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Foresight and STI Governance is an international interdisciplinary peer-reviewed open-access journal. It publishes original research articles, offering new theoretical insights and practice-oriented knowledge in important areas of strategic planning and the creation of science, technology, and innovation (STI) policy, and it examines possible and alternative futures in all human endeavors in order to make such insights available to the right person at the right time to ensure the right decision.

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Technology-Intense Service Offerings in the Light of Economic Complexity: Establishing a Holistic Service Ecosystem

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Abstract

Crisis situations, such as the COVID-19 pandemic, have historically been identified as times of enhanced innovation and entrepreneurial activities. Innovation actors are required to respond quickly to a new situation bearing in mind the effects of actions across their network of partners and competitors as well as rising economic complexity. Indeed, first indications suggest that this pandemic is no different and has facilitated the use of digital technologies. In order to assess these developments, this paper studies new service offerings based on digital technologies using the example of three major Russian banks. We found that banks have now evolved into technology platforms that use their experience to engage in areas like education, advanced robotics, and healthcare. Technologies developed by partner organizations, such as the integration of blockchain solutions, have spread rapidly. Thereby, banks have obtained a strategic advantage for launching innovations in the financial industry, including technology and knowledge transfers from other industries.

Keywords: banking; COVID-19; anti-crisis strategies; digitalization; diversification; economic complexity; service innovation; service offerings; technological platforms, fintech

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Introduction

The quality of service offerings at banks was as been driven by increasing economic complexity over the last decade (Lapatinas, 2019), rising income inequality (Hartmann et al., 2017), and financial innovation (Fan et al., 2015). This trend has resulted in the diversification of product lines (Tacchella et al., 2013). Service provision became more flexible, adaptable, complex, and knowledge-intensive. With the rising complexity and technological intensity of service development, the ecosystem-based approach inspired the development of technological platforms as collaborative tools in order to provide greater value for clients to meet their needs. Recent publications stressed the rise of economic complexity across a broad sample of high- and low- income countries (Nguyen et al., 2022; Nguyen, Su, 2021).

A specific case for the rising economic complexity marked the COVID-19 crisis, which dealt an exogenous shock to the economy (DesJardine et al., 2019; Kwong et al., 2019). Physical distancing, which was introduced as a preferred policy measure, proved disruptive to most established behavioral routines and switched the globalized economy into crisis mode (Nummela et al., 2020; Arner et al., 2020). However, the pandemic coincided with great technological change in the economy due to new production technologies, such as robotics[1], the rise of cyber-physical systems, and artificial intelligence (AI). Hence, a well-stocked toolbox stood ready to restructure established societal and economic processes.

The imposed lockdowns to fight the spread of COVID-19 also put a sudden stop to the physical connection between the clients of banks and the latter's brick-and-mortar outlets. Banking activities were reduced to digital channels, while digital payment options increasingly replaced the use of cash. The banking sector – historically at the forefront of technology uptake - could fall back on their innovation activities over the past decades which integrated technology platforms (especially software, hardware, and networks) into their business model. Digital technologies became part of the banks' technology portfolio through reverse product cycle innovation as proposed by Barras (1990). In a nutshell, Barras suggested that – contrary to the innovation in manufacturing – service providers adopt new technologies to improve the efficiency of their business activities and later convert their experience into new products or services.

Banks took a lead role by driving the digitization process of their business activities and thereby facilitating the uptake of new technologies across society. In order to do this, banks either developed their own digital offerings, or partnered with existing fintech companies (World Economic Forum, 2020). This is "squeezing" into routine (non-profitable) operations via remote channels that are cheaper than the job being done by an operator. In Western countries, the emergence of financial technologies in daily bank operations was a response to the rigidity of large banks with their legacy systems and heavy processes. In fact, in the past decade, banks have not only facilitated technological development and provided credit lines, but they themselves also increasingly acted as technology providers and data centers. A recent study by McKinsey (2021) showed that over half of the respondents in the financial sector already use at least one AI capability, mainly robotic process automation for structured operational tasks, together with conversational interfaces and fraud-detection applications. AI was originally used by banks as scorecards for assessing the risk of a borrower's default and whether it is worth lending. Later it was used to detect fraud and fight money laundering based on large data sets (e.g., client risk profiling or credit scoring) (Aitken et al., 2020).

Although exogenous shocks tend to render many innovation trajectories ineffective, the first signs indicate that the pandemic boosted the uptake and spread of digital technologies. Sectors at the forefront of digital business models, such as banks, especially sped up their innovation activities in order to take advantage of the new conditions. Thereby, the crisis acts as a facilitator in the digitalization of the economy. This paper asks if and how banks made use of their learning experiences around digital technologies to launch new technology-intensive services during the pandemic.

In order to shed light on these complex processes, this paper studies the rollout of new technology-intensive services by three banks in Russia during the COVID-19 pandemic. By means of the connection between technology uptake and the pandemic, we intend to show how leaders in digitalization used this exogenous shock to their technological advantage. Especially in atypical contexts, technological leadership is not well understood.

While there is widespread agreement that many of the introduced technologies will remain in place even after the pandemic, such as air disinfection, telemedicine, and online learning solutions, little is known about who introduced these technologies. Our analysis follows the body of literature that studies the role of technology-related services linked to greater social challenges. For example, the digital service offerings of banks were seen as a way to service the unbanked or underbanked populations.[2]

Thus, this paper widens the analysis of the impact of banking on the wider socioeconomic system, and thereby connects with the science and technology studies' perspectives on private and public engagement with science, technology, and innovation in a larger societal context.

Banks in Times of Crises

Historically, banking and finance stood at the forefront of technology-intensive service innovation: already in the 1960s, banks integrated the first electronic services with the use of ATMs, followed by card-based services in the 1970s. Banks were among the first to incorporate the World Wide Web and moved their services online. Subsequently, applications for the increasing use of smartphones were developed.

[1] We should clarify what can be meant by robots in banks. Actually, there might be three types of robots (Shabbir et al., 2022). First, banks use physical robots to optimize internal processes, most often for related business areas: logistics, storage, etc. Of course, there are robots for bank branches, but this is mainly used for entertaining the clients, rarely something valuable in terms of functionality. Second, there is a separate term «robotics» as the optimization of routine processes performed by employees, due to easily (low code, no code) customizable IT platforms. Such solutions significantly reduce the mechanical load on the performers and improve the quality and speed of the processes. For fraud detection, cyber-physical systems are widely used. Moreover, "robotization" is not related to AI, since the "robot" performs a step-by-step procedure instead of an employee, for example, text recognition and phased entry of data into the service registration forms. Third, AI is usually understood as an algorithm that can work autonomously within the rights granted to it, i.e., functions including decision making. The algorithm is also capable of self-learning (the accumulation of statistics of correct and incorrect decisions and conclusions from them). AI is such that the algorithm itself can interact with the client. Typically, banks use AI in conjunction with big data, when the algorithm uses the accumulated large database of customer interaction history from different IT systems for self-learning or predictive and retrospective analysis.

The COVID-19 pandemic has put the resilience of the worlds' healthcare and economic systems through an unprecedented stress test. Throughout the global economy, public administration and privately held companies were labeled as essential for the continuation of the provision of goods and services. Banks, as financial intermediaries, also perform a central function in the economy, as businesses require access to capital and private customers require transaction settlements. These institutions must maintain their clients' trust and the continuation of service provision - even under the most challenging conditions. The term used for the continuation of services even under the most disruptive circumstances is 'operational resilience', describing the ability of a system to adapt successfully to changes in response to stress or any other transition without losing any function, structure, or identity (Walker et al., 2004). The Bank of England[3] defines operational resilience, which is considered a priority issue for the financial sector, as "the ability to prevent, adapt and respond to, and recover and learn from technology, cyber-related and any other operational incidents."

Natural disasters or pandemics limit the ability of banks to continue their business activities. In the first case, banks themselves either are stricken by natural disasters or are no longer able to diligently analyze and evaluate loan applications. Hosono et al. (2016) studied the effect of the lending capacity of banks with regard to loan requests from firms after the Great Hanshin-Awaji (Kobe) earthquake, which hit the area around Kobe City and Awaji Island in western Japan in January 1995. Their findings show that bank lending capacity affects the activity of client firms even in an economy with well-developed financial markets and institutions. Berg and Schrader (2012) analyzed the effects of volcanic eruptions on borrowing from a microfinance institution in Ecuador, while De Mel et al. (2010) conducted a series of surveys of enterprises in Sri Lanka, following the 2004 tsunami, and examined their recovery from the disaster. Studies of pandemics and banking are very rare, and some early studies inspired by COVID-19 focus on policy responses from central banks, such as the The People's Bank of China (Funke, Tsang, 2020), the impact on the banking industry in India (Mainrai, Mohania, 2020), or in Germany (Flögel, Gärtner, 2020).

Innovation in the Service Industry

Innovations, irrespective of their appeal, are adopted at different speeds by different actors in an industry. Some industries follow longer investment cycles, while others suffer from a "functional fixedness", a preference for established ways of doing business (Adamson, 1952; Adamson, Taylor, 1954). Other users actively seek innovations and benefit from a first-mover advantage in technology adoption. Von Hippel (1986) introduced the term "lead user" to describe the group of actors seeking a solution for their needs in their quest for high returns. Due to their ongoing search for a solution, they are already using advanced technologies and act on the edge of the knowledge frontier. In order to move further, lead users develop their own versions of existing technologies or significantly modify a type of product which has been empirically proven (Urban, von Hippel, 1988; Franke, Shah, 2003; Lüthje, 2004). Lead users are of great relevance to innovation management as their current demand for a technological solution will subsequently be experienced by other market participants. For example, Morrison et al. (2000) showed that IT solutions developed by libraries could be sold to other users, and Lüthje (2003) came to a similar conclusion about the surgical innovations developed by surgeons at German university clinics.

If the environment in which a product or service is offered changes radically, the established solutions might no longer be suitable to serve customers' needs. New offerings will appear that adjust better to the new circumstances through a recombination of existing technologies, thereby opening new innovation trajectories. Corresponding to the extreme environment in which users search for solutions, von Hippel (2005) described this highly experimental and failure-tolerant group as 'extreme user innovators'. Should the new normal prove lasting, extreme user innovators will benefit from their head start (Christensen, 1997). Otherwise, their efforts result in a learning curve which often proves beneficial when reconsidering practices in the context of business-as-usual. The hardship of WWII and concomitant shortage of resources resulted in 'lean management' techniques applied by Japanese industry (Womack, Jones, 2005). Humanitarian emergencies and the need to work around destroyed infrastructure gave rise to radically new ways of logistics, communications, and healthcare (Ramalingam et al., 2009).

In this regard, Bessant et al. (2015) stress the role of entrepreneurs and the brokering role they take in recombining technological trajectories. Crisis situations, such as COVID-19, thus offer opportunities that entrepreneurs will likely pursue. Many of these opportunities will emerge due to the inability or unwillingness of actors (both state and private) to respond quickly enough to emergency situations (Gümüsay, Harrison, 2020).

During the second half of the 20th century, services became an increasingly important driver of economic growth. Service providers ranked among the most profitable firms in the economy,which attracted a rising number of well-trained people – and showed increasing demand for technologies. This shift in the economic paradigm attracted interest from scholars, such as Barras, who studied the service revolution (Barras, 1986a; Barras, 1986b) from a historic perspective. Barras drew similarities between the early 19th century phases of industrialization in England and the rise of the service industry. Both periods of steep economic growth were characterized by an "enabling technology" (Barras, 1990) that was readily available and cost-effective. While advances in mechanics resulted in increasingly powerful machines that gave rise to factories and manufacturing, it was the microchip and the resulting computational advances that supported the service industry. The true economic impact, though, is less an outcome of the properties of an emerging technology or the technology supply, but instead relies much more on its productive use. In order to change the economic paradigm, the presence of "vanguard sectors" in the economy is of paramount importance as they can successfully integrate these enabling technologies into their business activities. Once these sectors have proven the profitability of the new technologies, other industries follow

[2] https://globalfindex.worldbank.org/, accessed 07.11.2022.

[3] http://data.parliament.uk/writtenevidence/committeeevidence.svc/evidencedocument/treasury-committee/it-failures-in-the-financial-services-sector/written/97231.html, accessed 22.01.2023.

suit. Latecomers benefit from increased investor interest and simultaneous investments in the necessary infrastructure.

Still, manufacturing and services follow different innovation logics. In classic manufacturing, the uptake of technologies leads to product innovation followed by subsequent radical, though incremental, process innovations. Innovation in the service industries, in contrast, follows a "reverse product cycle" (Barras, 1986b). Here, new technologies are initially adopted to achieve improved process innovation - and thus assure a benefit from increased productivity. The experience gathered is then converted into more radical process innovation and subsequently results in new or significantly improved products. In Barras' words: "*these [new service products] in turn shift the competitive emphasis to product differentiation and performance, as firms in new and transformed industries strive to open up and capture new markets.*" Mostly, these new offerings replace existing offerings (Bhagwati, 1984).

Today, banks perform three basic functions: the creation of financial products, operational accounting of cash transactions, and regulatory reporting. Profits can be derived from maintaining operational accounting (investments, processing, cash operations center, settlement depository, etc.) and from the sale of various financial products. Digital financial products still allow financial institutions to capture a consumer niche due to their easy access through online distribution channels. In addition, financial institutions are issuing customized products by cooperating with actors from various industries and with large online merchant service enterprises (e-merchants) in the set-up of the service ecosystems.

The adoption of digital technologies has increased the cost-effectiveness of banks and enabled the global provision of services (Schmiedel et al., 2006; Beijnen, Bolt, 2009). While the number of people employed in the banking sector is decreasing, physical distances between banks and their clients is increasing (Petersen, Rajan, 2002). Here, technology has played a major role in the continuous improvements of services (DeYoung et al., 2011).

The uptake of new technologies also changes the structure of firms due to the changed structure of organizing costs. Consequently, successful adopters will expand their activities and grow in size (Gershuny, 1978). The changed economics of the firms also facilitated the emergence of multinational organizations. Today's banking sector, though, is increasingly shaped by actors who expand their services into banking and finance. Banks are increasingly experiencing competition from technology firms who benefit from their extended client base. In particular, the markets for payment services have been under pressure. Another threat appeared in the form of new startups - the fintechs – that apply technology in pursuit of new business opportunities. Fintechs serve the last mile and can create custom products for narrow segments, which has a positive effect on customer loyalty and satisfaction. Banks cannot cut cohorts of clients so finely, but they give fintechs their infrastructure upon which they are hosted. When fintechs proved the effectiveness of their technological solutions on niche markets, banks partnered with them and acquired fintech companies with strategic value for them. Thereby, banks have felt the need to develop further new technologies in order to maintain their dominance. Against the background of rising consumer expectations, banks are incentivized to increase their speed of innovations and will strongly integrate third parties into their innovation journeys.

Methodology

Banks have historically stood at the forefront of innovation activities. The shift from brick-and-mortar-banking to the online provision of services has become the subject of a meanwhile extensive body of literature reporting on business and management studies. At its center stand analyses of the acceptance of technologies (Pikkarainen et al., 2004), attitude formation (Karjaluoto et al., 2002), and building up trust in a digital consumer relationships (Bhattacherjee, 2002). Meanwhile, banks stand at the forefront of service digitalization.

Most recent studies that looked into the uptake of technological solutions by banks limited their analysis to immediate technical solutions, such as live chats or video calling (Vessey et al., 2020; McCarty, 2020). Buehler et al. (2020) stress the limitations of interactions in remote services and propose a proactive communication strategy by banks to limit reliance upon physical branches throughout all consumer segments, including the older population. Other contributions, such as Lewis (2020), have discussed the associated risks of potential fraudulent claims of applicants to access support schemes as well as increasing data security risks.

In line with the research topic of this paper, we studied the banks' technology engagement in response to COVID-19 based on their communication with stakeholders via websites as well as other means of communication from January 2020 by October 2022. During the COVID-19 lockdown, banks used their websites to inform their customers of opening hours, offered advice, as well as the introduction of new services. With the shift to more digitally offered banking services, corporate websites have become a prime means not only to offer services but also to communicate with clients – as, for instance, can be seen in the case of banks (Arora et al., 2016). These forms of digital representation include the firms' goals and financial information, public relations, and convey customer loyalty and service satisfaction. Using websites to analyze company strategy has become a well-established method. For example, Ertem-Eray (2020) studied ESG principles of two US giants – Amazon and Walmart – by conducting content analysis of their websites.

We additionally analyzed recent consulting reports on building and activating operational resilience in the wake of the COVID-19 pandemic. Further information was gathered from the "Press Releases" section of the banks' websites. In order to triangulate the findings, we consulted independent news coverage, such as Google News or industry experts, etc.

We analyzed the activities of the three banks according to three categories: "Technological development", "Changes in business strategy of banks", and "Support for clients and society". The category "Technological development" includes three sub-categories: "Products and services based on new technologies", "Technology-related events and organizations" and "Cybersecurity". The category "Changes in business strategy" includes two sub-categories: "Working conditions" (physical appearance of the office and remote working) and "HR strategy" (everything from staff support programs to agile initiatives). The last category, "Support for clients and society", combines four sub-categories: "Healthcare initiatives", "Raising COVID-19 awareness", "Charity", and "Survival products and education initiatives for clients". The series of activities of the three banks are presented in the Figure 1.

We apply a case study approach for analyzing the product line of three leading banks operating in Russia with a focus on

Figure 1. **Activities of Banks in Response to COVID-19 Across Their Type of Ownership**

Key activities	February – April 2020	May – July 2020	August – October 2020	November 2020 – October 2022
Technological development				
Products/services based on new technologies	State-owned: 3	State-owned: 2; Private-owned: 3	State-owned: 4; Private-owned: 2; Foreign-owned: 2	State-owned: 5; Private-owned: 4; Foreign-owned: 4
Technology-related events/organizations	State-owned: 1		State-owned: 1	State-owned: 1; Foreign-owned: 1
Cybersecurity		Foreign-owned: 1	State-owned: 1	State-owned: 2; Private-owned: 2; Foreign-owned: 1
Changes in business strategy				
Working conditions	State-owned: 2; Private-owned: 4; Foreign-owned: 1	Foreign-owned: 1	State-owned: 1	State-owned: 1
HR strategy		Private-owned: 1	State-owned: 1	State-owned: 1
Delivery services				Foreign-owned: 1
Support for clients and society				
Healthcare initiatives	State-owned: 3; Private-owned: 2; Foreign-owned: 1	State-owned: 1	State-owned: 1; Foreign-owned: 1	State-owned: 1; Foreign-owned: 1
Raise of COVID-19 awareness	State-owned: 1	Private-owned: 2; Foreign-owned: 1	State-owned: 4; Private-owned: 1	State-owned: 1; Private-owned: 1
Charity		State-owned: 1; Private-owned: 1	Private-owned: 1	Foreign-owned: 1
'Survival' products for clients and education initiatives	State-owned: 4; Private-owned: 5	State-owned: 1; Private-owned: 1		State-owned: 1; Private-owned: 6; Foreign-owned: 1

Source: authors.

State-owned bank — Private-owned bank — Foreign-owned bank

digital services for retail clients. Thereby, we applied three different criteria: firstly, the banks have to be systemically important as defined by the mega-regulator. Secondly, we decided to include the cases that hold a distinction in digital offerings through a top-20 ranking of digitally oriented banks in Russia. Third, the sample consists of three banks with different forms of ownership: private, state, or foreign owned banks for gathering insights from a diversified set of development strategies, corporate governance practices, and access to funds. Fourth, these three banks were public ones. This allowed us to use the non-financial reports (annual reports) and strategic documents, which were publicly available for investors.

Our study employs an exploratory and largely qualitative approach. Such an approach is widely applied in management studies where the aim is to explore new, emerging, or rapidly evolving topics (Yin, 2009; Edmondson, McManus, 2007). This often forms a step prior to undertaking large-scale sample surveys and the like, where tests of statistical significance can be meaningful. This study is not, however, seeking to describe the distribution of particular practices in all the sectors being considered. Our key goal was to provide new insights into how banks responded to the pandemic based on their technology-driven capabilities. For gathering the new insights, we use a multiple case study methodology (see e.g. Creswell, Poth, 2017; Yin, 2009).

We employ triangulation (Riege, 2003) by a) collecting the information from different sources – not only websites, but also from press releases, annual reports, and presentations to investors; b) comparing the collected data with those presented in media sources independent from the companies being examined. In addition, we employ the reflexivity (clarification of researcher bias) method (Lincoln, Guba, 1985) as the research team includes researchers of two different nationalities and institutions, from different fields and with different experiences (in terms both of career paths and durations). Thus, this allows us to critically reflect on, discuss, and minimize any impact caused by the values and beliefs of individual contributors. All the collected information was carefully coded, sorted, and systematically organized into a database (Lincoln, Guba, 1985) and analyzed in a systematic and structured manner (Golafshani, 2003; Riege, 2003).

Findings: Technology-Intensive Services during the COVID-19 Pandemic

Banks in Russia have gained considerable experience in the development of technologies for electronic service offerings. In response to the pandemic, banks introduced new services and products. Figure 1 provides an overview of these actions across the types of bank ownership. Table 1 presents the typology of technologies used in financial services, based on a bank's technology adoption and dissemination. The focus on AI during the pandemic resulted in numerous projects such as AI chatbots, AI cashback recommendation technology, an AI voice assistant in the contact center, and services for diagnosing COVID-19 or pneumonia symptoms. The overview of technology-intensive service offerings is provided as a timeline by taking into account the impact of the pandemic on Russian banking.

First actions in 02/2020-04/2020: overcoming the negative consequences of the sudden quarantine and developing health monitoring systems

Figure 2 sums up the first actions taken by banks in responding to the pandemic. At the onset of the pandemic, banks started creating services and products to support clients and

Table 1. **Three Categories for the Analysis of the Banks' Activities**

Category	Subsections
Technological development	• Products and services based on new technologies • Technology-related events and organisations • Cybersecurity
Changes in business strategy of banks	• Working conditions (physical appearance of the office and remote working) • HR strategy (everything from staff support programs to agile initiatives)
Support for clients and society	• Healthcare initiatives • Raise of COVID-19 awareness • Charity • Survival products and education initiatives for clients
Source: authors.	

society. Healthcare initiatives saw a rise during the pandemic: artificial intelligence was implemented in a free online test to check for COVID-19 symptoms (April 13, 2020).

Along with support for clients and society, banks demonstrated technological development in response to the pandemic. Banks partnered with third-party service providers who had already gained considerable experience in the provision of medical services. Together with a health start-up, the state-owned bank launched a COVID-19 testing service for people living in Moscow (April 17, 2020).

At the same time, banks provided support to society in overcoming the negative consequences of the sudden quarantine. As in most countries, Russia's education system struggled with the switch to distance learning. One of the privately owned banks reached out by launching a series of online programs on its education platform (April 28, 2020).

A game that addresses the challenge faced by clients during the isolation period was one of the first released services on April 30. The boardgame can be downloaded and printed and was developed by the state-owned bank. This team, which usually develops recruitment tools and customer engagement activities, now is producing a game that requires the smart use of medical masks, sanitizers, and electronic passes to complete the game.

Introduced services and products in response to the continuing pandemic - 05/2020-07/2020: supporting clients and society, monitoring the macro-data and developing blockchain technologies

The activities of the three banks in the "Support for clients and society" category included a series of initiatives (Figure 3) including a partnership with a health start-up which resulted in a free service to support older people during the COVID-19 pandemic (May 13, 2020).

The privately owned bank developed a corona index to monitor the development of Russia's economy during the pandemic, starting from May 21, 2020. Large banks in Russia were engaged in the development of educational technologies. In response to COVID-19, a state-owned bank further increased its focus on education initiatives. During the first few months of the pandemic, it launched webinars on financial and digital literacy during the pandemic (May 29, 2020). On June 3, 2020, another privately owned bank, which was also involved in development of educational technologies, launched a free online lecture discussing the work of IT companies, the tasks of product managers and analysts, and which IT tools are beneficial for other professions, and so on. Furthermore, the foreign-owned bank intensified its focus on SMEs and published its research study regarding the behavior of small businesses before and after the pandemic (June 9, 2020).

For wealthier clients, an interactive online travel map was created to indicate "where to fly after coronavirus" (June 18, 2020). In addition, this service incorporated gamification elements and certainly contributed to the well-being of its travel-starved clientele.

An AI application that interprets CT scans was launched by the artificial intelligence department of a Russian state-owned bank and is related to the sub-category "Survival products and education initiatives for clients" (July 14, 2020). Users can upload their lung scans and receive a diagnosis regarding pneumonia.

Technological development was crucial when the pandemic increased in scale. One of the Russian state-owned banks adopted robotics as a key technology and this facilitated the logical progression of automated banking services, such as ATMs with facial recognition and an updated biometrics system in its newly opened "Phygital" branches (September 28, 2020). For example, updated biometrics in these offices made it pos-

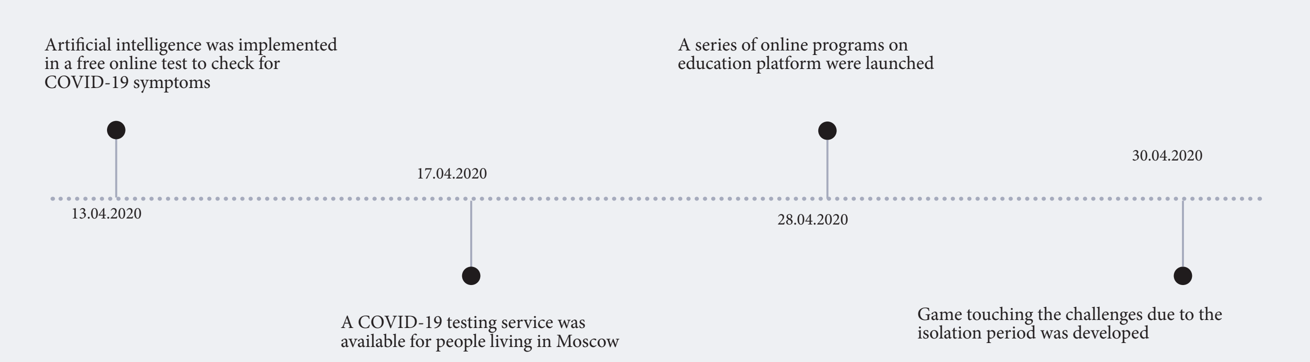
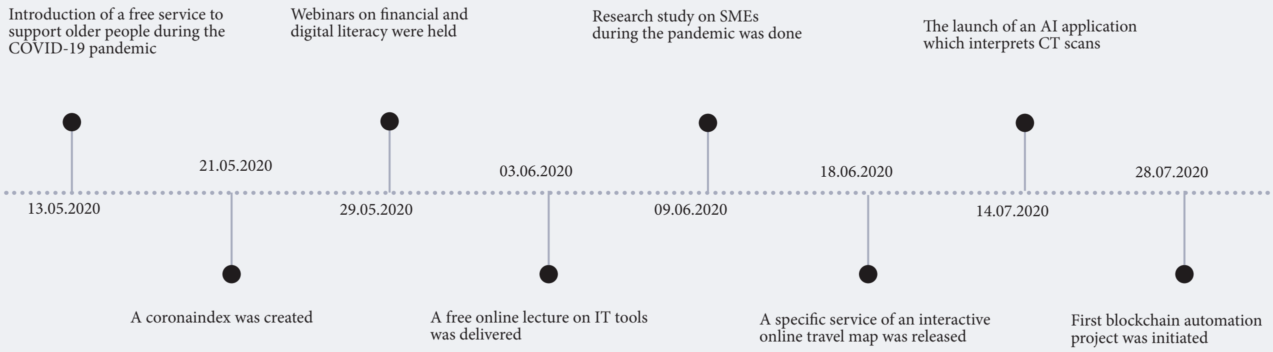


Figure 2. **Health Monitoring Systems Come First**

Source: authors.

Figure 3. **Actions to Support Clients and Society**



Source: authors.

sible to serve clients without passports, while ATMs with facial recognition allow customers to approve withdrawals with a smile.

Regarding the changes in business strategy, the "Future of Work" project was launched to develop and implement the best of remote and office work formats at one of the selected banks that is foreign owned. The declared objective was to find the best mixture of team flexibility and employee wellbeing. More than 5,000 of the bank's 9,000 employees participated (October 1, 2020).

Later, a free training course "Becoming an Entrepreneur" to guide young people from 14 to 25 years of age who plan to start their own businesses was initiated (October 15, 2020).

Introduced innovations during 08/2020-10/2020: automated services, online education, and improvements in the remote working format

During the second quarter of the pandemic (autumn 2020), banks mostly concentrated their attention and efforts on improving their remotely delivered services and designed online education products for setting up regular communication with the youngest people among their target client groups (Figure 4). As an example, one bank completely moved its fintech educational program online (August 5, 2020). At the same time, the bank linked up with airlines' blockchain platform to automate its own-settlement system and allow clients to pay instantly for tickets and services (September 2, 2020). Later, on September 14, there was a three-month free online course that taught students about the innovations in financial technologies, AI banking, the development of financial and IT ecosystems, and so on to provide insight into the creation of applications at large technology companies. Besides educational initiatives, banks also introduced other services and products beneficial for society as well. The map of "post-quarantine tourism 2020" was published (September 15, 2020).

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Banks continued introducing new technologies into their services and products 11/2020 – 10/2022: toward sustainability through digital products for clients and changes in business strategy

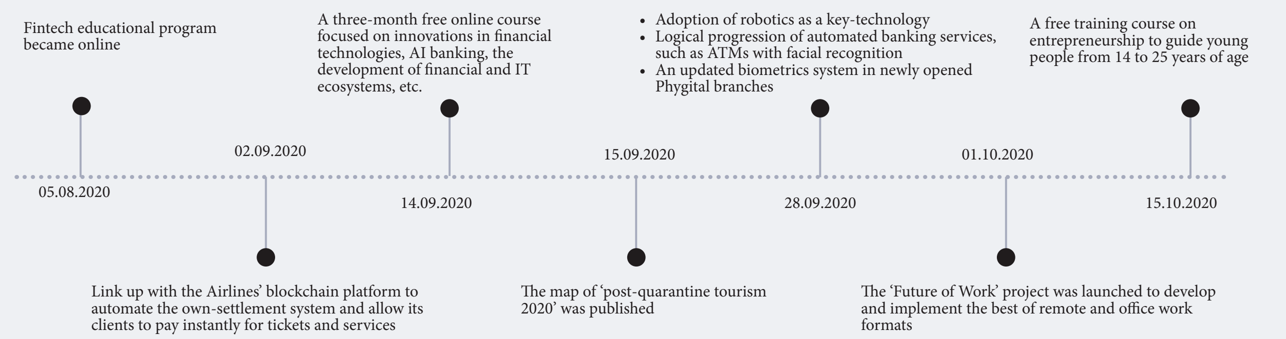
Active launches of new products and services continued in the last observed period of the pandemic (Figure 5). Thus, new applications of robotics appeared: a robot-dog to study the behavior of robots and the Cognitive Agro Pilot — an autonomous control system for agricultural machinery.

The need for talent in the fields of internet marketing, programming, machine learning, and artificial intelligence theory led the Corporate University of the state-owned bank to expand its "Personal Digital Certificates" project – which are part of the wider "Digital Economy" national project – by launching four advanced training programs in the fields mentioned above (November 2, 2020). Another major service was the implementation of its invoicing system for payments by QR-code managed by a Telegram-bot for SMEs. This is one of the earliest solutions on the Russian market that support invoicing directly from smartphones (November 25, 2020).

In cooperation with the broadcast and media players, a series of online lectures were created on numerous topics – cinema, fashion, ecology, beauty, editing – for clients wishing to study at home (December 8, 2020). Any one program (on one topic) consists of three interactive Zoom lectures with homework to be completed in two weeks' time.

[4] https://ifr.org/ifr-press-releases/news/record-2.7-million-robots-work-in-factories-around-the-globe, accessed 17.11.2022.

Figure 4. **Actions to Automate Banking Services and Remote Delivery**



Source: authors.

A day earlier, one of the largest Russian banks presented its first robot-disinfector of rooms. For this achievement, this bank was for the first time named one of the world's leading service robot developers – according to the annual report "World Robotics, Service Robots 2020" by the International Federation of Robotics[4] (December 14, 2020).

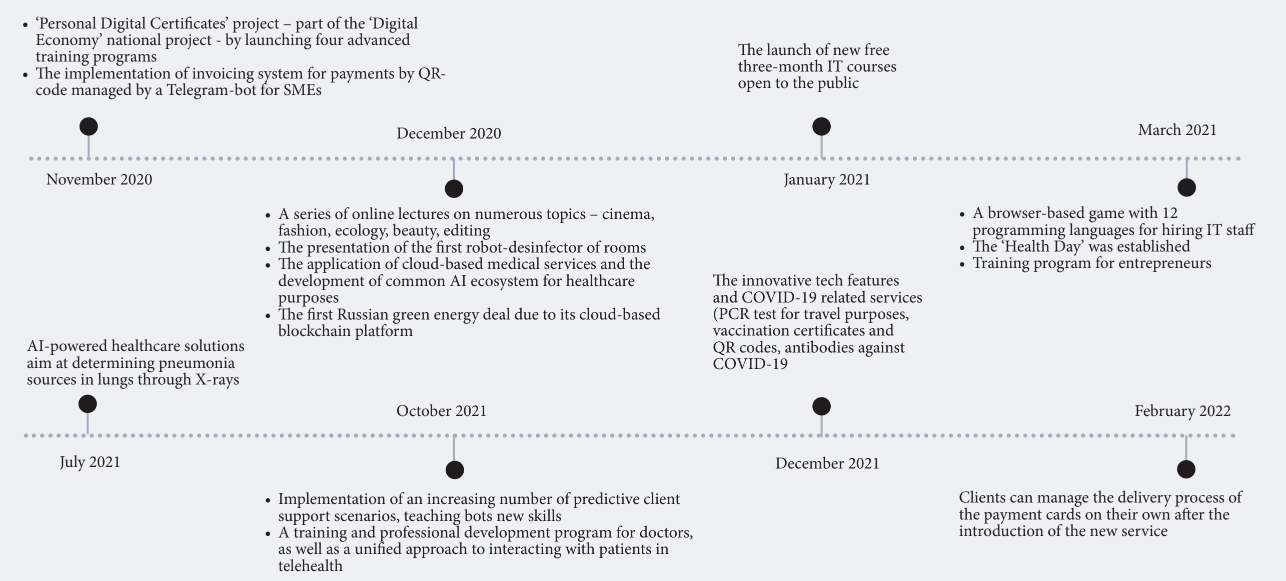
The state-owned bank announced plans to delve further into the application of its cloud-based medical services and now plans to develop a common AI ecosystem for healthcare purposes (December 18, 2020). This bank also implemented blockchain applications. For example, it was the first Russian bank to join the Federal Tax Service blockchain platform with the goal of helping businesses. Moreover, its collaboration with renewable energy players secured the first Russian green energy deal due to its cloud-based blockchain platform (December 28, 2020). The platform, developed by the bank, uses green Renewable Energy Certificates (REC) to verify the origin of energy.

In terms of support for clients and society, one of the reviewed banks introduced an algorithm analysis which diagnosed COVID-19 by means of having the client cough (January 12, 2021). In addition, one of the private banks announced the launch of a new free three-month IT course open to the public (January 13, 2021).

Along with technological development, changes in business strategy also took place. The project, a browser-based game with 12 programming languages for hiring IT staff, unites gaming, EduTech, and HR initiatives at the state-owned bank. While playing, candidates are required to write code which the underlying system analyzes automatically and thus rates all the candidates. Moreover, "Health Day" was established as an annual event (March 12, 2021). Regarding expanding partnerships, a training program for entrepreneurs was developed jointly with Google (March 31, 2021).

