N2000-2010 = 4,661,646 / N>2011 = 14,075,510 (OECD countries and China)

Figure 2 shows the evolution of patent filings in our five focus countries. While the number of applications in the Netherlands remains fairly stable, it is increasing in France, Germany and the US - although we see a decline in the annual number of applications from 2017 in the US and from 2018 in Germany. In China, on the other hand, the number of applications started to rise around 2005 and has increased tremendously since then.

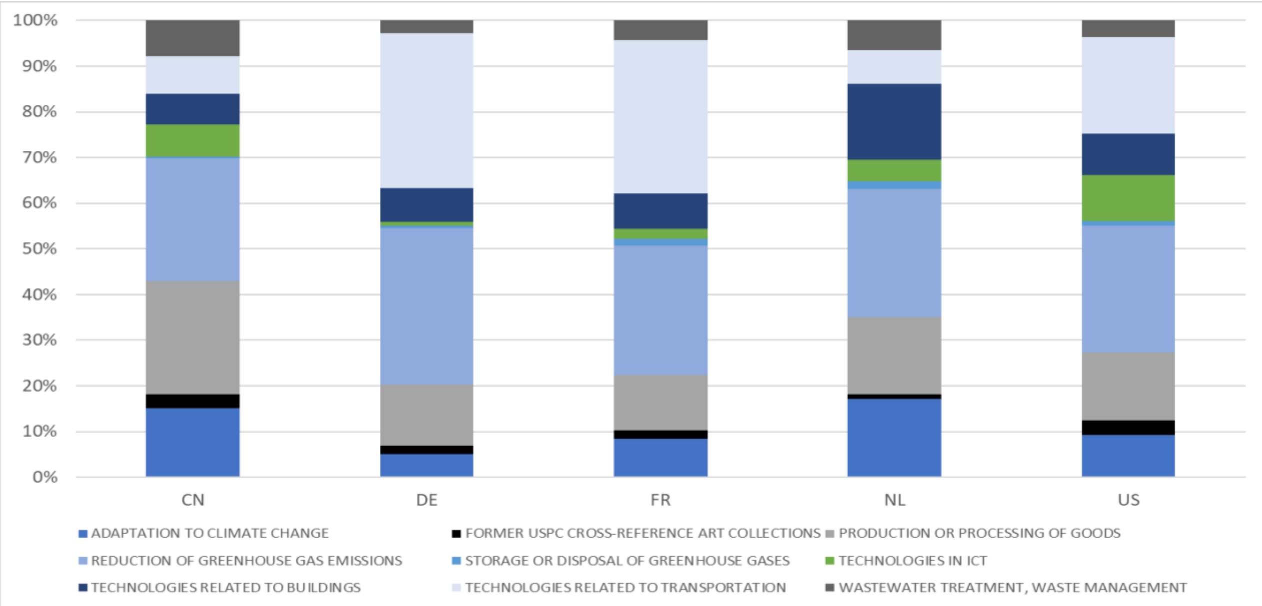
Figure 3: Yearly number of patent filings for sustainable technology between 2000 and 2020 in DE, FR, NL, US, CN



N2000-2020 = 1,207,968

Figure 3 shows the distribution of the various technology subfields (tags) within sustainable technologies. Interestingly, while China and the Netherlands have a relatively homogeneous distribution of tags, Germany, France and the United States have a strong representation of TRANSPORT RELATED TECHNOLOGIES. The latter is certainly due to the importance of the automotive industry in these countries. In the U.S., TECHNOLOGIES IN ICT is most strongly represented among the five countries, which can also be explained by the importance of this technology for the U.S.

Figure 4: Shares of patent filings in subfields of sustainable technology in 2010



$N_{>2010}$ = 2,166,254

Figure 4 shows a heat map ranking the OECD countries and China by the total number of sustainable technology patent applications from 2010, the average number of 5-year forward citations these applications received, the average size of the patent family, the share of patents granted by 2023, and the share of patents filed for radical inventions.

