Economics of Innovation and New Technology

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/gein20

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To cite this article: Alenka Guzman , Flor Brown & Edgar Acatitla (2020) Conditional factors Pushing catch-up across developed and emerging countries in the nanotechnology sector, 2000–2010, Economics of Innovation and New Technology, 29:7, 670-688, DOI: 10.1080/10438599.2020.1715059

To link to this article: https://doi.org/10.1080/10438599.2020.1715059

ECONOMICS OF INNOVATION AND NEW TECHNOLOGY
2020, VOL. 29, NO. 7, 670–688
https://doi.org/10.1080/10438599.2020.1715059

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Conditional factors Pushing catch-up across developed and emerging countries in the nanotechnology sector, 2000–2010

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ABSTRACT

The aim of this article is to test national and sectorial technological and innovation capability factors, as well as social capability indicators, which could explain a possible conditional convergence across countries in nanotechnology within the context of a model of innovative technological knowledge β convergence. Based on growth convergence models, our proposal also takes into account the Schumpeterian theory, the National System Innovation –NSI– approach, and particularly the sectorial system of innovation and the technological catch-up hypothesis, as well as theoretical and empirical literature on conditional convergence. The findings allow us to confirm that new nanotechnology knowledge convergence is conditioned by a higher growth rate of technological capabilities in nanotechnology: growth from the initial level of patents granted, cumulative knowledge, and links to technological and scientific activities. Finally, as regards social capabilities, only the institutional weakness variable (corruption index) associates negatively with β convergence. As an emergent paradigm, we realize that convergence and catch-up are starting processes, which could allow less technologically developed countries to benefit from higher growth of some of the factors identified.

KEYWORDS
Conditional catching up; nanotechnology; technological convergence

JEL CODES
O33; O39; O47

Introduction

The role of technology is implicit in the classic hypothesis of economic convergence across countries. A country's ability to grow more than the initial leader, under certain conditions, has been identified as central to this hypothesis (Abramovitz and David 1966). Historically, countries have developed differentiated skills, which in the long term have led to them converging in various technological paradigms. Nanotechnologies constitute an emerging paradigm where other technological paradigms converge cognitively and include the possibility of heralding a convergence toward social wellbeing (Roco and Bainbridge 2013; Chakravarthy, Boehem, and Christo 2018; Kaviarasi et al. 2019). This reflects the idea that knowledge convergence will contribute to solving technical problems in different fields, thus having a major social impact.

The United States has played a leading role in the nanotechnology paradigm progress, followed by other industrialized countries along with marginal yet growing innovative activity by emerging countries.

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The aim of this paper is to test which national and sectorial technological innovations and social capability factors could explain a possible conditional convergence across countries in the nanotechnology sector within the context of a β convergence model. This model is based on the growth convergence models of Barro and Sala-I-Martin 1995 and Rogers 2003 yet also considers other approaches, such as: technology catch-up (Posner 1961; Cornwall 1976; Fagerberg 1987; Gomulka 1990; Abramovitz 1986) the Schumpeterian model (Schumpeter 1947 and Antonelli 2017) and the national systems of innovation -NSI- (Lundvall 1992; Metcalfe 1995), particularly the sectorial system of innovation (Malerba 2002) for the automotive sector (Faria and Andersen 2017).

We have chosen to study conditional convergence in the case of nanotechnology, because as an emergent paradigm, we are interested in testing whether less developed countries could close the knowledge and ability gap with leading countries and adopt technologies that offer a radical change in technological problem solving.

The new nanotechnology paradigm (NNP) opens up huge innovation potential given that matter possesses different properties at nano scale or size. Nanotechnology encompasses three main opportunity categories: biotechnology-inspired molecular engineering; electronic technology based on semiconductors (Enomoto 2019), and devices and processes based on new materials (Tegart 2003; European Comission 2011; Enomoto 2019). It is accepted that 'Nanotechnology is already evolving toward becoming a general-purpose technology by 2020, encompassing four generations of products with increasing structural and dynamic complexity: (1) passive nanostructures, (2) active nanostructures, (3) nanosystems, and (4) molecular nanosystems.' (Roco 2011, 427; Sreeramana and Shubharajyotsna 2016; Human Paragon 2017). All this assumes a transition to a productive model where materials are made step by step, manipulating the atom to obtain the desired characteristics.

In relation to the ICT paradigm or biotechnology, nanotechnologies could spread or will converge, through cognitive leadership.[1] This refers to nano biotechnology and nano microelectronics.

Several studies agree on the major benefits of nanotechnology development, which will spread to various industrial and services sectors (Enrich 2019) and could have a wide impact on social and economic development (OECD 2013; Scrinis and Lyons 2017; Enrich 2019). So we can expect nanotechnology to be the convergence between science, economy, and future society (Roco and Bainbridge 2001; European Commission 2011). Such a technological revolution, however, presupposes institutional changes but will also cause socio-institutional shifts, as Pérez (2004) has analyzed in similar processes.

Considering the interdisciplinary nature, broader opportunities in research and development, and potential paradigms, we are interested in identifying the factors conditioning nanotechnology knowledge convergence across countries[2] that will lead countries to a new wave of social and organizational processes, products, and systems.

The key questions in this research are: Is conditional convergence possible across industrialized and emerging economies in the nanotechnology sector? On which factors would such convergence be conditioned? Why do just a few emerging countries seem able to catch up in the nanotechnology sector? What are the conditions that have enabled the happy few to try and catch up and excluded so many other countries?