AI-powered healthcare solutions aimed at determining pneumonia sources in the lungs through X-rays were developed

Figure 5. **Actions Towards Sustainability**



Source: authors.

Table 2. **The Examples of Technologies Applied in Offering Financial Services**

№	Types of technologies	Financial Services
1	**End-to-end technologies**, which are created by banks to improve the delivery of banking services. These technologies can be transferred to other industries.	• Remote identification (including Biometrics) • Bio-acquiring • Payments by QR-code managed
2	**Enabling technologies,** which banks adopted from IT services and IoT and incrementally transformed and disseminated them to other service industries.	• Artificial intelligence • Machine learning • Blockchain technologies • Cloud Computing • Big Data Analytics • Robotics (incl. achinery) • Ecosystems (Open API / Open Data) • Chatbots and IVR voicebot
3	**Disruptive technologies,** which banks pursued to deliver services remotely based on IT solutions implemented in other service industries (distance education or telemedicine)	• Health monitoring systems • Ed-Tech • HR-Tech

Source: author's classification.

with the further prioritization of patients who are in need of treatment based on a model that evaluates the risk of severe symptoms in hospitalized patients (July 20, 2021).

Since the start of the pandemic, the amount of traffic at banks' call centers has increased. They handled over 20 million phone calls from retail clients per month, and this number continued to grow. The only way for them to cope with such a heavy load is through automation, when an IVR voicebot answers typical questions and people pick up the phone for complex and non-routine cases. The largest state bank continued to implement an increasing number of predictive client support scenarios, including voicebots and chatbots (October 8, 2021).

New digital technologies of the state bank are already being implemented at a number of medical institutions. These technologies help improve the quality of life and the effectiveness of medical assistance. One of the Russian medical universities in partnership with the bank developed a training and professional development program for doctors, as well as a unified approach to interacting with patients in telehealth (October 14, 2021).

The innovative tech features and COVID-19-related services (PCR test for travel purposes, vaccination certificates and QR codes, antibodies against COVID-19) became available in the financial super-app of one of the private banks (December 30, 2021). Banks continue to develop applications for new technologies. For example, clients can manage the delivery process of the payment cards on their own after the introduction of a new service (February 15, 2022).

Conclusion and Discussion

This paper studied the introduction of technology-intensive services by three major Russian banks during 2020 - the year of the COVID-19 pandemic. Russia's fintech penetration is one among the highest in the world - 82% according to EY data for 2019 (EY, 2019). Russia's banks have acquired the infrastructure needed to collaborate with highly innovative actors such as fintech start-ups. Also, the level of return from such investments in Russia until recently was significantly higher than comparable international economic activities.

The assumption was that the imposed restrictions were acting as a facilitator for the introduction of digital service innovations. Of particular interest was the connection to the pandemic that provided a major interruption for the banks' business models. In line with the model of Barras (1990), we studied whether banks would use their experience gained in digital technologies in order to roll out new technology-intensive services.

All the banks investigated by this study have continuously increased their technology uptake in order to improve their service offerings, which had already been in place before the pandemic. During the period of observation, all three banks engaged extensively in new service offerings. Banks increased their online offerings and added more telephone-based services to engage with those clients who remained skeptical about online banking. Moreover, new digital technologies were introduced in order to support data-related tasks, such as fraud detection. All these key technologies in service automation are now used for streamlining client communications - mainly with the use of chatbots. Furthermore, gamification applications arrived some time ago to facilitate the recruitment processes at the banks. Thus, the experience gained through their investment in digital technologies has been converted into new offerings that have allowed the banks to keep up with their business activities despite the imposed lockdown. Consequently, Russia has the necessary financial potential to build up their own research capabilities and buy start-ups with innovative potential.

Banks obtained a strategic advantage in launching innovations in the financial industry, including for technology and knowledge transfers from other industries. By doing this, banks in Russia act as the drivers of technological innovation in society by achieving such strategic goals as profit, brand promotion, and the capture of promising business niches.

Banks have also benefitted from their experience with digital technologies in that their innovation ecosystem has become much more open. Hence, it has become easier to integrate other technologies developed by partner organizations, such as the integration of various blockchain-based solutions from tax agencies onto specialized trading platforms.

Furthermore, our observations revealed that, in addition to new service offerings as the continuation of the banks' traditional business activities and in line with Barras' model, banks also rolled out service offerings that were novel to their core business and were connected to the events of the pandemic. Chatbots became a key channel for communication with retail clients during the pandemic. However, banks are likely to move away from mobile phone apps and adopt a unified version of websites. This would free up IT talent. Still, the pandemic slowed down this process due to a decrease in financial activity, falling incomes, and general uncertainty. The retention of client's loyalty and personalization through mobile applications proved satisfactory with remote services compared to the less human oriented communication which clients used to observe. We might also expect that the pandemic might lead to a reduction in the number of riskier projects, therefore one may see instead a revision of banks' innovation projects toward a greater digitalization of services.

The first encounter with pandemic-related services was the download of an app in order to familiarize the user with pandemic-related behaviors. Here, the bank benefited from its gamification experience with regard to better user engagement and staff recruitment. Of particular interest is the engagement of banks with artificial intelligence for medical applications. Especially online services that benefit from an increased user engagement. Using the developed AI solutions to predict a COVID-19 infection either through checking symptoms or through an uploaded CT-scan is an interesting practice aimed at reducing the burden of already overwhelmed public or private healthcare organizations. The collaboration with other medtech services allowed for the offer of a technology-based solution to identify early symptoms and suggest treatments. Large banks are major employers, which put healthcare for employees high up on their priority lists. Cough recognition algorithms are based on the same platforms as the remote personal identification through voice recognition already in place, so banks already had the technical means for the implementation of functionality: ready-made platforms, developers, and a developed user base.

An interesting observation is the increasing engagement of banks with online educational programs. This was an opportunity to offer existing content to an extended public who were now interested in such offerings. Especially in times when imposed lockdowns confined people to their homes, demand for online education was high. In certain areas, these offerings also supported the public education system that struggled with the move to online learning. These outreach activities remove communication barriers with talented graduates who seek employment in banking and finance. Furthermore, they are central to a bank's HR strategy with regard to a techno-economic paradigm change to speed up internal organizational learning processes. The key strategic goal of banks for supporting online education was seeking talented candidates for their own staff. LMS platforms have become separate products to sell and develop for external users.

Our results certainly do not represent the entire picture of the operational resilience response of the Russian banking sector to the novel pandemic, as the research was limited to three major banking players only. Moreover, the study may reflect the positive 'skewness' of the gathered official news aimed at convincing clients and investors of the companies' credible reputations (Ageeva et al., 2020). Further research on the topic may involve a larger sample of Russian banks - or even be expanded to explore the operational resilience of banks in different countries.

This paper also did not make a deep-dive into cryptocurrency initiatives as they are still an open issue. For example, the Ministry of Finance talks about crypto, while the Digital Ruble, as a third type of national currency, rather has an effect on banks in the format of challenges to come up with new consumer products. It becomes relevant for retaining a client who owns a digital currency, which he can essentially withdraw at any other bank, even though he initially was issued the cryptocurrency through a conditional bank A. The Digital Ruble will affect the landscape of client financial services on the domestic market. Further, the legalization of the circulation of cryptocurrencies for external transactions is an unrelated factor and is rather a direction of trust management services at commercial banks.

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The New Strategy of High-Tech Companies – Hidden Sources of Growth

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Abstract

The recent increase in the share of zero-leverage firms is most pronounced in the Software and Services, Hardware Equipment, and Pharmaceutical and Biotechnical industries. The reasons for these industries' conservative debt policies are not fully disclosed. How companies in technological sectors manage to perform well attracting no debt and losing debt tax shield benefits is a mystery. This study aims to determine why high-tech firms are less likely to have debt in their capital structure. Using a sample of US-based firms from the RUSSELL 3000 index for the past 12 years, we identify the factors leading to a zero-debt structure. After dividing the sample into high-tech and non-high-tech subsamples, we demonstrate the gap between zero-debt motives for the technological and traditional sectors. We show that the common determinants of corporate structure cannot fully explain why high-tech firms choose a zero-debt policy. Testing the possible motives of debt financing avoidance, we find that high-tech firms are more financially constrained than non-high-tech firms. We further show that unconstrained high-tech firms may avoid debt to maintain their financial flexibility. On top of that, managerial entrenchment also adds to the zero-leverage choice of high-tech companies. This study's results are helpful for top-management teams and investors since they shed light on the specific style of financing choice for technological firms.

Keywords: capital structure; leverage; financial flexibility; financial constraint; zero-leverage; zero debt; high-tech firm; managerial entrenchment

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Introduction

Over the last three decades, the proportion of companies raising no debt increased from about 8% in 1988 to 30% in 2013 (Bessler et al., 2013). More than 34% of companies between 1996 and 2015 were zero-leverage at a certain point in time (Lotfaliei, Lundberg, 2019). The trend toward conservative debt policies could be found on both developed and emerging markets (Cui, 2020; Ghoul et al., 2018; Yasmin, Rashid, 2019). Earlier research notes that although zero-debt firms are not limited to specific industries, information technology and healthcare represent their most significant share, as illustrated in Figure 1.

During the same period, the market faced structural changes with the constant growth of high-tech firms. The success of technology firms has led researchers to explore their organizational structure and decision-making more intently. As capital structure is considered one of the most critical corporate decisions, exploring factors affecting high-tech firms' debt-to-equity ratio requires more attention.

Following the sectoral view, we find that pharmaceuticals, biotechnology, software, and hardware represent the highest fraction of zero-leverage firms as of 2016 (see Table 1). The concentration of zero-leverage firms in high-tech industries is consistent with real-life experience. High-tech firms with highly specialized products and a high fraction of intangible assets enforce higher costs on their staff, the users of their products, suppliers, and potential debtholders in the event of bankruptcy.

Although attempts have been made over the last several decades to expand the theoretical basis for optimal corporate structure choice, the zero-leverage puzzle still lacks a theoretical basis. Classical capital structure theories fail to explain the increased propensity of firms to follow zero-leverage policies (Graham, 2003). However, there are many ideas behind the choice of zero-leverage policy, including financial constraints (Devos et al., 2012), financial flexibility (DeAngelo et al., 2011), agency problems (Butt, 2020), and signaling (Miglo, 2020). Despite numerous attempts to explain this phenomenon, there is still a large gap between theoretical and empirical evidence from different sectors.

Given the specifics of high-tech firms and the high concentration of zero-debt firms in high-tech sectors, we look for the difference between the zero-leverage motives for high-tech and non-high-tech firms in this paper. Papers on the capital structure of high-tech firms have not yet reached a consensus on the reasons for firms avoiding debt (Coleman, Robb, 2012; Aghion et al., 2014). So, we contribute to the literature by demonstrating the different motives for zero debt at high-tech and non-high-tech firms and comprehensively analyzing high-tech firms' capital structure choices.

One more unique feature of the high-tech sector that has not been discussed above is its geographical concentration. In the United States, the high-tech firms are concentrated in four centers (Silicon Valley, San Diego, Seattle, and Washington, D.C.), making the US economy the best laboratory for studying the features of high-tech companies. Dealing with firms from one country also allows us to focus on firm-level and industry-level factors of zero-leverage so that the results are not biased by country-level cultural differences (El Ghoul et al., 2018).

Our key results are the following. We first argue that classical determinants of capital structure cannot explain the high share of high-tech firms with zero leverage. We show that zero-leverage policies are often the result of financial constraints rather than a deliberate choice of high-tech firms. However, high-tech firms also choose a conservative debt policy for financial flexibility which means that with the growing share of high-tech firms, we expect to see lower interest in the corporate debt market. Finally, we show that high-tech firms with higher shares of insider ownership may choose a zero-leverage policy because of managerial entrenchment.

We contribute to the literature with a thorough comparative analysis of zero-debt policy at high-tech firms. Previous studies either provide the results of various determinants testing for a zero-leverage sample of US-based firms (Dang, 2013) and firms from developed markets (Bessler et al., 2013), or a divided sample based on a selection parameter, such as dividend-paying status (Strebulaev, Yang, 2013). Unlike these studies, this paper considers high-tech firms separately and in contrast to firms from traditional sectors to promote a more in-depth understanding of the capital structure choice of the most capitalized industries in the US. Moreover, we investigate several possible motives for choosing zero-leverage (financial constraints, financial flexibility, managerial entrenchment), allowing us to obtain a broader picture of high-tech firms' financing policies.

The share of companies with conservative leverage or zero debt policies is also increasing on emerging capital markets (Machokoto et al., 2021; Ghoul et al., 2018). An analysis of firms from 21 emerging markets (Asia, South and Central America, East Europe, Africa) showed the predominance of financial flexibility as a major reason to choose a zero-leverage policy, which is followed by the motive of financial constraints (Iliasov, Kokoreva, 2018). That is not surprising keeping in mind the specifics of emerging markets that lead to higher barriers for capital access: asymmetry of information, high levels of state ownership, and the presence of pyramidal ownership structures (Bekaert, Harvey, 2003; Buchanan et al., 2011; Sprenger, Lazareva, 2021). Although the research shows the relevance of financial constraints and financial flexibility for emerging market firms, there are no insights into the choice of capital structure by high-tech firms. Moreover, the research on high tech companies on emerging markets is challenging at the moment given the small amount of available data.

Still, we have at least two reasons why the results of our paper could be of interest for high-tech industries on emerging markets. First, the results of zero-leverage policy on emerging markets revealed that the major determinants of zero debt policy are those connected with the unpredictable future results of the firm (Iliasov, Kokoreva, 2018), which is especially relevant for high-tech firms. Secondly, it was shown that the significance of macroeconomic parameters is lower than internal corporate factors. Thus, based on research on developed capital markets, we can anticipate how relevant these results would be for emerging capital markets and develop strategies for optimal capital structure choices by technology companies.

Table 1. **Distribution of zero-leverage firms by sectors in the US**

Industry	% of ZL
Pharmaceuticals, Biotechnology, and Life Sciences	37
Software and Services	36
Technology Hardware and Equipment	28
Retailing	26
Semiconductors and Semiconductor Equipment	25
Healthcare Equipment and Services	22
Automobiles and Components	21
Consumer Durables and Apparel	21
Commercial and Professional Services	17
Consumer Services	16
Transportation	14
Capital Goods	11
Telecommunication Services	8
Food, Beverages, and Tobacco	8
Energy	7
Household and Personal Products	7
Media	7
Materials	6
Food and Staples Retailing	6

Source: Capital IQ and authors' calculations.

Literature Review and Development of Hypotheses

While many attempts have been made to broaden the theoretical basis for optimal corporate structure selection, the zero-leverage puzzle has no theoretical rationale. Standard capital structure theories (trade-off theory, pecking order theory) fail to explain why many firms follow a zero-debt policy (Myers, Majluf, 1984; Fisher, 1933).

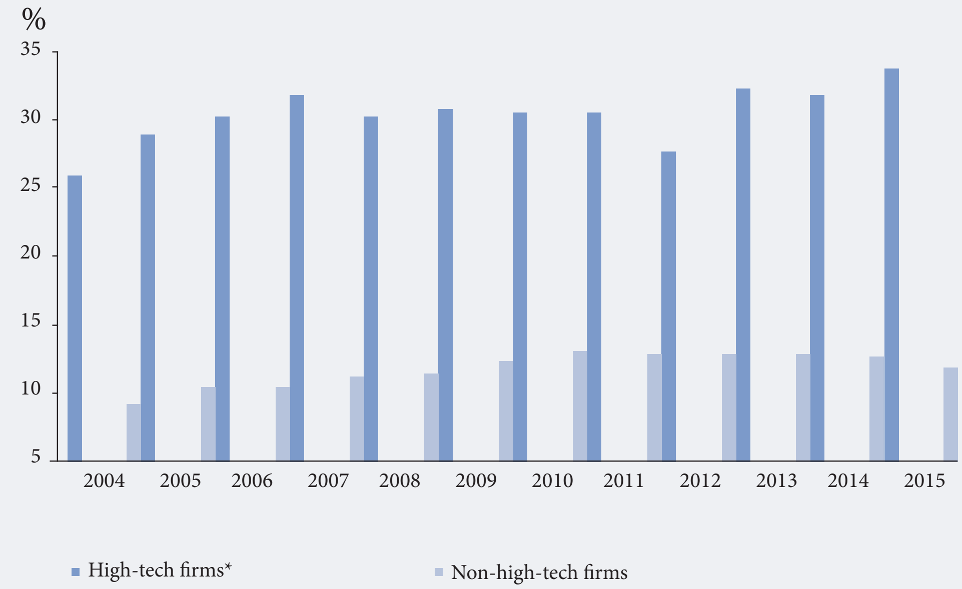
Graham (2003) found some factors that offset the debt tax shield, which leads to an 'underlevered puzzle' and a conservative capital structure policy. Later, Minton and Wruck (2001) investigated the low leverage puzzle and found that financial conservatism is widespread, not limited to specific industries and countries.

As this growth in the share of companies without debt goes hand in hand with the growth of companies in the high-tech sectors (Bessler et al., 2013), the latter firms deserve special attention. High-tech firms differ in several ways from traditional sectors. First, high-tech firms are more R&D intensive, which leads to more significant uncertainty surrounding outcomes and greater risks. Here the asymmetric information problem is added since the insiders have more information on the probability of the firm's success. As soon as the high-tech firms' products are, in general, more specific, outside investors face difficulties with cash flow forecasting.

Moreover, evidence shows that high-tech firms are smaller (Talberg et al., 2008) and, in general, younger, which goes in line with the greater prevalence of riskier firms participating in recent IPOs (Bessler et al., 2013). As a result, high-tech firms meet the demand for higher risk premiums on external financing (Hart, Moore, 1994, Rampini, Viswanathan, 2010). Thus, we focus our research on the zero-leverage choice of high-tech firms.

We contribute by identifying the difference in capital structure choice of high-tech and non-high-tech firms based on determinants and applicable theoretical explanations. We focus on common capital structure determinants (size, tangibility, profitability, growth opportunities) and three possible theoretical explanations for zero-leverage policy: financial constraints, financial flexibility, and managerial entrenchment.

Figure 1. **The percentage of zero-leverage firms from 2004 to 2015**



* Including firms from RUSSEL 3000 index relating to Software and Services, Technology, Hardware and Equipment, Pharmaceuticals, Biotechnology, and Life Sciences.

Source: authors.

Common capital structure determinants as drivers of the choice to zero-leverage

Previous research defined a set of indicators likely to have a higher predictive power concerning the choice of debt-to-equity level (Rajan, Zingales, 1995; Hang et al., 2018). The four indicators we focus on in our study are size, profitability, asset tangibility, and growth opportunities. We call them common determinants in our study.

Hadlock and Pierce (2010) show that the *size* of a firm negatively correlates with the probability that the firm follows a zero-debt policy. Similarly, a firm with higher total assets has a better reputation and is more likely to obtain favorable conditions for debt (Saona et al., 2020). We expect that high-tech firms are smaller than their counterparts from traditional industries in terms of assets.

Tangible assets allow firms to decrease the cost of debt financing, as they could serve as collateral for bank loans (Molina, 2005). In the case of default, debt-holders will more likely convert tangible assets to cash. Therefore, *tangibility* is supposed to have a positive relationship with leverage. Despite the increase in the debt supply, no evidence was found for the impact of tangibility on the demand side, suggesting a declining propensity for zero leverage (Morais et al., 2020). We anticipate that high-tech firms have fewer tangible assets than non-high-tech firms, leading to a higher probability of zero-leverage.

According to the pecking order theory, more profitable firms are less likely to initiate debt financing as they have sufficient internal financing. On the other hand, the high profitability of a firm serves as a positive sign for banks to attract more debt (Morais et al., 2020). Therefore, it is not clear how *profitability* affects the propensity to choose a zero-leverage policy. There is no confidence about whether high-tech firms are more or less profitable than non-high-tech firms. However, technology-based firms are often more volatile, reducing the mean value for the whole sector.

The market-to-book ratio demonstrates investor expectations relating to a firm's growth opportunities. A high market-to-book ratio means that investors are confident in the firm's prospects. A company's growth opportunities are directly related to the financial resources the company needs. From the perspective of pecking order theory, for companies with high growth opportunities, investment needs to exceed retained earnings, which means that external sources must be raised, resulting in a high debt burden. However, in an environment of high information asymmetries (which is especially true for high-tech firms), investors with a lack of knowledge regarding the firm's value and future growth opportunities ask for higher premiums (Myers, Majluf, 1984), resulting in lower debt ratios.

Moreover, adherents of the trade-off theory conclude that companies with high growth opportunities will have lower debt burdens due to the high potential costs of financial distress. Thus, capital structure theories provide different explanations for the growth opportunities' role in conservative debt policy. Still, empirical evidence shows that debt ratios are negatively related to a market-to-book ratio (Frank, Goyal, 2009). We expect that the high-tech firms demonstrate higher market-to-book ratios and, consequently, a greater propensity toward zero leverage.

To summarize, at least three of the four common determinants of capital structure, namely size, tangibility, and growth opportunities, can positively affect the propensity toward zero-leverage policies for high-tech firms. Firm size and asset tangibility are naturally lower for high-tech firms, which on average increases uncertainty and reduces financial leverage, and thus increases the propensity for zero-leverage policies. Growth opportunities can increase leverage in a perfect market. However, high information asymmetry in an emerging market leads to a significant increase in the cost of debt due to a serious increase in risk, which together leads to the popularity of zero-debt policies.

In other words, we expect that the common determinants of capital structure are relevant for high-tech and non-high-tech firms. Moreover, we expect to find a higher probability that high-tech firms are unlevered. Thus, our first hypothesis is as follows:

H1. There is a persistent difference in the likelihood of choosing a zero-leverage policy between high-tech and non-high-tech firms that is not fully driven by the common determinants of capital structure.

However, we assume common factors cannot fully explain the difference in the number of zero-leverage firms between high-tech and non-high-tech companies. Thus, our further research focuses on capturing the peculiarities of high-tech firms' motives to follow a zero-debt strategy.

The financial constraints hypothesis

The financial constraints hypothesis is broadly used in the literature to explain why firms are debt-free. The financial constraints hypothesis refers to a forced motive to stay unlevered as constrained firms face costly external financing.

While most scholars accept the importance of this factor, there is no clear answer on which proxy should be used to measure the level of financial constraint. Diamond (1989) noticed that constrained firms are less likely to have a credit history; they often lack tangible assets commonly used as collateral. Eisfeldt and Rampini (2009) explored whether such firms often rely on lease financing rather than external financing to buy an asset. These firms usually switch to debt financing when the financial constraints relax and the cost of debt decreases.

As dividend payouts and share repurchases compete with capital investments for funds, firms with investment opportunities and a high external finance costs must reinvest most of their net income. Therefore, financially constrained firms are less likely to pay dividends or repurchase shares before the observation date. Korajczyk and Levy (2002) use a combination of a high retention rate and existing investment opportunities.

Another measure, the KZ Index, introduced by Kaplan and Zingales (1997), uses five variables to estimate financial constraints: cash flow, market-to-book, leverage, dividends, and cash holdings. The index was updated by Hadlock and Pierce (2010), who characterized a financially constrained firm as a small young firm with limited access to debt financing or with a poor reputation. As with the KZ Index, the research applies the coefficients developed for the size-age (SA) index in the subsequent research (Farre-Mensa, Ljungqvist, 2016).

As high-tech companies are generally younger, smaller, and have fewer tangible assets in their asset structures, we expect financial constraints to be a relevant driver of the sustainable choice of zero-leverage (Talberg et al., 2008). There is much evidence indicating that high-tech firms tend to be riskier due to their products' intangible nature, which leads to a high level of uncertainty among potential debtholders (Coleman, Robb, 2012). Moreover, high-tech firms are involved in innovations that lead to more volatile cash flows due to the high uncertainty of investment outcomes. As a result, high-tech firms tend to face a higher cost of debt and risk premium required by shareholders. Financial constraints for innovative firms mean potential problems with credit access, especially in times of crisis (Hall et al., 2016).

We, therefore, present our second hypothesis.

H2: High-tech firms are more financially constrained than non-high-tech firms, often resulting in a zero-debt policy

We expect that high-tech firms are more financially constrained, which is one reason why the high-tech industry has a large proportion of zero-debt firms.

We thus assume that the choice of constrained and unconstrained firms differs and should be approached separately.

The financial flexibility hypothesis

There is much evidence that financially constrained firms are more debt-free than unconstrained firms (Devos et al., 2012; Dang, 2013; Cunha, Pollet, 2020). While it seems easy to explain why financially constrained firms remain unlevered, it is much more challenging to find the incentives for unconstrained firms that deliberately maintain zero leverage (Bessler et al., 2013).

Another explanation of why firms maintain zero leverage is the financial flexibility hypothesis. The firm's financial flexibility is defined as a firm's ability to respond to unfavorable market conditions in a value-maximizing manner. In contrast to financial constraints, the financial flexibility motive is a deliberate choice of firms to stay unlevered. When the firm is temporarily unlevered, it accumulates cash to save its debt capacity for future investment projects (Gamba, Triantis, 2008, Favara et al., 2021). Consequently, unlike financially constrained firms, such firms strategically maintain zero leverage to be more flexible in the future and preserve debt capacity for market downturns (Dang, 2013).

Bessler et al. (2013) describe financial flexibility as a firm's ability to react to sharp changes in economic conditions and investment opportunities. It is more critical for high-tech firms than firms in traditional industries. Thus, the motive is particularly pronounced for firms with future growth opportunities.

While the financial flexibility motive is understudied for the zero-leverage policy, in contrast to (Lundberg, Lotfaliei, 2020), we suppose that financial flexibility plays a vital role for high-tech firms. High-tech industries are high-growth industries where firms must be flexible in their investment policies. At the same time, financial flexibility should be an essential motive only for companies without significant financial constraints. That leads us to the third hypothesis.

H3: The financial flexibility motive for zero leverage is stronger for high-tech firms than for non-high-tech firms.

The managerial entrenchment hypothesis

Another possible explanation for zero-leverage is the managerial entrenchment hypothesis (Strebulaev, Yang, 2013).

The supporters of this hypothesis find a positive relationship between managerial entrenchment and the debt ratio. Some authors argue that entrenched managers maintain zero leverage to protect their human capital (Fama, 1980). At the same time, others claim that a conservative debt policy allows management to reap the corporate benefits of decreasing interest payments (Stulz, 1990).

One of the main features of managerial entrenchment is a high percentage of shares owned by the CEO or insiders. Strebulaev and Yang (2013) test the managerial entrenchment theory on a sample of US-based firms and obtained supportive results. They find evidence that firms stay unlevered by weak governance mechanisms. They show that family firms and firms with higher CEO ownership and longer CEO tenure are more likely to have zero debt, especially if boards are smaller and less independent.

Our fourth hypothesis is as follows.

H4: Managerial entrenchment in high-tech firms increases the probability of a zero-leverage policy

Following Strebulaev and Yang (2013), we believe managerial entrenchment significantly impacts staying unlevered. Moreover, we suppose that high-tech companies are less diversified on average than traditional industries. Thus, in line with arguments by (Ji et al., 2019), we believe that managerial entrenchment has a more significant effect on corporate decisions.

Data and Methodology

Sample

We collected annual financial data from the Bloomberg database and non-financial data from the Capital IQ database for 2004-2015. The entire sample consists of large and mid-cap firms from the RUSSEL 3000 index, excluding utilities and financial companies due to differences in their business models. There were 2,189 firms in 2004 and 2,242 firms in 2015 in the initial sample. We divided the sample into two subsamples according to the CIQ industry classification. The first subsample represents high-tech firms and combines firms from Software and Services, Technology Hardware and Equipment, Pharmaceuticals, Biotechnology, and Life Sciences industries. The second subsample contains other firms from the index. All variables are winsorized at the 2.5% and 97.5% levels. We have a final panel dataset, which includes 17,199 firm-year observations.

An overview and the calculations of all the variables are provided in Table 2.

Methodology

In the first stage of the research, we conducted a univariate analysis. The purpose of the univariate analysis is to investigate whether the difference between the critical characteristics of high-tech and non-high-tech firms is significant.

In the second stage, we first run annual probit regressions to estimate the propensity to have zero-leverage. The dependent binary variable is 1 for a zero-leverage policy and 0 otherwise. Explanatory variables are market-to-book ratio, size, tangibility, and profitability (Rajan, Zingales, 1995). Then, using the estimated coefficients, we compute the probability for each high-tech firm to be debt-free. The expected percentage of zero-debt firms is obtained by averaging individual probabilities across all non-high-tech firms in a year. Finally, we subtract the expected percentage from the actual and obtain the difference, which is not explained by common capital structure determinants.

As (D'Mello, Gruskin, 2021) demonstrated, the set of factors influencing the decision to eliminate debt differs from the determinants for reducing leverage. Thus, we assume that there is a difference in the determinants of choosing between zero and non-zero policies and the level of the debt-to-equity ratio. Therefore, in the multivariate analysis, we run probit regressions to examine firm-specific factors determining the firm's propensity to maintain zero debt and tobit regressions to account for the censored nature of the leverage (Nivorozhkin, 2015).

Table 2. **Description of variables**

Variable	Description
Market leverage	Long-term debt divided by long-term debt plus the market value of equity
Age	Number of years since the date of incorporation
Market-to-book	Current market capitalization plus long-term debt divided by total assets
Size	Natural logarithm of total assets
Tangibility	Tangible assets divided by total assets
Profitability	Earnings before tax and interest divided by revenue
R&D	Research and development expenditures divided by total assets
CapEx	Capital expenditures divided by total assets
Cash holdings	Cash and cash equivalents divided by total assets
Dividend payout ratio	The proportion of net income paid out to investors
N of directors on board	Number of directors on board
% of independent directors	% of shares owned by independent directors
% of insider ownership	% of shares owned by insiders and affiliated persons

Source: authors.

To test the financial constraint hypothesis, we run several steps. We start by comparing the characteristics of high-tech and non-high-tech firms commonly used in the literature to forecast the possibility of financial constraints. We expect to see that high-tech firms are younger, smaller, and have fewer tangible assets but higher growth opportunities.

Following (Hadlock, Pierce, 2010), we apply the size-age (SA) index to divide the sample into constrained and unconstrained firms. We chose this measure of the financial constraints based on the transparent characteristics, which are not easy to manipulate by management, and based on the information available for all companies. The SA index based on the loadings on size, size squared, and age is calculated as follows:

$$SA = -0.737 * SIZE + 0.043 * SIZE^2 - 0.040 * AGE \qquad (1)$$

where SIZE is the logarithm of the total assets, and AGE is the number of years the firm is listed or years after the IPO took place.

We divide the sample into quartiles based on the index levels and determined that the quartile with the highest index level is the constrained subsample. The quartile with the lowest level of the index is considered unconstrained. We drop the second and third quartiles from this part of the analysis to avoid misleading results.

To test the flexibility hypothesis, we follow the methodology of Arslan-Ayaydin et al. (2014) and Lee et al. (2011). We approximate financial flexibility with retained earnings and cash holdings. We construct a dummy variable equal to one if the company has cash holdings or retained earnings above the sample medians by industries. Thus, all other companies with both cash and retained earnings below medians demonstrate a low level of financial flexibility. Using probit and tobit regressions, we estimate the influence of financial flexibility on the probability of zero-leverage choice and leverage of unconstrained firms.

Finally, we approximate managerial entrenchment with corporate governance characteristics demonstrating CEO power and monitoring (board size (Yermack, 1996) and the share of outside directors on the board (Weisbach, 1988)). Boone et al. (2007) find that smaller and less independent boards give CEOs more freedom, power, and influence. We also include the percentage of shares owned by insiders. We follow (Strebulaev, Yang, 2013) to approximate managerial entrenchment through ownership and governance indicators.

Results in Descriptive Statistics

The descriptive statistics are provided in Table 3. A univariate analysis proved the significance of all the differences; the results are represented in Table 4.

The descriptive statistics support the financial constraints hypothesis for high-tech and non-high-tech firms. First, we find that ZL firms are usually smaller (Devos et al., 2012). Secondly, ZL firms have a lower share of tangible assets, and high-tech firms have a lower tangibility ratio than other firms. This finding demonstrates that high-tech firms are more financially constrained than traditional industries. Therefore, it may be a major reason forcing them to eschew debt. Secondly, there is clear evidence that ZL firms are younger, with high-tech firms being younger than non-high-tech firms.

Another important finding is that ZL firms are less profitable than levered firms. It supports the financial constraint hypothesis, as firms with low gross margins are less likely to access debt capital markets. However, this contradicts the pecking order theory since a low-profit margin leads to internal financing, which forces firms to initiate new debt. High-tech ZL firms are less profitable than other firms in the sample.

Next, our results support the financial flexibility hypothesis. First, high-tech and non-high-tech ZL firms have a higher market-to-book ratio than levered firms. The descriptive statistics show that high-tech firms demonstrate a high market-to-book ratio (2.7 for ZL and 1.9 for non-Z.L.), showing higher growth opportunities and a high need for financial flexibility.

All non-ZL firms from the sample have higher cash balances, which is not consistent with Dang (2013), who found that ZL firms deliberately stay unlevered to be financially flexible in the future but corresponds to the financial constraints' hypothesis.

We may also observe greater insider ownership at ZL firms; thus, we could expect managerial entrenchment to be a significant factor in choosing an unlevered financing policy.

The results show that the R&D expenditures are much higher for high-tech firms, whereas the highest capital expenditures could be seen at non-ZL, non-high-tech firms. These results underline the technological factor of firms belonging to different subsamples.

Empirical Results

It is essential to check whether high-tech firms tend to be unlevered for the same reasons as non-high-tech firms. Table 5 shows that the number of zero-leverage high-tech firms has increased. In contrast, the mean values of common capital structure determinants have not changed dramatically over the period (Table 6), which indicates that these variables do not predict zero-leverage correctly for high-tech firms. We use an approach similar to Fama and French (2001) and Denis and Osobov (2008). We run the probit regressions to evaluate firms' probability of ZL based on common factors. Then we estimate the predicted proportion of ZL firms for high-tech firms based on the results obtained and compare that with the actual figures. The results from the first stage of the study are provided in Table 7.

The actual share of zero-leverage firms varies from 32% to 36.06% over the period, while the predicted values lie between 22.39% and 26.44%. The predicted ratios are consistently and significantly lower than the actual ones. This finding is consistent with the hypothesis that common corporate structure determinants are less likely to predict the probability of high-tech firms remaining unlevered, and can also predict this decision for non-high-tech firms. Given that common capital structure determinants failed to explain the increased percentage of zero-leveraged high-tech firms over the sample period, there should be other significant factors.

We provide further evidence supporting the difference between high-tech and non-high-tech firms by running a probit regression with four common determinants of capital structure and a high-tech dummy. Panel B of Table 7 shows that the high-tech dummy is significant, reflecting the high probability of high-tech firms being unlevered. This result corresponds to Hypothesis 1.

Financial Constraints

We tested the financial constraint hypothesis (Hypothesis 2) by dividing the sample into constrained and unconstrained firms. The descriptive statistics of subsamples (the first and fourth quartiles) are represented in Table 8. The unconstrained firms are much older, larger, more profitable, and have more tangible assets. The growth opportunities are higher for the constrained firms that appear to be younger, less profitable at the moment, and hold a lower volume of tangible assets. The ratio of high-tech firms in the constrained subsample is more than a third (37%), whereas the unconstrained subsample has

Table 3. **Mean Values of Variables**

Variable	High-tech		Non-high-tech	
	ZL	*Non-ZL*	*ZL*	*Non-ZL*
Market leverage	0.01	0.12	0.03	0.25
Age	14.64	20.35	23.99	29.53
Market-to-book	2.71	1.91	2.16	1.38
Size	6.08	7.02	6.05	7.71
Tangibility	0.17	0.17	0.22	0.30
Profitability	0.04	0.09	0.10	0.15
RandD	82.65	177.45	35.29	79.28
CapEx	–74.18	–162.88	–50.04	–382.14
Cash holdings	329.22	1314.15	144.39	616.59
Dividend payout ratio	22.24	22.49	54.66	44.53
N of directors on board	7.62	8.52	7.73	9.37
% of independent directors	76.17	78.50	75.38	79.21
% of insider ownership	8.78	6.19	8.51	5.18

Note: A firm is treated as zero-leverage (ZL) if it has no long-term debt in a given year.