China is clearly number one in terms of patent applications (patent quantity) but is at the bottom of the rankings for the patent value variables. The U.S., Germany and France are also among the leaders in terms of patent quantity. However, the U.S. is also far ahead in terms of forward citations (technological value of the invention) and the radicalness of the inventions. Although the Netherlands is only in the upper midfield in terms of the number of patent applications, it ranks well in terms of 5-year forward citations and family size (market value). It should be noted that the size of the patent family may also be partly determined by the size of the domestic market. Interestingly, the Nordic countries (Denmark, Norway, Sweden, Finland) are very strong in all dimensions (quantity and value).

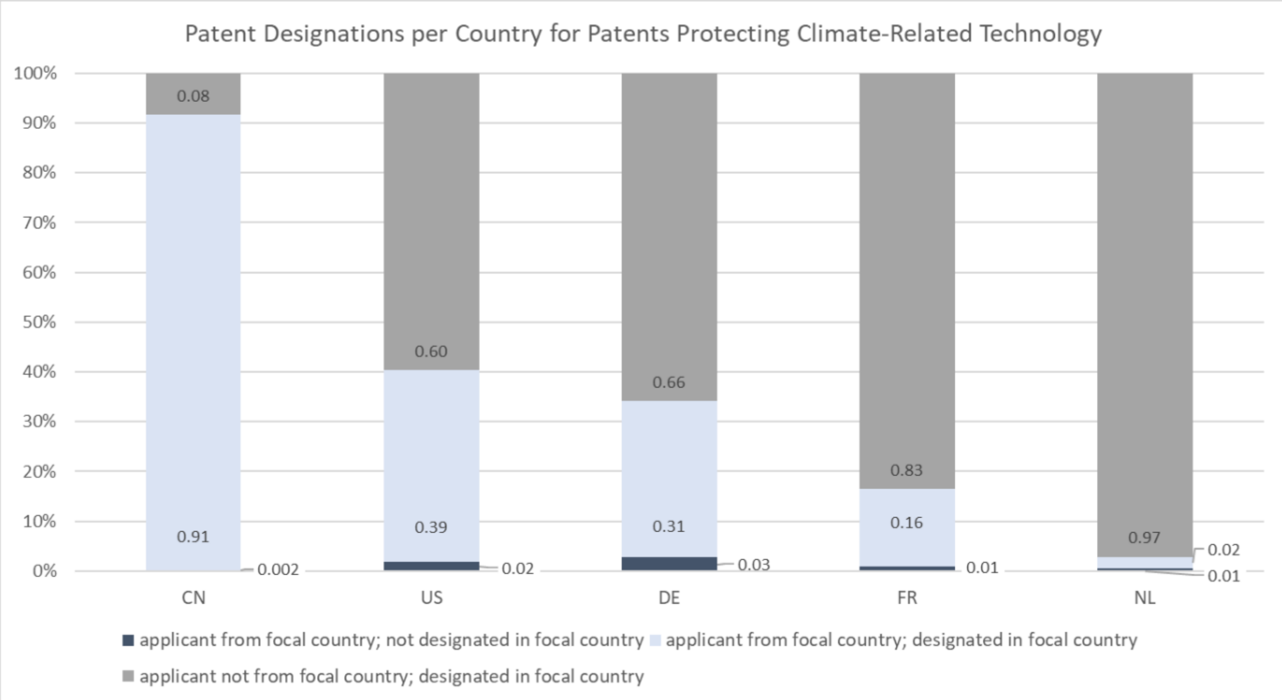
Figure 5: Rankings of the countries by patent quantity and patent value indicators

Country	Total number of patentfilings (>=2010)	Average number of 5-year citations	Average family size	Share patents granted by 2023	Share radical inventions
CN	1	27	37	11	36
JP	2	20	29	18	34
KR	3	21	34	29	32
US	4	1	18	31	9
DE	5	18	24	5	25
FR	6	22	16	35	20
GB	7	8	10	9	17
IT	8	25	17	3	26
CA	9	3	20	17	4
CH	10	9	7	13	14
ES	11	26	21	34	27
NL	12	12	14	33	24
AT	13	15	13	25	19
SE	14	7	6	27	10
DK	15	10	8	15	13
AU	16	17	19	22	12
FI	17	11	2	24	2
BE	18	13	5	20	22
IL	19	2	11	21	7
NO	20	16	4	26	15
MX	21	33	32	7	23
CZ	22	32	25	32	11
GR	23	34	33	28	33
IE	24	6	9	16	18
HU	25	23	27	6	21
LU	26	19	1	23	5
CL	27	28	12	1	6
NZ	28	5	3	8	1
PT	29	31	26	10	28
CO	30	36	28	2	3
SK	31	35	30	12	30
SI	32	29	23	36	16
LV	33	37	36	30	35
LT	34	30	31	37	29
EE	35	24	22	14	31
IS	36	4	15	19	8
CR	37	14	35	4	37