As a hypothesis, we expected technological and innovation convergence in nanotechnologies across countries in the long term, conditioned by their innovation and technological capabilities and also by their national technological and social capabilities. We expected that technological and innovation catching-up in the nanotechnology sector across countries might be conditioned by: i) a higher average annual growth rate (AAGR) of technological and innovation capabilities in nanotechnology than the leading country (initial conditions of inventive activity; accumulation of technological knowledge; links between scientific and inventive activities; inventive capabilities of researchers; novelties generated); ii) higher growth rates of technological absorption capabilities nationally (innovative effort; human capital; production capabilities; relative technological level; technological absorption capability), and iii) higher growth rates of countries' social capabilities (human development; efficiency of public institutions; macroeconomic stability) and lower institutional weakness AAGR. Therefore, we expected that only a few emerging countries would be able to achieve those three capabilities and follow a convergence or catching-up path.

In the second of the five sections in this paper, we summarize the theoretical background of economic technological convergence and catch-up. The third section analyzes technological and innovation dynamics, as well as their nature and gaps in nanotechnologies across countries. In the fourth section, we estimate and analyze conditional convergence across countries in this sector and propose policy recommendations based on our results. We also estimate the effect on the dependent variable caused by a marginal change in the independent variables in order to propose policy recommendations. Finally, we summarize the main findings of our research.

Theoretical background of economic and technological convergence and catch-up

This section presents the theoretical background of the paper by first examining the theoretical and empirical debate concerning economic convergence across countries and then pointing out technological and innovation convergence and catch-up. Finally, we highlight some preliminary ideas about convergence in the nanotechnology sector.

Is economic catching-up possible across countries?

The stylized facts reveal huge income differences, variation in productivity growth rates and a productivity gap across countries. How can we explain the relationship between these last two? Why are some countries so poor and others so rich? Are the poorest countries able to decrease the economic gap with their richer counterparts? These are just some of the questions addressed by notable economists in various theoretical and empirical studies.

Solow (1957) suggests that in the long term, all countries must converge toward the same level of capital per capita if they have the same savings rate. Numerous empirical studies using different theoretical approaches have attempted to show the validity of this hypothesis (Gerschenkron 1962; Baumol 1986; Delong 1988; Summers and Heston 1991; Barro and Sala-i-Martin 1992, among others).

Other authors associate convergence between countries to institutional factors (technical capabilities, educational system efficiency, financial, political, or commercial institutions) that may strengthen or hinder it. Within this framework of analysis, Abramovitz (1986) underlines that poor countries catching up to wealthy countries not only occurs due to the potential derived from the development gap but also depends on the *social capabilities* that less developed countries have to achieve it.

In the AK model, convergence could be explained by technological transfer rather than initial capital differences (Aghion and Howitt 1998). Convergence could even happen when there are constant scale returns. Endogenous growth models reveal that convergence across countries occurs in growth rates but not the levels, so that the initial gaps between countries remain. In this case, the long-term equilibrium path depends on the economy's initial conditions.

Regarding the endogenous growth approach, different empirical studies attempt to prove the hypothesis of convergence at the levels of income per capita and the nature of returns on capital. However, their results reveal two trends. On the one hand is convergence between two industrialized countries, while on the other, maintenance of the existing gap between poor and rich countries.

Other authors coincide on the absence of convergence. Hausmann and Hidalgo (2011) underscore that more than just convergence, countries experience divergence of capabilities. The more advanced ones have better conditions for accumulating even more capabilities. In contrast, less developed countries are unable to break into complex global production chains.

Knowledge diffusion could be important for the learning process between neighboring countries but does not necessarily assure a convergence process, because the assumption of the free flow of technological knowledge is not satisfied (Bahar, Hausmann, and Hidalgo 2014; Boschma 2017).

In their conditional convergence study, Barro and Sala-i-Martin (1992) test whether convergence toward the same stationary state is possible if all countries possess the same preferences and technology. This study confirms the predictions in the sense that convergence is associated with levels of human capital, higher skills, and greater technological progress rate growth (Romer and Sala-i-Martin 1990 and Lucas 1988). The insufficiency of the latter element reinforces backwardness in poor countries and hinders convergence. Amable (1993) confirms the predictions for backwardness in countries that lag far behind, characterized by weak social capabilities (low education level among the population and deficient innovation development in the country).

By considering that endogenous growth models do not include institutional variables, the evolutionary neo-Schumpeterian approach provides theoretical arguments to include institutional variables that could influence or foster the initial or progressive levels of the technological factors (Romer and Sala-i-Martin 1990).

Technological and innovation gaps, convergence and catch-up

Processes of economic convergence or divergence and catch-up have been associated with differentials in technological development and human capital (Abramovitz 1986; Baumol 1986), among other factors.