Source: authors.

only around 11% of the high-tech representatives. Panel B of Table 8 shows approximately 77% of constrained firms in high-tech and 41.5% in non-high-tech sectors. Thus, we see that high-tech firms tend to be more financially constrained.

Table 9 presents the results of financial constraint hypothesis testing. The results support the financial constraints hypothesis as constrained firms are more likely to eschew debt. When we divide this group into high-tech and non-high-tech firms, we find that financial constraints for the high-tech firms only is significant. From the descriptive statistics, we expected financial constraints to be valid for the non-high-tech firms, although less significant. The results we obtained are even more striking since we see that for non-high-tech firms, financial constraints are not significant in predicting zero-leverage choices.

Table 4. **Univariate Analysis**

Variable	Non-high-tech		High-tech		Mean Difference
	N	*Mean*	*N*	*Mean*	
Market leverage	12881	21.60	4216	0.08	21.52***
Age	11388	28.19	3730	17.58	10.61***
Market-to-book	12927	1.44	4272	2.03	–0.59***
Size	12927	7.45	4272	6.67	0.77***
Tangibility	12921	0.29	4272	0.17	0.12***
Profitability	12815	0.14	4216	0.07	0.07***
RandD	10590	72.25	3882	143.40	–71.15***
CapEx	12915	–332.35	4268	–131.45	200.9***
Cash holdings	12846	545.46	4250	963.60	–418.14**
Dividend payout ratio	10444	45.82	2930	22.25	23.57***
N of directors on board	3023	9.14	1160	8.26	0.88***
% of independent directors	8744	78.80	2929	77.91	0.89***
% of insider ownership	6579	5.39	2410	6.60	–1.20***

Note: A firm is treated as zero-leverage (ZL) if it has no long-term debt in a given year. ***, **, and * indicate the significance at the 1%, 5%, and 10% levels, respectively.

Source: authors.

Thus, we state that financial constraints are essential for high-tech firms, so it is pretty often the case that for high-tech firms, zero-leverage is not an option but the result of an impossibility to obtain debt.

Financial Flexibility

Table 10 presents the results of testing Hypothesis 3. This hypothesis is tested on a subsample of unconstrained firms. First, we show that financial flexibility does not affect the probability of zero-leverage for unconstrained firms but affects the chosen debt level (Columns 1-2).

Second, we demonstrated the effect of financial flexibility on the probability of zero-leverage high-tech and non-high-tech firms. Financial flexibility is still insignificant for traditional industries, while financial flexibility significantly reduces the probability of zero debt (Columns 3-4). This fully confirms Hypothesis 3. For the choice of debt level, this dependence holds, i.e., financial flexibility has a more significant effect on the level of debt for tech companies (Columns 5-6).

Managerial Entrenchment

Table 11 presents the results of testing the managerial entrenchment hypothesis. First, we show that the choice of zero-leverage is encouraged by insider ownership (the indicator is only significant at the 15% level). At the same time, a large board and its independence reduce the likelihood of a zero-leverage policy choice. The choice of leverage is also influenced by insider ownership and independent directors. However, board size no longer plays a role.

Second, we identified a difference between high-tech and non-high-tech firms. In high-tech firms, insiders significantly increase the probability of choosing a zero-debt policy, consistent with the results (Strebulaev, Yang, 2013). For traditional sector firms, the influence of insiders is insignificant. At the same time, independent directors play a significant moderating role for traditional firms, while only board size plays a significant role in high-tech firms.

Table 5. **Distribution of Unlevered Firms in Time**

Year	High-tech			Others		
	All	*ZL*	*%*	*All*	*N*	*%*
2004	287	74	25.78%	1 040	95	9.13%
2005	315	91	28.89%	1 083	113	10.43%
2006	322	97	30.12%	1 118	116	10.38%
2007	332	105	31.63%	1 158	127	10.97%
2008	358	108	30.17%	1 201	134	11.16%
2009	384	118	30.73%	1 247	154	12.35%
2010	399	122	30.58%	1 278	167	13.07%
2011	445	126	28.31%	1 342	171	12.74%
2012	501	138	27.54%	1 399	176	12.58%
2013	554	178	32.13%	1 461	187	12.80%
2014	587	187	31.86%	1 506	189	12.55%
2015	609	205	33.66%	1 528	180	11.78%

Note: A firm is treated as zero-leverage (ZL) if it has no long-term debt in a given year. This table demonstrates the frequency of zero-leverage firms over time for the whole sample, which includes both high-tech and non-high-tech companies.

Source: authors.

Table 6. **Mean Values of Common Capital Structure Determinants of High-Tech Firms**

Variable	2004	2015
Profitability	0.04	0.06
Tangibility	0.17	0.17
Size	6.47	6.77
Market to book	2.27	2.24

Note: The table represents the mean values of common capital structure determinants of high-tech firms at the beginning of the examining period (2004) and the end (2015).

Source: authors.

Table 7. **Propensity Model and Probit Model with High-Tech Dummy Variable**

Table 7a. Panel A.

Year	Actual	Predicted	Actual - Predicted
2004	32.00	22.64	9.36***
2005	36.44	24.94	11.51***
2006	35.77	25.60	10.17***
2007	35.45	26.13	9.32***
2008	33.33	23.16	10.18***
2009	35.48	25.41	10.07***
2010	36.06	26.19	9.87***
2011	33.06	26.44	6.62***
2012	32.13	25.32	6.81***
2013	34.75	26.37	8.38***
2014	34.36	23.89	10.48***
2015	34.03	22.39	11.64***

Note. Predicted % of zero-leverage firms are obtained using estimated coefficients from annual probit regressions on the whole sample of the firms with the following determinants: size, profitability, growth opportunities, and tangibility. A firm is treated as zero-leverage (ZL) if it has no long-term debt in a given year. ***, **, and * indicate the significance at the 1%, 5%, and 10% levels, respectively. ***, **, and * indicate the significance at the 1%, 5%, and 10% levels, respectively.

Table 7b. Panel B.

Variables	z
profitability	0.29** (0.13)
tangibility	–0.98*** (0.21)
size	–0.53*** (0.03)
MB ratio	0.10*** (0.02)
Ht_dummy	1.33*** (0.12)
Constant	1.29*** (0.22)
Observations	16 925
Number of companies	2017

Panel B. Panel B. Probit regression with high-tech dummy. A firm is treated as zero-leverage (ZL) if it has no long-term debt in a given year. ***, **, and * indicate the significance at the 1%, 5%, and 10% levels, respectively.

Source: authors.

The limitation of testing the hypothesis on managerial entrenchment is that we tested it only for the latest period, since 2013. Before 2013, the disclosure level is not sufficient to verify the hypothesis.

Discussion

Our results indicate that high-tech firms tend to be more conservative in their capital structure choice. This conservative policy cannot be fully explained by the common capital structure determinants. Industry-specific factors influence financing policy. First, the nature of high-tech firms with uncertain cashflows adding to financially constraints can partially explain the zero-leverage policy. Financially constrained high-tech firms are forced to turn down debt financing. This is especially relevant for firms in the early stages of their life cycles (Lundberg, Lotfaliei, 2020). As the firm moves along the life cycle and information asymmetry between a firm and creditors diminishes, the role of the financial constraints deteriorates as well. At the same time, interestingly, financially constrained firms with high-medium productivity are prone to investments in innovation instead of investments in internationalization (Roelfsema, Zhang, 2018).

However, we show that unconstrained high-tech companies are also prone to zero debt. The second point we should mention concerning sector-specific issues is that the business models in technological sectors may require higher financial flexibility, since the research and development demonstrating high time uncertainty is a part of the business process. In this study we show the sector-specific relevance

Table 8. Comparative Statistics of the Constrained and Unconstrained Subsamples

Table 8a. Panel A.

Parameters	Status					
	Unconstrained			Constrained		
Stat	**mean**	**p50**	**N**	**mean**	**p50**	**N**
Age	61.78	56.00	4043	6.78	6.00	4058
Profitability	0.16	0.15	4035	0.04	0.10	3941
Tangibility	0.29	0.21	4042	0.22	0.13	4056
Size	7.95	7.95	4043	6.08	5.72	4058
MB ratio	1.33	1.03	4043	1.99	1.39	4058
ht	0.11	0.00	4043	0.37	0.00	4058

Table 8b. Panel B.

ht	Variable	mean	p50	N
0	constrained	0.42	0	6147
1	constrained	0.77	1	1954
Total		0.50	1	8101

Note. The sample division into constrained and unconstrained is based on the SA index. We divide the sample into quartiles based on the index levels and assign the quartile with the highest index level as the constrained subsample. The quartile with the lower level of the index is assigned as unconstrained. Panel B of the table presents the distribution of constrained firms between high-tech and non-high-tech firms.

Source: authors.

Table 9. Financial Constraint Hypothesis Testing Results

Variables	Whole sample	High-tech	Non-high-tech
	z	*z*	*z*
Size	–0.56*** (0.05)	–0.33*** (0.07)	–0.70*** (0.07)
Profitability	0.17 (0.18)	–0.12 (0.23)	0.45 (0.28)
Tangibility	–0.64** (0.30)	0.28 (0.49)	–1.10*** (0.40)
MBratio	0.05* (0.03)	0.10** (0.04)	0.01 (0.04)
Ht-dummy	1.30*** (0.16)	–	–
SA_constrained	0.32* (0.17)	0.65** (0.32)	0.21 (0.20)
Constant	1.11*** (0.380)	0.56 (0.62)	2.07*** (0.53)
Observations	7933	1879	6054
Number of companies	1504	430	1074

Note: KA firm is treated as zero-leverage (ZL) if it has no long-term debt in a given year. ***, **, and * indicate the significance at the 1%, 5%, and 10% levels, respectively. The sample's division into constrained and unconstrained is based on the SA index. We divide the sample into quartiles based on the index levels and the quartile with the highest index level respresents the constrained subsample. The quartile with the lowest level of the index is unconstrained.

Source: authors.

of financial flexibility and managerial entrenchment. Could we claim that we have found the reliable motives behind the lack of debt in the capital structure of these companies? And can the internal sources and equity financing be a strategically wise industry-specific decision for high-tech firms' development? Here we go to the third sector-specific issue: in a highly uncertain macroeconomic environment strengthened by the volatility in the sector, high-tech firms try to mitigate any incremental risks, even if the financing decision they make looks financially unfavorable in the short term.

Moreover, conservative debt policy could be a result of shifting the focus of capital structure choice from choosing a value-maximizing debt ratio to providing reliable access to funding (DeAngelo, 2022). As funding is essential to implement necessary research and development and further investments and thus, to the strategic development and the firm's value, focusing on funding could help us with more insights into zero-debt policies. Investment opportunities are highly uncertain in terms of time and volume in the high-tech sector. COVID-19, which has contributed to the dramatic growth of technology and has driven technological innovation to a new level, is an indisputable example (OECD, 2021).

DeAngelo states that management's insufficient knowledge for optimizing capital structure should lead to a new understanding of comprehensive debt-to-equity choice (DeAngelo, 2022). Given the role of intellectual capital in the business models of technology companies, we can presume that the proportion of managers considering capital structure choice in the new, broader paradigm is greater in high-tech firms (Fritsch, Wyrwich, 2019).

Therefore, keeping a firm's option to borrow and its ability to accumulate (excess cash) and raise internal funds when new investment opportunities appear could be a key to understanding successful zero-leverage high-tech firms. The ability to run a successful technology business without external debt or with a close-to-zero-debt is also demonstrated by companies in the S&P500 index, such as Intuitive Surgical, Inc. (the robotic-assisted surgery industry), Amdocs Limited (CRM services), and SEI Investments (a fintech company).

Conclusions

This paper investigates why there are so many zero-leverage firms in high-tech industries and the mo-

Table 10. **Financial Flexibility Testing**

Variables	whole sample	whole sample	high-tech	non-high-tech	high-tech	non-high-tech
	z	*ltd*	*z*	*z*	*ltd*	*ltd*
Size	–0.660*** (0.11)	0.03*** (0.00)	–0.43** (0.21)	–0.71*** (0.19)	0.02 (0.01)	0.03*** (0.00)
Profitability	0.55 (0.55)	–0.04** (0.02)	–0.03 (1.13)	0.81 (0.62)	0.09* (0.05)	–0.07*** (0.02)
Tangibility	–1.36** (0.61)	0.06*** (0.02)	2.673 (1.68)	–1.73** (0.71)	–0.08 (0.08)	0.07*** (0.02)
MBratio	0.19*** (0.07)	–0.03*** (0.00)	0.47*** (0.16)	0.13 (0.08)	–0.02** (0.01)	–0.03*** (0.00)
Flexibility	–0.17 (0.22)	–0.04*** (0.01)	–1.60*** (0.50)	0.17 (0.25)	–0.06*** (0.02)	–0.04*** (0.01)
Constant	1.29 (0.90)	0.06** (0.03)	1.07 (1.85)	1.56* (0.94)	0.14 (0.09)	0.06** (0.03)
Observations	4022	3409	452	3570	388	3021
Number of companies	499	439	66	433	58	381

Note: A firm is treated as zero-leverage (ZL) if it has no long-term debt in a given year. ***, **, and * indicate the significance at the 1%, 5%, and 10% levels, respectively. The financial flexibility is approximated with retained earnings and cash holdings. A dummy variable is equal to one if the company has cash holdings or retained earnings above the sample medians by industries.

Source: authors.

Table 11. **Managerial Entrenchment Testing**

Variables	whole sample	whole sample	high-tech	non-high-tech
	z	ltd	z	z
Size	-0.89*** (0.10)	0.02*** (0.00)	-0.58*** (0.13)	-0.98*** (0.13)
Profitability	-0.37 (0.43)	-0.10*** (0.02)	-0.51 (0.52)	0.60 (0.51)
Tangibility	-0.13 (0.48)	0.07*** (0.02)	1.43* (0.82)	-0.27 (0.56)
MBratio	0.26*** (0.07)	-0.03*** (0.00)	0.22*** (0.08)	0.13* (0.078)
Insider ownership	0.02 (0.01)	0.001** (0.00)	0.03* (0.02)	0.00 (0.01)
Independent directors (%)	-0.02* (0.01)	-0.001*** 0.00	-0.00 (0.01)	-0.02** (0.01)
Board size	-1.05** (0.42)	0.01 (0.01)	-1.08* (0.62)	-0.56 (0.49)
Constant	5.01*** (1.12)	0.17*** (0.04)	4.03** (1.57)	5.43*** (1.35)
Observations	4057	2955	1107	2950
Number of companies	1951	1442	538	1413

Note. A firm is treated as zero-leverage (ZL) if it has no long-term debt in a given year. ***, **, and * indicate the significance at the 1%, 5%, and 10% levels, respectively. The managerial entrenchment is approximated with ownership and governance indicators..

Source: authors.

tives and factors leading to the zero-debt puzzle for high-tech firms. We try to demystify the mystery of zero-leverage for high-tech sectors.

Based on a sample of Russell 3000 companies for 2004-2015, we provided evidence showing the increasing number of unlevered high-tech firms over the considered period. A similar trend among non-high-tech firms is not as dramatic. We show that size, profitability, tangibility, and growth opportunities usually described as common determinants of corporate structure cannot fully explain why high-tech firms choose a zero-debt policy.

In the second part of the paper, we tested the possible motives for avoiding debt financing. First, we demonstrated that high-tech firms are more financially constrained than non-high-tech firms. Thus, high-tech firms more often have no access to debt financing, automatically resulting in zero leverage. So, zero leverage is not always a choice.

Second, we investigated unconstrained companies. We show that financial flexibility is even more critical for unconstrained high-tech firms than for firms in traditional industries. This is an important result since we show that high-tech firms tend to choose zero-leverage not only when they face financial constraints, but also due to financial flexibility factors.

Third, we revealed the different effects of managerial entrenchment on high-tech and traditional companies. Managerial entrenchment aggravates the choice of high-tech firms for zero leverage. We showed that insiders' ownership increases the probability of choosing a zero-debt policy for high-tech firms. At the same time, the board of directors plays a more critical role for traditional companies. As controversial as it may sound, people matter even more in high-tech companies.

As the role of high-tech firms in the economy increases, we expect to see more firms with zero or close to zero debt policies. High-tech sector-specific factors make us consider a zero-debt policy as a new best practice rather than a conservative debt policy.

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Reconfiguring the Battery Innovation Landscape

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Abstract

Batteries are critical for energy transition strategies. This paper offers a comprehensive assessment of the trends and developments in battery innovation. Over 700,000 patents from the period of 2005-2019 are compiled and analyzed. Leading patent applicants and countries of origin are identified. Major patent applicants are mostly large East Asian companies, while Japan and South Korea are the leading countries followed by the US, Germany, and China. Different battery designs, the main battery components, and interactions with other clean technologies are examined. Based on the operative definitions for incremental/radical and product/process innovations, a battery innovation typology is set forth. Main findings are that patenting in batteries has risen robustly and lithium-ion batteries are the most vibrant technology; the lead-acid set-up maintains consistent innovation activity; lithium-sulfur and flow batteries are the most notable emerging technologies; electrodes are the most salient battery component, followed by electrolytes, separators, and cell housing; and the most significant interactions of batteries with clean energy technologies are between battery charging and photovoltaic energy as well as between battery charging and electric vehicles. Incremental innovation represents more than half of patents, while product innovation represents approximately 70% of total patents.

Keywords: secondary batteries; innovation; technological trajectory; patent data

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Introduction

The need to reduce CO_2 emissions and mitigate the climate crisis was recognized by the 195 countries that signed the Paris agreement in December 2015.[1] TThis challenge has motivated efforts toward a transformation in energy production and use. One avenue is shifting from a situation of nearly total dependence on fossil fuels to a scenario where low-carbon energy sources play an increasingly significant role in world energy production (Fagerberg et al., 2016). In recent years, the deployment of wind and solar photovoltaic (PV) energies has risen significantly, reaching 10% of the global electricity production in 2021 (IEA, 2021a). It is expected that investment in climate change-mitigating technologies will continue to grow over the next several decades (IEA, 2021a). The urgency to accelerate these investments has been highlighted by the Sixth Assessment Report of the Intergovernmental Panel for Climate Change (IPCC, 2021). Additionally, the energy crises that emerged at the end of 2021 in the context of the lifting of coronavirus lockdowns and geopolitical conflicts further stressed the need for an accelerated transition to energy infrastructures less dependent upon conventional systems. Hence, new ways to make energy supply-demand connections less subject to shocks and bottlenecks are at a premium.

The increasing use of intermittent and non-controllable power sources poses, nevertheless, a key conundrum in power grid management and, hence, a severe constraint in the ability to achieve a sustainable socio-technical reconfiguration (Sovacool et al., 2020). Wind and photovoltaic (PV) energy output is largely determined by environmental conditions, with production peaks not necessarily matching demand and usage behavior. Thus, energy storage is essential to adapt energy delivery to users' needs as it allows for harnessing surpluses and injecting them into the grid when necessary, thus avoiding waste and reducing stress on distribution infrastructure (Castillo, Gayme, 2014). Enabling power adjustments and signal quality control is a fundamental benefit of using energy storage. For instance, small electricity producers have the opportunity to accumulate energy surpluses and sell them when the sales price is higher, not only smoothing the volatility of the system, but also improving its economic efficiency (Diesendorf, Wiedmann, 2020). Moreover, it is known that frequently the potential financial profits are among the stronger motivations for installing small renewable energy systems (Hansen et al., 2022). Therefore, the development of working storage solutions is part of a broad set of much needed "systemic eco-innovations" (Jesus, Mendonça, 2018; Lehmann et al., 2022). The increased deployment of storage has the potential to increase the competitiveness of renewable electricity and enable a larger transition to a smarter, cleaner, entrepreneurial, more inclusive, and circular society.

Among the many energy storage alternatives, secondary rechargeable batteries (or simply batteries here) represent a robust approach. Due to their high energy density, modularity, and low response time, batteries are a very attractive solution for a wide range of energy storage applications (Van Noorden, 2014). Battery storage also enhances the stability and reliability of electricity grids while the bolstering flexibility on the demand side to accommodate supply shocks and overall heightened uncertainty (IEA, 2022). Advances in battery technologies are thus expected to smooth the workings of power systems while opening new markets and technological opportunities (Shapiro, 2020). Battery evolutionary pathways do matter for energy decarbonization, since they are on par with government efforts to electrify domestic and mobility systems (Velázquez-Martínez et al., 2019). They are further critical for energy security, since they constitute buffers against breakdowns in the short run and provide increased adaptation options over the long run (Azzuni, Breyer, 2019; Jindal, Shrimali, 2022).

One of the main questions this paper aims to address is how progress is taking shape in battery technologies. In recent years, several studies have addressed innovation in energy technologies (Lee, Lee, 2013; Albino et al., 2014; Wong et al., 2014; Silva et al., 2015; Kittner et al., 2017). Other studies focused more narrowly on battery innovation, both analyzing different aspects of lithium-based technological trajectories (Wagner et al., 2013; Stephan et al., 2017), as well as alternative ones (Aaldering, Song, 2019). Similarly, the innovation activities taking place along the electric vehicle value-chain have been analyzed (Feng, Magee, 2020; Golembiewski et al., 2015), and the specific R&D trends of battery technology in electric vehicles were also addressed (Zhang et al., 2017). Additionally, the environmental challenges of the battery value chain and the circular business model in lithium-ion batteries has been analyzed (Albertsen et al., 2021; Dehghani-Sanij et al., 2019; Levänen et al., 2018) while others have studied the impact of policy instruments on the innovation of environmentally friendly technologies (Bergek, Berggren, 2014). Recently, a joint report by the International Energy Agency (IEA) and the European Patent Office (EPO) analyzed the main patent trends in the field of electricity storage in the context of a project concerning pathways to a decarbonized economy (IEA, EPO, 2021). Patent data highlight global, regional, national, and even local topics of wide policy significance, and have been a recent focus as an underutilized evidence base for mapping and measuring promising technologies, leading companies, supporting institutions, and geographical hotspots (IEA, EPO, 2021).

We seek to contribute to this agenda by committing to two research approaches. First, in the context of systemic interdependencies, we adopt a neo-Schumpeterian perspective to motivate an evolutionary study of

[1] https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement, accessed 16.01.2023.

electric batteries as "new combinations" that adapt to the evolving usage/production landscapes when facing modern-day challenges in stationary and mobile storage needs and requirements (Castellacci et al., 2005; Caraça et al., 2009). Second, our empirical strategy takes on more than 700,000 patent applications as an indicator of technological progress in order to profile the battery innovation patterns, namely in what concerns the rate and direction of technical change (see Lhuillery et al., 2017). What make batteries interesting is that they provide ready resilience and actionable opportunities, but also the accumulation of capabilities is heavily knowledge-intensive and slow to materialize in the marketplace (Mendonça et al., 2019).

Batteries in the Energy Transition

The role of storage in the evolving energy system

Energy storage is a puzzle with many pieces: some older, bigger, and more stable; others less defined, shifting in importance or just starting to take shape. By far, the most important electricity storage technology in the world is pumped hydropower, presently accounting for more than 95% of the grid-connected power storage.[2] Despite being a mature technology with low response times and a very large capacity range, hydropower stations need particular geographical and climate conditions; these limitations constrain their use to certain regions and seasons while, at the same time, bringing about large pressures in terms of land usage and water management (Schulz et al., 2017). Several alternative energy storage solutions are available, ranging from mechanical approaches such as compressed air storage (CAES) to chemical and electrochemical solutions such as fuel cells or batteries.

Secondary rechargeable batteries harness electricity in the form of electrochemical energy, promoting the interchange between these forms of energy. The electricity stored in a battery can be used at a later moment, and possibly, in a different place. During battery charging, the electricity is transformed into electrochemical energy, a process that entails the interaction of the battery with the electricity production/supply technologies. When there is an electricity demand, the battery converts the electrochemical energy back to electricity, therefore, responding to the need while adding to the security of the energy system as a whole. The specific features of energy demand are profoundly dependent upon the type of application, and, in fact, batteries have a set of characteristics that allow them to adapt to very diverse applications.

As already mentioned, batteries are an interesting choice for very distinct applications. Presently, there are two emerging storage markets for which electrochemical batteries are the option of choice: power grids and electric mobility. Although lithium-ion and lead acid batteries are presently very competitive, it is expected that in the coming years, emerging battery technologies will reach a relevant market share while enabling new battery applications (IEA, 2020a). The raw material extraction needed to fuel the expected growth of the electric mobility and grid storage markets will put increased pressure on ecosystems and socioeconomic systems (IEA, 2021b). This issue is of particular concern if the current situation in which battery market growth mainly occurs at the expense of Li-ion technology remains entrenched. It is therefore important to expand the technologies and raw materials used in the manufacture of batteries and it is particularly relevant to identify the most promising emerging battery technologies (Metzger et al., 2023). Moreover, the energy and transport systems are at forefront of the digitalization revolution (Turovets et al., 2021), which poses new challenges for energy storage systems and battery technologies. Such challenges in "critical technology areas" call for innovation (Aaldering, Song, 2019; Golembiewski et al., 2015; IEA, 2020b; IEA, 2021b), especially in a post-pandemic/geopolitical conflicts/decoupling scenario where supply-chains are already under strain. Surely, one of the main limitations of battery storage scale-up (and further price decrease) is the availability of raw materials; the minerals (namely lithium and cobalt) required for their manufacturing are themselves non-renewable resources and environmentally expensive to extract, process, and manage (Metzger et al., 2023).

Battery innovation through a neo-Schumpeterian lens

This paper analyzes innovation dynamics in the different electric battery technologies. Battery, as any technology, is an artefact with a variety of practical applications in contemporary society (Dodgson, 2008). The knowledge base that enables it is derived from many disciplinary domains (some more science-based, like electrochemistry and materials science; some emerging from actual production and usage in actual settings, like mechanical engineering and design). The usefulness of batteries, however, is manifested in a particular context: that is, they are a medium that crucially interacts with other technologies that channel power to them and are fed by the power they harness (Berndt, 2003, p. 3).

Today, batteries lie at the heart of complex engineering-intensive energy systems (Prencipe et al., 2005) that are themselves going through a rapid pro-sustainability structural change (Schot, Steinmueller, 2019). Batteries are touchstone devices that receive, store, and deliver energy. They exist in a cobweb of interdependencies, i.e., these devices are contingent upon dominant power sources and there are several varieties of applications affecting them in the long-term (see Malhotra et al.,

[2] https://sandia.gov/ess-ssl/gesdb/public/statistics.html, accessed 08.08.2022.

2021). Likewise, the downstream context of battery applications matters as it exerts selective pressures that are interpreted by innovation agents so as to promote adaptation and evolutionary responses. In other words, available knowledge contributes to explaining the momentum of technical change, while certain socioeconomic issues encourage or penalize the development of specific solutions. This combination of "supply-pushes" in power generation alternatives and "demand-pulls" in competing domains of application give rise to patterned dynamics often called technological trajectories (Dosi, 1982; Nelson et al., 2018). This evolutionary perspective on innovation recognizes that knowledge development is a problem-solving activity but also that not all pathways are traveled (Hung et al., 2022). That is, of all the possibilities that can be followed only a few end up being pursued, gain momentum, and become the basis for cumulative progress. Technical change is uneven in the problem space and, over time, technological solutions cluster and consolidate around specific choices (engineering/societal compromises).

Batteries have long been deployed in a variety of roles in networks of energy availability and use. Lately, electric generation and transmission players are increasingly interested in the use of batteries for large-scale energy storage in order to optimize grid operations (IEA, 2020a). Also, the increasing deployment of highly variable renewable options opens new opportunities to batteries in stationary applications (IEA, 2021a). Moreover, while for many decades batteries have been used as jump-start devices in conventional internal combustion engine vehicles, they have progressed to an even more central position in fully electrical approaches to mobility. It is expected that the use of battery-powered electric vehicles will register an eight-fold increase in the next decade (Dhakal, Min, 2020). Hence, batteries are increasingly present in electric transport, renewables-supported energy systems, smart grids, and new consumer electronic devices. These applications are gradually becoming woven together in new socio-technical systems (i.e., smart homes, sustainable mobility, smart cities, etc.), and the use environment shapes the technological trajectories that emerge over time (Malhotra et al., 2021). These forces push, shape, sustain, and constrain technical change. Hence, characterizing the key characteristics and functions that make batteries operative in this unfolding environment is a relevant empirical research agenda. This agenda contributes to further understanding the diverse institutional roles, industrial dynamics, and public policy opportunities in the contemporary economy.

Approach and Data

Patents as yardsticks

Patents are helpful for surveying innovative efforts and exploring the factors behind patterns of sectoral activity, geographic location, the evolution of the body of knowledge, and so on. (Bathelt et al., 2017; Nagaoka et al., 2010; Patel, Pavitt, 2005). Despite the vast body of literature on possible approaches and methodologies to measure innovation, a method to unambiguously evaluate innovation cannot be established (Dziallas, Blind, 2019; McKelvey, 2014). Measuring qualitatively different phenomena remains problematic (Smith, 2006) but continues to hold promise (Mendonça et al., 2021). The shortcomings of patents are well known and include non-patenting (including the preference for trade secrets as forms of appropriation), differing propensities to patent across technologies and firm sizes, etc.; but, in spite of these drawbacks, they remain useful for understanding the evolution of medium-high tech industrial artefacts (Mendonça et al., 2019). Therefore, using patents as an indicator is a matter of compromise, judgment, and the management of methodological trade-offs. Limitations of this indicator can be kept in check if the filings refer to more clearly delimited technologies if they are high in volume and coming from distributed places. When considering which batteries are concerned, it surfaces that not only are the numbers very robust (for most technological variants) and growing above general patenting activity (especially during the 2010s), but also that battery patents account for nearly 90% of all electrical energy storage (IEA, EPO, 2020).

Patents are a by-product of dynamic economic activity, providing the holder with a monopoly in the territory covered by the patent for a certain period of time. It also represents an exclusive ticket to technology markets, that is to say, it is an intangible asset that can be transacted commercially and also waged as a resource in litigation battles. Another point to bear in mind is that the economic significance of patents varies immensely; it is contingent upon a number of non-technology-related factors such as the country (different patenting policies and operational rules in each patent office regarding patentability thresholds) and industry (mainly due to the knowledge-based specificities and respective sectoral competitive regimes). In what this paper is concerned, patent applications are the chosen innovation indicator since they have substantive informational value regarding advances along the technological frontier and remain unique appropriability tools in medium-high and high-tech innovative industries, including when emerging technologies, which are critical for sustainability, are concerned (Leiponen, 2014; Mendonça et al., 2021).

Empirical evidence

The source for this study is the Global Patent Index (GPI), a source curated by the European Patent Office (EPO), allowing for the retrieval of thousands of entries per search while providing a format amenable to immediate statistical representation. Besides the quality and quantity of the data, the practical aspects of data handling are of great importance in empirical patent analysis.

In this study, we used the International Patent Classification (IPC) system. The IPC is composed of a coding scheme with a tree structure that becomes more specific as we descend in the hierarchy. The order of this hierarchy is section, class, subclass, group, and subgroup. A patent may cover several classification codes involving very different technological categories belonging to different industries, i.e., different sub-groups in distinct sections. Although it might be argued that this is a weakness of the patent indicator, it can translate into valuable information as it reveals patterns of multidimensionality of a given technology which, as the current analysis will leverage, can be highly beneficial for the purposes of analysis. In particular, a given patent that was allocated to different categories can be taken to be more combinatorial (in the classic Schumpeterian sense of innovation as a "new combination") relative to others.

The time elapsed between the patent application and its publication can range from one year to a year and a half. Thus, patents published in one particular year were submitted about two years before. From here on, we will consider the date of publication as the reference one but keeping these data features in mind. Likewise, it is considered that at the time of extraction, the database was already consolidated since the patents published between 2005 and 2019 were extracted during December 2020.

In this study, a choice was made to use as database patent applications regardless of the patent office where these were filed, instead of narrowing the database to a single patent office (Lee, Lee, 2013) or a limited group of patent offices (Kim, Lee, 2015). Our aim is not to measure the value of patents, for which other approaches would be preferable, such as the use of patent families (Martínez, 2011), but to identify the main developments and technological trajectories in terms of the exploration of the battery knowledge space without regard to the prospective economic value of the invention (Tahmooresnejad, Beaudry, 2019). Studies based on patent families are known to exclude many inventions (Criscuolo, 2006). In our case, this could lead to losing less salient trends, such as the interactions between technologies or changes in innovation types. Furthermore, the fact that our study and the already mentioned IEA & EPO (2020) report both identify similar general trends in battery innovation is reassuring regarding the validity of our approach. Patterns are also corroborated by the results of Malhotra et al. (2021), who focuses on a narrower specification of batteries for a longer time using a different indicator construct. For a complementary study, see (Metzger et al., 2023) with different patent evidence but corroborating results.

Technology identification

Electric batteries can be found in the IPC subclass H01M, which assembles patents related to the direct conversion of chemical energy into electricity. Three groups of the subclass H01M represent the different components of a battery system – electrodes, secondary cells, and non-active parts (Table 1).

To extract patent applications that refer to only one battery component, the database was searched for "NAP only" (for non-active parts), "Electr only" (for electrodes) and "SC only" (for secondary cells). The multicomponent patent applications were collected using the following queries: "Non-active parts + Electrodes", "Non-active parts + Secondary cells", "Electrodes + Secondary cells", and "Non-active parts + Electrodes + Secondary cells". The ensemble named "Batteries all" was obtained by adding results from all these queries.

Table 1. **Patent Classification for Battery Components, IBC-based**

Groups	Contents
Non-active parts	
H01M 2 – constructional details, or manufacturing process, of the non-active parts	Technical matter regarding casing, wrapping, or covering the cell, connectors, sealing materials, separators, electrolyte containers, shock absorbers, etc.
Electrodes	
H01M 4 — electrodes	Advances related to electrode manufacturing, specific electrodes and electrodes materials, which are key battery components in terms of capacity, power and energy density (Mei et al., 2019).
Secondary cells	
H01M 10 – secondary cells; manufacture thereof	General manufacture details of the cell, electrolytes, accumulators, power tools, cooling mechanisms and so on.
Charging	
H02J 3/32	Subclass H02J contains patents for circuit arrangements or systems for supplying or distributing electric power and systems for electric energy storage. Group H02J3 includes circuit arrangements for AC mains and distribution networks, while the subgroup H02J3/32 refers to arrangements for balancing the network load using batteries for energy storage.
H02J 7	Group H02J7 contains the patents associated with circuit arrangements for charging or depolarising batteries, or for supplying load from batteries.
B60L 53	Subclass B60L contains applications related to the driving force of electrically propelled vehicles. Group B60L53 includes batteries' charging methods, specially adapted for electrical vehicles and charging stations.
H01M10/44	Applications of secondary cells charging or discharging methods.
Source: authors.	

The extraction method allowed all the patent applications to be separated according to the key-component topology, without data duplication.