$N_{>2010}$ = 2,539,636

Figure 5 provides an overview of the origin of inventions filed in our five focus countries. In China, more than 90% of patent applications in sustainable technologies come from national applicants. In the Netherlands and France, the situation is the opposite. 97% (NL) and 83% (FR) of sustainable technology patent applications come from foreign applicants and only 2% (NL) and 16% (FR) from national applicants. In the U.S. and Germany, applications are more balanced between national and foreign applicants. In Germany, however, the proportion of patent applications filed by German applicants in other countries but not in Germany itself is the highest of all five countries (3%).

Figure 6: Patent designations per country for patents protecting sustainable technology

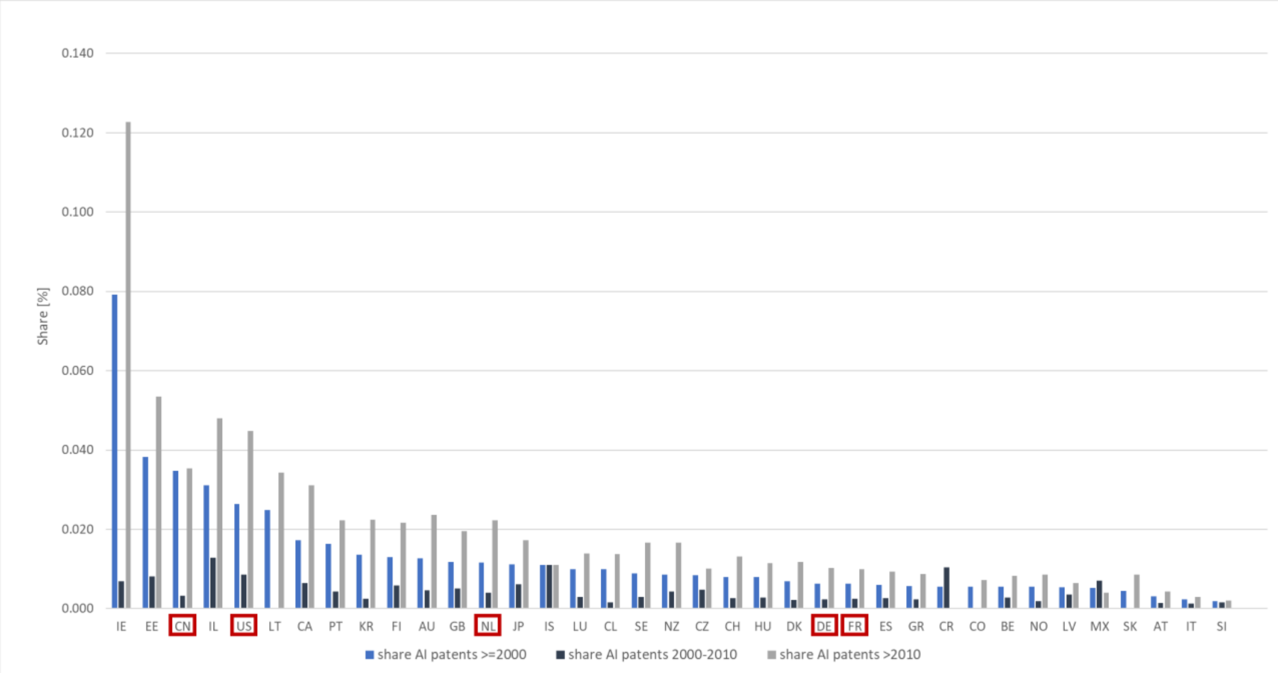


$N_{>2010}$ = 2,327,167

5.2.2 Artificial Intelligence

Figure 6 shows the share of patent applications for AI-related technologies from 2000 and for the time windows 2000-2010 and after 2010 separately. For AI we see strong differences between countries, with Ireland, China, Israel, and the U.S. showing the highest shares. Hardly any country shows a higher share of AI patent applications in the earlier period. Almost all countries show a huge increase in AI patent applications over time. While China and the U.S. are in the first third of the distribution in terms of patent applications, and the Netherlands is in the middle, Germany and France are at the end of the distribution.