According to the *technology gap* hypothesis (Posner 1961; Cornwall 1976; Abramovitz 1986; Fagerberg 1987; Gomulka 1990), labor productivity growth is greater in countries with lower levels of initial productivity insofar as they are able to take advantage of existing technology in advanced countries through processes of technological assimilation and, consequently, develop convergent processes in relation to leading countries in the long term. Nevertheless, this possibility has led to theoretical discussion, according to empirical evidence. On the one hand, some authors discover that productivity labor gaps increase even more in the long term (Fagerberg and Srholec 2005), although some countries defy their lag, confronting leading countries and achieving a pattern of convergence and catch-up. Others, on the other hand, find that productivity convergence is located in specific sectors associated with structural changes (Hidalgo 2009; Rodrick 2011; Chansomphou and Masaru 2013). Moreover, countries with capabilities in new technology acquisition and dissemination experience faster growth (Rogers 2003).

A factor that helps explain convergence and catch-up of technology and economic growth between countries is technology transfer –TT– (Gerschenkron 1962; Gomulka 1990). However, the strategies used by some countries to take advantage of TT can differentiate them. The first study cited considers that countries might transfer technology easily through the coordination of market forces alone, without efforts to build some level of human skills and infrastructure. On the contrary, Gerschenkron finds it necessary to rely on these human and physical capabilities, including 'some degree of active intervention in markets by outsiders … ' either by private or government organizations, in order to be successful in the catch-up process (Fagerberg and Godinho 2003, 4).

Other authors suggest that catch-up by such countries as Japan is associated with an imitation process, which led to improvement of local technology, especially in open trade; higher investment; a high growth rate, and consequently an increase in imports (Baumol 1986; Gomulka 1990). Therefore, countries started to join the convergence club (Castellacci and Archibugi 2008; Rodrick 2011).

Thus, technological dissemination, direct foreign investment, and international trade affect the rate of technology transfer, with a positive impact on growth rates of innovation and labor productivity in technology by importing countries. Under such circumstances, less advanced countries can converge and catch up to the leaders, considering some specific aspects (Abramovitz 1986; Keller 2001).

There is a wide range of what has been defined as *technological capabilities* in different approaches and levels. But overlap exists when considering the term to mean effective skills for the use, assimilation, adaptation, and eventual profitable innovation from the absorption of technological knowledge and the R&D efforts made. (Westphal, Kim, and Dahlman 1984; Lall 1992; Kim 1997).

However, the ability of poor countries to catch up to wealthy ones depends not only on the potential derived from development gaps but also on the initial and further *social capabilities* that less developed countries possess (Abramovitz 1986) before reforming their institutions (Unido 2005) and, in particular, improving all the relevant factors of national technology and social capabilities (Fagerberg and Srholec 2017). Poorer countries will have a higher growth rate than richer countries until they build up their R&D efforts. Therefore, these countries could have opportunities to improve institutions and the necessary conditions for following a convergence path (Howitt and Mayer-Foulkes 2005). Intellectual property rights (IPR) systems and other institutions, such as free trade in different countries, are examples of the role institutions play in technology catch-up (Manca 2009). Consequently, institutional factors can boost or hinder convergence.

In terms of technology catch-up, there is a '… process by which countries may benefit from the existence of a stock of production knowledge available in the rest of the world (generally called a technology gap)' (Rogers 2003, 43). When the first initial relative technological level of backward countries is very low, then the technological appropriating process might also be low. Therefore, effort is required of developing countries to learn and absorb technology from the rest of the world. The absorptive capability 'must be high relative to the growth rate of technology in the leader country and the strength of the appropriate technology gap' (Rogers 2003, 52). These are necessary conditions for catch-up.

Investment in physical and human capital in underdeveloped countries must reach higher growth rates, but they should also undertake and essentially increase research and development activities. Once the imitative and innovative model settles, the interrelationship established between R&D and patents, capabilities for innovation, technology transfer, and growth of productivity will probably enable follower countries to join the path of technology and innovation convergence and catch-up. Global strengthening of intellectual property systems linked to trade agreements is a factor that could become a barrier for the imitation-innovation path.

Nevertheless, there are countries where the generation of knowledge that goes beyond R&D, labs, and patents is also key to the generation of technological capabilities encouraged for a knowledge governance context in follower countries that will favor the absorption of knowledge spillovers (Rogers 2003; Fagerberg, Fosaas, and Sapprasert 2012; Barletta et al. 2016). The evidence is clearer in the case of industrialized countries, but it has also been extended to newly industrialized (South Korea, Taiwan, Hong Kong, and Singapore) and emerging countries (China, India, and Ireland) (Fagerberg and Srholec 2005). Additionally, the gradient of capabilities between R&D profiles –informal R&D, innovation efforts without R&D, and no efforts at all– is very important when considering a firm's R&D profile.

An imitative approach allows less developed countries to boost their development, whereas catching up means that they have transitioned to endogenous innovative activity (Gomulka 1990). On the contrary, countries with weak social capabilities will maintain their technology and growth deficit (Amable 1993; UNCTAD 2003).

In the case of new sectors or new technological paradigms, poor countries are far away from the technological frontier, but their priority to acquire TT and increase scientific and technological efforts in order to learn and absorb novelties and profit from the trade in knowledge externalities in a modern institutional context could be an initial step toward breaking into these new sectors. East Asian countries have developed previously nonexistent high-technology sectors, such as information and communication technologies (ICT), biotechnology, and recently, industry 4.0 and nanotechnology (see the case of China: Zhang and Chang 2015).

Why studies with patents?