During data collection, to avoid the inclusion of patents that are not related to secondary batteries, we made sure to exclude the subclasses of primary cells (H01M 6), fuel cells (H01M 8), hybrid cells (H01M 12), as well as those of electrochemical current generators (H01M 14), and combinations of electrochemical generators (H01M 16). In this way, the collected evidence is exclusively devoted to the battery system construction set-up or to electrochemical storage in general. We used Boolean operators in the search protocol to exclude the aforementioned groups. Whenever possible, the queries were made based on the IPC classifications (classes, subclasses, groups, and subgroups). In the remaining cases, and for the sake of completeness, the queries were based on the presence of specific words in patent title/abstract. The reason for this choice was that IPC codes point directly to the technical field covered by the application, being more reliable than the appearance in the patent title/abstract of words like "battery" or "cell".

To analyze battery-charging technologies, we created a further search query with three groups that do not belong to the subclass H01M: H02J 3/32, H02J7, and B60L53 (see Table 1). The search query related to battery cooling uses, the expressions H01M10/60, H01M10/443, H01M10/486, H01M50375, or H01M50/581 include all the groups related to battery cooling or thermal management.

We made new queries to study the different battery technologies where the key battery component groups (H01M 2, H01M 4, H01M 10) were cross-checked with keywords from the patent front page, identifying the different batteries technologies. For instance, to identify lead-acid batteries patents, the keywords "lead-acid or "VRLA" (Valve Regulated Lead Acid) or "SLA" (Sealed Lead Acid) or "lead acc" (Lead accumulators) were introduced in the search queries. Since some of the emerging battery technologies analyzed do not have an IPC code, no specific battery-type IPC code was used in order to avoid a technology bias. We also made a specific search query for flow battery patents. Since flow batteries belong to the subgroup H01M 8/18, which is within the fuel cell hierarchy, we performed a survey including the H01M 8 group and adequate keywords (see Appendix A). In the last several years solid-state batteries have been gaining a lot of attention. These batteries use solid electrodes and solid electrolytes, which can be made of several different materials. In fact, this technology branch overlaps with a few of the technologies previously mentioned. The search query on solid state batteries was made by crossing the key battery component groups[4] with the keyword "solid state".

To inspect the interactions between patenting in batteries and photovoltaic/wind technologies, new search queries were implemented, inspecting the intersections between any IPC battery group and the groups related to PV/wind energies. To analyze the interactions of batteries with electric mobility, battery patents groups were cross-inspected with groups B60L 11 and B60L 50[5] associated with the power supply within electric vehicle systems. Finally, to examine the interactions of battery charging/supplying with other technologies, the charging/supplying load query was crossed with the wind/PV energy and the electric vehicle group codes. For this goal, some keywords were added to the search query. Moreover, the subgroup H02J 7/35, related to charging batteries with PV energy, was included in the charging battery-PV search. The details of the methodological protocols are further described in the Appendix A.

Innovation categorization

Possibly the most classic breakdown between types of innovation is the *product innovation* concept, i.e., the introduction of a new or significantly developed output in the economic system, and the *process innovation* concept, i.e., a novel or more sophisticated method of production or distribution (Fagerberg, 2004). Product innovations refer to outputs, whereas process innovations refer to the linkage between inputs and outputs. Recently Domnich (2022) made a survey of empirical studies on the impact on productivity with a specific emphasis on product and process innovation. In the case of batteries, an example of product innovation may be the refining of the battery design and an example of process innovation may be related to assemblage features.

Innovations can also be characterized by impact, being classified as incremental when representing smooth elaborations on prior set-ups of the technology or radical when a breakthrough causes a discontinuity with the established knowledge bases (Dodgson, 2008). Radical innovations combine more and unconnected knowledge domains, making them more encompassing and riskier than technologies that work in just one domain, thus providing a platform for new technological trajectories (Hesse, Fornahl, 2020). In the case of batteries, this may imply for example a new architecture of the cell. This paper adopts these criteria in order to distinguish between varieties of advancements in state-of-the-art battery technologies.

The extant literature does not provide unequivocal guidance on how to operationalize the product/process and radical/incremental concepts, and much lies

[3] Unlike the remaining, the searches related to cooling technologies and solid state batteries were made during 2022 using the 2022.01 version of IPC classification.

[4] In the 2022.01 version of IPC classification group H01M 50 replaced group H01M 2.

[5] B60L 11 was transferred to B60L 50 after the 2019.01 version of IPC classification.

in the hands of analysts facing the particular empirical materials and research goals (Dziallas, Blind, 2019; Katila, 2000). Based on the patent content and classifications (title, claims, descriptions, IPC categories, etc.), this study distinguishes between product and process innovations as well as radical and incremental innovations by considering a number of methodological options. Considering that there are several IPC subgroups related to the manufacture of battery components, a patent application containing at least one of these subgroups is considered a process innovation, and the applications not containing any of them are treated as product innovations. To characterize innovation impact, we posit that innovation is incremental if there is innovation in just one battery dimension (i.e., Electrodes, Non-active parts, and Secondary Cells) and radical if there are advances in at least two battery dimensions, proxying for the possible step-jumps stemming from connecting previously unrelated characteristics (Castaldi et al., 2015).

Our study goes through more than 700,000 patents applications for the period 2005–2019. The analysis of this database provides insight into the most significant aspects of battery breakthroughs and innovation protagonists. The systematic interactions with renewable energies and mobility technologies are also analyzed. Based on the previously established definitions of incremental/radical and product/process innovation, the most important innovation types are weighed in. A number of stylized facts immediately come forth.

Results

Leading patent applicants

Figure 1(a) presents the leading 25 battery corporate applicants of the period 2005–2019. This list of heavy-duty applicants is almost entirely composed of large companies. Thirteen of these companies are Japanese, four are South Korean, three - Chinese, two - German, and two are from the US. The only non-corporate entity (a public research lab) that appears on this list is French, the Centre Energie Atomique (CEA).

The striking performance of Far Eastern players is in line with the results of IEA & EPO (2020). The notable role played by Japanese and South Korean corporations in patent applications may be justified, on the one hand, by the great importance of the higher-tech/export-oriented sectors in these countries in areas that are heavily dependent on batteries, such as consumer electronics and automobiles. On the other hand, it is widely recognized that the ambitious R&D policies, anchored on their own industries' priorities, developed by Japan and South Korea over the years with respect to "clean energy" technologies, including batteries since the 1990s, are strongly implicated in these technological achievements (IEA, 2008; Jeong, Mah, 2022). It is worth mentioning, by contrast, the example of Germany, that despite its ambitious energy transition strategy expressed in its successive energy research programs, in the absence of strong battery-related industrial interests, energy storage and rechargeable batteries were only established as research priorities in 2011[6].

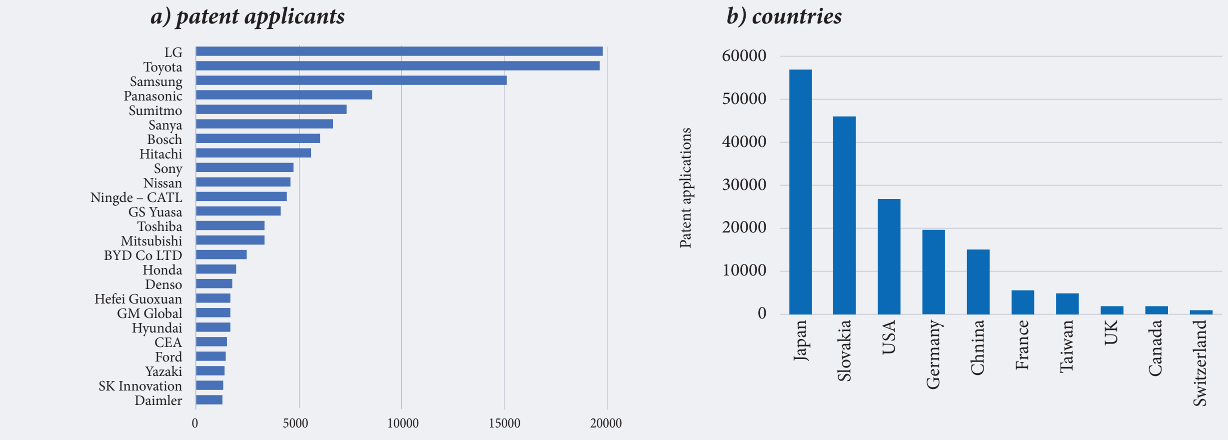
In Figure 1(b) it can be observed that the main innovation national players in batteries in the period 2005–2019 are Japan (JP) and South Korea (SK), followed by the United States (USA), Germany (GER), and China (CN). It is worth mentioning that when focusing on the patents published in the last five years, the rapid rise in patenting by large Chinese companies (IEA, EPO, 2020) is striking, a trend that if maintained will likely introduce significant changes in the leadership of battery innovation. Overall, the vibrant performance of the "Global East" appears largely attributable to deliberate national strategies for the development of clean energy technologies (Tan, 2010; Malhotra et al., 2021; May et al., 2018). The expansion rates of battery-related productive knowledge show that effective policy support is within reach as way to allow for greater global ambitions (IEA, 2022).

Main battery development pathways

Figure 2 displays the patenting trends across battery types (log-scale), and at least four empirical regularities can be outlined. First, Li-ion batteries are hegemonic throughout the field of batteries, sustaining an average annual growth rate of 17%, coming to represent more than three-quarters of all patents published in the period 2005–2019. The high inventive activity related to lithium-ion (Li-ion) technology can be attributed to its deployment in very different uses. Different applications have different performance criteria, but this technology has provided effective solutions (for mobility and stationary purposes) at declining relative prices (IEA, EPO, 2020, pp. 46–48). Second, there has also been resilient performance by the lead-acid (Pb-acid) type of batteries, a mature technology that maintains a steady innovation flow and a relevant role on the growing market of stationary storage applications (May et al., 2018). Third, some evidence of structural change can be identified: two battery approaches, redox-flow and lithium-sulfur (Li-S), took off around 2010 and have achieved growth rates of over 30% in the remainder of the period under analysis. Finally, a third kind of regularity can be noticed, the numbers for lithium-air (Li-air) and sodium-sulfur (Na-S) batteries are still marginal even if these two technologies have been pointed out as very promising, particularly Na-S having been suggested as valid option for grid storage applications (Hirsh et al., 2020). It must be highlighted that more than three quarters of battery-

[6] https://www.bmwk.de/Redaktion/DE/Publikationen/Energie/6-energieforschungsprogramm-der-bundesregierung.html, accessed 16.01.2023.

Figure 1. **Top 25 Key Patent Applicants and Top 10 Countries with the Most Battery-Related Patent Applications (2005–2019)**



Source: authors.

related patents do not mention a specific technology and correspond to technological developments on specific battery components that can be inserted into batteries of very different technologies.

The pursuit of battery energy density and safety has boosted the interest in approaches based on solid electrolytes (Kim et al., 2015). Although solid state batteries are not a technology branch per se, but a specific construction form that intercepts several technologies, it is worth mentioning the rapid growth rate of patents in the last several years (since 2011 over 30% year-on-year). In 2019 the number patents associated with solid state batteries was already higher than for all non-lithium-ion battery technologies, a sign that this solution is becoming more important and emerging as a possible future trajectory.

Overall dynamics and key component technologies

The dynamics of battery patent applications over time is presented in Figure 3. The aggregate applications, i.e., "Batteries all" (read in the secondary axis), rise throughout, increasing five-fold through the entire period. This pattern is in line with the conclusions of a recent report by (IEA, EPO, 2020, p. 44) stating that the technical developments in batteries have signaled "a burst of innovation in this area" as trends have been faster than in general patenting. Moreover, there seems to be a chronology during this period: an early stage of growth (up to the early 2010s), then a moment of stagnation (until the mid-2010s), and a recovery until the end of the decade.

By breaking down battery dimensions and components, i.e., by highlighting the particular elements of a battery set-up, we come to see that the "Secondary cells only" displays the most vibrant growth, followed by the "Non-active parts only", "Electrodes+SC", and "Non-active parts+SC". This fact comes across as a clear sign of strong investment in these specific dimensions of battery technology. The technology segment labeled "Electr only" did not recover from its relative stagnation and clearly diverged from the other single component technology groupings.

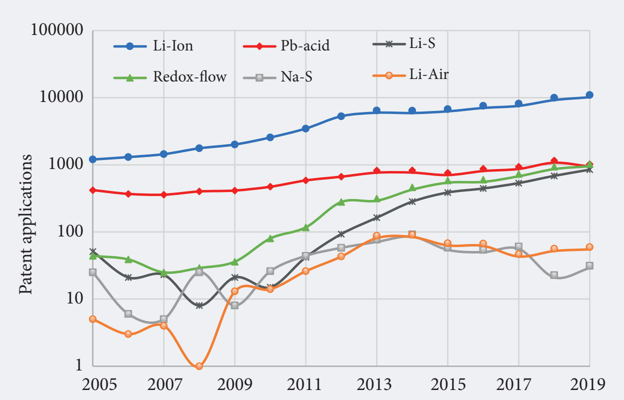
Among the multi-component patent applications, the packages "Elect+SC" and "NAP+SC" stand out from the rest, maintaining consistent growth over the analyzed period. In recent years these "packages" (i.e. specific configurations of battery components) even surpassed the "Electr only" and reached the level of "NAC only", suggesting a growing trend to submit patents covering more than one technological dimension. Conversely, "NAP+Elect" and "NAP+Elect+SC" packages had a very low number of patent applications in the period 2004–2019, showing that is not common to submit patents that address simultaneously non-active parts and electrodes (either with secondary cells or not).

Table 2 presents the number of patents with reference to the main battery components. Electrodes are by far the most innovative component of battery technology and is an indication that improving battery performance is the most important driving force for innovation. Other significant components are Electrolytes, Cell Housing, and Separators. While patenting in Electrodes and Electrolytes is associated with the quest to increase battery capacity, particularly its energy density, the growing number of patents in cell housing and separators can be attributed to the need to adapt batteries to a growing number of different applications that range from small consumer electronic devices (cell phones, tablets, etc.) to several different electronic mobility solutions (ex: cars, bikes, scooters, or unmanned aerial vehicles) (Golembiewski et al., 2015; IEA, EPO, 2020).

Battery charging and cooling

Figure 4 presents the upward trend of patents associated with battery charging/supplying load technologies (H02J3/32 and H02J7). It can be observed that since 2009, the number of applications has been rising

Figure 2. **Patent Applications for the Main Battery Varieties in the Period 2005–2019 (log-scale)**



Source: authors.

steeply, sporting an average annual growth rate of 19%. The substantial increase in solutions related to charging/supplying load technologies can be attributed to the required adaptation of these interface capabilities in the context of new applications. In particular, it is acknowledged that the need to deal with the emerging problems associated with the rising use of batteries is strongly related to the pressure to develop fast-charging technologies for electric mobility (Tomaszewska et al., 2019) and to adapt the battery charging/discharging to intermittent energy sources (Zhao et al., 2018).

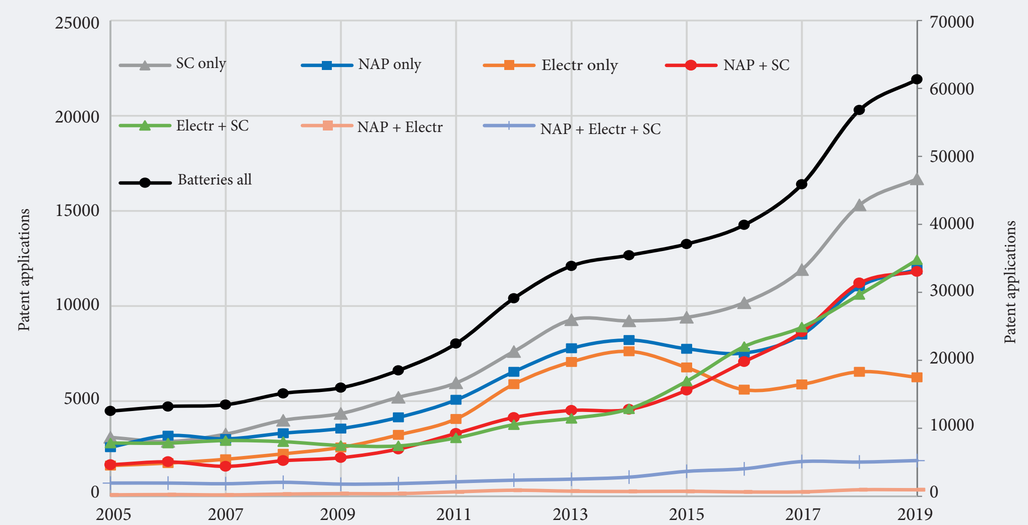
Due to its increasing energy density and the growing use of fast charging technologies, heat management in batteries has become a pressing issue, particularly in electric vehicle applications (Lu et al., 2020). Consequently, the number of patents with references to battery cooling technologies has increased steeply registering an average growth rate of 35% per year in the period 2005–2019, reaching over 8,000 patents in 2019, which is higher than for all non-electrode components.

Interactions with other clean technologies

One of the objectives of this study is to explore the existence of synergies of batteries with other "clean" technologies, namely renewable energies and electric vehicle technologies. The joint patenting between batteries/charging and wind energy is found to be unremarkable. In fact, is unlikely that this outlook will change in the near future since hydroelectric and CAES systems are more cost-effective choices to store wind energy than batteries (Barnhart et al., 2013; Ding et al., 2012).On the other hand, relevant interactions are found between battery technologies and other upstream (i.e., solar PV) and downstream developments (i.e., electrical vehicles), especially when charging is considered.

Figure 5 shows that the number of patents covering battery charging and PV technologies has been increasing consistently over the past decade, accounting for more than 20% of patenting in battery charging in recent years, a sign that the specific needs of associating batteries with PV systems have become a "focusing device" for battery innovation. It can also be observed that the evolution of the overlap between patenting in battery charging and the EV applications is likewise remarkable: by 2019 joint patenting accounted for more than a quarter of the total number of patents in battery loading.

Figure 3. **Patenting in Battery Technology Combinations (2005–2019)**



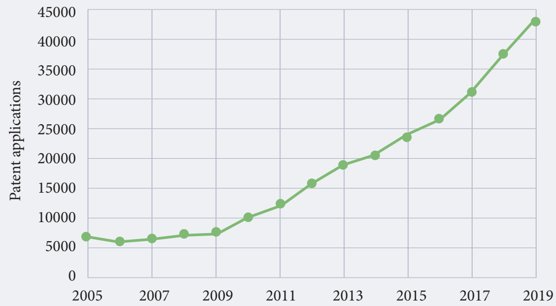
Note: The series «Batteries all» reads in the yy axis on the right.
Source: authors.

Table 2. **Number of Patents with Reference to the Main Battery Components in the Period (2005–2019)**

Component	Number of patents
Electrodes	1.7×10^5
Electrolytes	4.8×10^4
Cell housing	5.2×10^4
Separators	3.3×10^4

Source: authors.

Figure 4. **Patenting Activity in Charging/ Supplying Loads from Batteries**



Source: authors.

General battery innovation patterns

A final analysis of innovation trajectories in this study is implemented by deploying the concepts of incremental/radical innovation and product/process innovation. Figure 6 shows the dynamics of different types of innovation over time. Besides the steady growth in patenting for all types of innovation (with the exception of incremental innovation in the 2014–2016 period), Figure 6 points out that incremental innovation is more common, as expected, but that evidence of an increase in the share of "radicalness" can be observed in later years. Moreover, the sharp rise in the number of incremental innovation patents and a subsequent decrease between 2014–2016 correlates well with the trend of "Electrodes only" patenting (Figure 3), suggesting that the temporary increase in incremental innovation patents was mainly driven by the boost in electrode innovation that reached its peak in 2014, after which a burst of patenting in multiple technology battery packages promoted the uptake of radical innovation. Most battery patents apparently cover products (artefacts or systems) and not so much processes (manufacturing assemblages and methods). It must be mentioned that, although all the innovation types witnessed a very significant increase in the total number of patent applications in the period 2005–2019, the shares of incremental/radical and product/process innovations remained mostly stable.

In Table 3 the relative shares of different types of innovation are presented. During the period 2005–2019, 62% of the battery patenting represents incremental innovation and 38% radical innovation, while 74% of the patents published correspond to product innovation and the remaining 26% represent process innovation. Thus, product innovation patents tend to be incremental, while process innovation patents are somewhat more radical.

Innovation type by technology

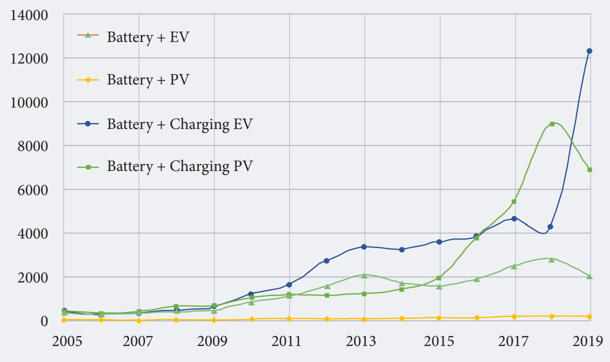
To further the analysis, the distribution of patents by the different innovation types was put into perspective by focusing on the four technologies with the highest innovation activity: Li-ion, Pb-acid, Li-S, and Flow batteries. In Figure 7 the variation in the period 2004–2019 of incremental and radical innovations for these four technologies is presented.

For Li-ion batteries, incremental and radical innovations were split almost evenly within the total number of patents. However, different trends can be observed over time: after a strong increase of incremental innovation until 2014 (which correlates well with the growth of electrodes only and non-active parts only, see Figure 3), when it reached two-thirds of all the patents, it fell and was overtaken by radical innovation. It is worth noting the burst of radical innovation in mature Li-ion technologies, which is most likely associated with the need to adapt the technology to new applications. Two-thirds of Pb-acid patents represent incremental innovation, while the remainder corresponds to radical innovation. Such a share distribution, which remained stable over time, is quite expected for a mature technical technology like Pb-acid. For the emergent Li-S, two-thirds of patents represent radical innovations. The explosion of radical innovation patents occurred after 2014 when this type of innovation took the lead for Li-S technology. Finally, for the emergent flow-batteries, incremental innovation represents three-quarters of all the patents, and both innovation types maintain steady growth rates. The particular nature of flow-batteries (which is very different from the remaining battery technologies), and the fact that its applications are very focused on grid storage, might contribute to a concentration of the innovation effort in the improvement of battery performance, and not so much in non-active parts, such as separators, cell housing, etc., which can justify the trend to mainly patent incremental innovations.

It must be recalled that, as already mentioned, three-quarters of all patents make no mention of a specific battery technology, most of these patents represent innovation in a particular battery component, contributing to the overall "incremental innovation" of battery technologies, which represents 62% of all the patents.

In Figure 8, the variation of product and process innovation for the four main battery technologies is presented. One can observe that for the four technologies analyzed most of the patents correspond to product innovation (a trend corroborated by Malhotra et al., 2021).

Figure 5. **Evolution of the Joint Patenting of Battery Technologies with Electric Vehicle (EV)and Photovoltaic Energy (PV)**



Source: authors.

Table 3. **Share of Battery Patents in the Period 2005–2019 by Innovation Type (%)**

Innovation type	Degree of novelty		Total Prod/Proc
	Incremental	Radical	
Product	51	23	74
Process	11	15	26
Total Inc/Rad	62	38	100

Source: authors.

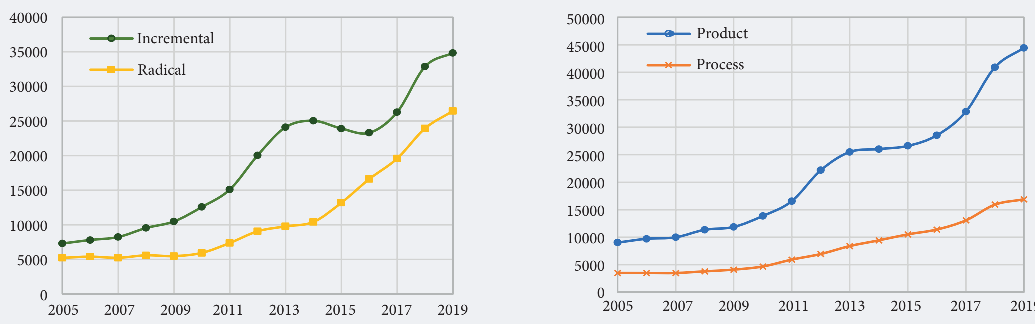
For the Li-ion technology, one third of patents represent process innovations. Both product and process innovations increase the number of patents over time and the relative shares are kept more or less stable. One third of the Pb-acid related patents represent process innovations, and although product and process innovations increase patenting over time, from to 2005 to 2019, the share of process innovations increased from 28% to 42%. One third of the Li-S technology patents represents process innovations, but product innovations have significantly increased its share in recent years reaching 75% in 2019. Finally, more than 90% of the patents on flow-battery technologies represent product innovations. In fact, while product innovations have experienced a significant growth in the analyzed period, patenting in process innovations is still modest. It is noteworthy that while for Li-ion and Pb-acid technologies, the share of process innovations tends to increase over time, the opposite trend is observed for Li-S and flow-battery technologies – such patterns are consistent with the maturity level of these technologies.

Overall, battery innovations are developing strongly. Large East Asian consumer electronics and automobile companies dominate the list of main patent applicants. Electrodes are found to be the most dynamic of battery components. Besides the more mature technologies like lithium-ion and lead-acid, the battery technologies that arise as the most promising in terms of innovation are lithium-sulfur and flow batteries. Synergies of battery technologies with upstream (i.e., energy production) and downstream technologies (i.e., energy use) occur mainly through battery charging/discharging. Incremental product innovations have been the dominant technological trajectory, but radical product innovations account steadily for nearly a quarter of the patents published in the period 2005–2019. All-in-all, by drawing on ample and detailed patent evidence on the rate and direction of technical change across the battery innovation ecosystem, this study presents findings that are of use to both private and public sectors, including market-oriented investors and independent regulators.

Conclusions

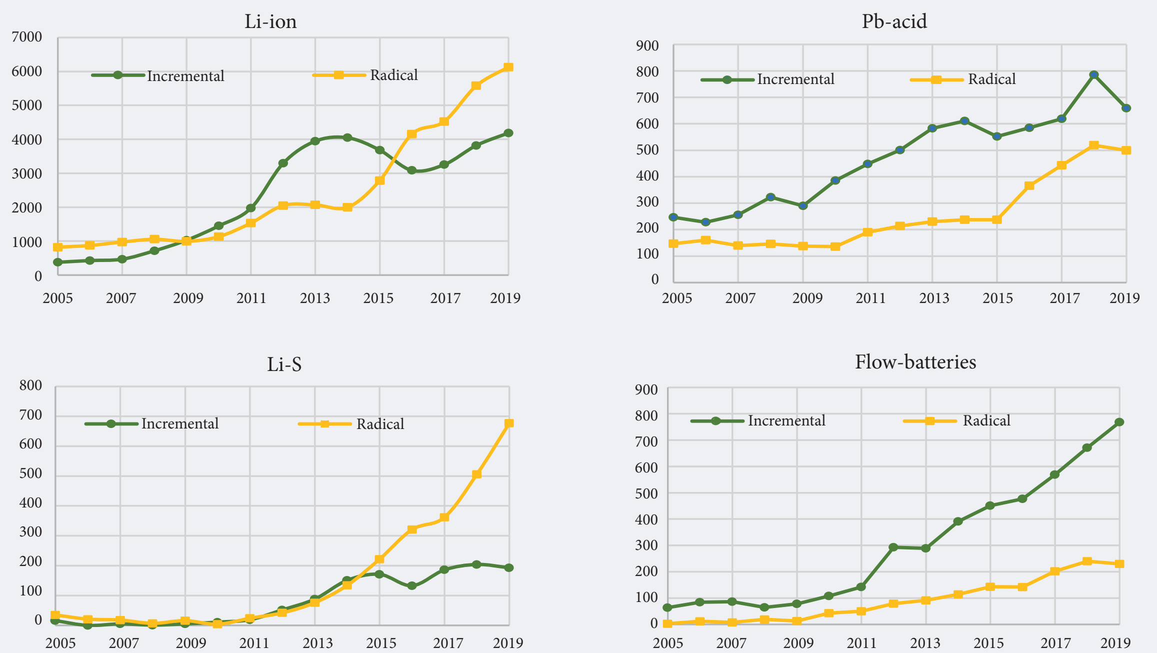
Over the last several decades, the concern with the role of new technology in pre-empting and mitigating climate change has emerged at top of the policy agenda across many national and international constituencies, largely driven by the synergies between the digital and sustainability challenges. The assumption of this paper is that electricity harnessing, storage, and dispatching has a pivotal role to play in the socio-technical transition toward a cleaner and more connected mode of innovation, production, distribution, and consumption. The theoretical baseline of this paper is founded on the

Figure 6. **Evolution Overtime of Innovation by Type**



Source: authors.

Figure 7. **Dynamics of Incremental and Radical Innovation for the Four Main Batteries Technologies**



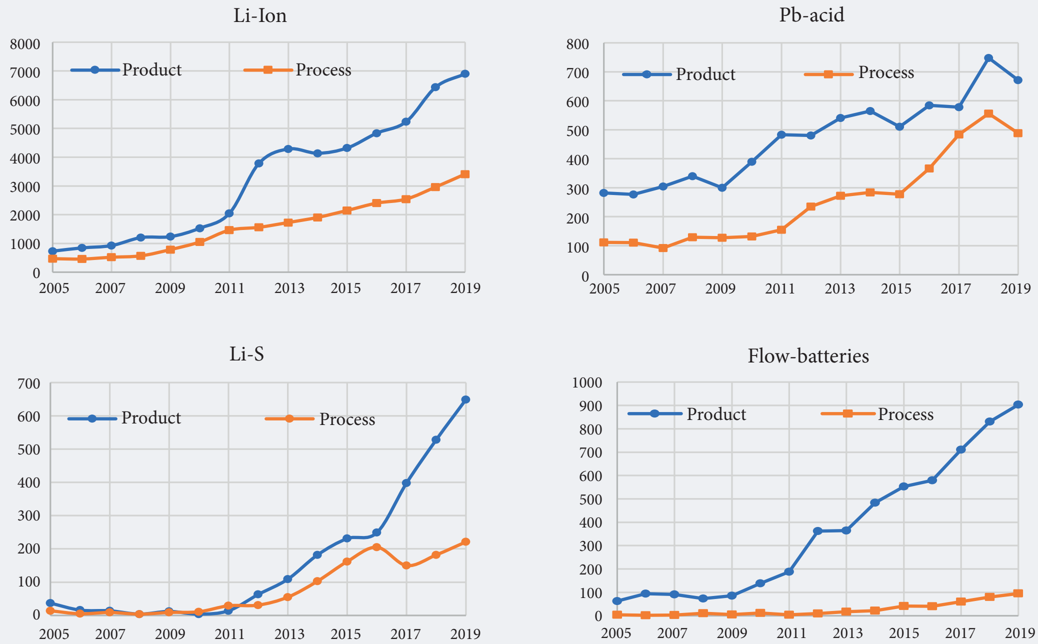
Source: authors.

understanding that innovation is an uneven, uncertain, and evolutionary phenomenon. By focusing on batteries and adopting a long-term perspective in what has become a rapidly moving field, we stress how functionalities and applications interact over time in what become technological trajectories. The large patent database assembled yields a set of results that correspond to a general picture in which battery breakthroughs have been gaining momentum at an irregular tempo, but consistently across a range of specific technology variants. These results may also provide some guiding principles for the development and investment in batteries and complementary low carbon energy technologies.

Patent evidence for 2005–2019 shows that innovation in battery technologies is increasing strongly in a variety of technological aspects. The countries that most contribute to this increase are Japan, South Korea, USA, Germany, and China. Lithium-ion batteries are currently the main driving force of battery innovation, framing the most significant trends of the field. Lithium-sulfur and flow batteries assert themselves as the most promising emerging technologies, and their development should be attentively followed in the next several years. Lately, solid state batteries have been gaining a lot of attention and patent data for the period 2005–2019, indicating these to be a promising technological direction. Battery implementation challenges are highly sector-specific and define innovation pathways that are relevant for stakeholders engaged in decarbonizing strategies. The quest to increase battery capacity contributes to the electrodes being the most dynamic battery component. The need to increase energy density and reduce the battery charging time has boosted research on innovative battery cooling technologies. The specific features of energy production technologies, like PV, and energy usages like the electric car, have contributed to the rise of battery charging/supplying load to the most innovative technological component. In fact, the interactions of battery charging with these two technologies have become empirically notable. The overall evolution of the battery innovation typologies shows a steady growth of product, process, incremental, and radical innovation types, with stable shares of product/process and incremental/radical innovations. Incremental product innovation tended to be the main mode of advancement overall over the past two decades.

The constructive engagement with science and technology processes that address major global societal challenges reflect the realm of possibilities for further progress. Following from this observation, it is clear that energy-relevant institutions (policy-setting entities, regulatory authorities, standard bodies, etc.) should bring an explicit dynamic view into their sectoral development agendas. Energy transformation is contingent upon continuous, sustained, and strategic commitments to innovation. Progress in storage technologies requires a diversity of sources of knowledge, experimentation avenues, and forceful investments. This unfolding set of learning paths reveals signs that can guide public and private decision-makers, in what is a dynamic and shifting technological frontier. Reports by national and international agencies could

Figure 8. **Evolution Overtime of Product and Process Innovation**



Source: authors.

benefit, for instance, from systematically following research and innovation indicators. since being able to hold a long-view horizon is an urgent task in times of climate shocks and systematic scarcity.

One limitation of a patent-based study like ours is that patents detect more easily innovations put forward by large companies than by smaller ones. Also, by looking at individual patents, one cannot perceive unambiguously if these belong to an ensemble of patents that jointly protect a certain innovative package (meaning expert panels could be mobilized in future studies to add qualitative appraisals to science and technology indicators in order to provide more holistic assessments).

Finally, the analysis of the geographical distribution of patent applications suggests that countries that pushed through ambitious, consistent, and long-term R&D programs symbiotically coordinated with large industrial players on clean energy technologies, and particularly within the battery field, such as Japan, South Korea, and more recently China, have obtained an innovation edge that places them in a very favorable position in the energy transition process. These examples are a reminder that purposeful change is possible across the world.