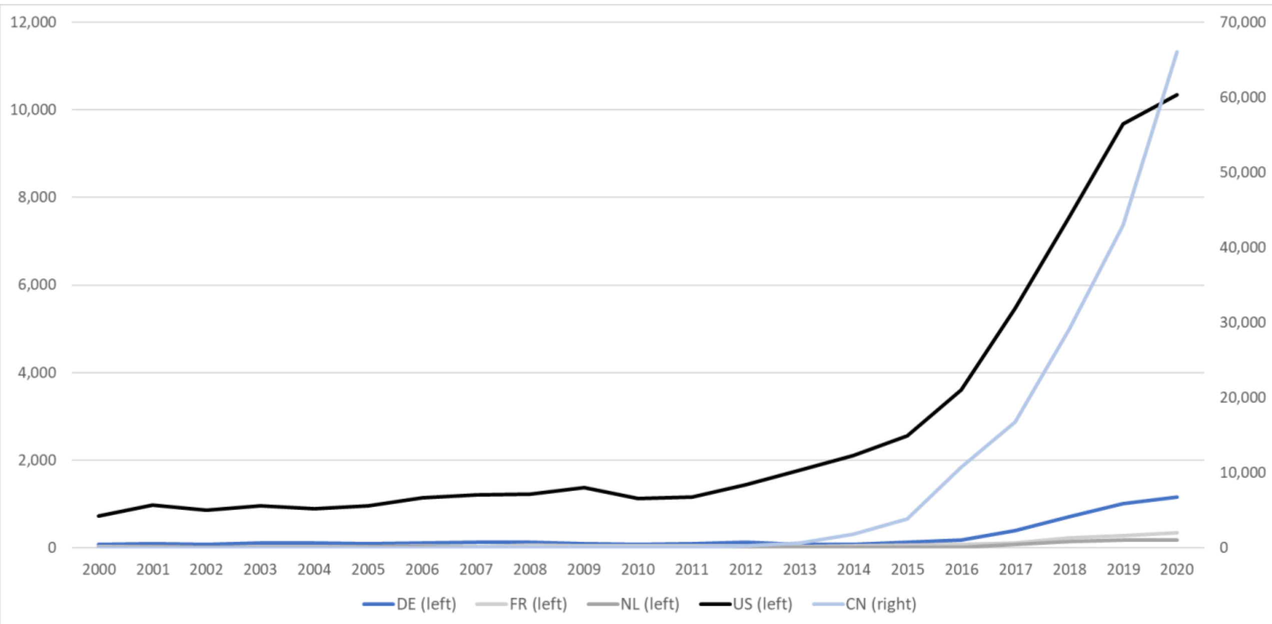
Figure 7: Share of patents protecting artificial intelligence-related technology



OECD countries and China; $N_{>2000}$=18,737,156 / $N_{2000\text{-}2010}$ = 4,661,646 / $N_{>2011}$ = 14,075,510

Figure 7 shows the evolution of patent applications in our five focus countries. While the number of patent applications in France and the Netherlands remains stable, the number of patent applications in Germany increases - but only from 2016 onwards. In the U.S. and China, on the other hand, the number of patent applications started to increase around 2013 and has since risen sharply in both countries.

Figure 8: Yearly number of patent filings for AI-related technology between 2000 and 2020 in DE, FR, NL, US, CN



$N_{2000\text{-}2020}$ = 256,800

Figure 8 again shows a heat map that ranks the OECD countries and China by the total number of AI patent applications from 2010 and our four patent value indicators. China is again number one in terms of patent applications (patent quantity), but it is again at the bottom of the rankings for patent value variables. The U.S., Germany, France, and the Netherlands are also among the leaders in terms of patent quantity. The U.S. is again far ahead in terms of forward citations (technological value of the invention) - but not in terms of radicalness of the inventions. The Netherlands and France rank well in terms of family size (market value). France also ranks 11th in terms of the radicalness of AI inventions. Again, the Nordic countries (Denmark, Norway, Sweden, Finland) are very strong in all dimensions.