Several studies have recognized the importance of patents as a systematized and complete source of technological information for studying the path of innovations (Schmookler 1962), their nature and the flows of technological knowledge (Jaffe and Trajtenberg 2002) and specifically the flows from developed to developing countries (Hall, Jaffe, and Trajtenberg 2005), and the importance of inventions and their commercial value (Criscuolo, Narula, and Verspagen 2001). Regarding the importance of using patents for the analysis of technological capabilities and competitiveness, a study discovered that technological factors, as well as investment intensity and patents, are key for sectorial market shares, in addition to cost advantages/disadvantages (Dosi, Grazzi, and Moschella 2015).[3] Recognizing and benefiting from the potential of patent data, this work offers to study the phenomenon of technology convergence, which is explained below.

Is there empirical analysis of nanotechnology convergence across countries?

In the case of nanotechnologies, an analysis of convergence and catch-up in the sector estimates the technology gaps, first between the leading countries in the Middle East and other countries in the region, then among the leading countries in Asia, and finally in relation to the United States, the global nanotechnology leader (Gholizadeh, Naeni, and Moini 2015).

Another study aimed at estimating nanotechnology sector gaps among leading countries and followers is based on estimations of technological efficiency (Kim, Kim, and Yongrae 2014). As regards technological convergence in other sectors where patents are used as indicators, the authors identify the strategic positions of firms in the process by estimating patent network indices, based on patent citations.

As we see, studies of convergence in nanotechnology across countries are still scarce. Therefore, we attempt to contribute by modeling the conditional convergence in the nanotechnology sector across countries.

Within technological catch-up and NIS framework and a β convergence model, this research aims to test the factors that might explain possible conditional convergence across countries in the nanotechnology sector. In other words, once the conditional convergence model has been specified, we analyze 14 regressions with the different factors of innovation capabilities in the nanotechnology sector, technological absorption capabilities at the national level, and the social capabilities of the countries. Consequently, we seek to test the β convergence and find out which variables are correlated to the process.

Technological and innovation progress in the nanotechnology paradigm

This section characterizes the emergent nanotechnology paradigm and the differences in the nature of technology and innovation across countries. First, we take a brief look at the development of nanotechnology, followed by a comparative analysis of R&D efforts and the patents granted in the sector. Specifically, we then identify the technological and innovation nature in this new paradigm through patent data analysis by country. Finally, we show the innovation gaps across countries.

Emergence of nanotechnologies

Nanotechnology is recognized as an emergent paradigm (Drexler and Smalley 2003; Maldonado 2007; Poole and Owens 2007; Guzmán and Toledo 2009; Takeuchi and Mora Ramos 2011; Chakravarthy, Boehem, and Christo 2018; Kaviarasi et al. 2019), as it becomes an initial knowledge base of various scientific opportunities for future technological innovations and a restricted set of heuristics or search procedures on how to take advantage of them and ensure their appropriation. As it develops, we can consider it as a new technological paradigm, which implies a radical change in the solution to technological problems resulting in a new wave of processes, products, and organizational and social systems (Freeman and Pérez 1986).

The importance of nanotechnology is linked to the fact that it involves a scientific and technological revolution based on knowledge and abilities in order to measure, manipulate, and organize matter at the nanoscale of one-millionth part of one millimeter (Royal Society 2004;

Wennersten, Fidler, and Spitsyna 2008). Nanotechnology is predicted to become a fundamental convergence nucleus of science, economy, and future society (Bainbridge 2007; Roco 2011). Within this framework of knowledge convergence in nanotechnologies, some experts in the field consider it pertinent to discuss the arrival of a new technological revolution (Wennersten, Fidler, and Spitsyna 2008; Bainbridge and Roco 2016; Wang 2018).

In the new technological paradigm for nanotechnology, convergence is understood in terms of the ability of less developed countries to close the knowledge and ability gap with leader countries, manipulate and organize matter at the nanoscale, and achieve widespread adoption of technologies that offer a radical change in solving technological problems. The result is a new wave of social and organizational processes, products, and systems. Convergence implies a confluence on the cognitive and technological planes and in human activity (Roco and Bainbridge 2013; Bainbridge and Roco 2016; Du et al. 2019). The lines of communication between science and technology also underscore the complexity of the sciences.

Particularly, development and findings in nano sciences, characterized by the merging of the fields of physics, chemistry, biology, scientific and engineering materials, enable studying, designing, creating, and improving materials, devices, and systems at the nano scale (including thermal, electrical, magnetic, optical, and chemical properties). In the case of nanotechnologies, technological disciplines merge and find several application sectors in four fields (Abicht, Freikamp, and Schumann 2006, 17; Alvarez et al. 2018).

The joint approach is currently even higher, with the merging of nanotechnology-biotechnology-ICT-cognitivism (Confluence Nano-bio-ICT-cogno or simply NBIC). Today, the convergence of knowledge and technology for the benefit of society project –CKTS–, supported by several institutions in various scientific fields and countries, acknowledges that such convergence is the core opportunity for progress in the twenty-first century (Bainbridge 2007; Roco and Bainbridge 2013; Alvarez et al. 2018).

Due to their interdisciplinary nature, nanotechnologies open broad opportunities in research and development, and potential paradigms in nano materials, mass application nano manufacturing of products, molecular medicine and health, environmental processes, ecosystem and energy innovation, biotechnology and agriculture, electronics, information and communication technologies (ICT), and national security (Tegart 2003; OECD 2013; Scrinis and Lyons 2017; Alvarez et al. 2018; Marchiol 2018; Enrich 2019).