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Appendix A. **Methodological protocols of the study**

Battery components groups

Battery system component	Search query
Non-active parts	(((IPC = H01M2+) and (PUD [20050101, 20191231])) AND NOT (IPC = H01M4+ OR H01M10+ or H01M6+ OR H01M8+ OR H01M12+ OR H01M14+ OR H01M16+ OR H01M18+))
Electrodes	(((IPC = H01M4+) and (PUD [20050101, 20191231])) AND NOT (IPC = H01M2+ OR H01M10+ or H01M6+ OR H01M8+ OR H01M12+ OR H01M14+ OR H01M16+ OR H01M18+))
Secondary cells	(((IPC = H01M10+) and (PUD [20050101, 20191231])) AND NOT (IPC = H01M2+ OR H01M4+ or H01M6+ OR H01M8+ OR H01M12+ OR H01M14+ OR H01M16+ OR H01M18+))
Non-active parts and electrodes	(((IPC = H01M2+ and H01M4+) and (PUD [20050101, 20191231])) AND NOT (IPC = H01M10+ or H01M6+ OR H01M8+ OR H01M12+ OR H01M14+ OR H01M16+ OR H01M18+))
Non-active parts and secondary cells	(((IPC = H01M2+ and H01M10+) and (PUD [20050101, 20191231])) AND NOT (IPC = H01M4+ or H01M6+ OR H01M8+ OR H01M12+ OR H01M14+ OR H01M16+ OR H01M18+))
Electrodes and secondary cells	(((IPC = H01M4+ and H01M10+) and (PUD [20050101, 20191231])) AND NOT (IPC = H01M2+ or H01M6+ OR H01M8+ OR H01M12+ OR H01M14+ OR H01M16+ OR H01M18+))
Non-active parts, electrodes and secondary cells	(((IPC = H01M2+ and H01M4+ and H01M10+) and (PUD [20050101, 20191231])) AND NOT (IPC = H01M6+ OR H01M8+ OR H01M12+ OR H01M14+ OR H01M16+ OR H01M18+))
Charging	(IPC = H02J7 or H02J3/32 or B60L53 or H01M10/44) AND (PUD [20050101, 20191231])
Cooling	(((IPC = (H01M00106* or H01M0010443* or H01M0010486 or H01M0050375 or H01M0050581)) and (PUD [20050101, 20191231])) AND NOT (IPC = H01M6 OR H01M8 OR H01M12 OR H01M14 OR H01M16))

Types of battery technologies

Battery type	Search query
Lead-acid	(((IPC = H01M2 OR H01M4 OR H01M10) and (PUD [20050101, 20191231])) AND (ABEN = (VRLA OR SLA OR lead +2w acid OR lead +2w acc+)) AND NOT (IPC = H01M6 OR H01M8 OR H01M12 OR H01M14 OR H01M16 OR H01M18))
Lithium-air	(((IPC = H01M2 OR H01M4 OR H01M10) and (PUD [20050101, 20191231])) AND (ABEN = (Lithium +2w air OR Li +2w air OR lithium +2w oxygen OR LiO2 OR Li +2w O2)) AND NOT (IPC = H01M6 or H01M8 OR H01M12 OR H01M14 OR H01m16 OR H01M18))
Lithium-ion	(((IPC = H01M2+ OR H01M4+ OR H01M10+) and (PUD [20050101, 20191231])) AND (ABEN = (Li +2w ion OR LiFePO4 OR LiPo OR Li +2w Poly OR lithium +2w ion OR Lithium +2w cobalt OR Lithium +2w manganese OR Lithium +2w phosphate OR Lithium +2w iron +2w phosphate OR Lithium +2w titanate OR Lithium +2w Polymer)) AND NOT (IPC = H01M6+ OR H01M8+ OR H01M12+ OR H01M14+ OR H01M16+ OR H01M18+))
Lithium-sulfur	(((IPC = H01M2 OR H01M4 OR H01M10) and (PUD [20050101, 20191231])) AND (ABEN = (li +2w S OR lithium +2w sulphur OR lithium +2w sulfur)) AND NOT (IPC = H01M6 or H01M8 OR H01M12 OR H01M14 OR H01m16 OR H01M18))
Magnesium-ion	(((IPC = H01M2 OR H01M4 OR H01M10) and (PUD [20050101, 20191231])) AND (ABEN = (magnesium +1w ion OR Mg +1w ion)) AND NOT (IPC = H01M6 OR H01M8 OR H01M12 OR H01M14 OR H01M16 OR H01M18))
Nickel-cadmium	(((IPC = H01M2 OR H01M4 OR H01M10) and (PUD [20050101, 20191231])) AND (ABEN = nickel +2w cadmium OR Ni +2W cd OR Nicd) AND NOT (IPC = H01M6 OR H01M8 OR H01M12 OR H01M14 OR H01M16 OR H01M18))
Flow	(((IPC = H01M2 OR H01M4 OR H01M8 OR H01M10) and (PUD [20050101, 20191231])) AND (ABEN = (Flow +2w batter* OR Redox +2w flow +2w batter* OR RFB OR Vanadium +2w redox +2w batter* OR Vanadium +2w redox +2w flow OR VRB OR Zinc +2w bromine +2w flow OR Zinc +2w bromine +2w batter* OR ZNBR OR Iron +2w chromium +2w flow OR iron +2w chromium +2w batter*)) AND NOT (IPC = H01M6 OR H01M12 OR H01M14 OR H01M16 OR H01M18))
Sodium-sulfur	(((IPC = H01M2 OR H01M4 OR H01M10) and (PUD [20050101, 20191231])) AND (ABEN = (sodium +2w sulfur OR sodium +2w sulphur OR Na +0w S)) AND NOT (IPC = H01M6 OR H01M8 OR H01M12 OR H01M14 OR H01M16 OR H01M18))
Solid state batteries	((IPC = H01M2 or h01m4 or h01m10 or H01M50) and ((ABEN = solid +2w state)) AND (PUD [20050101, 20191231]))

Interactions with other technologies

Interaction	Search query
Batteries and PV	(IPC = (h01m10+) and (H02S+ or H01L 27/142 or H01L31/00 or H01L31/02 or H01L31/024 or H01L31/04 or H01G9/20 or H02S10/ or H01L31/042 or G05F1/67 or F21S9/03 or H01G9/20 or H01M14 or H01L31/0525 or B60K16/00 or B60L8)) and (PUD [20050101, 20191231]) AND not (IPC = H01M6 or H01M8)
Batteries and Wind	(IPC = (h01m10+) and (F03D+)) and (PUD [20050101, 20191231]) AND not (IPC = H01M6 or H01M8)
Batteries and Electric Vehicles	((IPC = H01M2 or h01m4 or h01m10) and ((IPC = B60L50 or B60L11) or (ABEN = electric +2w vehicle or ev or electric +2w mobility)) AND (PUD [20050101, 20191231]))
Charging Electric Vehicles Batteries	(((IPC = H02J7 or H02J3/32 or H01M10/44) and ((IPC = B60L11 or B60L50) or (ABEN = electric +2w vehicle or ev or electric +2w mobility))) or IPC = B60L53) AND (PUD [20050101, 20191231])
Charging Batteries with PV	(IPC = ((H02J7 or H02J3/32 or H01M10/44) and (H02S+ or H01L 27/142 or H01L31/00 or H01L31/02 or H01L31/024 or H01L31/04 or H01G9/20 or H02S10/ or H01L31/042 or G05F1/67 or F21S9/03 or H01G9/20 or H01M14 or H01L31/0525 or B60K16/00 or B60L8)) or H02J7/35) AND (PUD [20050101, 20191231])

Battery process innovation IPC sub-groups

IPC Code	Process Classifications
H01M 4 – Electrodes	H01M 4/04, H01M 4/08, H01M 4/10, H01M 4/12, H01M 4/139, H01M 4/1391, H01M 4/13915, H01M 4/1393, H01M 4/1395, H01M 4/1397, H01M 4/1399, H01M 4/16, H01M 4/18, H01M 4/20, H01M4 /21, H01M 4/22, H01M 4/23, H01M 4/26, H01M 4/28, H01M 4/29, H01M 4/30, H01M 4/82; H01M84; H01M 4/88
H01M 10 – Secondary elements	H01M 10/04, H01M 10/058, H01M 10/0583, H01M 10/0585, H01M 10/0587, H01M 10/12, H01M 10/14, H01M 10/16, H01M 10/28, H01M 10/38

Adapting Innovation Development Management Processes to Improve Energy Efficiency and Achieve Decarbonization Goals

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Abstract

The study focuses on decarbonization problems as a systemic priority for the innovative transformation of the national economy at a time when the global economy faces new challenges. The research hypothesis confirms a dual effect in the scope of the "innovation - energy efficiency - decarbonization" triad, with each item being affected by the two others. We applied econometric models, testing them using data from 83 Russian regions for 2016-2020. The identified effects are critical for developing a conceptual framework to adjust management goals related to the energy efficiency and decarbonization of the Russian economy. The paper suggests that Russian regions should adopt the triad approach in drafting their energy efficiency and decarbonization plans. It also provides a deeper understanding of the relations between the triad elements. The results can be useful for practitioners aiming to improve the sustainability of national economies. Importantly, our findings could be applied by countries at different economic development levels using a different mix of energy sources to accomplish decarbonization or carbon neutrality goals.

Keywords: innovative development; improving energy efficiency; decarbonization; dual influence effects; managing energy system transition

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Introduction

An appreciable increase in the international community's attention to the green climate agenda has set a new global trend toward the decarbonization of national economies. The devastating effects of climate change are becoming so apparent, including in the Russian Federation, that denying them no longer seems to be possible (Porfiryev et al., 2021). Moreover, in our country, the climate change issue is more acute than on average across the planet (Zhigalov et al., 2018). The emerging trend toward decarbonization matches the sustainable development paradigm which combines global environmental, socioeconomic, and science and technology goals and outlines the prospects for global economic development (Bohra et al., 2022; Hernan, et al., 2022; Ye et al., 2022).

Despite the global nature of the problem under consideration, when determining one's attitude toward the climate agenda and predicting the scale of potential changes in the economy, one should proceed primarily from national interests (Gatto et al., 2021; Levenda et al., 2021; Porfiriev, 2021). At the same time, the uncertainty of the relevant processes, further aggravated by the changes in the geopolitical situation, should be fully taken into account. Many of the previously proclaimed and seemingly unshakable global economic development priorities, such as, for example, the complete rejection of the use of coal in the short term or replacing traditional fuels with alternative energy sources, are gradually being disavowed.[1]

Under the current circumstances, denying the existence of major challenges when making strategic decisions about Russia's future is fraught with unpredictable and irreversible consequences for national security (Pakhomova et al., 2021). Due to ongoing attempts to use the green agenda as a new tool for applying economic and political pressure, the level of potential threats has dramatically increased, which can lead to serious problems in various industries and activity areas (Kryukov et al., 2021; Makarov et al., 2021). All this creates the need to promptly deal with a wide range of new issues related to the decarbonization of the global economy as a key prerequisite of achieving carbon neutrality (Bashmakov, 2020).

Given the current disagreements about the approaches to solving existing problems, most researchers recognize the special role of innovative energy efficiency improvement strategies in the interests of decarbonization. However, so far the mechanisms for their implementation essentially remain undeveloped, while the possible effects of mutual impact in the scope of the "innovation - energy efficiency - decarbonization" triad are understudied.

Literature Review

The problems associated with introducing energy-efficient innovations are discussed in the context of different national economy levels, with a particular emphasis upon assessing the impact of various factors including the dynamics of fuel and energy prices (Brutschin et al., 2016), the export-import orientation of the economy (Urpelainen, 2011), the scope for transferring advanced technologies (Wan et al., 2015), the amount of foreign investments, and so on. Considerable attention is paid to supporting energy efficiency-related innovation, among other ways through government initiatives to promote innovation in the field of energy technologies (Winkler et al., 2011; Fri et al., 2014). Despite the existence of numerous approaches to improving energy efficiency through innovation, researchers from different countries agree on the importance of dealing with this issue to promote economic development (Patterson, 1996; Bobylev et al., 2015; Costantini et al., 2017).

Research aimed at achieving the sustainability of energy systems based on, in particular, innovative solutions such as smart grids, smart devices (Hyytinen et al., 2015), and other technologies received a serious impetus. Effort taken in this area promoted the development of advanced data collection, processing, and analysis technologies to support managerial decision-making (Luong, 2015), improve energy infrastructure (Thoyre, 2015), and develop energy efficiency strategies based on new opportunities (Liu et al., 2016; Ruiz-Fuensanta, 2016). To date, the approach that assesses the increase in energy efficiency of national economies on the basis of the reduction in energy resources consumed to produce products/services, and sees this area as the most important for meeting current development challenges, continues to prevail (Bolson et al., 2021; Panait et al., 2022; Wu et al., 2021). The effect of energy conservation and energy efficiency improvements on achieving strategic development goals is frequently ignored (Zakari et al., 2022).

Researchers addressing the improvement in the energy efficiency of national economies tend to see innovation as the most important factor of and a necessary condition for such changes (Newell et al., 1999; Popp, 2002; Urpelainen, 2011). Enterprises which pursue active innovation policies demonstrate higher levels of energy efficiency and tend to apply the best available technologies (Song et al., 2015; Sohag et al., 2015). Examples of major technological projects in this area include the international Energy Star program (Boyd et al., 2008; Qiu et al., 2019) and the Chinese Top 100-1,000-10,000 Enterprises program (Lewis, 2011; Zhao et al., 2016; Qi et al., 2020). All this allows one to conclude that increasing energy efficiency based on the broad adoption of innovations remains a key priority for the development of national economies.

Due to the aggravation of the climate agenda in recent years, decarbonization issues have become particularly relevant (Table 1). Reducing the environmental impact of production activities not only does not contradict the goal of increasing its efficiency, but on the con-

[1] https://www.vedomosti.ru/business/articles/2022/04/26/919731-globalnaya-energetika-vozvraschaetsya-k-ugolnoi-generatsii , accessed 25.08.2022.

Table 1. **Main Areas of Decarbonisation Research**

Research area	Literature
Achieving competitive advantages through the introduction of green technologies	(Kuhn et al., 2022; Lenox, 2021; Wang et al., 2022)
The relationship between energy production and consumption on the one hand, and carbon emissions on the other	(Dalla Longa et al., 2022; Natali et al., 2021; Pandey et al., 2022)
Increasing energy efficiency as a key area of national economies' decarbonisation	(Mier et al., 2020; Obrist et al., 2022; Pakhomova et al., 2021)
The relationship between investments in renewable energy sources and CO2 emissions	(Acheampong et al., 2019; Ikram et al., 2020; Mehmood et al., 2022)
The Impact of government initiatives to promote decarbonisation on economic performance	(Al Mamun et al., 2022; Rissman et al., 2020; Stephenson et al., 2021)
Managing companies in the context of the introduction of a "carbon tax"	(Dixit et al., 2022; Domon et al., 2022; Reaños et al., 2022)
Rebound effect of energy efficiency	(Chen et al., 2021; Baležentis et al., 2021; Berner et al., 2022)
Source: authors.	

trary serves as an important development incentive (Dell'Anna, 2021; Koval et al., 2021; Sarkar et al., 2021).

Despite the differences in the current approaches to many of the fundamental energy transition issues (Gatto, 2022; Shahbaz et al., 2022; Bompard et al., 2022), most experts agree on the critical contribution of energy efficiency improvements to achieving carbon neutrality (Zeka et al., 2020; Nam et al., 2021; Khan et al., 2022). At the same time, their positions are often reduced to simply noting a significant contribution of increased energy efficiency to solving climate problems, without disclosing management mechanisms applied to accomplish decarbonization objectives in terms of identifying mutual impact in the scope of the "innovation-energy efficiency-decarbonization" triad.

A review of the current state of the problem under consideration reveals that, despite the attention the scientific community pays to various green agenda aspects, no consensus has yet been reached on possible ways to adapt the existing government mechanisms to meet the current global challenges and overcome threats.

Methodology

Methodologically, this study is based on the results of our previous research (Melnik et al., 2021). Using data from various Russian regions, it first of all confirmed the presence of a mutual impact of increased energy efficiency and innovation-based development processes; secondly, it revealed its basic nature, which largely determines additional positive effects in various industries and activity areas; and thirdly, through the empirical testing of the proposed assumption, one of these effects was assessed, which confirmed the potential for stepping up Russian regions' exports as their energy efficiency increases.

Further development of the previously suggested methodology is aimed at adapting it to address decarbonization problems. A hypothesis was put forward in the course of the study about the dual effects of mutual impact in the scope of the "innovation-energy efficiency-decarbonization" triad. To confirm it, it was proposed to divide the study into two stages. In the first stage, the existence of the triad itself is postulated for subsequent consideration of the effects arising within it. The objective of this stage is to avoid randomly including any other intuitively obvious parameters in the triad without sufficient grounds to expect the presence of paired relationships between its elements. To accomplish the set goals and confirm the above effects, paired direct and paired inverse models were used.

Compared with the previous ones, the proposed approach proceeds from a broader understanding of the nature of paired relationships between the processes under consideration. This allows one to assess not only the effects of the direct paired impact, e.g., of innovation in the dependencies "innovation → energy efficiency" and "innovation → decarbonization", but also those of the inverse one: "energy efficiency → innovation", and "decarbonization → innovation" (Figure 1). This statement also holds true for the effects of direct and inverse paired impact in "energy efficiency → decarbonization" dependencies. By modeling the impact of a factor attribute on the resulting one, one could assess the effects of direct and inverse paired impact in the dependencies under consideration, presented as follows:

a) direct and inverse paired impact in the "decarbonization – innovation" relationship:

$$D = f(I); \quad I = f(D), \tag{1}$$

b) direct and inverse paired impact in the "decarbonization - energy efficiency' relationship:

$$D = f(E); \quad E = f(D), \tag{2}$$

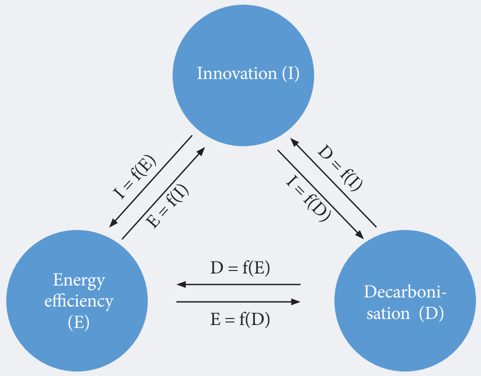
c) direct and inverse paired impact in the "innovation - energy efficiency" relationship:

$$I = f(E); \quad E = f(I), \tag{3}$$

where I are indicators applied to assess the innovation-based development level; E are indicators applied to assess energy efficiency; and D are indicators applied to assess the level of harmful emissions.

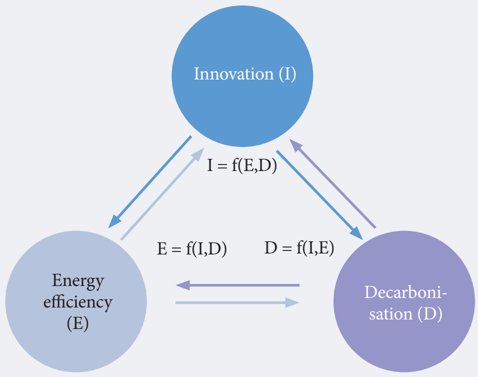
At the second stage, after substantiating the composition of the triad, an econometric approach was applied to confirm the suggested hypothesis about the dual ef-

Figure 1. **Paired Impact in the Scope of the "Innovation-Energy Efficiency–Decarbonization" Triad**



Source: authors.

Figure 2. **Dual Effect of Mutual Impact in the Scope of the "Innovation–Energy Efficiency–Decarbonization" Triad**



Source: authors.

fects of mutual impact in the scope of the "innovation-energy efficiency-decarbonization" triad. A system of interrelated equations describing the impact was used for this purpose.

The validity of the applied approach is confirmed by the fact that, as follows from dependencies (1) - (3), each of the presented components of the "innovation-energy efficiency–decarbonization" triad is affected by two parameters, which implies the presence of complex relationships between the processes under consideration: e.g., innovation and energy efficiency simultaneously impact decarbonization, energy efficiency is simultaneously impacted by innovation and decarbonization, while innovation – by energy efficiency and decarbonization. Along with a direct impact (e.g. by innovation on the solving of decarbonization problems), there is also an indirect one: of energy efficiency improvements achieved through the application of energy efficient innovations. In this case, to test the suggested hypothesis, the assumed dependencies in the triad can be presented as a system of interrelated (concurrent) equations:

$$\begin{cases} D = f_D\,(I, E) + \varepsilon \\ E = f_E\,(I, D) + \varepsilon \\ I = f_I\,(E, D) + \varepsilon \end{cases} \qquad (4)$$

where f are functions linking the triad indicators to a set of exogenous factors, and ε is random error.

In this case all three indicators D, E, I are endogenous; in the course of solving system (4), the equations will be supplemented with exogenous variables to ensure the system's solvability. A two-step least squares method (2LSM) was applied to solve the constructed simultaneous equations system.

For simulation purposes, the simultaneous impact of two factors on the third one (the resulting one in the triad under consideration) will be called the "dual effect of mutual impact". The starting point for further reasoning is the hypothesis that each of the two factors make both direct and indirect impacts on the resultant one, by changing the other factor (Figure 2). In the actual study, the target model will be selected depending on which triad component is considered the resulting one, and which are the factorial ones. Thus in the context of decarbonization, assessing the direct impact of innovation on accomplishing this goal involves taking into account its indirect impact too (through increased energy efficiency).

The suggested methodology can be applied to make decisions aimed at achieving the decarbonization of the Russian economy to promote sustainable global development (Figure 3).

Effects of the Paired Direct and Inverse Impact in the Scope of the "Innovation-Energy Efficiency–Decarbonization" Triad

In the framework of the chosen methodology, at the first stage empirical calculations were conducted to identify the effects of paired relationships in the "innovation-energy efficiency–decarbonization" triad. They were based on panel data for 83 Russian regions for 2016-2020. To assess the innovation performance at various life cycle stages (including research and development (R&D), application of innovations, commercialization, and scaling of the results obtained), official statistical data published by the Russian Federal State Statistics Service (Rosstat) were used.[2] At the first stage of the life cycle, innovation activities were identified using such indicators as number of R&D per-

[2] https://rosstat.gov.ru/statistics/science, accessed 25.08.2022.

sonnel, internal R&D expenditures, and expenditures specifically on environmental innovation. Regional enterprises' efforts at the implementation stage were assessed via the share of companies which have implemented technological, organizational, and marketing innovations in the reporting year in the total number of surveyed companies, and the number of advanced production technologies applied by Russian regions. Finally, at the commercialization and scaling stage the performance was calculated on the basis of the value of shipped innovative products/provided services, and their share in the total value of all shipped products/provided services.

Rosstat data also served as the source of information for assessing regions' energy efficiency. It was calculated as the ratio of gross regional product (GRP)[3] (in constant 2016 prices) to electricity consumption in the region.[4]

Indicators for assessing regional pollutant emissions into the environment were based on Rosstat and the Federal Service for Supervision of Natural Resources data.[5] The key indicator is atmospheric emissions from stationary and mobile pollutant sources, including sulphur dioxide, nitrogen oxides, carbon monoxide, volatile organic compounds, ammonia, and so on, which largely determine decarbonization targets. Stationary sources are understood as immovable technological units (installations, devices, apparatus, etc.) emitting air pollutants during operations; mobile sources primarily mean road and rail transport. In the absence of alternative and equivalent statistics, pollutant emissions fit the context of our study best. Thus, some authors note that a reduction in greenhouse gas emissions directly correlates with a decrease in the concentration of other pollutants in the atmosphere (Rauner et al., 2020; Bobylev et al., 2022).

During the second stage of work, various indicators used in the empirical calculations can be applied in models as control or instrumental variables. These include, in particular, GRP (Baev et al., 2013; Frenkel et al., 2013; Safiullin, 2021), electricity consumption (Solovieva, Dzyuba, 2016), value of in-house-produced shipped goods (Strizhakova, 2019), per employee electricity consumption (Yakunin, 2017), etc. All variables included in the calculations are presented in Table 2.

To accomplish the objectives set for the first stage of the study, random effect (RE) and fixed effect (FE) models were applied, which allowed for taking into account unquantifiable individual differences between objects (Hsiao et al., 2010). These differences are interpreted as an extra parameter to be excluded. The use of such models allows one to confirm a direct relationship between the parameters under consideration. To improve the models' reliability, key variables' lags and unobservable time effects were taken into account. In the model itself, robust standard errors were used to level the explanatory variables' autocorrelation. The model specification was tested using the Hausman test to compare fixed and random effects models, and the Breusch-Pagan test to compare the random effects and linear models (Greene, 2003). The simulation results are presented in Table 3, the interpretation of the empirical calculations in Table 4.

The results obtained during the first stage of the study using data on Russian regions' economic development allowed the authors to substantiate the actual existence of the "innovation-energy efficiency-decarbonization" triad for the subsequent study of the dual effects of mutual impact arising within its scope.

The Study of the Dual Effects of Mutual Impact in the Scope of the "Innovation-Energy Efficiency–Decarbonization" Triad

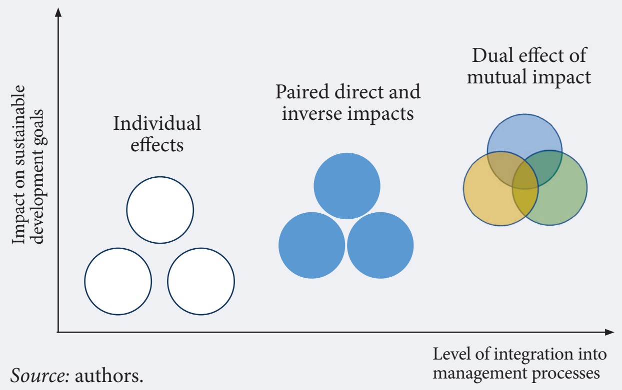
In accordance with the chosen methodology, at the second stage of the study, empirical calculations were carried out to assess the dual effects of mutual impact in the scope of the "innovation-energy efficiency-decarbonization" triad using panel data for 83 Russian regions for 2016-2020. Based on the analysis of the correlation matrix of indicators (the results are presented in Table 2), the constructed system of interrelated equations (4) takes the following form:

$$\begin{cases} D\_L\_vibros = E\_L\_eef + I\_L\_inproduct + L\_vrp + I\_L\_pers + I\_L\_cost + I\_L\_mantech + \varepsilon_1 \\ E\_L\_eef = D\_L\_vibros + I\_L\_inproduct + L\_vrp + I\_L\_pers + I\_L\_cost + I\_L\_mantech + \varepsilon_2 \\ I\_L\_inproduct = D\_L\_vibros + E\_L\_eef + L\_vrp + I\_L\_pers + I\_L\_cost + I\_L\_mantech + \varepsilon_3 \end{cases} \quad (16)$$

The endogenous variables to assess the level of innovation development, energy efficiency, and harmful emissions were defined as D_L_vibros, E_L_eef and I_L_ inproduct, respectively, and the control variables as follows: GRP as L_vrp, number of R&D personnel as I_L_pers, internal R&D expenditures as I_L_cost, developed advanced manufacturing technologies as I_L_mantech. The following indicators were used as instrumental variables: shipped in-house-produced products L_product, in-house-produced products shipped in the previous period L_product(t-1), electricity consumption L_electropotr, electricity consumption in the previous period L_electropotr(t-1), GRP in the previous period L_vrp(t- 1), per employee electricity consumption L_electro, specific expenditures on environmental innovation in the previous period L_ecocost(t-2), innovation activity in the previous period L_innactiv(t-2).

[3] https://rosstat.gov.ru/statistics/accounts, accessed 25.08.2022.
[4] https://rosstat.gov.ru/regional_statistics, accessed 25.08.2022.
[5] https://rosstat.gov.ru/folder/11194, accessed 25.08.2022.

Figure 3. **Effect of Mutual Impact in the Scope of the "Innovation–Energy Efficiency–Decarbonization" Triad**



Source: authors.

The presented system of simultaneous equations is over-identifiable, so 2LSM can be used to estimate its parameters. The estimates are presented below, excluding variables which did not significantly impact the resulting one:

$$\begin{cases} D\_L\_vibros = -5.832 - 0.947 * E\_L\_eef - \\ 0.144 * I\_L\_inproduct + 1.144 * L\_vrp + \varepsilon_1 \\ E\_L\_eef = -5.442 - 0.995 * D\_L\_vibros - \\ 0.15 * I\_L\_inproduct + 1.156 * L\_vrp + \varepsilon_2 \\ I\_L\_inproduct = -31.305 - 4.265 * D\_L\_ \\ vibros - 4.251 * E\_L\_eef + 5.45 * L\_vrp + \varepsilon_3 \end{cases} \quad (17)$$

According to Student's t-test, for the given variables the statistical significance threshold is 1%. The model is also adequate at significance level of 1% according to Fisher's F-test. The tools applied to construct a multiple regression must be, firstly, exogenous (i.e., they must not correlate with the model's random errors), and secondly, relevant (i.e., they must correlate with endogenous regressors). Tools meeting both these requirements are considered valid, while the use of a two-step LSM ensures the validity of the coefficient estimates obtained.

During the calculations, the requirements for the selected instrumental variables were checked and their validity substantiated (Table 5). To assess the relevance, reference values for the corresponding F-statistics were obtained by testing the hypothesis about the significant contribution of the applied tools to explaining the changes in the endogenous variable. In practice, the following rule is typically used: tools are considered relevant if the calculated reference value of the F-statistic for testing this hypothesis exceeds 10 (Stock et al., 2002). As the calculations carried out in line with this principle show, all the applied tools are relevant.

The tools' exogeneity was tested with the Sargan test (the overidentifying restrictions test), which is only possible if the number of applied tools exceeds the number of endogenous regressors. The test's null hypothesis is that all of these tools are exogenous, and the alternative one is that at least one of them is endogenous. At a 1% significance level, all the tools applied in the calculations are exogenous. An additional Hausman test allows one to decide about the advisability of using 2LSM, or applying ordinary LSM. The confirmed validity of the applied tools is a prerequisite for this test. Its null hypothesis is that the least squares estimates of the model coefficients are consistent. If it is not rejected, the ordinary least squares method is suitable for estimating the coefficients: the results will be valid. If the null hypothesis is rejected, it means LSM is not suitable for assessment, so 2LSM should be used. On the basis of the test results, the hypothesis was rejected, which confirmed the need to use 2LSM. To assess indicators' elasticity in a system of interrelated equations, a 95% confidence interval (17) was built.

No variable's confidence interval contains a zero value; this confirms that corresponding indicators impact the explanatory variable, which for a number of variables is elastic. The interpretation of empirical calculations' results is presented in Table 7.

The quality of the calculations was assessed using the first equation in system (17) as an example, which reflects the dual effects of the impact of improvements in innovation development and energy efficiency on accomplishing decarbonization goals. A plot of observed and calculated values of the D_L_vibros variable (Figure 4) shows that statistics (marked by the red "+" symbol) and data obtained from the constructed models (marked by the blue "x" symbol) are close enough to each other, which reflects the high predictive potential of the constructed regression equation. Deviations of the calculated values from the actual ones observed for some equations can be caused both by errors in the initial data and by factors not taken into account in the model. Without refuting the statistical reliability of the obtained empirical regression equations, this necessitates further research.

The partial elasticity coefficients E calculated below show the change in the dependent variable (as a percentage) when the corresponding factor changes by 1% (Florens, 2007). In particular, the comparison showed that the first equation in system (17) which describes the dual effects of mutual impact in the scope of the "innovation-energy efficiency-decarbonization" triad has a 1.85% higher energy efficiency elasticity coefficient than the mutual impact model (5) (Table 8). That is, if in model (17), which describes the dual effects energy efficiency, changes by 1%, emissions will decrease by 1.96%, while in the mutual impact model (5) they will only decrease by 0.109%. A similar ratio of effects was found for the second equation in system (17) and model (9) for innovation activity, and for the third equation in system (17) and model (15) for emis-

Table 2. **Indicators Applied in the Calculations**

Indicator	Designation	Unit
Energy efficiency	E_L_eef	roubles/kwh.
Atmospheric pollutant emissions from stationary and mobile sources	D_L_vibros	thousand tons
Number of R&D personnel	I_L_pers	people
Internal R&D expenditures, by Russian region	I_L_cost	roubles
Specific expenditures on environmental innovation	I_L_ecocost	roubles
Developed advanced production technologies, by Russian region	I_L_mantech	units
Regional organisations' innovation activity compared to all organisations'	I_L_innactiv	%
Value of shipped innovative products/provided services	I_L_ inproduct	roubles
Share of innovative products/provided services in total value of shipped products/provided services	I_L_vesproduct	%
Shipped in-house-manufactured products	L_product	million roubles
Per employee electricity consumption	L_electro	kwh
GRP	L_vrp	thousand roubles
Electricity consumption	L_electropotr	million kwh
Share of investments made for restructuring/modernisation purposes in total amount of capital investments	L_invest	%
Share of investments in machinery, equipment, and vehicles in total amount of capital investments for restructuring/modernisation purposes	L_investm	%
Labour productivity index, by Russian region	L_trud	% of previous year
Actual household monetary income	L_dohod	% of previous year
Source: authors.		

sions. The obtained data indicates that in terms of impact, dual effects in the scope of the considered triad exceed paired effects, which is particularly important for choosing investment strategies aimed at promoting decarbonization.

The results obtained using data for Russian regions confirm the suggested hypothesis about the dual effects of mutual impact in the scope of the "innovation-energy efficiency-decarbonization" triad.

The further application of the proposed methodology has significant potential for accomplishing various applied objectives of meeting decarbonization targets and addressing a wide range of research issues. We are talking about forecasting various factors, in particular total greenhouse gas emissions (or individually sulphur dioxide, nitrogen oxides, carbon, etc.), returns on innovations created to promote decarbonization, and constructing dynamic models of innovation activity indicators related to the implementation of sustainable development goals at various levels. Solving analytical problems related to strategic development seems to be a promising area, which combines academic feasibility studies for meeting various decarbonization targets under different science and technology development scenarios with regulatory forecasting, and identifying necessary conditions for such development.

The list of possible objectives and application areas can be expanded or adjusted to meet specific management levels, priorities, and time periods.

How Energy Efficiency and Decarbonization Objectives are Reflected in Russian Regional Innovation-Based Development Programs

The identified dual effects of mutual impact of the processes under consideration provided the basis for further research. An analysis of the progress in increasing energy efficiency and accomplishing decarbonization objectives, and of their reflection in the published innovation development programs of 83 Russian regions revealed the following areas for more detailed consideration:

1. Inclusion of measures aimed at increasing energy efficiency and decarbonization into these programs.
2. Inclusion of the results of implementing measures aimed at increasing energy efficiency and decarbonization in the list of key performance indicators for these programs.
3. Evaluation of the contribution of the implemented measures aimed at increasing energy efficiency and decarbonization to meeting regional innovation development targets.
4. Evaluation of the division of responsibility for the results of innovation activities, and for improving energy efficiency and decarbonization at the regional level.

The analysis allowed us to draw the following conclusions. First, innovation development management models implemented in different Russian regions

Table 3. **Simulation Results for Calculating Paired Relationships' Effects in the Scope of the "Innovation-Energy Efficiency–Decarbonization" Triad**

Model No.	Dependent variable	Method	Independent variables	Coefficient	Standard error	P-value	R-square	Hausman test	Breusch-Pagan test
(5)	D_L_vibros	FE	Const	–5.175	2.914	0.079*			
			E_L_eef	0.387	0.231	0.098*			
			L_trud	0.503	0.242	0.041**			
			L_vibros_1	0.8	0.19	6.28e–05***			
			Dt_2	0.349	0.054	7.43e–09***			
			Dt_3	0.352	0.054	7.05e–09***			
			Dt_4	0.139	0.044	0.002***	0.989	0.159	0.057
		RE	E_L_eef	–0.053	0.022	0.016**			
			L_trud	0.381	0.231	0.099*			
			L_vibros_1	1.011	0.03	3.03e–243***			
			Dt_2	0.319	0.037	2.55e–017***			
			Dt_3	0.307	0.032	1.11e–020***			
			Dt_4	0.085	0.013	2.62e–010***			
(6)	E_L_eef	FE	Const	15.612	1.553	4.56e–016***			
			D_L_vibros	–0.057	0.010	7.162e–07***			
			L_electropotr	–0.71	0.072	1.65e–015***			
			E_L_eef_1	0.191	0.107	0.077*	0.995		
		RE	D_L_vibros	–0.014	0.008	0.099*			
			L_electropotr	0.014	0.007	0.065*		6.49e–028	0.978
			E_L_eef_1	0.986	0.008	0***			
		MHK	D_L_vibros	–0.011	0.006	0.092*			
			L_electropotr	0.013	0.006	0.028**	0.986		
			E_L_eef_1	0.992	0.006	1.99e–102***			
(7)	I_L_ecocost	FE	Const	63.154	29.2676	0.0338**	0.43	0.05	6.75e–011
			E_L_eef	–5.381	2.653	0.0457**			
(8)	I_L_ mantech	RE	Const	–2.452	3.018	0.4165	0.85	0.712	5.62e–057
			E_L_eef	0.469	0.275	0.0879*			
(9)	E_L_eef	FE	Const	10.518	0.106	8.81e–089***	0.99	0.003	1.77e–109
			I_L_inproduct	0.06	0.012	6.42e–06***			
			I_L_vesproduct	–0.06	0.013	3.73e–05***			
			I_L_ecocost	–0.002	0.0009	0.02**			
(10)	D_L_vibros	FE	Const	9.227	0.984	1.063e–014***	0.965	1.19e–021	3.94e–019
			I_L_inproduct	–0.442	0.112	0.0001***			
			I_L_vesproduct	0.441	0.106	7.580e–005***			
			I_L_ecocost_2	0.022	0.009	0.02**			
(11)	I_L_pers	FE	Const	7.02	0.143	2.11e–062***	0.995	1.13e–007	2.17e–171
			D_L_vibros	0.109	0.026	0.0001***			
(12)	I_L_cost	FE	Const	8.426	0.236	1.17e–051***	0.99	1.06e–013	5.8e–159
			D_L_vibros	–0.129	0.043	0.0042***			
(13)	I_L_ mantech	FE	Const	4.617	0.959	9.49e–06***	0.857	0.001	1.85e–044
			D_L_vibros	–0.292	0.167	0.0859*			
(14)	I_L_ innactiv	RE	Const	1.342	0.233	8.64e–09***	0.69	0.877	4.39e–068
			D_L_vibros	0.152	0.04	0.0002***			
(15)	I_L_ inproduct	FE	Const	12.133	0.947	1.93e–021***	0.93	3.21e–016	2.62e–095
			D_L_vibros	–0.537	0.176	0.0031***			

Note: ***p < 0.01, **p < 0.5, *p < 0.1. Models (5) and (6) are described in detail, in models (7) - (12) estimated coefficients are presented in accordance with the results of the Hausman and Breusch-Pagan tests.