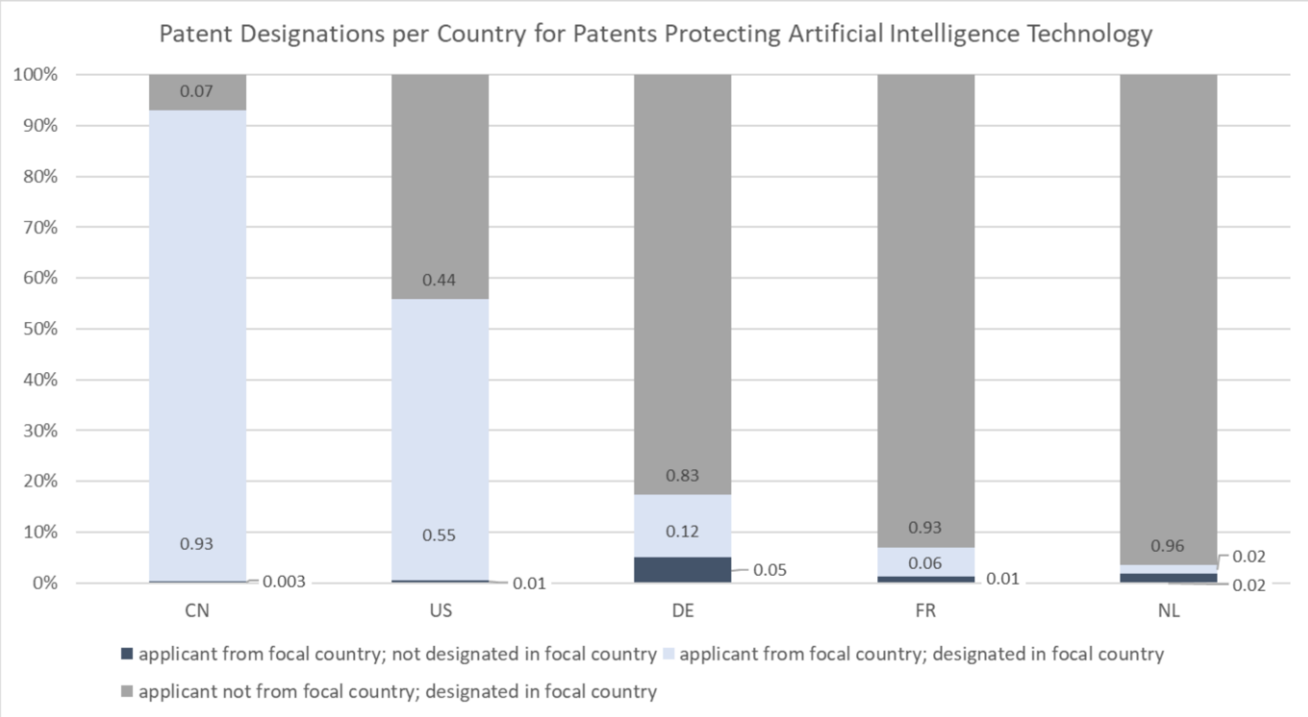
Figure 9: Rankings of the countries by patent quantity and patent value indicators