In relation to the ICT paradigm, the extent of its diffusion and application, not only to several economic sectors and new paradigms (biotechnology) but also to the human way of life, has been identified. Emerging nanotechnologies also have the potential of being recognized as meta-systems,[4] as this new paradigm extends to several technological paradigms related to its leadership. It also seems that they will modify society's way of life, with huge impacts in the economic and social fields and production processes in general.

Increasing efforts in innovation

R&D spending on nanotechnology during the 1980s is not easily identifiable. Most likely, such funding can be more accurately traced to nano science projects at universities and institutes, which were the seedbeds for nanotechnology (Cooper and Larsen-Basse 2006). Feynman's 1959 lecture was seminal for the future development of nano science and nanotechnology, while other groundbreaking works contributed to the development of nanotechnology (Drexler and Smalley 2003). In the early stages, there was much uncertainty about investing in this new field of knowledge, so R&D was not the focus of much investment.

By the early twenty-first century, there was a substantial commitment to funding R&D activities in this emerging paradigm. From 1997 to 2009, government spending on R&D worldwide had an AAGR of 16.6%. The figure in the United States (US) was 19.5%, compared to 25.4% for the European Union and 24.7% in Japan. The most surprising growth was achieved jointly by newly industrialized (South Korea and Taiwan) and emerging countries (China, Russia, and India, among others). In 2008, global R&D spending with private and public funding amounted to 15 billion dollars, of which the United States contributed 3.7 billion dollars (Roco 2011). Since 2009, various countries have reached major public R&D growth rates, such as the Russian Federation, Japan and Germany after 2014 (OECD/NNI 2013).

Per capita R&D spending on nanotechnology is another indicator that helps measure differentials in efforts devoted to developing new knowledge in this emerging paradigm. In 2008, Japan moved into the lead with 7.3 USD per capita, followed by Korea with 6 USD per capita, the US with 5.1 USD per capita, the European Union countries jointly reporting 4.6 and Taiwan 4.5.

During the 80s, inventive activity in nanotechnologies was marginal, and its growth was slow, perhaps because the nano sciences were at an initial stage of development and diffusion. Furthermore, entrepreneurs, institutions, and individuals were uncertain and did not invest heavily in R&D efforts. It was not until the 90s that patented knowledge in new nanotechnologies underwent exponential growth, showing the emergence of the NNP. From 1983 to 1989, USPTO granted 193 nanotechnology patents to residents and non-residents, and the AAGR was 22.8%. The number of patents granted over the next decade increased to 3,463, and the AAGR was 27.8% higher. From 2000 to 2010, the number of patents doubled, reaching 8,331, although growth was lower (11.7% AAGR).[5]

This significant performance accounts for the expansion of nanotechnologies as a radical change in the solution of technological problems accepted by firms, institutions, and individuals. Therefore, the growing evolution of nano patents suggests a faster diffusion of the NNP in the last decade.[6]

The dynamic of logarithm growth of R&D and patents across countries between 1997 and 2011 varies, as the figures show. Some have higher growth in R&D but not in patents (Figure 1).

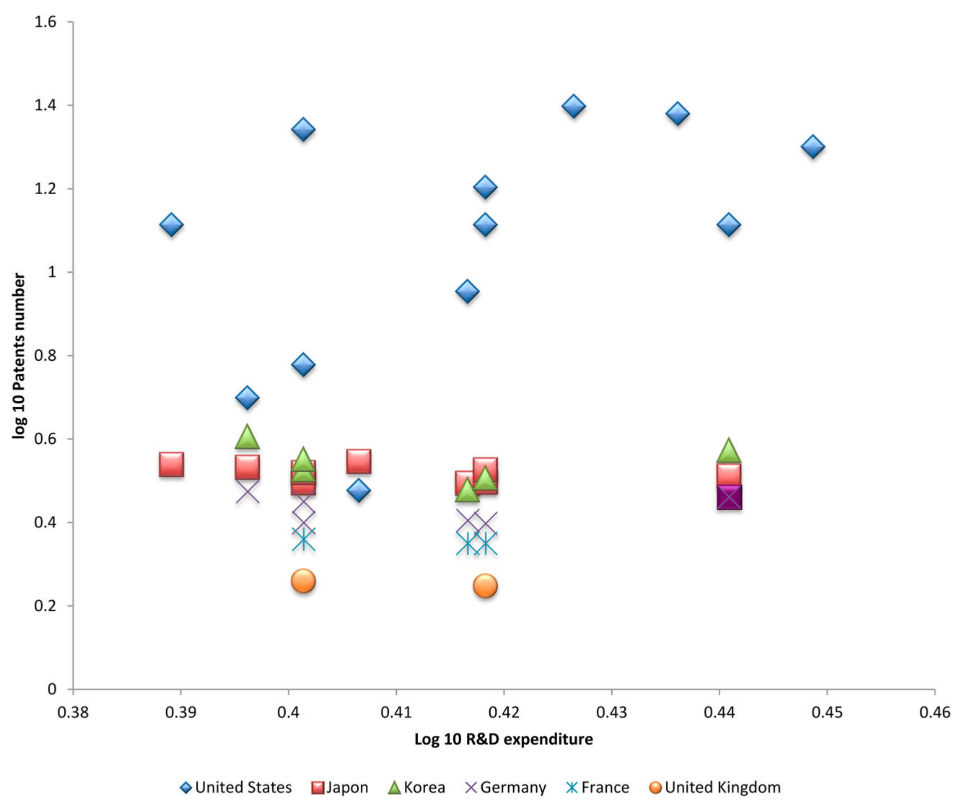

Figure 1. Nanotechnology R&D expenditure logarithm growth vis à vis nanotechnology patent logarithm growth in industrialized countries, 1997–2011. Source: Own estimation based on: OECD/NNI (2013), Key Nanotechnology Indicators, http://oe.cd/kni; and OECD, Main Science and Technology Indicators Database, www.oecd.org/sti/msti.htm, October 2018 and, USPTO CCL/977/700–863.