Source: authors.

largely reproduce the structure and characteristics of the federal governance model.

Secondly, all Russian regions currently pay significant attention to improving energy efficiency. Almost all of them consider this area a priority in their innovation development programs, and the relevant indicators are among the key ones. At the same time, regions' progress in accomplishing decarbonization objectives remains in its infancy, and relevant indicators are not yet directly applied to evaluate innovation development results. Improvements here apparently should be expected only when a number of methodological limitations are overcome at the federal level.

Thirdly, although energy efficiency objectives set in regional programs are declared a priority, in reality in most cases they remain unrelated to the most important innovation development targets, i.e., they apparently are not considered critical from a strategic point of view. Until recently decarbonization was not included among the set of priorities either.

Table 4. **Interpretation of Empirical Calculations to Assess Paired Relationships' Effects in the Scope of the "Innovation-Energy Efficiency-Decarbonization" Triad**

Model No.	Regression equation	Interpretation
	«Energy efficiency – decarbonisation» D = f(E), E = f(D)	
(5)	Direct relationship: D_L_vibros = –1.51 – 0.0528 * E_L_eef – 0.00216 * L_L_product + 0.381 * L_trud + 0.319 * dt_2+ 0.307 * dt_3 + 0.0845 * dt_4 + 1.01 * D_L_vibros_1	Increased energy efficiency contributes to reduced emissions.
(6)	Inverse relationship: E_L_eef = 0.0421 – 0.0116 * D_L_vibros + 0.0134 * L_electropotr + 0.992 * E_L_eef_1	Emissions increase with decreased energy efficiency.
	«Energy efficiency – innovation» I = f(E), E = f(I)	
(7) (8)	Direct relationships: I_L_ecocost = 63.2 – 5.38 * E_L_eef I_L_mantech = –2.45 + 0.470*E_L_eef	Increased energy efficiency reduces the need to invest in environmental innovation. Increased energy efficiency promotes development of innovative technologies.
(9)	Inverse relationship: E_L_eef = 10.5 + 0.06 * I_L_inproduct – 0.06 * I_L_vesproduct – 0.002 * I_L_ecocost	Increased innovation activities at all life cycle stages contribute to energy efficiency.
	«Innovation – decarbonisation» D = f(I), I = f(D)	
(10)	Direct relationship: D_L_vibros = 9.23 – 0.442 * I_L_inproduct + 0.441 * I_L_vesproduct + 0.0220 * I_L_ecocost_2	Increased innovation activity at various life cycle stages leads to reduced emissions of pollutants. At the same time expenditures on environmental innovations contribute to reducing emissions with a two-year delay.
(11) (12) (13) (14) (15)	Inverse relationships: I_L_pers = 7.03 + 0.109 * D_L_vibros I_L_cost = 8.43 – 0.129 * D_L_vibros I_L_mantech = 4.62 – 0.293 * D_L_vibros I_L_innactiv = 1.28 + 0.164 * D_L_vibros I_L_inproduct = 12.1 – 0.538 * D_L_vibros	Increased pollutant emissions make a statistically significant impact on increasing innovation activities at various stages of its life cycle, and lead to increased number of R&D personnel, indicate a decrease in innovation expenditures, number of innovative technologies, and production of innovative products.

Source: authors.

Table 5. **Tools' Validity Tests and the Spplication of 2LSM for the Interrelated System Equations (17)**

System (17) equation, dependent variable	F-statistics	P-value (F)	Sargan test, p-value	Hausman test, p-value
D_L_vibros	123.243	5.55e-46	0.069	4.013e-006
E_L_eef	14.638	1.09e-08	0.058	0
I_L_ inproduct	20.252	1.46e-11	0.019	3.701e-017

Source: authors.

Table 6. **Interval for Dey Variables of Interrelated System Equations (17)**

System (17) equation, dependent variable	Variable	Coefficient	95% confidence interval	
D_L_vibros	I_L_inproduct	–0.143	–0.251	–0.036
	E_L_eef	–0.947	–1.279	–0.614
E_L_eef	I_L_inproduct	–0.150	–0.246	–0.054
	D_L_vibros	–0.995	–1.328	–0.661
I_L_ inproduct	l_eef	–4.251	–6.298	–2.204
	l_vibros	–4.265	–6.477	–2.052

Source: authors.

Fourth, innovation development programs and reports on their implementation do not reflect the impact of relevant efforts on energy efficiency and decarbonization indicators on the one hand, and the latter's inverse impact on regions' innovation development progress on the other. The existing legal framework does not allow for the monitoring and evaluation of the identified dual effects of mutual impact in the scope of the "innovation-energy efficiency-decarbonization' triad.

Fifth, in all Russian regions, and at the federal level, the organizational systems for managing innovation, energy efficiency, and decarbonization function independently of one another. Various regional executive authorities' divisions are responsible for these areas; they develop and adopt their own program documents and targets, set procedures for planning and implementing them and monitoring the progress, establish mechanisms and formats for providing administrative, financial, economic, and legal decision-making support, and ultimately independently report results. Managing these processes at different levels at the same time leads to inconsistency, which can adversely affect the achievement of the goals.

Sixth, a wide range of issues related to innovation activities aimed at improving energy efficiency and the decarbonization of the economy to date remains unregulated by the Russian legislation. No flexible mechanisms have yet been designed to regulate innovation in the context of the rapid transition of the energy sec-

Table 7. **Interpretation of Empirical Calculations to Assess the Dual Effects of Mutual Impact in the Scope of the "Innovation-Energy Efficiency-Decarbonization' Triad**

Assessed element	System (17) equation	Interpretation
Decarbonisation D = f(I,E)	D_L_vibros = –5.832 – 0.947 * E_L_eef – 0.144 * I_L_ inproduct + 1.144 * L_vrp + ε_1	Increased energy efficiency, and increased production of innovative goods/services simultaneously contribute to reduced emissions.
Energy efficiency E = f(I,D)	E_L_eef = –5.442 – 0.995 * D_L_vibros – 0.15 * I_L_ inproduct + 1.156 * L_vrp + ε_2	Increased emissions, and increased production of innovative products simultaneously impact energy efficiency. Increased emissions indicate a decrease in energy efficiency. Increased production of innovative products has a similar effect.
Innovation I = f(E,D)	I_L_ inproduct = –31.305 – 4.265 * D_L_vibros – 4.251 * E_L_eef + 5.45 * L_vrp + ε_3	Increased energy efficiency, and increased emissions simultaneously affect innovation activity. Decreased energy efficiency indicates an increase in innovation activity. A decrease in emissions has a similar effect.

Source: authors.

tor to a new technological paradigm, and toward decarbonization.

The reflection of initiatives to increase energy efficiency and especially decarbonization in Russian regional (and federal) innovation development programs tends to be rather formalistic. At the same time, accomplishing relevant objectives remains outside the approved strategic priorities and does not set the innovation activity vector in Russia. A simplified approach to increasing energy efficiency and decarbonization in the scope of socioeconomic development still prevails at all government levels. Typically these objectives are seen from a tactical point of view, losing sight of not only strategic economic modernization issues, but also of the global sustainable development agenda based on carbon neutrality policy.

Thus the mutual impact in the scope of the "innovation-energy efficiency-decarbonization" triad is not considered when program documents for the development of the Russian economy are prepared at various levels of government,. Stepping up the effort to implement the green agenda requires taking these effects into account when shaping innovation policies to improve energy efficiency and address decarbonization challenges.

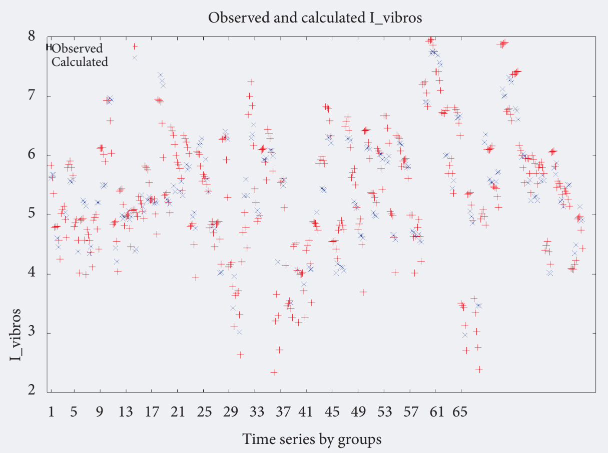
Conceptual Basis for Managing Innovation Development to Increase the Energy Efficiency and Decarbonization of the Russian Economy

Adapting the existing system for managing the processes under study, taking into account the revealed effects of mutual impact in the scope of the "innovation-energy efficiency-decarbonisation" triad, requires meeting the following conceptual requirements.

First, shaping policy in this area, one should proceed from the global climate agenda proclaimed at the UN level in line with the sustainable development paradigm. As the largest country in the world in terms of territory, the amount of fuel and energy resources supplied to the world market, the ferrous metallurgy, chemical, petrochemical, and other industries' output, the amount of industrial and natural greenhouse gases emissions into the atmosphere, and a number of other indicators, Russia cannot ignore these processes.

Secondly, developing a conceptual basis for the relevant policy and predicting the possible extent of the expected changes, one should focus on national interests and strategic goals. These are determined by the officially approved government priorities, the historical structure of the economy, the competitive advantages in the global goods and services markets, the achieved technological development level, and the availability of

Figure 4. **Observed and Calculated Values of Variable D_L_vibros for the Studied Panel Data**



Source: authors.

Table 8. **Assessment of Various Ractors' Impact on the Dependent Variable in Constructed Models**

Model No.	Dependent variable	Factor	Partial elasticity coefficient E
(5)	D_L_vibros	E_L_eef	-0.109
(6)	E_L_eef	D_L_vibros	-0.011
(7)	I_L_ecocost	E_L_eef	-15.686
(8)	I_L_mantech	E_L_eef	1.764
(9)	E_L_eef	I_L_ecocost	-0.0006
		I_L_inproduct	0.05
		I_L_vesproduct	-0.005
(10)	D_L_vibros	I_L_ecocost	0.015
		I_L_inproduct	-0.765
		I_L_vesproduct	0.082
(11)	I_L_pers	D_L_vibros	0.076
(12)	I_L_cost	D_L_vibros	-0.089
(13)	I_L_mantech	D_L_vibros	-0.531
(14)	I_L_innactiv	D_L_vibros	0.405
(15)	I_L_inproduct	D_L_vibros	-0.31
(17)	D_L_vibros	E_L_eef	-1.96
		I_L_inproduct	-0.249
	E_L_eef	I_L_inproduct	-0.272
		D_L_vibros	-0.48
	I_L_inproduct	D_L_vibros	-1.234
		E_L_eef	-2.348

Source: authors.

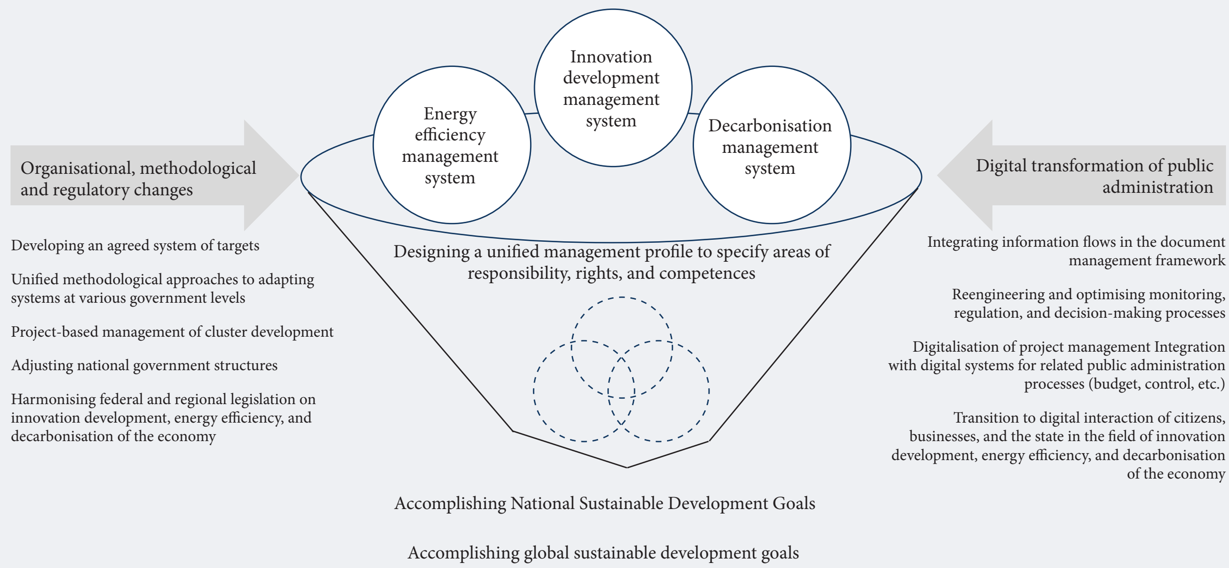
material, financial, human, and other resources for the energy transition.

Thirdly, a unified approach is needed at the federal and regional levels to adapt the mechanism for managing innovation-based development aimed at improving the energy efficiency and decarbonization of the economy. We are talking about developing a coordinated system of target indicators based on a single methodological platform.

Fourth, the adaptation of the administrative mechanism should first of all include integrating energy efficiency and decarbonization management processes into the innovation, science, and technology policy system, to create synergy. Such adaptation should on the one hand contribute to the strategic growth of the energy sector, and on the other, to accomplishing decarbonization objectives as part of the Russian economy's transition to an innovative development path.

Meeting the above conceptual requirements implies taking steps toward harmonizing federal and regional legislation on innovation development, energy efficiency, and decarbonization; coordinating relevant targets, and structuring them by management levels; adopting a systemic approach founded on project- and cluster-based development principles; developing a system for monitoring innovation development, energy efficiency, and decarbonization progress in the scope of a uni-

Figure 5. **Main Areas for Adapting the Mechanism for Managing Innovation Development, Energy Efficiency, and Decarbonization**



Source: authors.

fied management profile, with an appropriate division of responsibilities and competences at each level. The digital transformation of public administration plays key role here, consolidating information flows into a document management system using big data technologies, reengineering, optimization of monitoring, regulation, decision-making, and so on. (Figure 5).

The proposed integration of the energy efficiency and decarbonization processes with innovation management will ensure the coordination of these three areas in the scope of a single profile covering various regulation levels. Harmonizing legislation on these three areas will optimize the relevant public support mechanisms. Implementing the described approach to adjusting the organizational structure will give priority status to the processes under consideration in a situation where new challenges and threats are emerging.

Conclusion

In recent years, almost all countries have been paying particular attention to various aspects of decarbonization, which has come to the fore of the global green agenda. Numerous studies have been published on choosing approaches to meeting new environmental challenges under various scenarios. Despite their differences, almost all of them emphasize the role of innovation as a tool to increase energy efficiency and promote decarbonization. However, specific mechanisms for their implementation remain insufficiently developed. To fill this gap, our study is the first to implement an integrated approach to addressing decarbonization issues by identifying dual effects of mutual impact in the scope of the "innovation-energy efficiency-decarbonization" triad.

TThe focus on improving energy efficiency through innovation to facilitate achieving the decarbonization goal is due to the fact that the former is a key parameter of most modern technological processes and a characteristic of various types of products. Concentrating on increasing energy efficiency further will help create a technological foundation for developing basic industries, capable of giving an impetus to the whole economy. From a decarbonization point of view, energy efficiency can become a catalyst for developing technological solutions for entire production chains in various industries, from mining raw materials to final consumption. In its turn, this will allow entities to step up innovation processes throughout the national economy.

The results of the study confirm the suggested hypothesis about the dual effects of mutual impact in the scope of the "innovation-energy efficiency-decarbonization" triad. For this purpose, empirical calculations were conducted, using data for 83 Russian regions and yielding statistically significant results.

The theoretical importance of the obtained results is in confirming the dual effects of mutual impact in the scope of the "innovation-energy efficiency-decarbonization" triad and substantiating the need to take them into account when designing a conceptual framework for adapting the innovation development management system to accomplish energy efficiency and decarbonization objectives in the framework of a single management profile. The proposed methodology can support integrated decision-making on the decarbonization of the economy in the interests of global sustainable development, with national development goals having unconditional priority given sanctions pressure. The results of the study expand the scientific understanding of possible approaches to achieving these goals.

More important areas of future research may include, firstly, assessing the potential for the development and industrial application of critical domestic technologies to accomplish decarbonization goals in the context of limited access to advanced foreign technologies. Scientifically and methodologically substantiating strategic investments in sustainable economic development in the context of the decarbonization problem seems to be a productive area for analysis. It would also make sense to develop a mechanism for adjusting science and technology development indicators to match the specified objectives, while maintaining high growth rates of the Russian economy.

The proposed methodology, which was tested using data on the Russian economy, can also be useful for countries at different science and technology development levels and with different availabilities of resources to address practical problems associated with the energy transition and designing relevant mechanisms, including various aspects of decarbonization.

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Innovation Scenarios for Ecuadorian Agrifood Network

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Abstract

The purpose of this study is to explore plausible scenarios and identify the desired one for the agrifood beef network in Santo Domingo, Ecuador until the year 2035. A methodological approach based on the processes of participation and collective reflection is proposed, which integrates methods from the French School of Prospective Thought and The Futures Triangle V. 2.0. Four plausible scenarios were developed for the object of study: Innovate Against the Tide, National Pioneers, Obsolescent Gait, and Missed Opportunity. Of these, National Pioneers was deemed the desired scenario, because it integrates the high innovation in the beef agrifood network with favorable environmental conditions. This study contributes to anticipating the evolution of Santo Domingo's innovation in the agrifood network, which can determine a favorable trajectory for the province's sustainable development.

Keywords: scenarios; futures studies; innovation; prospective; foresight; agrifood networks

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Introduction

Cattle ranching has transformed the socio-spatial dynamics of the province of Santo Domingo de Los Tsáchilas in Ecuador (Rivas et al., 2016). This territory has gone from being a land of sparse settlements in the 1970s to hosting the third most populated city in Ecuador (Gondard, Mazurek, 2001). The presence of land with high agricultural potential, relevant expertise of the population, growth of a local consumer market, and its location between the country's two main cities (Quito and Guayaquil) has boosted the province's development. However, the complexity of the agrifood system and the volatility of the behavior of its variables generate uncertain scenarios that call into question the system's capacity for innovation and development in the medium and long terms.

Futures studies rely on using tools that reduce the level of uncertainty for decisionmakers and allow for the construction of knowledge inputs to coordinate the actions of various actors to guide the development of the territories toward the desired scenarios. In this context, this study designs potential scenarios for the evolution of the agrifood beef network in the province of Santo Domingo de Los Tsáchilas (hereafter ABNSDT) up to 2030. In doing so, we hope to map the opportunity space, including different variables and pathways, that should be considered for the modernization of beef agrifood networks in Latin America using the ABNSDT case.

Conceptual Foundations: Future Studies and the Agrifood Sector

The field of Futures Studies articulates diverse perspectives and paradigms for exploring the potential residing in different futures. According to (Ortega, 2016), four schools are predominant, as shown at Table 1 – prospective, forecasting, foresight, and human and social welfare.

This research is based on the postulates of the Prospective school of thought, because this discipline favors participation and collective reflection, as well as the development of interdisciplinary studies. In addition, being premised on a voluntarist Futures Studies school of thought, the Prospective approach possesses a constructive focus and global vision, it employs quantitative and qualitative variables – both known and potential, it considers dynamic relationships, is based on mixed models, and contemplates the future as multiple and uncertain (Godet, Durance, 2011). This comprehension of the future surpasses a determinist perspective, which maintains a predictive vision and considers the future unitary and knowable.

The Prospective school of thought has been consolidated as a discipline through the contributions of three intellectuals: Berger (1957), from a philosophical approach, gave it the name Prospective; De Jouvenel (1967), as a political scientist, integrated the concept of futuribles – possible futures; Godet (1993), with his knowledge of economics, structured a model by applying various specialized methods and their mathematical bases. Gándara and Osorio (2017) recognize Prospective as an intellectual discipline because it has pre-established methodologies, although they are not unalterable paths. Most foresight exercises are based on collective reflection processes articulated in three phases: identification of key variables, an analysis of the actors' game, and scenario building (Van Dorsser, Taneja, 2020).

Throughout a Prospective process, systemic thinking is streamlined. This facilitates addressing complex problems characterized by the interaction of numerous variables, such as the future of the agrifood sector. Indeed, this issue has been addressed systemically. For Rastoin et al. (2010), agrifood systems are "*...an interdependent network of actors located in a given geographical space and participating directly or indirectly in the creation of flows of goods and services aimed at satisfying the food needs of one or more groups of local or external consumers in the area under consideration*." Thus, prospective exercises contribute to the understanding of the future of these systems.

The link between agrifood systems and the systemic approach makes it possible to study the diversity of interrelated links in the journey of agrifood goods from producers to consumers. As Sims et al. (2015) point out, network logic encompasses all stages of the production, transformation, marketing, distribution, and the consumption processes. The dynamics and efficiency of networks, from Drouillard's (2018) perspective, largely depend on their capacity for innovation within organizations, on the inclusion of technologies, and on human talent management. Thus, the development of agrifood systems depends both upon the quality of final products and on communicative, technological, commercial, and logistical aspects. Flaig et al. (2021) define innovation as the strategic generation of disruptions in productive, operational, management, and marketing issues to increase the value perceived by the actors participating on a specific market. In view of this, it is important to ask: to what extent has the beef agrifood sector been able to operationalize innovations to enhance its development in the long term?

The Beef Agrifood Sector in the Future

According to the Food and Agriculture Organization of the United Nations (FAO) (2020), world meat production is around 340 million tons per year. Of this amount, 63 million tons correspond to beef. A noteworthy element is that, in addition to having an important share in the global protein supply, the global price index of beef exceeds that of other types of meat (sheep, poultry, pork). Increasing technology integration at all stages in the food system is central to boosting beef production. Schwab (2016) explains that agribusiness 4.0 has encouraged not only the acquisition of machinery and process automation through mechatronic designs, but also data and information management. Paliszkiewicz (2020) notes the importance of Big Data in agricultural production and its importance in decision making. By combining precision livestock farming with massive data analysis, it is possible to create historical records detailing the condition of each animal throughout its life.

However, the outlook for this industry is uncertain. According to data from the Organization for Economic Co-operation and Development (OECD, 2020), global beef demand decreased from about 63 to 60 million tons between 2018 and 2020. In developing countries, FAO estimates a 15% decrease in their beef exports, a quota that would be covered by developed countries (FAO, 2020).

Latin America lost its share in world trade of beef products following the emergence of COVID-19 coronavirus. However, it remains the region with the highest production in the world. This apparent contradiction can be understood by the changes in global food consumption. In recent years, Europe and Asia have been trading with the most developed producers in terms of food security and sustainability, such as the United States, India, and Russia. As detailed by Brugarolas et al. (2020), European and Asian countries are entering greater trade agreements involving these producers because of their strong alignment with the Global Agenda for Sustainable Livestock raised by FAO (2020), as well as for their excellent traceability systems and the adoption of precision livestock farming.

For their part, the beef agrifood systems of several Latin American countries are beginning to stand out for their innovations. According to Aceituno (2020), Argentina and Chile have managed to realize their innovation policies in the beef agrifood sector through the construction of biotechnology laboratories and circular economy models. This has allowed them to harness what was previously considered "waste" and transform it into profitable by-products such as fertilizers and feed with high nutritional value for livestock, preserving the sense of being organic and sustainable (Tena et al., 2018). The case of Argentina is also striking because they import and manufacture technological devices and systems for the management of livestock agrifood systems (Aceituno, 2020; Arrieta et al., 2020). The main actors underpinning this initiative are private companies and public research centers. In recent years, innovation in these systems has been reflected in the installation of 4G antennas to connect various devices that enter information in real time via algorithms designed for each farm. Simultaneously, information is collected and systematized from collars, sensors, drones, artificial intelligence, and automated feeders, among other devices that provide data and answers instantly (Drouillard, 2018).

In the Ecuadorian case, state-of-the-art technology seems to have a less important role in the bovine agrifood sector. Nonetheless, according the Ministry of Agriculture and Livestock[1], the annual beef production is around 220,000 metric tons. This production allows the sector to be self-sufficient and even exceed domestic demand (200,000 tons per year), as is the case with other livestock derivatives, such as dairy products. Based on a diverse territorial configuration, the country has built several local and regional agrifood beef networks and established a competition for national leadership (Barragán-Ochoa, 2020).

The agrifood beef network of the province of Santo Domingo de Los Tsáchilas is one of the most dynamic at the national level. This province ranks fifth in number of animals with almost 160,000 head of cattle, according to ESPAE (2016).

Foresight exercises applied to the agricultural sector in Ecuador are rare. The Ecuador Agroalimentario initiative (2019) formulated long-term objectives for various agrifood networks.[2] This initiative comprises the sum of all agrifood networks in Ecuador and their actors in their different activity-domains: primary production, processing, marketing, exports, and related services (Hernández, Hurtado, 2020). However, the COVID-19 pandemic reduced the validity of the forecasting exercise with a 10-year time horizon. Therefore, carrying out new foresight work for the most important agrifood sector in the national economy means updating the foreseen challenges and strategic pathways.

Methodological Approach: from the Present to the Construction of Future Scenarios

The challenge of understanding future scenarios for the agrifood beef network of Santo Domingo must be approached by using complementary foresight methods. Adopting a mixed approach, we use methodological tools of foresight and Prospective. The

[1] https://www.agricultura.gob.ec/ecuador-esautosuficiente-para-cubrir-demanda-nacional-de-carne-bovina/, accessed 17.08.2022.

[2] https://ecuadoragroalimentario.com/wp-content/uploads/2019/06/EcuadorAgroalimentario-Junio-2019.pdf, accessed 14.06.2022.

Table 1. **Main schools of futures thought**

School	Country of origin	Brief Description
Prospective	France	Proposes mixed and highly flexible approaches that recognize the actors as the foundation of the construction of futures
Forecasting	United States	Relies upon mathematical constructs to calculate forecasts
Foresight	United Kingdom	Based on qualitative methods based on the criteria of experts
Human and social welfare	Italy	Combines global responsibility, justice and solidarity to manage social change

Source: authors, based on (Ortega, 2016).

methodological approach is divided into six phases: expert selection, understanding the system, identifying key variables, structural analysis, analysis of actors, and the development of plausible scenarios.

Phase 1: Expert selection

Initially in the prospective process, the group of experts who contributed to this study's various participatory workshops was selected. Their expertise was confirmed by supplying a questionnaire to measure their expert competence coefficient K (Barroso et al., 2019; Cabero et al., 2020). This coefficient includes the knowledge coefficient Kc and the argumentation coefficient Ka. The first (Kc) measures how informed the expert is regarding the topic to be addressed through a self-applied scale, while the second (Ka) focuses on the sources of arguments that the experts will use in their contributions, covering work experience, previous studies, the reviewed literature, and, finally, the experts' intuition.

After applying these tools, a panel of 12 experts was formed. In this case, all the participants achieved a high score, according to the parameters of Cabero et al. (2020). Gándara and Osorio (2017) consider this number of experts to be adequate; they noted that a greater number of experts would complicate communication and could harm the quality of the results.

The profile of the expert panel reflects its diversity: eight experts have postgraduate training (five with master's degrees and three with doctorates); work experience is between seven and 30 years; ages range between 28 and 68 years; in terms of gender, 66% are men and 34% women. Due to their activities and relationship with the system, three subcategories are established: professors and researchers (average K = 0.91), beef producers (average K = 0.90) and public servants focused on the regulation and control of quality in the sector (average K = 0.95).

Phase 2: Understanding the system

Cruz and Medina (2015) suggest the use of business science and foresight tools to identify drivers of change. To understand the dynamics of ABNSDT, we conducted an *environmental scanning* exercise. We weighted the current systemic conditions by evaluating matrices of internal and external factors. To do this, we followed David's (2003) methodological guidelines, and defined expected changes for the future, according to Godet's stipulations (1993). Once the diagnostic phase was completed, we obtained the first list of variables, and subsequently refined it with the use of statistical tests.

To identify drivers of change, an expert consultation instrument was applied and analyzed in statistical software. One of the intermediate results is the definition of the system's constituent variables. A large number of variables were obtained, to which a Kendall's W coefficient of concordance was later applied. Through this process, 23 variables were discarded, because they could be subsumed into others or because they did not correspond to the system under study. The obtained level of agreement between the experts' judgments was 93.60%, a high value, since, as Ramírez and Polack (2020) indicate, the percentage value ranges from 0% (no concordance) to 100% (total concordance). Therefore, by obtaining p-value of less than 0.05, there is sufficient statistical evidence to affirm that there is consensus among the 12 experts in the selection and discarding of variables, going from 54 to a total of 31.

Phase 3: Identifying key variables

In this phase, variables that did not have a major impact upon the system or those that were duplicated were discarded by giving a survey to the experts. This instrument obtained a Cronbach's Alpha coefficient equal to 0.889; which allowed for validating the consistency of the following scale: 1 (totally agree), 2 (partially agree), 3 (neutral), 4 (partially disagree), and 5 (totally disagree). In addition, following Ramírez and Polack (2020), Kendall's W test was applied to identify the level of agreement between the experts' assessments. Moreover, to establish a definitive list of variables, only those with a mean and mode equal to or greater than 2 and 1, respectively, were accepted.

Phase 4: Structural analysis

In the fourth phase, the mixed method MICMAC (Matrix of Cross Impacts and Multiplication Applied to a Classification) was applied. Godet and Durance (2011) believe this method can successfully link the system's representative variables with environmental variables in an orderly manner to assess the levels of influence and dependence of each one. In this way, this method reveals which variables are critical for a system's future evolution. For Hernández and Cisneros (2020), the development of this phase begins by ordering the selected variables and assigning a code that will represent them when using the software.

Phase 5: Stakeholder analysis

In this phase, the mixed method MACTOR (Matrix of Alliances and Conflicts: Tactics, Objectives, and Recommendations) was applied. For Godet and Durance (2011), this method aims to define the correlation of forces existing between the involved actors and pinpoint their positions in relation to the possibilities of the system's evolution. Similarly, Winkowska and Szpilko (2020) recognize that this method offers specific advantages over others by setting out the information in mathematical matrices that relate the actors to the strategic objectives arising from the key variables identified in the Map of Indirect Influences/Dependencies. On the other hand, in the Matrix of Valued Positions (2MAO), each stakeholder's position with respect to future challenges was individually captured.

Phase 6: Development of plausible scenarios

The construction of plausible scenarios was performed with the process laid out in Fergnani's Futures Triangle 2.0 (2020). This method, as in Inayatullah's (2008) first version, considers that three forces shape the long term: the weight of history, the push of the present, and the pull of the future. However, in the latest version, more visual resources are used. The main phases considered methodological recommendations from various authors and include the following: mapping the future (Inayatullah, 2008), generating a 2x2 matrix of scenarios (Schwartz, 1991), designing the Triangle of Futures 2.0 (Fergnani, 2020), and narrating the desired scenario.

Revealing Optional Futures for a Dynamic Agrifood Sector

The system under study (ABNSDT) is highly dynamic due to the involvment of a large number of variables that behave differently. To understand this system, we first analyzed the variables to identify which of them are strategic when studying the system's evolution. Next, the behavior of the actors and the identified future challenges were analyzed. Finally, the scenarios and their narrative were developed.

Strategic variables

Not all the variables at play in complex systems such as ABNSDT have the same weight or role, as seen in the Matrix of Indirect Influences/ Dependencies. Each variable's location depends on the «dependence» and «influence» scores obtained. In this case, values of 350 on both axes delimit the conflict zone; that is, the box that contains the key variables, understanding that the possible values for the X and Y axes are in a range between 0 and 400, according to the Proportions Matrix produced by the MICMAC software (Table 2).

In order to interpret the importance and role that the variables have on the future of the system, they have been organized into eight categories as stated by Godet and Durance (2011). The results are displayed in Table 2. In the resulting graph (Figure 1), which is based on the diagonal strategic bisector and the centric circumference, eight groups of variables are categorized, as suggested by Hernández and Hurtado (2020). To interpret the above results and the importance of the variables upon the system's dynamics, the eight groups of variables are described in Table 3.

A system modified by various actors

The group of experts, following the guidelines of Poli (2018), identified a total of 36 social actors with the capacity to modify the dynamics of the ABNSDT (Table 4). The behavior of these actors, in terms of their capacity to influence the system and their dependence upon the behavior of the system's variables, is observed at the level of influences and dependencies between actors (Figure 2). These behaviors, following Godet and Durance (2011), can be classified into four groups of actors, as described in Table 5.

To further identify agreements and discrepancies, the graphs of convergences (Figure 3) and divergences (Figure 4) between actors are presented. The greatest convergences are between: the Cattle Ranchers Association of Santo Domingo, Municipal Market Networks, the Ministry of Agriculture and Livestock, the National Secretariat of Higher Education, Science, Technology and Innovation, the academic sector, and the National Autonomous Institute of Agricultural Investment. The convergence here is established on the basis of a link between local and national institutions and the academic sector, which shows the need and potential for the formulation of territorial public policies and their articulation with academia. In contrast, the greatest divergences are observed between: the Ecuadorian Business Committee, Other Producer Associations, Provincial GAD, Ecological Value Association, and Municipal GAD. It is noteworthy that the greatest divergences are observed between local and regional actors, which indicates a diversity of local views on the future of ABNSDT. This underscores the need for developing and applying local territorial planning tools with time horizons that go beyond short-termism and position the ABNSDT as an innovative development strategy that positions Santo Domingo in the national and international contexts.

The challenges of long-term territorial planning are established from multiple perspectives. One of the fundamental ones is the generation of agreements between different actors who have divergent views and unequal weights in the system's dynamics. In fact, the Cattle Ranchers Association of Santo Domingo (Qi = 1.7), the Municipal Market Networks (Qi = 1.6), Other Producers' Associations (Qi = 1.5), and the Ministry of Agriculture and Livestock (Qi = 1.5) accumulate great weight, which is expressed in the power ratio Qi.[3] These indicators were constructed considering the results of convergences and divergences of order 3, which expresses the direct and indirect modes of influence (passing through a third party) (Chung, 2009).