Country	Total number of patentfilings (>=2010)	Average number of 5-year citations	Average family size	Share patents granted by 2023	Share radical inventions
CN	1	29	36	9	32
US	2	4	24	31	26
KR	3	32	33	27	27
JP	4	16	11	30	23
DE	5	23	21	4	19
GB	6	9	7	12	24
CA	7	5	22	18	15
FR	8	26	10	21	11
IL	9	3	19	25	20
IE	10	7	28	28	30
NL	11	19	15	10	28
CH	12	13	14	15	14
SE	13	11	13	17	18
FI	14	14	17	8	13
AU	15	22	23	33	10
ES	16	21	26	19	28
IT	17	24	4	2	22
BE	18	20	6	11	21
DK	19	17	12	6	6
AT	20	15	3	13	5
NO	21	12	1	14	7
LU	22	25	18	32	31
CZ	23	10	32	26	16
PT	24	18	16	3	25
GR	25	31	35	29	12
HU	26	2	9	22	16
NZ	27	28	8	20	8
EE	28	1	5	7	9
LT	29	34	29	34	33
CL	30	6	2	35	2
MX	31	27	27	16	3
CO	32	8	20	5	3
SK	33	36	31	1	33
LV	34	33	25	36	33
SI	35	30	30	23	1
IS	36	35	34	24	33
CR	37	37	37	37	33

$N_{>2010}$ = 455,476

Figure 9 provides an overview of the origin of inventions registered in our five focus countries. In China, as in the case of sustainable technologies, more than 90% of patent applications in AI technologies originate from national applicants. The situation is reversed in the Netherlands, France, and Germany. 96% (NL), 93% (FR), and 83% (DE) of patent applications for sustainable technologies come from foreign applicants and only 2% (NL), 6% (FR), and 12% (DE) from national applicants. In the U.S., applications are more balanced between national and foreign applicants. In Germany, again, the share of patent applications from German applicants in other countries but not in Germany itself is the highest of all five countries (5%).

Figure 10: Patent designations per country for patents protecting AI technology



$N_{>2010}$ = 462,914

6. Discussion and Implications

From the existing literature, we learn that IPR are positively correlated with economic growth. However, we also see that IPR are filed in industries with higher economic performance, possibly because these industries are particularly attractive. Our own analysis confirms this two-sided relationship. Interestingly, however, we find that it is not the quantity of patent applications that is positively correlated with annual growth in real GDP per capita, but the value of patents (measured by grant rates, forward citations, patent family size, and radicalness of the underlying invention). We can use these findings to inductively derive implications for innovation policy.

Going back to what we know about policy instruments to promote innovation, the instruments to promote investment in R&D (e.g. tax incentives or direct funding) and IPR (e.g. fee reductions or patent box regimes) as well as the indirect mechanisms are primarily aimed at increasing the quantity of output. It is difficult, if not impossible, to say which of these policies is most effective, as these mechanisms have been offered in parallel in most OECD countries for many years. Countries are therefore almost interchangeable in terms of their R&D and IPR funding landscape. Germany may be an exception here, as it has only introduced tax incentives for R&D in 2020 and abolished the patent box regime in 2022. However, the effectiveness of these measures cannot be assessed at this early stage. Another exception in terms of R&D and IPR funding is China, which relies mainly on government subsidies and explicitly wants to increase the number of patents in technologies that are critical for the country (Chang et al. 2022). Looking at the figures for sustainable technologies and AI in particular, the goal of significantly increasing the number of patents has been achieved. In terms of patent applications, China is far ahead of all other countries with extreme annual growth rates. However, as Chang et al. (2022) point out, there is little correlation between patent intensity and the value of gross industrial output in China. Given our findings on the importance of patent value, this may be because the value of Chinese patents in both focus technologies lags far behind that of OECD countries. Since around 90% of patents with scope of protection in China originate from domestic applicants, China can also benefit comparatively little from spillover effects from applications from other countries in its own country. Chinese firms must go abroad themselves, for example through subsidiaries or R&D facilities in the U.S. or other technology leading countries. Another way to benefit from knowledge spillovers would be either to send Chinese employees abroad for a period or to employ foreign knowledge workers in a company in China.

Overall, policies should be designed to encourage quality rather than quantity. Patent box schemes could be a good example, at least if they are not abused, as they offer reduced corporate tax rates for income derived from patents and other intellectual property rights. It does not matter whether this income is derived from one patent or many patents. However, focusing solely on outcomes without considering inputs may overlook the importance of encouraging the risk-taking necessary to generate radical inventions. Radical inventions typically arise from high-risk projects with a significant chance of failure, but with the promise of extraordinary returns if successful. A notable policy that exemplifies support for such innovative ventures is the Advanced Research Projects Agency-Energy (ARPA-E) in the U.S. This agency invests in high-risk, high-reward research with the potential to dramatically advance the nation's economic, security, and environmental goals by fostering breakthrough technologies that may be too speculative for private sector funding.[eee] Another example, as mentioned above, is the Federal Agency for Disruptive Innovation (SPRIND GmbH) in Germany, which supports and accelerates the identification and development of radically innovative ideas. As we show, such radical inventions have the strongest influence on economic growth.