Innovation in nanotechnology by sector

In order to analyze the nature of innovation in nanotechnology, we built a sample of patents.[7] Concerning the different technological nanotechnology sectors, we identified that more than two fifths of patents belong to nanostructure (41.5%), a third to nano biotechnology and one quarter to nano chemistry. But if we take into account the classification by Jaffe and Trajtenberg (2002), a bigger technological class scope can be seen. Chemistry has the highest relative importance (37.2%). Nanotechnologies are also contributing to other new technological paradigms, as are ICTS (electrical & electronic, 18.3% and computer and communication, 1.3%) and biotechnology, 15.2%.

Innovation gaps in nanotechnology across countries

The United States is identified as the leader in inventive activity in nanotechnology, based on patents granted to residents and non-residents by the USPTO, with 63% of the total patent sample granted by the organism. Countries like Japan (10%), South Korea (7%), Germany (4%), Taiwan (3%), and China (2%) are much further behind. When we estimate a technological and innovation gap index in this sector, looking only at the number of patents granted, United States leadership is evident, while the closest followers are Japan and South Korea.

The gaps in inventive nanotechnology activity across countries are better reflected by the patents per million inhabitants index, where we have estimated each country's score based on that of the United States. This kind of index shows how other countries, such as South Korea, Taiwan, Ireland, and Israel, might surpass the United States as nanotechnology leader in a few years (see Figure 2).[8]

Factors affecting conditional convergence and catch-up in new nanotechnology knowledge across countries

This section develops the empirical study. We take a look at the hypothesis and how it will be tested and point out the data and the model proposed.

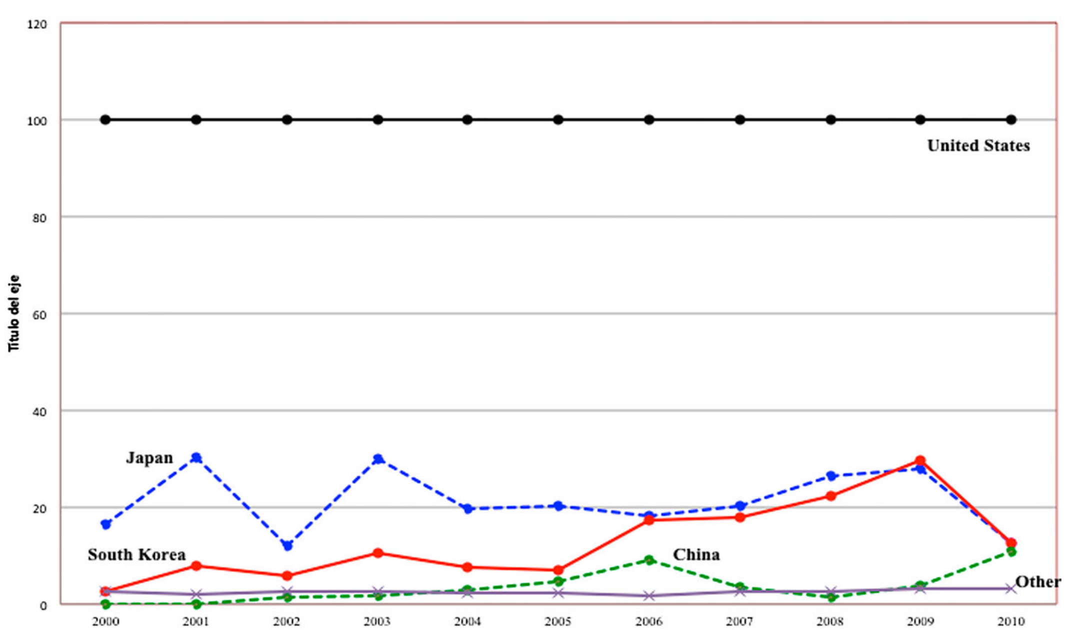

Figure 2. Technological and innovation gaps index across countries in nanotechnology, based on USPTO by million people. United States = 100.0. Source: Own estimation based on a random sample of 376 USPTO patents in nanotechnology granted to residents and non-residents CCL/977/700–863.

How do we test the contribution of factors to new knowledge conditional convergence in new nanotechnology knowledge?

The aim of this section is to propose and estimate technological and innovation convergence and catch-up across countries in the nanotechnology sector model conditioned to a higher growth of: i) technological and innovation capabilities in nanotechnology[9] than the leading country; ii) technological absorption capabilities at the national level; and iii) social capabilities of countries and smaller growth of institutional weakness.