Convergences and divergences, when analyzed in greater detail, are expressed not between actors, but between challenges for the future. Each of them has a degree of mobilization that results from the relationship between agreements and disagreements. In other words, the social actors are not indifferent to the milestones expected for the system and share visions of change, as shown in Table 6.

Table 2. **Variables list**

№	Long title	X axis	Y axis	Code
1	Alternatives for financing innovation	334	327	AFI
2	Animal biotechnology	377	376	BA
3	Quality of final product	389	376	CPF
4	Climate change	342	285	CC
5	Demographic changes	331	312	CD
6	Legislation changes	326	286	CL
7	Changes in the target's preferences	360	373	CPT
8	Production capacity	320	344	CP
9	Quality certifications	324	330	CCA
10	Agroecological conditions	299	290	CA
11	Sanitary controls in foreign markets	316	316	CSE
12	Costs of logistics services	283	295	CSL
13	Innovation strategies	393	378	EI
14	Market structure	326	268	EM
15	Differentiating factors of the products	282	321	FDP
16	Human capital development	365	368	FCH
17	Administrative management	303	275	GA
18	Government incentives	381	372	IG
19	Internationalization of the Ecuadorian agrifood sector	266	311	ISA
20	Investment in Research, Development and Innovation	276	302	IDi
21	Mitigation of the pandemic's effects	303	316	MEP
22	Economic model	230	306	ME
23	Modernizing of infrastructure	288	279	MI
24	Local academic offerings	303	314	OAL
25	Rural development programs	365	364	PDR
26	Food security	312	307	SA
27	Traceability systems	259	315	ST
28	The country's macroeconomic conditions	359	255	SMP
29	Food sovereignty	236	332	SAL
30	Sustainability of the agrifood network	336	350	SRA
31	Transition towards the bioeconomy	375	356	TB

Note: translated from Spanish; the codes reflect the Spanish titles.
Source: authors, using LIPSOR Software, MICMAC Version 6.1.2.

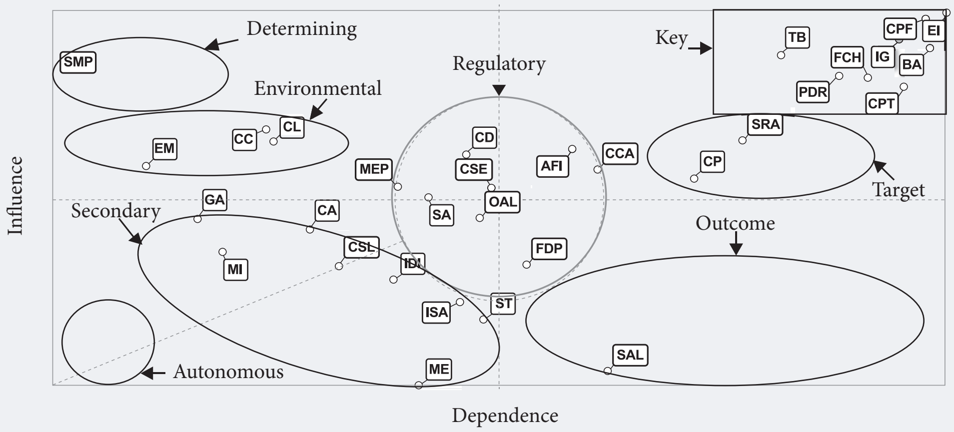
Development of Plausible Scenarios

Among the main results, four future alternatives were identified with the support of a participatory workshop in which all the learning obtained throughout the study was used to map the future. After this, two sets of variables were formed. The first, called «Innovation in the agrifood network», had the possible movements of «high» or «low». The variables included therein are: innovation strategies, product quality, animal biotechnology, and transition to a bioeconomy. In a complementary way, the second set, whose name is «Environmental conditions», had the possibilities of «favorable» and «unfavorable» movement. This set includes the variables: changes in the target's preferences, formation of local human capital, government incentives, and rural development programs. These associations were made by the expert group, depending on the capacity that the system itself or its environment would have to promote the evolutionary deployment of a certain variable.

Once the axes were formed in a 2x2 matrix, four titles were assigned to the plausible scenarios, considering the characteristics, trends, discontinuities, weak signals, wild cards, driving forces, and social actors that should be emphasized for each alternative. In this way, with the experts' collaboration, the dynamics that the system would have if each of the alternatives were to be materialized. The four future alternatives are summarized in Table 7.

[3] It is the strength ratio of the actor taking into account its maximum direct and indirect influences and dependencies and its feedback.

Figure 1. **Map of indirect influences/dependencies**



Source: authors, using LIPSOR Software, MICMAC Version 6.1.2.

Design of the Futures Triangle 2.0

The Futures Triangle 2.0 represents an important resource in refining the future narratives. In the first participatory round, it became evident that several edges corresponding to different scenarios coincided in their scores. Therefore, according to Fergnani's (2020) methodological guidelines, these should be redone so that the long-term visions reflect non-redundant possibilities. With the second participatory round, narratives were developed that further accentuate the characteristics that differentiate these plausible futures. The average values obtained for the four scenarios are displayed in Figure 6.

Narrating the desired scenario: "National Pioneers"

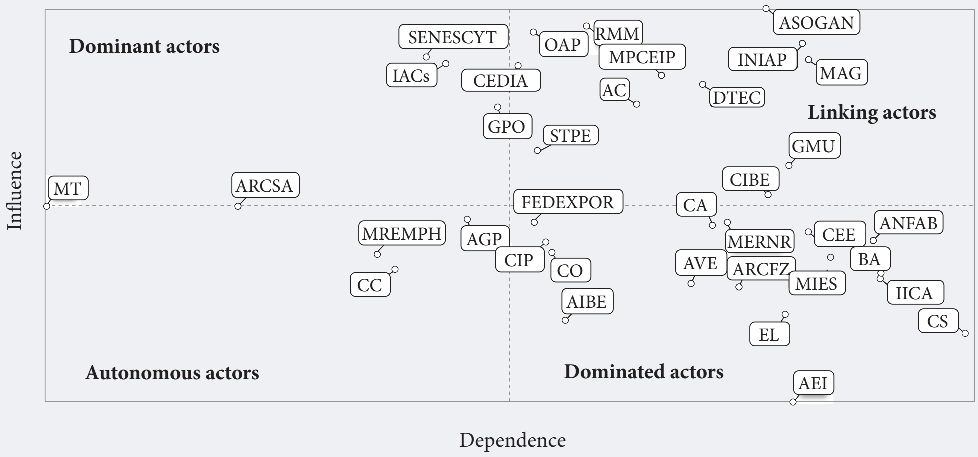
In the year 2035, the conditions have favored the Santo Domingo beef agrifood network regarding the placement of beef products at the national and

Table 3. **Groups of analyzed variables**

Group	Description
Determining variables	Contextual systemic variables that do not depend on the system's behavior, but have an impact on it, such as the macroeconomic situation.
Environmental variables	Variables that influence the system, but are not very dependent on it, although they are more integrated than the determining variables. They may refer to various topics such as climate change or the legal framework.
Secondary variables	They show a similar level of dependence to the environmental variables, but their influence on the system is somewhat lower. Their effects upon the system are more specific and less generalized, i.e. the impact of their dynamics is more localized and specific to some of the phases of the ABNSDT.
Autonomous variables	No autonomous variables were identified, which can be explained in two ways. The first is methodological and expresses that all the identified variables considerably integrated into the system's dynamics, either by their influence or by their dependence. The second way in which this absence can be explained is that, according to Godet (1993), these variables correspond to past trends or inertias of the system. Their absence therefore shows the recent dynamics in the formation of the ABNSDT.
Regulatory variables	Fundamental variables in the functioning of the system. They are variables that have the possibility of generating important changes in the dynamics of the ABNSDT, both from the point of view of potentialities and limitations.
Outcome variables	Variables that, although they will have very little impact on the dynamics of the system, depend to a large extent on its behavior, and are therefore considered good indicators of the final results obtained, such as food sovereignty.
Target variables	Variables at which the dynamics of the system should be aimed; that is, the behavior of the variables previously analyzed should underpin the behavior of the target variables. In the context of ABNSDT these variables are related to production and its sustainability.
Key variables	These variables make it possible to operationalize the system's dynamics. These variables constitute strategic elements where efforts such as rural development and animal biotechnology programs can be strengthened. From the consumers' point of view, they include the target's preferences and the quality of the final product; whereas from a more transversal point of view, human capital development, government incentives and innovation strategies that mobilize a transition to the bioeconomy stand out. This view reveals the challenges in the ABNSDT that cannot be seen unilaterally or by sector, which is one of the key findings of the Prospective process.

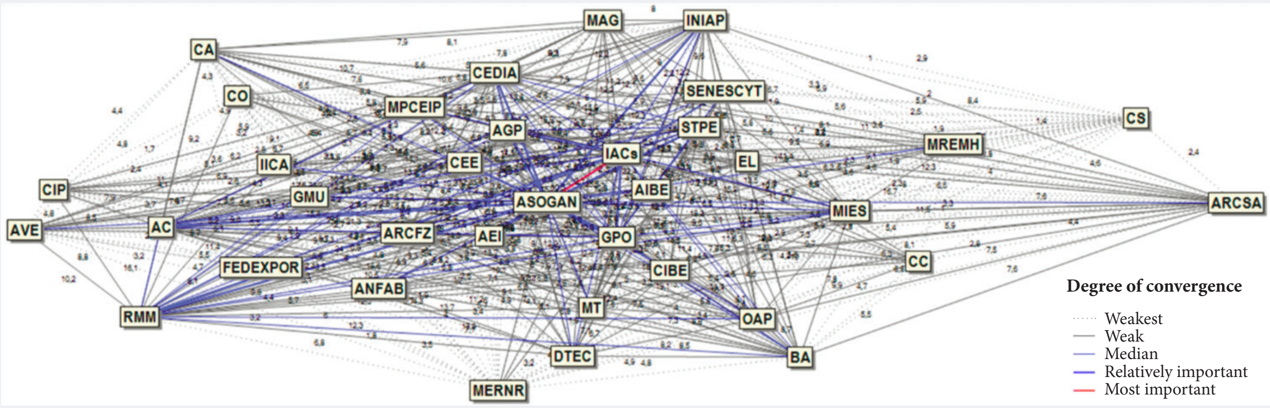
Source: authors.

Figure 2. **Map of influences and dependencies among actors**



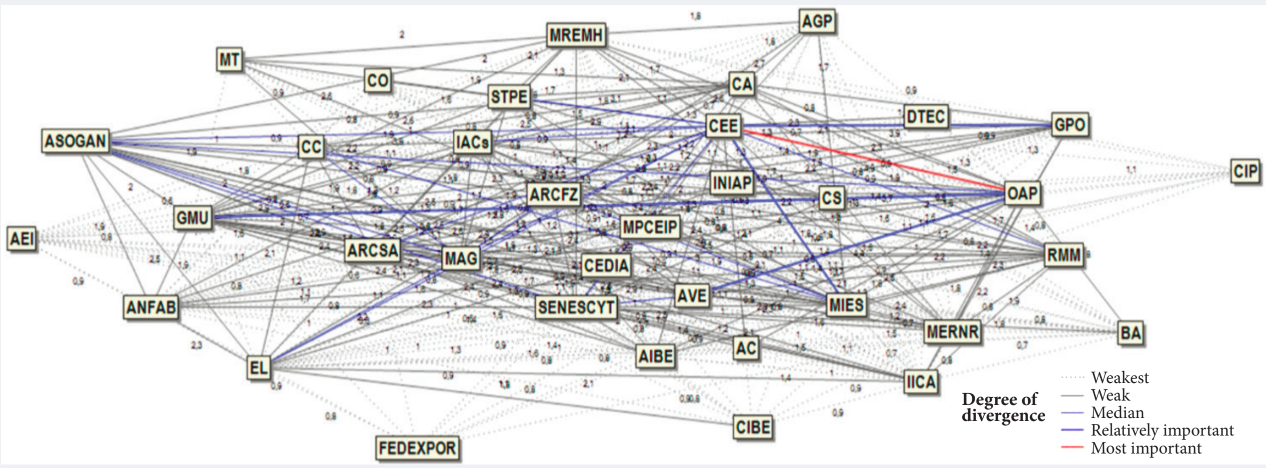
Source: authors, using LIPSOR software, MACTOR version 6.1.2.

Figure 3. **Convergences between actors**



Source: authors, using LIPSOR software, MACTOR version 6.1.2.

Figure 4. **Divergences between actors**



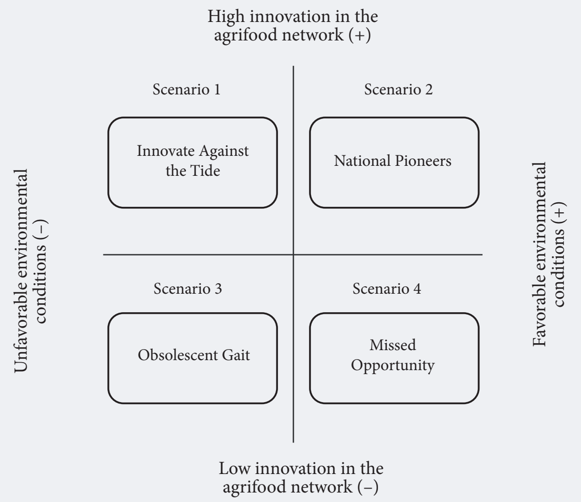
Source: authors, using LIPSOR software, MACTOR version 6.1.2.

Table 4. **List of actors**

№	Name of the actors	Code
1	Academic Sector	AC
2	Phytosanitary and Zoosanitary Regulation and Control Agency	ARCFZ
3	National Agency for Health Regulation, Control and Surveillance	ARCSA
4	Agropesa	AGP
5	Alliance for Entrepreneurship and Innovation	AEI
6	Cattle Ranchers Association of Santo Domingo	ASOGAN
7	Association of Non-Alcoholic Beverage Industries of Ecuador	AIBE
8	Association of Ecological Value	AVE
9	National Association of Food and Beverage Manufacturers	ANFAB
10	Banks	BA
11	Supermarket chains	CS
12	Meatpacking plants and municipal slaughtehouses	CC
13	Chamber of Agriculture	CA
14	Chamber of Industries and Production	CIP
15	Biotechnological Research Center of Ecuador	CIBE
16	Ecuadorian Business Committee	CEE
17	Consumers	CO
18	Ecuadorian Corporation for the Development of Research and Academia	CEDIA
19	Technology developers	DTEC
20	Logistics businesses	EL
21	Ecuadorian Federation of Exporters	FEDEXPOR
22	Municipal GAD	GMU
23	Provincial GAD	GPO
24	Sustainable Trade Support Institutions	IACs
25	Inter-American Institute for Cooperation on Agriculture	IICA
26	National Autonomous Institute of Agricultural Investments	INIAP
27	Ministry of Agriculture and Livestock	MAG
28	Ministry of Energy and Non-Renewable Natural Resources	MERNR
29	Ministry of Economic and Social Inclusion	MIES
30	Ministry of Production, Foreign Trade, Investments and Fisheries	MPCEIP
31	Ministry of Foreign Affairs and Human Mobility	MREMH
32	Ministry of Telecommunications	MT
33	Other producer's associations	OAP
34	Municipal market networks	RMM
35	National Secretariat of Higher Education, Science, Technology and Innovation	SENESCYT
36	Technical Secretariat Planifica Ecuador	STPE

Note: translated from Spanish; the codes reflect the Spanish titles.
Source: authors, using LIPSOR software, MACTOR version 6.1.2.

Figure 5. **2x2 Matrix for scenario construction**



Source: authors.

foreign levels. This has been possible with the application of proactive and opportunistic innovation strategies that originated in the year 2022, which have given anticipatory responses to variations in preferences caused by new members of the network. As a result of the above, the Cattle Ranchers Association of Santo Domingo, the Technical Secretariat Planifica Ecuador, and the institutions supporting sustainable trade have invested heavily in research in order to become as the most important network in the country in terms of technical and market dominance.

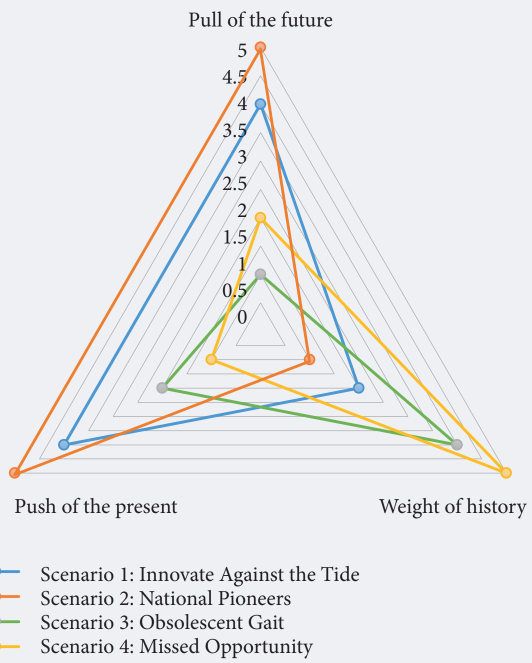
Therefore, the quality of the final product in the regular and premium supply exceeds national standards and competes with excellent results on European markets. In addition, livestock production in Santo Domingo is considered to have the highest genetic value due to the appropriate integration of biotechnology, which has enhanced animal breeding and reproduction. Similarly, the automation of production processes has been achieved through the use of technological packages from government incentives.

Moreover, a system of organic beef production has been consolidated in response to new sustainability demands and the national desire to establish circular economy models with eco-friendly production. Similarly, the agrifood beef network has been supplied with technical devices and computer products designed by local human capital that has been specialized with the support of SENESCYT. Also, with the help of rural development programs promoted by the provincial government and the Ministry of

Table 5. **Types of actors**	
Type	**Description**
Dominant actors	Actors who have a high capacity to influence and, in turn, are little influenced by the other actors in the system. These are mainly institutional external actors who represent mainly the central or decentralized State (provincial autonomous governments).
Linking actors	Fundamental actors in the system since they largely depend on the behavior of the other actors. In turn, they have a high impact on the dynamics of the ABNSDT. The profile of these actors is diverse and includes national and local government institutions, private actors that go through all phases of the ABNSDT and the Academic sector. This diversity shows that the major challenges in the ABNSDT are multiple and cannot be addressed by a single actor, but rather through participatory processes of joint interaction that enhance agreements and resolve disagreements. In this sense, it is important to identify convergent and divergent positions from the perspective of this diversity of actors.
Autonomous actors	Actors with low capacity to influence and low dependence on other actors in the system. In this case, their actions have a minor, but not absent, relevance in relation to the system's dynamics. These are actors with little room to maneuver in the formulation of their strategies.
Dominated actors	These are actors with low capacity to influence, but very dependent on the other actors in the system. These are, in general, businesses, trade unions and civil society actors that will be greatly impacted by the dynamics of the ABNSDT. In the case of national public institutions in this category, these are actors that deal with the central theme of the system in a complementary manner, without the ABNSDT being an essential part of their competences.

Source: authors.

Figure 6. **Futures 2.0 triangle of the 4 plausible scenarios constructed**



Source: authors.

Agriculture and Livestock, the national beef agrifood network has been established with greater integration between all players. As a result, the creation of a bioeconomy system based on the production, utilization, and conservation of biological resources for resupply has been consolidated, integrating producers outside the Cattle Ranchers Association of Santo Domingo and municipal market networks that have been strengthened with the support of crowdfunding.

Conclusions

In this study, four plausible scenarios were established for innovation in the Santo Domingo beef agrifood network by 2035. The relevance of these visions of the future lies in their anticipatory and strategic utility, which can guide decision makers. Therefore, they should be considered an input for the next plan generated by the Autonomous Decentralized Government of the province, since the development of the rural and livestock sectors appears as one of its main institutional competencies.

As an essential part of this research, the eight key variables of the system under study were determined. This showed that, from the perspective of innovation, the axes that shape the future of the agrifood network are related to its capacity for tech-

Table 6. **Challenges for the system to the year 2035**

Future challenges	Number of agreements	Number of disagreements	Degree of mobilization
1. To lead in the placement of beef products at the national level through the adoption of offensive and opportunistic innovation strategies.	48.2	–0.7	48.2
2. Increase the quality of the final product in the regular and premium offerings to the level of foreign competition.	39	–3.4	35.6
3. To convert Santo Domingo's livestock production into the one with the highest national genetic value through the integration of animal biotechnology.	39.7	–2.8	36.9
4. Automate production processes with partial support from government resources.	46.2	–2.6	43.6
5. Consolidate an organic beef production system in response to changes in target preferences.	51.9	–0.6	51.3
6. To supply the agrifood beef network with technical devices and IT products designed by specialized local human capital.	42	–3.8	38.2
7. Establish the national beef agrifood network with greater integration with the help of rural development programs.	37.2	–3.1	34.1
8. Create a bioeconomy system based on the production, utilization and conservation of biological resources for replenishment.	37.5	0	37.5
Source: authors.			

Table 7. **Description of scenarios**

Scenario	Description
Innovate against the Tide	The high level of innovation in ABNSDT is achieved through the private initiative, since the government's capacity for action is limited by budget issues and political interests.
National Pioneers	The level of innovation in the ABNSDT is exceptional and places it as the most important beef agrifood network in Ecuador. This is achieved with the link between the private companies, the public sector, the Academic Sector and other relevant social actors. This scenario meets all the future challenges for the ABNSDT.
Obsolescent gait	The level of innovation is low in the ABNSDT, due to the poor management of the public and private sectors. The main problems are the disarticulation of social actors and the scarce investment in the agrifood sector.
Missed opportunity	The low innovation in the ABNSDT is the result of the waste of government funds by the ranchers. Organizational and leadership problems in the agrifood network prevent the receipt and use of state allocations.
Source: authors.	

nical advancement and modernization in each link and to the surrounding conditions. In addition, due to the correct selection of experts and the use of specialized software, this phase could be carried out without major calculation problems, but will require repeated consultations to collect the necessary data.

Similarly, the strength and position of the 36 social actors that affect the system were identified. This was instrumental in mapping futures as it provides clarity by revealing the number of agreements and disagreements, as well as the degree of mobility for future challenges stemming from the key variables. In addition, the mathematical power of the selected method provided the Qi force relationships, which clarified the importance of convergences and divergences, since it demonstrated that alliances are established between actors with a high incidence and that conflicts occur with those that have moderate incidence.

On the other hand, an appropriate course of action was defined to achieve the desired scenario: National Pioneers. This will help local planners and decision makers recognize the priority changes to be made through the formation and implementation of programs and projects that will develop the conditions for all established innovative pathways to be fulfilled and ultimately achieve the desired vision in an estimated term of 15 years. As in previous phases, the work with experts was essential for organizing future challenges. At this point, however, three elements - the collective learning achieved, the common language created, and the solid knowledge of the system - helped to quickly group the challenges and identify tentative deadlines for their fulfillment.

Finally, it is recommended that policymakers continue with the prospective process and delve into the strategies to follow. In this way, the policies generated by the public sector and the programs and projects formulated by the private sector will be able to converge in planning documents that are more technically grounded in shared resources. It is also important to consider all technical assistance and economic support offered by international organizations, since several of them are constantly looking for long-term plans in developing countries. This, once again, shows the value of collaborative processes in foresight, not only in the study phases, but also during implementation.

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Evaluating the Impact of Technology Transfer from the Perspective of Entrepreneurial Capacity

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Abstract

This paper examines the benefits of and barriers to technology transfer from academia to industry perceived by entrepreneurs, and those particularly associated with the dimensions of Entrepreneurial Capacity. The presented study is one of the first in which the analysis of the topic goes beyond the high-tech sectors. It is based on a survey of representatives of Small and Medium Enterprises (SMEs) dedicated to the production of Leather and Footwear in Peru. The main findings were that the Absorption Capability dimension had a positive relationship coefficient with the understanding of the benefits of and barriers to technology transfer, while the Networking Diversity dimension presented a negative relationship coefficient. Likewise, this study shows that the main barriers to technology transfer were the fear of information leaks and the lack of training. The results of this research can add value for decisionmakers in industry, academia, and government agencies interested in science and technology policies.

Keywords: entrepreneurial capacity; strategies; technology transfer; SMEs; absorption capability; networking diversity; STI policy.

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Technology transfer comprises the exchange of skills, technology, or knowledge between academic institutions and industry (Henry et al., 2009). In recent years, this topic has begun to take on greater relevance due to its contribution to business competitiveness, especially in the Small and Medium Enterprises (SME) sector. Technology transfer involves a process that requires collaboration between companies, universities, research institutes, Technology Transfer Offices (OTT), and financing agents, among others, where the necessary conditions for favorable interactions can also be established (Rücker et al., 2018). All this can lead to creating sustainable innovative ecosystems with a vision for the future (Komlósi et al., 2019).

At the macro level, as the Triple Helix Model points out, the interaction between Business, Academia, and the Public Sector can occur through OTTs, Technology Parks, and Innovation Centers (Etzkowitz, Leydesdorff, 2000). These entities can help SMEs overcome the limitations they face such as the lack of unified networks that streamline the linking process (Shmeleva et al., 2021), access to infrastructure and human resources (Arredondo et al., 2016), as well as the lack of experience and strategic vision (Rogers, 2003; Jung, 1980). Unquestionably, universities play a key role in this process, since they offer a variety of technological services and products that favor productive development (Guerrero, Molero, 2019; Maresova et al., 2019; Baglieri et al., 2018), including the generation of new tools according to each context (Apa et al., 2020). Several Latin American countries such as Colombia, Mexico, Chile, and Peru have found a key element in this field to improve the competitiveness of their industries, allowing them to adopt new tools, transform their processes, and create value to meet the demand of the national and international market (Shmeleva et al., 2021; Garrigós, Nuchera, 2008).

Particularly, in the public sector of Peru, programs are offered to support adoption and technology transfers by providing access to financial resources, as well as strategic training. However, only 14.7% of companies, especially SMEs, include technology transfer activities in their innovation processes (CONCYTEC, 2016). To discover the factors that influence entrepreneurs to undertake technology transfer activities or eschew them, this paper examines the benefits of and barriers to this activity using the Entrepreneurial Capacity approach. Considering that SMEs were those with the greatest limitations in terms of technology transfer activities, they were chosen to be studied for this reason, specifically SMEs in the Leather and Footwear sector in Peru. For the purposes of this study, technology transfer is related to Entrepreneurial Capacity through two of its dimensions. First, Absorption Capability, which represents the ability to obtain and process data from the environment to improve company decisions, and secondly, Networking Diversity, which is focused on the network of contacts that the company has to improve its strategic orientation.

Technology Transfer and Entrepreneurial Capacity

Technology transfer comprises the exchange of skills, technology, or knowledge between different entities, primarily academia and businesses (Henry et al., 2009). In the last two decades, various models have been proposed for the link between both entities (Maresova et al., 2019)], involving the public sector as a facilitator agent that can promote the success of transfer programs (Shmeleva et al., 2021; Tunca, Kanat, 2019; Baglieri et al., 2018). Technology transfer involves a process that not only entails important benefits but also barriers, elements that have been addressed mainly using descriptive and qualitative approaches (Hafeez et al., 2018; Collier et al., 2011; Shen, 2017). These studies highlight the need to have intermediate communication mechanisms and channels that make scientific and technological exchange feasible (Gilsing et al., 2011; Balconi, Laboranti, 2006), which requires legal support (Kenney, Patton, 2009) as well as financial resources (Mojaveri et al., 2011; Martyniuk et al., 2003). To facilitate the interactions between companies and universities, the latter use Technology Transfer Offices (TTOs) and the public sector employs its equivalent, Linkage Centers, to overcome barriers and highlight the benefits of the technology transfer process (Goel et al., 2017).

Several benefits that produce technology transfer activities have been identified as drivers of innovation, new product development, improvement of products and services, access to financial resources, infrastructure improvement, and shared risk among participants. Through technology transfer, companies have also developed new management competencies and improved the professionalization of their people (O'Reilly, Cunningham, 2017; Hofer, 2009), increasing their competitiveness. On the other hand, for a successful technology transfer, various barriers must be overcome, for example, the lack of financial resources, support from senior management, qualified human resources, training, proper guidelines for the implementation of new technologies, and trust between partners. Futhermore, skepticism poses a barrier, as does limited planning and forecasting, scarce R&D activities, inadequate or insufficient information, deficient communication, cultural barriers, resistance to change, as well as organizational and country risks. (O'Reilly, Cunningham, 2017; Khan et al., 2017; Hofer, 2009).

Although various barriers and benefits have been detected in technology transfer activity, it would add a lot of value for SMEs to also examine their relationship with Entrepreneurial Capacity to identify opportunities for development and strategic linkages. According to Rodríguez-López and Souto (2020) and Zeithaml and Rice (1987), Entrepreneurial Capacity is an ability acquired by entrepreneurs to develop a project or business while minimizing risks, making decisions in uncertain environments, adapting to rapid growth in volatile contexts, and maintaining an efficient work network with other companies in the sector. In this way, Entrepreneurial Capacity integrates the strategic vision and understanding of the context where the project or business is developed (Bacigalupo et al., 2016; Shane, Venkataraman, 2000; Frese, Gielnik, 2014), for which the analysis of information (information analysis) with a long-term vision is essential. In addition, Entrepreneurial Capacity is often associated with the company maturity level (Dunham, 2010; Kodithuwakku, Rosa, 2002) and productive efficiency (Rodríguez-López, Souto, 2020).

In particular, Radoslaw (2014) proposes that Entrepreneurial Capacity comprises two critical dimensions, which were considered for this study. The first, Networking Diversity, establishes a number of inter-organizational links between the company and external partners at local, regional, and national levels while taking into consideration information and knowledge connections. The second dimension is Absorption Capability, which represents the efficiency of companies in understanding, processing, as well as using information internally and correctly, transforming it into knowledge that generates value, thus facilitating the identification of opportunities.

Current State of the Leather and Footwear Industry in Peru

According to the Banco Central de Reserva del Perú (2021), total national Non-Primary Manufacturing in Peru accounts for 8.4% of Gross Domestic Product (GDP). The Leather and Footwear sector is included in this category, and it represents 1.1% of total national Non-Primary Manufacturing previously mentioned, which means it accounts for 0.13% of GDP (BCRP, 2021), generating employment for more than 45,557 people in the country, 42.3% of which corresponds to the La Libertad region encompassing the cities of Trujillo, El Porvenir, Florencia de Mora, and La Esperanza. In these cities, there are a total of 3,148 formal businesses, from micro-enterprises to small and medium-sized enterprises (Cosavalente, 2019). However, a large part of these entrepreneurs lack access to information and financing, limiting their entrepreneurial capacity for technology transfer (Roca, 2015). Centers for Productive Innovation and Technology Transfer (CITE) financed by the government are key agents for reducing this gap, since they can facilitate the adoption of knowledge and technological resources that lead to better performance. Although there are studies related to technology transfer in Latin America, their focus has been mainly associated with highly technical industries, such as the study by Arenas (2018) specifically focused on start-ups. Therefore, it is important to delve into other fields, such as the SME sector, which is more traditional.

Peruvian entities, such as the National Council for Science, Technology, and Technological Innovation (CONYTEC) and the Center for Productive Innovation and Technology Transfer for Leather and Footwear (CITEccal), promote the identification of potential technologies to be transferred in the leather and footwear industry to support the tanning and dressing of leather, the manufacturing of footwear and leather articles such as trunks, suitcases, handbags, briefcases, wallets, document holders, covers, cases, saddlery, garments, and clothing accessories, among others. In addition, CONCYTEC and CITEccal promote research projects on the development of new products and services in the leather, footwear, and related industries, including the reuse of waste as a way of innovating, as well as the use of clean technologies, and new techniques to reduce the negative impact on the environment. Particularly, CITEccal is developing various technological research projects such as the use of tanned fish skin in leather goods, preserving their color and patterns, and the recovery of chrome shavings for their reintroduction into the tanning process, and determining the optimal hydrolysis process for the recovery of hydrolyzed collagen and chromium salts. Likewise, CITEccal is continuously identifying technological advances such as leather dyeing through natural colorants, the functionalization of leather surfaces through the application of nanomaterials, and the technologies associated with the design and manufacture of comfortable and ergonomic footwear. For instance, the personalized footwear trend represents an opportunity to use technologies such as 3D printing for footwear and customized insoles, the 3D image of the foot using smartphones, biomechanical footwear for people with obesity, and personalized insoles to prevent pressure from ulcers in diabetic patients.[1]

So far in Peru there is no research that analyzes technology transfer and its relationship with the Entrepreneurial Capacity at SMEs. Given the importance of both elements for the development of companies, this paper seeks to examine the benefits of and barriers to technology transfer, and relate them to the dimensions of Entrepreneurial Capacity, for which four hypotheses were formulated, through which a descriptive model was proposed:

1) There is a positive correlation between Networking Diversity and perceived barriers to technology transfer.

2) There is a positive correlation between Networking Diversity and the perceived benefits of technology transfer.

3) There is a positive correlation between Absorption Capability and the perceived barriers to technology transfer.

4) There is a positive correlation between Absorption Capability and the perceived benefits of technology transfer.

[1] https://citeccal.itp.gob.pe/boletin-vigilancia-tecnologica-en-cuero-y-calzado/, accessed 25.01.2023.

Research Methodology

This study was developed through a non-experimental correlational-descriptive analysis in two phases. The first phase was the development of a questionnaire, which was divided into two sections. In the first section, Radoslaw's proposal was used to measure Entrepreneurial Capacity in two dimensions: Network Diversity and Absorption Capability (Radoslaw, 2014). For this, a total of 13 questions were established based on the indicated proposal, five of which correspond to the first dimension that considers local, regional, and national networking. The other eight questions focused on the ability of entrepreneurs to acquire, process, and transform information from the environment. The second section of the questionnaire was based on the Hofer (2009) scheme to assess the opinion on barriers to and benefits of technology transfer perceived by businessmen, for which 17 questions were established based on the aforementioned scheme. Nine of them focus on benefits, while eight focus on barriers. To record the responses, a 7-point Likert scale was used, with values ranging from 1 (totally disagree) to 7 (totally agree).

To determine whether the questions used in this research presented an adequate level of reliability, a Cronbach's Alpha coefficient was used for statistical verification. This coefficient was applied to a pilot test of 15 entrepreneurs representing the Center for Productive Innovation and Technology Transfer of Leather, Footwear and Related Industries (CITEccal) Trujillo from the La Libertad region in Peru, obtaining values greater than 70%, which confirm the reliability of the questions considered in the questionnaire. This demonstrates high internal consistency and the validity of the questions (Easterby-Smith et al., 2015), whose detailed parameters are shown in Table 1.

The second phase of the study involved sending a questionnaire to entrepreneurs enrolled at CITEccal, who had participated in training, services, and technology transfer processes between 2018 and 2021, who had at least five years of experience in the sector. For this, we worked with a database of 115 businessmen registered at CITEccal Trujillo, who met these criteria. A total of 81 businessmen answered the questionnaire over a period of two months, from May 20 to July 10, 2021.

For the processing of the obtained results, SPSS (version 22) software was used, through which the Spearman Rank Correlation Coefficient was analyzed as an inferential statistical method, thus verifying the relationship between the variables (Anderson et al., 2008).

Figure 1 shows the main barriers and benefits that influence technology transfer activities that are particularly present in SMEs in the Leather and Footwear sector in Peru. These elements were assessed via a questionnaire on a Likert scale to understand how they were perceived.