Our analysis also indicates that policies for technological innovations should be conceived and developed with a global perspective, rather than being confined to national boundaries. In most countries, the majority of patents are filed by foreigners, and the export of goods and services is one of the strongest predictors of economic growth. Open markets and international cooperation have become self-evident prerequisites for economic prosperity and social welfare. This should be reflected in innovation policies designed to stimulate economic growth. International cooperation should be encouraged rather than discouraged to increase knowledge sharing and spillovers across borders. This includes inviting foreigners to innovate in each country as well as commercializing foreign innovations locally.

It remains to be seen how effective current policy instruments in sustainable technologies will be, such as the Net Zero Industry Act in Europe[fff] or the Inflation Reduction Act in the U.S.[ggg], both of which aim to accelerate the transition to climate neutrality. In the area of AI, it will be particularly interesting to see how the current legislation in Europe (AI Act)[hhh] will affect innovation. There are different views on this. While companies are primarily concerned that the strong regulation could put Europe at a disadvantage in terms of innovation, lawmakers are more likely to believe that the regulation will create confidence and thus encourage investment in AI in Europe.

Another interesting result is that in both focus technologies, the four Nordic countries (Denmark, Sweden, Finland, Norway) are particularly strong, both in terms of quantity and value of patents. What makes the Nordic countries so strong? These countries also offer the usual incentives and policy instruments to promote R&D and IPR. However, these countries are also characterized by a particularly high level of education, a culture of collaboration (especially among the Nordic countries and with universities, but also with other partner countries), a very strong entrepreneurial spirit, and an abundance of natural resources. Another important factor is that the Nordic countries are known for their focus on quality of life. This includes a different attitude towards a clean environment and sustainable development. This focus on a liveable environment has led the Nordic countries to invest early in renewable energy, for example to reduce their carbon footprint. As a result, Nordic companies have become early experts and technology leaders in the field of sustainability. In the area of AI, the Nordic countries are characterized by a well-developed data infrastructure and regulations that prioritize data privacy and protection, but without making data inaccessible. The Nordic countries are also among the early adopters of digital technologies, including AI, in various sectors such as healthcare, finance, transportation, and public administration. Other countries can learn from the Nordic countries, especially when it comes to identifying further measures to promote innovation in sustainable technologies and AI in addition to the existing policy instruments.

7. Conclusion

Returning to the first question that this report seeks to answer, i.e., how policy instruments should be designed to promote economic growth, we conclude that policy should incentivize not only the quantity of innovation but also its value. This can be achieved by encouraging firms to take on high-risk, high-reward projects and by rewarding not only the quantity but also the quality of innovation output, such as its degree of radicalness or value for technological progress. Turning to the second question about Europe's future competitiveness in key technology areas, we can see that, in both AI and sustainable technologies, Europe already appears to be competitive in terms of value but is lagging behind in terms of quantity of patent applications. Within Europe, the Nordic countries, which have taken a leading role in both AI and sustainable technologies, can serve as role models. For long-term competitiveness, it will be crucial that companies continue to invest in IPR and R&D, and that these investments are supported by a robust policy framework. Governments and European institutions should foster an innovation-friendly environment that not only encourages such investment, but also facilitates collaboration between academia and industry and across borders, streamlines regulatory processes and provides incentives for radical research. Only a holistic approach will ensure that Europe remains at the forefront of technological progress and maintains its competitive edge on the global stage.

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[eee] https://arpa-e.energy.gov/about, last accessed on March 21, 2024.
[fff] See https://single-market-economy.ec.europa.eu/industry/sustainability/net-zero-industry-act_en, accessed on March 17. 2024.
[ggg] See https://www.energy.gov/lpo/inflation-reduction-act-2022, accessed on March 17, 2024.
[hhh] See https://artificialintelligenceact.eu/, accessed on March 17, 2024.