Data

Our research is focused on a sample based on a population of 18,467 patents granted by the USPTO in 977 classes, where all patents in the technological field of nanotechnologies have been grouped together from 1995 to 2013.[10]

From the sample of nanotechnology patent data, we take into account: the number of backward patent citations, the number of citations of scientific articles made by nanotechnology patent applications, the size of teams of inventors in nanotechnology patents and the number of nanotechnology patent application claims. Other indicators and sources of information by country from 2000 and 2010 were also included, such as human capital, spending on research and development as a percentage of GDP, human development index, global competitiveness index, a country's relative technological level, the technological absorption capability of firms, the efficiency level of public institutions and the level of macroeconomic stability and institutional weakness (level of corruption) (The World Bank, n.d.).[11]

We are including 17 countries with nanotechnology patents granted by the USPTO systemically between 2000 and 2010: the United States, Japan, South Korea, Germany, Taiwan, France, the United Kingdom, Canada, China, Israel, Spain, the Netherlands, Ireland, Italy, Sweden, India, and Russia. Out of these, eight are industrialized, three are newly industrialized, and six are emerging countries. The United States, Japan, and Germany present a strong initial condition, in other words, a high initial level of inventive activity in nanotechnology. Although they present lower relative levels, other countries, such as Sweden, South Korea, Italy, Taiwan, United Kingdom, Canada, and Ireland, report high AAGRs for nanotechnology innovation.

Conditional convergence model for the nanotechnology sector. A proposal

The proposed model of conditional β convergence is formally specified in the following equation:

$$PatNano_{i,2000-2010} = \beta lnPatNano2000, i + \alpha_1 X_{1,i} + \alpha_2 X_{2,i} + \alpha_3 X_{3,i} + \varepsilon_i$$

where the dependent variable is: $PatNanoi_{2000-2010}$ = Growth of inventive activity in nanotechnology across countries in the period 2000–2010. This variable is expressed as the annual average growth rate of nanotechnology patents granted in country i for the period 2000–2010. β = the estimated coefficient of the study; $X_{1,I}$ = technological and innovation capabilities in nanotechnology of country$_i$; $X_{2,i}$ = Technological absorption capabilities at the national level and $X_{3,i}$ = Social capabilities of country i.

We define each variable and explain the proxy variable used in the following Table 1.

Statistical description of the model variables

Nanotechnology inventive activity growth across countries with a proxy as we indicated above ($Patnanoi_{2000-2010}$) has a mean of 2.1 and a relatively high standard deviation 12.3; it suggests big gaps of new nanotechnology knowledge growth rate across countries, as shown by the minimum of France (−16.97) and the maximum of Sweden (23.9). It means that the growth rate differs among the countries analyzed.

Table 1. Independent variables.

Variable	Definition	Proxy variable
$X_{1,i}$ = technological and innovation capabilities in nanotechnology of country *i*		
lnPatNano0,i	Natural logarithm of the number of nanotechnology patents granted in country *i* in the first year (2000).	Average percentage change of initial conditions of inventive activity in the group of countries.
$AtechNanoi_{2000–2010}$	Accumulation of nanotechnology technological knowledge country $i_{2000–2010}$	Nanotechnology backward patent citations applied AAGR for in country *i*.
$ScTecLinkNano_{2000–2010}$	Links between scientific activity and inventive activity in country $i_{2000–2010}$.	Citations of scientific articles made by nanotechnology patents applied AAGR for in country *i*. (Guzmán, Acatitla, and Vázquez 2016).
SizeRTNanoi2000–2010	Inventive capabilities of researchers in country $i_{2000–2010}$.	size of teams of inventors in nanotechnology patents AAGR in country *i*.
ClNanoi2000–2010	Invention scope of each nanotechnology patent in country $i_{2000–2010}$.	Novelties generated, recognized as claims in nanotechnology patents granted AAGR in country *i*. It is associated to: national practices diffusion; complexity of research activities; emergence of new sectors, and patent strategies.
A higher growth rate for each variable is expected to increase the propensity for innovation in the sector and favors the convergence of the nanotechnology sector of countries toward the leaders in ($\beta < 0$)		
$X_{2,i}$ = *Technological absorption capabilities at national level*		
$R\&D/GDPi_{2000–2010}$	Innovative effort in country $i_{2000–2010}$.	R&D in relation to country's GDP AAGR.
$Hki_{2000–2010}$	Human capital in country $i_{2000–2010}$.	R&D researchers by millions of inhabitants of $country_i$ AAGR.
$ProdCompi_{2000–2010}$	Production capabilities in country $i_{2000–2010}$.	Production and competitiveness global index of $country_i$ AAGR.
$TechHeighti_{2000–2010}$	Relative technological level in country $i_{2000–2010}$.	Technological index of $country_i$ AAGR.
$TechAbsCapFi_{2000–2010}$	Technological absorption capability	Firms absorption capability of $country_i$ AAGR.
A higher growth rate for each variable is expected to increase the propensity for innovation in the sector and favors the convergence of countries toward the leaders		
$X_{3,i}$ = Social capabilities of country *i*		
$DHIi_{2000–2010}$	Human development index in country *i*.	Country *i*'s index of human development AAGR.
$IPEi_{2000–2010}$	Efficiency of public institutions in country *i*.	Efficiency level of public institutions of $country_i$ AAGR.
$MacStrengthi_{2000–2010}$	Macroeconomic stability in country *i*.	Level of macroeconomic stability of $country_i$ AAGR.
$InstWeaki_{2005–2010}$	Institutional weakness in country *i*.	Level of corruption of $country_i$ AAGR.
A higher growth rate for each variable is expected to increase the propensity for innovation and therefore favor a convergence process across countries except of a higher institutional weakness AAGR.		