Results and Discussion

The results of the descriptive statistical analysis carried out are presented in Tables 2 and 3. The first table shows that the majority of businessmen who participated in technology transfer activities in the last three years and responded to the survey are: women (59.26%), owners of a company in a managerial position (48.1%), people with five to 15 years of experience in the Leather and Footwear industry (56.8%), and with ages ranging between 19 and 35 years (39%). On the other hand, the results in Table 3 show the perceived barriers to and benefits of technology transfer that entrepreneurs constantly face. As mentioned, the questions were prepared on a Likert scale with values ranging from 1 (totally disagree) to 7 (totally agree). The average value obtained in relation to the perceived barriers ranges between 4.963 and 5.383. These values are considered high as they are between 1 and 7 points and above the average. In the case of perceived benefits, the results range between 4.469 and 5.383, also considered high values. Among the three most notable barriers for entrepreneurs are the fear of information leaks, the lack of management of indicators, and the lack of information on how to use a technology (Table 3). Regarding the perception of benefits, businessmen consider that technology transfer allows them, above all, to promote three key elements: access to new clients and markets, links to universities and suppliers, as well as access to financing from public and private institutions. Furthermore, other benefits also motivate them to carry out technology transfer activities.

In order to evaluate the four hypotheses indicated in the previous section, inferential statistics were applied to determine correlation coefficients, showing the findings in Tables 4 and 5. Table 4 shows the first correlation between the Networking Diversity dimension and the perceived barriers to technology transfer of the 81 participating entrepreneurs, obtaining a p-value greater than 0.05, that is, a negative relationship ($p = 0.414$), for which reason Hypothesis 1 is rejected. Likewise, the second test presented corresponds to the

Table 1. **Cronbach's Alpha Values for the Studied Variables**

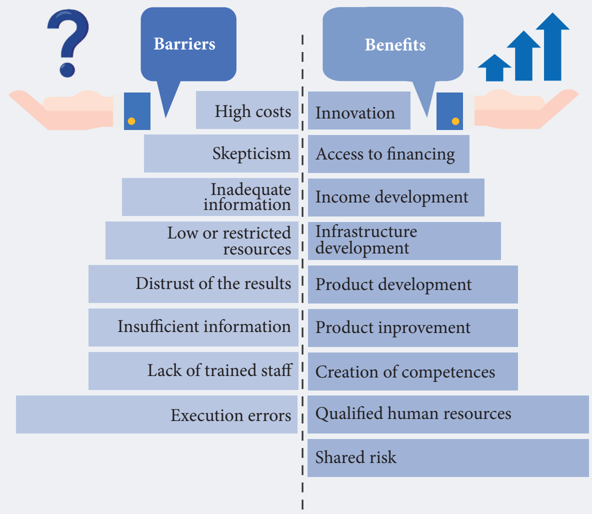
Variable	Cronbach's Alpha
Dependent Variables (Barriers, Attributes and Benefits of Technology Transfer)	
Barriers Perceived	0.909
Benefits Perceived	0.834
Independent Variables (Entrepreneurial Capacity Dimensions)	
Networking Diversity	0.840
Absorption Capability	0.836
Source: authors.	

Table 2. **Demographic Characteristics of the Respondents**

Item	Number of respondents	Share (%)
Gender		
Male	33	40.74
Female	48	59.26
Work Position		
Administrative Manager	12	14.8
Operations manager	5	6.2
General Manager	25	30.9
Owner	39	48.1
Work Experience in the Leather and Footwear Industry		
5–15 years	46	56.8
15–25 years	20	24.7
25–35 years	10	12.4
Over 35 years	5	6.2

Source: authors.

Figure 1. **Technology Transfer's Barriers and Benefits**



Source: authors.

relationship between the Networking Diversity dimension and the perceived benefits of technology transfer where a p-value of 0.997 was obtained, which is higher than 0.05 and leads to a negative relationship; therefore Hypothesis 2 is also rejected.

Table 5 shows the relationship between the Absorption Capability dimension and the perceived barriers to technology transfer, obtaining a p-value of less than 0.05 and a Rho coefficient = 0.352, which is considered a weak positive or valid relationship by virtue of the coefficient found, confirming Hypothesis 3. Finally, the Absorption Capability dimension was evaluated with the perceived benefits, obtaining a p-value less than 0.05 and a Rho coefficient = 0.558, which represents a moderate positive relationship, confirming Hypothesis 4.

Based on these results, a descriptive model is proposed of relationships between the Networking Diversity and Absorption Capability dimensions corresponding to Entrepreneurial Capacity with the barriers to and benefits of technology transfer, as shown in Figure 2. This model is the result of the analysis focused on SME entrepreneurs of the Center for Productive Innovation and Technology Transfer (CITE) of Leather and Footwear in the La Libertad region of Peru. It can be seen that the Networking Diversity dimension has a negative relationship both with the barriers to and the perceived benefits of technology transfer by entrepreneurs. While the Absorption Capability dimension presents positive relationships with the barriers and perceived benefits. In this sense, the study carried out shows that relationships with business partners and suppliers (Networking Diversity) do not necessarily favor the development of technology transfer activities.

Table 3. **Descriptive Statistics of Exogenous Variables (Perceived Barriers to and Benefits of Technology Transfer)**

Evaluated parameters	Mean value	Standard deviation
Barriers Perceived		
Fear of information leak	5.321	1.2925
Lack of management of indicators	5.284	1.1207
Lack of information on how to use a technology	5.272	1.0608
Skepticism	5.210	1.1260
Limited human resources	5.160	1.2496
Negative impact	5.160	1.2496
Uncertainty of results	5.111	1.2748
High costs	5.099	1.4196
Difficulty of adaptation	4.963	1.3365
Benefits Perceived		
Access to new markets	5.383	1.3093
Links with universities and providers	5.284	1.1644
Obtain external financing	5.259	1.2528
Reduce shortfalls in operations	5.000	1.2649
Ability to hire HR	4.975	1.3321
Product and process improvement	4.889	1.2942
New products and processes developed	4.630	1.0179
Processes to attract collaborators	4.469	1.6054

Source: authors.

Table 4. **Rho Spearman Coefficient of Diversity Networking and Barriers, Benefits, and Attributes (p<0.01)**

Independent Variable - Diversity Networking	Statistical indexes			
	Dependent Variable	N	Rho Spearman coefficient	P-Value
Variable 1	Barriers	81	0.092	0.414
Variable 2	Benefits	81	0.000	0.997

Source: authors.

Table 5. **Rho Spearman Coefficient of Absorption Capability and Barriers, Benefits, and Attributes (p<0.01)**

Independent Variable - Absorption Capability	Statistical indexes			
	Dependent Variable	N	Rho Spearman coefficient	P-Value
Variable 1	Barriers	81	0.352	0.001
Variable 2	Benefits	81	0.558	0.001

Source: authors.

On the other hand, the Entrepreneurial Capacity in this group of entrepreneurs is mainly based on their ability to process information from the environment (Absorption Capability), which allows them to better understand the characteristics and benefits of technology transfer.

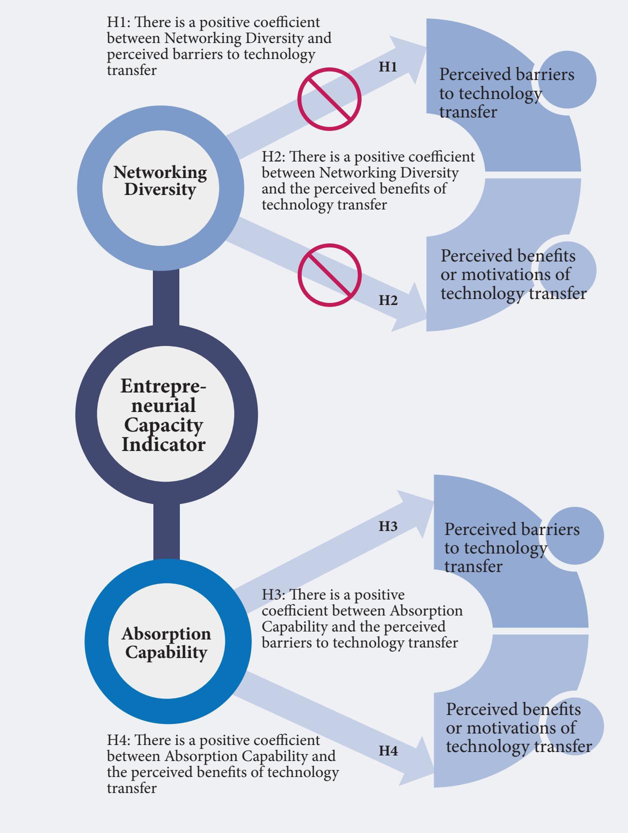
Conclusion

The objective of this research was to examine the benefits of and barriers to technology transfer relating it to the dimensions of Entrepreneurial Capacity for a total of 81 entrepreneurs registered at the Center for Productive Innovation and Technology Transfer (CITEcall Trujillo) for Leather and Footwear in the Libertad region of Peru. Research on technology transfer in this country is incipient. The most recent studies have focused on analyzing the effect of technology transfer on the development of ventures such as startups or spin-offs, but there are no references focused on traditional SMEs as in the case of Leather and Footwear.

The results of the descriptive analysis showed that the participants who carried out technology transfer processes in the last three years are mainly between 19 and 35 years old and have between five and 15 years of experience in this industry. Entrepreneurs in this sector have a high level of barriers, essentially due to fear and lack of personnel as well as poor readiness to take on new challenges. The benefits that most attract these entrepreneurs to carry out technology transfer activities are being able to reach new markets and form connections with specialized research centers at universities. The inferential analysis that was carried out shows that the Networking Diversity dimension of Entrepreneurial Capacity has a negative relationship with the perception of barriers and benefits by entrepreneurs, while the Absorption Capability dimension of Entrepreneurial Capacity presents a positive relationship with the aforementioned barriers and benefits. This shows that the ability of SME entrepreneurs to analyze information from the environment allows them to better understand the characteristics of technology transfer, while relationships with business partners and suppliers do not favor this process.

This result allows us to identify a clear opportunity to improve planning processes and the strategic management of technology transfer at SMEs in key sectors in Peru, such as Leather and Footwear, which represents 0.13% of GDP. This information can be useful for government agencies and decisionmakers in academia and industry, who could improve communication channels and linking activities to consolidate a diverse system of relationships for the benefit of technology transfers. Likewise, entrepreneurs could be trained to

Figure 2. **Descriptive Model of Entrepreneurial Capacity and Perceived Benefits of and Barriers to Technology Transfer**



Source: authors.

eliminate the barriers that affect confidence in technology transfer in the country, especially by reinforcing positive relations in the sector.

A limitation of this study is that this research did not consider all 115 businessmen registered in the Leather and Footwear CITE of the La Libertad region who have carried out technology transfer activities. However, 81 of them were interviewed, meaning 70.43%, to investigate Entrepreneurial Capacity and the perception of barriers to and benefits of technology transfer. Future research could compare the results with a higher percentage of interviewees within the same sector, as well as explore the similarities and differences of the results with other sectors in which the Peruvian government also invests, such as the textile and agricultural industries, to promote technology transfer. It is also recommended that one carry out a further analysis of business groups at the international level.

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Smart Automation for Enhancing Cybersecurity

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Abstract

In an intelligent automation ecosystem, namely in the context of Robotic Process Automation, there is a need to review the development and operation processes and practices. One must combine competences from these two areas for any organization's security. It is with security that quality, efficiency, and profitability become possible.

The elaboration of guidelines and best practices for the application of a DevSecOps culture is absolutely essential for Agile software development at any organization. In the digitalization era, teams increasingly need a collaborative method to involve several competencies and capabilities, from analysis to the implementation and evolution of a software product. Information security must be an integral part throughout the entire product's lifecycle, as without it, fundamental aspects of confidentiality, integrity, and availability put information and software security at risk of serious implications for the organization's business activities.

Without losing focus on customer needs, it is necessary to model software development practices, following more agile methodologies. In this way, teams can model the software throughout its lifecycle, focusing on adding value for the customer and ensuring they have greater certainty that requirements, plans, and results are 100% aligned with their needs.

This paper presents an analysis of and proposal for the continuous improvement of an intelligent automation platform at a large-scale multinational organization. In parallel, aspects that generate resistance to the implementation of a DevSecOps methodology within the scope of RPA code development are considered.

Keywords: robotic process automation (RPA); business process management; DevSecOps; intelligent automation

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Introduction

At any company or organization, there are numerous low-risk administrative tasks that are mandatory for the proper functioning of business processes. However, many of these tasks are repetitive and, in addition to being time-consuming, are obsolete, outdated, and could be performed more efficiently. Thus, an increasing number of companies are seeking to minimize their impact upon the productivity and efficiency of each employee.

Meetings, administrative tasks, e-mails, and answering phone calls consume a lot of employees' time at an organization and are sometimes are a source of distraction during the execution of certain repetitive tasks. As a result, performance and focus are inevitably reduced substantially, reflecting upon employee productivity and their contribution to the most important tasks for the organization.

According to research published in a Harvard Business School article, some breaks can be welcome for those who have been working hard, but the fact remains that humans are easily bored by repetitive tasks. The study found that when assigning a repetitive task to an employee for much longer than necessary, the person prefers to prolong this tedious task rather than finish it as quickly as possible (Brodsky, Amabile, 2018).

RPA, or Robotic Process Automation, is a technology that uses robots to do tasks previously performed by humans. These are not just any tasks, but rather repetitive activities that do not require critical thinking. Leading global giants such as Bosch, Siemens, Caterpillar, and others are constantly coming up with innovative ideas to optimize their processes. The main areas of automation are the inventory of products, the movement of goods around production facilities and warehouses with logistics optimization, safety monitoring, document management, and many more (Lu et al., 2020). By implementing these new technologies, manufacturers have more opportunities to speed up the production cycle, minimize human error, and improve productivity and product quality (Quazi et al., 2022).

However, the higher the degree of automation, the higher the cybersecurity risks and threats to the functioning of organizations. Proactive, customer-focused security opens the opportunity to anticipate, rather than react to, data breaches or cyberattacks. DevSecOps (an acronym for development, security, and operations), when implemented correctly from the beginning of a software lifecycle, allows one to reduce the costs associated with fixing security flaws by incorporating security into every step of the software development process. This approach can also be applied in the context of Robotic Process Automation (RPA).

Information security should be intrinsic in all Robotic Process Automation platforms, as well as in all planning, design, construction, testing, implementation, and evolution activities, focusing on data security, privacy, and authentication. One must enfore role-based access control to restrict access to the application based on the functions of each user.

Better control and management of activities within the scope of RPA, through the application of DevSecOps practices and with the automation of code review, is a significant asset for the quality of software releases, significantly reducing the number of incidents in production.

Robotic Process Automation

Robotic Process Automation or RPA is a software technology that streamlines the construction, implementation, and management of software robots that emulate human actions interacting with other software and digital systems. These robots perform a set of tasks following a process without any human intervention. All these technologies reduce the manual workforce, allowing organizations to automate business operations in an agile and cost-effective manner.

RPA can use Application Programming Interface (API) integrations as well as other automation technologies including Artificial Intelligence, Machine Learning models, and cognitive services such as Chatbots, Natural Language Processing, and Optical Character Recognition.

Through this technology, repetitive tasks can be automated, allowing employees to focus on more specialized and critical work. Furthermore, it can be seen in organizations as a potential method to streamline business operations, reducing personnel costs and reducing human error. This consistency can lead to fewer errors in key processes and, ultimately, increased revenue and improved customer service, which leads to greater customer satisfaction.

RPA presents itself as an efficient and productive solution for many tasks. For example, processing invoices is among the most time-consuming tasks. Invoices arrive through various channels and are then combined with purchase orders, and often need to be approved by different people for payment. In this way, it is possible to create rules to automatically send invoices to the right entity for approval, thus creating an improvement in the payment approval workflow. It is also possible to automate the purchase order review process using a checklist for further review before submitting for payment.

RPA implementations are popular in the banking and manufacturing sectors, it is also notable for its implementation in insurance, healthcare, high technology, and utilities such as telecommunications and energy in terms of accounts payable, accounts receivable, and general ledger processing. Whereas card activation, fraud claim discovery, claims processing, new business preparation, reporting automation, and system reconciliation process have high potential in banking and financial services, insurance, and healthcare sectors (Madakam et al., 2019).

DevOps vs DevSecOps

Modern development practices rely on Agile methodology, which prioritizes continuous improvement as opposed to the Waterfall sequential approach. If development teams work in silos without considering operations and security, the product developed may have operational problems or security vulnerabilities that may be financially or operationally inefficient.

DevOps (acronym for development and operations) has gained notoriety in recent years for combining key operating principles with development cycles, recognizing that these two processes must co-exist during the product lifecycle. Siloed post-development operations can make it easier to identify and address potential issues, but this approach slows software delivery. Implementing operations in parallel with software development processes allows organizations to reduce implementation time and increase overall efficiency (Lwakatare et al., 2019; Azad, Hyrynsalmi, 2021). DevOps is used by many large companies from the fields of electronics, online commerce, and delivery services (e.g., Starbucks, Etsy, Apple, Airbnb, Ashley Madison, etc.) and government agencies (US Federal Reserve, NASA, etc.) (Plant et al., 2022; Rzig et al., 2022).[2]

DevSecOps is an evolution of the DevOps approach, extending its capabilities by focusing on proactive cybersecurity assurance. DevSecOps is the efficient integration of testing and security protection throughout the software development and deployment lifecycle. Therefore, it will be necessary to think about the security of the application and the infrastructure from the beginning. In this multi-layered security approach, the focus is not just on establishing a layer of protection around applications and data, but on the entire context of implementation and integration, operation and maintenance, and use by end consumers.

Just like DevOps, DevSecOps is a mindset that needs to be shared by all team members who participate in the development and implementation of software. The adoption of an information security and cybersecurity culture along with other requirements, allows for sharing responsibility for any specific technology or technique, developing security methodologies that allow for greater control and speed in the management of vulnerabilities and security risks.

The goal of DevSecOps is to release software with higher quality, quickly and safely, thus following the same logic as DevOps. If security is implemented only at the end of the development pipeline, organizations using DevOps can become less efficient, as by not adopting built-in security, the likelihood of duplicate revisions and unnecessary recompilations increases, resulting in a longer delivery time, or even creating less secure code (Rajpakse et al., 2022).

DevSecOps is the movement working on the development and integration of modernized security methods that can keep up with DevOps. DevSecOps is a tactical three-pronged approach that connects three different areas: development, information security, and operations (Myrbakken, Colomo-Palacios, 2017). The goal is to seamlessly integrate security into the Continuous Integration & Continuous Delivery/Continuous Deployment. The CI/CD pipeline is a series of automated steps that must be performed to deliver a new version of the software. We can consider it a complete set of activities performed to improve the efficiency and effectiveness of software delivery throughout the software development lifecycle via automation.

DevSecOps has been successfully implemented by very different companies - Microsoft, Verizon, and the Pokemon Company - to ensure that their development and security teams work together smoothly (Swinhoe, Nadeau, 2019). For example, Verizon created a dashboard to monitor the occurrence of vulnerabilities in its business applications at all stages of the lifecycle (when it occurred and by whose fault). A comprehensive picture of vulnerabilities gives developers near real-time signals of the risks they may pose to the business, allowing them to find ways to improve their skills. The Pokemon Company, using DevSecOps, created a security framework to prevent leaks of the personal data of online game users, which improved the overall corporate security culture.

Finally, Microsoft created a tiered system of communication and experience sharing between different development teams. At the entry level, all employees are trained in standards of business conduct, including security. The next level allows for more in-depth security issues for all employees. The third level is for Microsoft engineers only. This is closed-door training that introduces them to what threat actors do and helps them understand the landscape

[1] https://threatpost.com/apps-built-better-devsecops-security-silver-bullet/167793/, accessed 22.01.2023.

[2] See also: https://digital.ai/catalyst-blog/9-companies-you-wouldnt-expect-to-be-using-devops/, accessed 22.01.2023.

of global risk. Developers and engineers learn the reasons behind Microsoft's security practices, the methods and tactics used by hackers, and the engineering tools available. The goal is to help them build a network of peers and resources that can be used to secure any project. The overall conclusion is that the better security professionals and developers understand what the other team is doing, the more responsive and cooperative they will be in the development process. This will lead to fewer vulnerabilities in the final product and faster fixes.

As new types of cyberattacks increase, securing development and CI/CD environments becomes increasingly important. An effective focus on security at the early stage of the development cycle, continuing throughout the product lifecycle, ensures that developers write more secure code, adopt security best practices, and respond quickly to vulnerabilities.

Case Study – DevSecOps Integrated into the RPA Platform

For business processes, the term RPA often refers to setting up software to do work previously done by people, such as transferring data from various input sources, such as email and spreadsheets, to systems of record, such as Enterprise Resource Planning (ERP), and Customer Relationship Management (CRM) (Lacity et al., 2015).

Deloitte posits that the design of the process is more relevant for the Return on Investment than the technology used. A published use case refers to the experience of a bank in the implementation of RPA technology, in which the bank redesigned its claims process, introducing 85 robots to run 13 processes, handling 1.5 million claims per year. The bank added capacity equivalent to 230 full-time employees at approximately 30% of the cost of recruiting more employees (Schatsky et al., 2016).

Regarding the present case study, Siemens Global Business Services focuses on digital solutions for business process optimization and, increasingly, value-add digital services. In 2017, Siemens decided to implement its first global RPA platform to serve the various internal services. The chosen RPA technology was from Blue Prism, as it is one of the most reputable market leaders. One of the key aspects was the fact that it was one of the most pioneering and mature brands on the RPA technology market. Assessing the state of the current RPA market, Gartner (Gartner, 2022) has identified 15 of the most notable RPA providers that offer complete enterprise solutions that can support an intelligent automation ecosystem or enterprise-wide RPA utility, where it features Blue Prism as a leader. Blue Prism's solutions are designed for large companies. It provides strong support for back-office automation and therefore it has become more suitable for industrial manufacturing companies and healthcare companies (Khan, 2020).

Compared to what the competition offered at the time, Blue Prism stood out for its centralized management, providing for the easy deployment of autonomous robots (fully automated runtime resources), but also meeting Siemens' mandatory financial and security policies so that it would be possible to implement this technology in the context of services within internal control over financial reporting (ICFR). Blue Prism fulfilled the main requirement for a Siemens technology partner in compliance with all these rules. ICFR is a process consisting of control policies and procedures to assess financial reporting risk and provide reasonable assurance that an enterprise prepares reliable financial statements. This prevails in the Sarbanes-Oxley Act (SOX), which requires companies to disclose their financial practices.

In this research, the RPA platform is analyzed in terms of its efficiency regarding the integration of the DevOps methodology with the security requirements of the organization. Siemens AG, in the context of digital services, has developed a shared service that includes support for internal Business Process Management. A centrally managed Blue Prism RPA platform automates repetitive, routine, and rules-based processes based on structured data entry. The RPA platform also integrates with other technologies to drive end-to-end automation. This platform is designed considering development, test, and production environments. All environments follow logical and physical segregations, and, at the level of the production environment, there is also the physical segregation of data.

Blue Prism software runs a predefined algorithm on the Runtime Client, i.e., a software robot, which allows the software to authenticate itself to the target applications in an encrypted form and interact with the GUI (Graphical User Interface) of the target applications such as running read/write data into user interface fields, interacting with elements like buttons or sliders, and so on, just like a human user would. An automated process is capable of operating multiple target applications. To operate a target application, the robot needs a user account and appropriate permissions within the target system, therefore, the robot is subject to the segregation of duties, respecting the principle based on shared responsibilities of a key process that disperse the critical functions of this process by more than one person or department. In this case, the same authentication in a system, for example SAP, could not register a purchase order and approve it.

Automated process diagrams are business workflows, which behave like software programs. These diagrams use basic programming concepts and create operational process flows as flowcharts. They are basically graphical representations of workflows to create, analyze, modify, and scale the capacity of the business. Every RPA developer has access to the Blue Prism application development environment. For this, environment segregations were created so that it is possible to maintain the Segregation of Duties in accordance with what is required for the security of the entire RPA platform. It is in this environment that processes and objects are created, which are then tested in the test environment and only after the User Acceptance Test has been successfully performed is the automation distributed to production, all this integration is executed and managed by the Release Manager, by CI/CD, or on an ad-hoc basis.

In the RPA service created exclusively for the Siemens organization, this approach aims to provide services for the development and management of the operation of RPA automations, for different business units of the organization. It appears that the demand for automated internal services is growing and technological integration is heterogeneous. It can be said that each automation task performed by RPA implies a specific level of development, which makes each software robot unique, both in terms of access to applications and in the diagram of the developed process.

The development of RPA automations based on the software factory approach can bring benefits when compared to conventional software development approaches. Among these benefits, consistency in delivery stands out, as it is possible to share the same resources and similar logic, although it is necessary to share knowledge such as training, documentation, and frameworks. However, using this approach to consistently apply previously acquired knowledge while developing multiple RPA automations can be an inefficient and error-prone process. Another benefit is the quality, due to the integration of reusable code it is possible to save time and resources in the development of automation, allowing one to dedicate more time to working on the unique functionalities of each automation. The expectation is that the probability of design flaws and code errors will be reduced, but without consistency in delivery excellence, it will be difficult to reduce the effort to deliver with quality. Finally, productivity, efficiency, consistency, and quality are discussed and allow for the delivery of each project in the shortest possible time with greater capacity to deliver new projects using the same resources.

Even after release for production, continuous monitoring is carried out. Whenever there is an irrecoverable failure in the robot's operation, the control room manager must alert the developer and the process owner to the fact that the robot is unable to perform the programmed task. Evidence of the operation is collected and the error is checked in detail. The incident can originate from different root causes. It could be something related to the software running on the virtual machine, communication/network issues, or automation issues. The latter might be identifiable if something in the application to be automated changed, or even whether the business process itself changed, but these changes were not reflected in the RPA process. In case of failure at the workflow level of the RPA process (process diagram), developer intervention will be required to resolve the issue.

In cases where it is necessary to correct an automation that is already in production, most of the time the developer will need to access the application to be automated in production to understand the differences in relation to what was developed in the quality environment. To fill this gap, a Blue Prism environment for emergency changes was created.

In the emergency Blue Prism environment, it is possible for the developer to use the production systems to minimize any differences found between the quality environments and the production environments. Therefore, in an automation for handling invoices or purchase orders in SAP, sometimes the quality assurance (QA) environments do not have the same quality in terms of data volume or its heterogeneity, which makes automation training difficult with dummy data.

Development in this emergency environment is part of Siemens' plan for its Business Continuity Management, thus enabling faster recovery from a failure, restarting the service as quickly as possible so that the business does not suffer major impacts due to downtime caused by an incident or disaster.

In the continuous integration and delivery process, an automation approach is adopted, integrating the RPA concept into pipeline management. The RPA automation itself generates the concept of a CI/CD pipeline, allowing all delivery management of new automations to be carried out in an automated way.

It is important that there are no inconsistencies in the tests performed on the UAT for new automations and major change requests. Documentation should show what type or level of tests were performed to facilitate the assessment of code integrity and resiliency. This procedure is not yet fully automated and it is at this stage that the quality control and acceptance of the authorization terms for passing the code to production is determined. The higher the number of incidents or bugs, the higher the reoccurrence of debugging in the emergency environment, which leads to a higher number of Emergency Change Requests, which in turn increase the CI/CD delivery pipeline. In certain cases, such as minor changes, validations, or tests, steps are skipped and the move to production is straightforward.

Intelligent Automation

RPA solution technologies, especially Blue Prism, allow people other than software developers to automate certain business processes quickly and cheaply. It is aimed at processes that are highly rule-oriented and whose requirements are very tactical or short-lived, aimed at justifying development in IT organizations that follows a service-oriented architecture (SOA), as well as those that encompass a set of tools of business process management (Slaby, 2012).

The Intelligent Automation Platform constitutes an RPA tool that has the capability of a workforce driven by software robots. The software is developed in the Microsoft.Net Framework and supports several platforms such as IBM Mainframe, Windows, Windows Presentation Foundation (WPF), as well as Java or the web. The tool offers visual design in a top-down approach, a view from the most general level to the most specific level with drag-and-drop functionality, allowing even non-technical users to automate a process by dragging components through a user-friendly interface.

Such characteristics ensure compliance with established security policies (configurable) and provide robust features as this system protects data through encryption and obfuscation. Algorithms ensure secure connectivity, storage, and access to data.

In terms of access control, this allows management to restrict functions by the group of users, such as authorizing specific user access to groups of robots, processes, and objects. Blue Prism software supports Payment Card Industry Data Security Standards (PCI-DSS), the Health Insurance Portability and Accountability Act (HIPAA), and the Sarbanes-Oxley Act (SOX) in order to provide the necessary security and governance.[4]

Such programs enable scalability with centralized management. This tool is designed to work intelligently without the need for manual interaction in all executions that occur in the automated process. To this end, the software provides a scheduling management module (Control Room), which allows for the automatic execution of an automated process according to a specific time. Thus, all processes can be automated as needed and can be monitored centrally. An enhanced monitoring tool provides detailed real-time feedback on robot status and health for a complete view of the entire digital workforce.

Blue Prism software is also known to be one of the main choices for large-scale implementation. In April 2015, Telefónica O2, owned by Telefónica Group, deployed more than 160 Blue Prism "software robots" that process between 400,000 and 500,000 transactions per month, generating a three-year return on investment of between 650% and 800% (Lacity et al., 2015).

Analysis of the Continuous Improvement Process

Siemens GBS strives for excellence in its digital services and is looking for continuous improvement processes that allow it to adapt its services to the most demanding quality controls.

Quality assurance has the potential to reduce errors or failures in the delivery of a provided service. In the case of RPA, the methods used aim to accommodate any development in the quality assurance of the target applications – systems that will be manipulated by RPA automation – which are not the best environment to develop processes with more resilience to errors. Therefore, it is necessary to create other mechanisms that can help create processes with the best quality. Increasing security automation in the development cycle reduces the risk of errors and the danger of misadministration, which could inadvertently lead to attacks or outages in the RPA service.

A code review aims to improve the quality of the final product, in this case, we will cover the RPA code. It is a systematic approach to reviewing other developers' code for bugs and many other quality metrics. Additionally, a code review verifies that all requirements have been implemented correctly. This process must be planned and executed at an early stage of development, timing is paramount as the review must be anticipated as soon as possible because a late and unplanned code review is more likely to be forced when robots are already running in production, which creates complications.

Security should be the focus throughout the development lifecycle. It is essential to regulate RPA security issues with a set of specialized controls. Creating threat models during the design phase, educating developers on secure programming practices, and

[3] https://www.blueprism.com/products/intelligent-rpa-automation/, accessed 22.01.2023.

[4] https://www.blueprism.com/resources/white-papers/how-blue-prism-sets-the-standard-for-secure-rpa/, accessed 22.01.2023.

conducting frequent code reviews with the relevant security teams will help increase overall code quality and reduce the number of issues reported during a secure code review.

An unplanned approach to continuous improvement creates the potential for business continuity risks, more specifically, this is the case when a large volume of objects is based on an old version of a given application. There is no RPA automation that is not affected by time, every week new technologies appear on the market and Siemens monitors the necessary updates so that its infrastructure remains secure to avoid the existence of software that is no longer supported and at the end of its life cycle. Due to these changes and innovations, it is necessary to pursue development in RPA as something changes.

As part of a robotic process automation governance framework, regular risk reviews and audits of RPA processing activities are required. Employees under the responsibility of the RPA service must be clear about their security responsibilities, which include managing access to the robotic process automation environment, logging and monitoring operations, and so on. There should be defined duties for conducting regular RPA information security compliance assessments and a checklist of security requirements for existing robotic process automation technologies. The respective cataloging of Confidentiality, Integrity, and Availability (CIA) levels of each RPA process must be considered in order to speed up the identification of risks in consequent audits of Internal Control over Financial Reporting (ICFR). CIA describes three crucial components of data and information protection which can be used as guides for establishing the security policies at an organization. If security on the RPA platform fails, the operations logs will need to be examined and reviewed by IT and security teams. Robotic process automation logs must be stored on a separate system in order to protect their security and forensic integrity.

The process of developing new RPA automations, in the first instance, needs to involve more criteria regarding the security and quality of the code. A secure code is higher quality code. Automated code review tools are essential for standardizing and scaling RPA code development efforts. It is necessary to review the RPA script or code as early as possible, so that the time spent on development is not in vain and to minimize the chances of repreatedly rewriting the code.

Conclusions and Future Work

RPA has already seen significant uptake in practice to support an intelligent automation ecosystem or enterprise-wide RPA utility. Contrasting with this practical adoption is the relative lack of attention to RPA in the academic literature (Syed et al., 2020; Ivancic et al., 2019). With the purpose of contributing to initiatives to achieve significant advances in the field, this study was conducted. It was based on the large-scale implementation of an RPA service at Siemens GBS, which in its portfolio of RPA use cases has hundreds of processes and objects for intelligent automation. The essential criteria for the theoretical foundations and practical understanding of the DevOps model in the areas of intelligent automation were approached, thus allowing for the implementation of DevSecOps in the RPA service of Siemens GBS. For this concept to work, it was essential to implement an Agile methodology by all teams inherent to the service, maintaining a culture of cooperation and involvement in aspects of continuous improvement and security throughout the entire life cycle of the product/RPA code.

It is necessary to provide tools that allow developers and operations to benefit from the efficiency and quality employed in the development of an RPA code and thus reduce bug fixing after delivery in production to considerably reduce downtime in the service of RPA robots. This goal will only be possible if both teams work on a collaborative model. By switching from a separate delivery model to the operations model, benefits are gained in terms of maintaining RPA after production delivery. The advantages can be significant when it comes to a large-scale implementation, which requires constant adaptations or changes to the already developed code.

An automatic code review solution mirrors the existence of flaws in the RPA code that need to be corrected. The use and integration of this solution in the Siemens GBS RPA service will be able to promote quality and thus improve resource management. It will be a major investment for the stabilization of the RPA platform, allowing for the development of safer, more stable and resilient automated processes that require less effort.

It is important to review the test controls by architects or senior developers, as the ease of debugging in production increasingly creates a risk at the security level. During a code change, fundamental security aspects must be taken into account, not only by looking at the developed code, but also at the entire process inherent in the development of a change in RPA use. This could involve the need to deliver a code for production without the correct testing process, or the non-involvement of the customer which poses the potential risk of the need for debugging in the post-production stage. Test environments should simulate all potential functionalities as much as possible and if it is not possible to apply all functional requirements, the development team should involve the operations team in the first instance as well.

The stability of an RPA platform in production is only achieved if there are fundamental requirements that are not ignored, as such exceptions increase risks and make cybersecurity attacks targeting RPA platforms more likely.

Most companies prefer to develop RPA software robots over multiple iterations using an Agile development methodology as this delivers faster value to customers. However, RPA implementations can include a mix of heterogeneous applications, components, and technologies running on multiple operating systems. As automation becomes an integral part of the digital transformation, organizations are increasingly embracing robotic process automation as it is easy to implement and uses software bots that reduce operational costs and improve efficiency. The actual costs of an RPA implementation largely depend upon the scalable power of the platform, as well as the quality provided during robotic process development. The lower its quality, the higher the maintenance costs. The inoperability of a software robot entails maintenance costs for a platform without the desired profitability.

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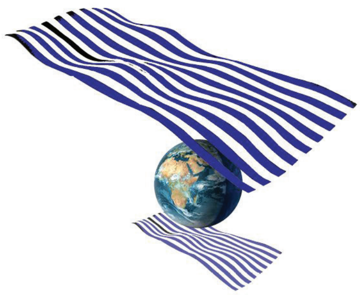

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