Relating to the initial value, $lnPatn{\sim}_{2000i,}$ the mean and the standard deviation (−1.3 and 0.6, respectively), where the minimum value corresponds to Taiwan, Spain, the Netherlands, and Sweden, with only a patent in the year 2000, according to our sample. While, the maximum value belongs to the Unites States, with 79 patents in the initial period in the sample. Even if in the logarithm terms the differentials are not so large, in absolute terms they are.

Concerning the other independent variables of technological and innovation capabilities in nanotechnology of countries ($X_{1,i}$) all of them have a negative mean, suggesting an AAGR decrease between 2000 and 2010. It could be interpreted that countries still have erratic building of their technological and innovation capabilities in nanotechnology. In contrast, almost all the independent variables have a high standard deviation. Therefore, we appreciate the bigger differentials among countries concerning these capabilities in this emergent paradigm, especially when we observe the minimum and maximum values. In the case of $AtechNano_{i2000–2010}$, $ScTecLinkNano_{2000–2010}$, $SizeRDNano_{2000–2010}$, and $ClNanoi_{2000–2010}$, the countries with minimal values are: Russia, Israel, the United Kingdom, and Taiwan, respectively. In turn, the maximum values are from the Netherlands, Sweden, and Canada for each variable.

Regarding the technological absorption capabilities at national level variables ($X_{2,}$), the mean is negative, too, for the case of $ProdCompi_{2000–2010}$, and $TechHeighti_{2000–2010}$. But, related to $R\&D/GDPi_{2000–2010}$ and $Hki_{2000–2010}$, and $TechAbsCapFi_{2000–2010}$, the mean is positive (2.3 and 2.5 and 3.8

respectively) and shows that on the average, countries are growing their innovative efforts, human capital, and technological absorption capabilities at the firm level. The technological performance of nations could favor the research and development activities on nanotechnologies conjointly with researchers and firms involved. So, countries in our sample that have made inroads in R&D activities, have also progressed in the academic training of researchers, increased capabilities of firms, and improved production capabilities and relative technological level. The standard variation shows that the gaps of technological absorption capabilities across countries are not as big as in the first independent variables group. In the case of $R\&D/GDPi_{2000-2010}$, the minimum and maximum values are for India and Israel. In the case of human capital, India has the minimum value and South Korea the maximum value.[12] Concerning $ProdCompi_{2000-2010}$ and $TechHeighti_{2000-2010}$ variables, Russia reports the minimum value for both; and the maximum value belongs to the United States twice.

Finally, in relation to social capabilities of countries' independent variables ($X_{3,i}$), we find that mean also has a negative annual growth rate for all the variables, slightly excluding $MacStrengthi_{2000-2010}$. It suggests that on the average, countries are not really improving the human development index, the efficiency of public institutions and reversing institutional weakness (measured by the index of corruption), although macroeconomic stability seems to show very little progress. The standard deviation shows lower differences among countries, probably because we are taking into account some developed and some emerging countries. The minimum values for $DHIi_{2000-2010}$, $IPEi_{2000-2010}$, and $MacStrengthi_{2000-2010}$ are from India, Russia, and Israel; the maximum values of these variables are reported by Taiwan, the Netherlands, and Russia.

This statistical analysis seems to confirm the speed at which countries are building the sectorial and national technological and social capabilities that could have conditional influence on nanotechnology knowledge convergence and catch-up (Table 2).

The United States, Japan, and Germany present a strong initial condition, in other words, a high initial level of inventive activity in nanotechnology. Other countries such as Sweden, South Korea, Italy, Taiwan, the United Kingdom, Canada, and Ireland, while presenting lower relative levels, report high AAGRs for nanotechnology innovation.

Model estimation

Based on the prior analysis, we specify the following final proposal for the model, for which the variables have been defined previously.

By analyzing the countries chosen, we realized that we did not have enough data to test the entire conditional model for convergence in newly proposed nanotechnology knowledge. Nevertheless, we

Table 2. Description statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
$PatNanoi_{2000-2010}$	17	2.108	12.292	−16.978	23.385
lnPatn∼2000i	17	−1.315	0.681	−2.800	−0.190
$AtechNano_{i2000-2010}$	17	−2.733	28.158	−100.000	26.484
$ScTecLinkNano_{2000-2010}$	17	−0.368	19.280	−28.313	59.417
$SizeRDNano_{2000-2010}$	17	−0.886	7.019	−11.491	10.216
$ClNanoi_{2000-2010}$	17	−2.695	5.713	−10.816	10.193
$R\&D/GDPi_{2000-2010}$	17	1.741	2.277	−0.744	6.566
$Hki_{2000-2010}$	16	3.124	2.499	−1.129	8.657
$ProdCompi_{2000-2010}$	17	−0.322	0.845	−1.450	1.283
$TechHeighti_{2000-2010}$	17	−1.578	1.340	−4.279	0.475
$TechAbsCapFi_{2000-2010}$	17	1.179	3.760	−6.252	9.928
$DHIi_{2000-2010}$	15	−0.046	0.322	−0.651	0.725
$IPEi_{2000-2010}$	17	−1.382	1.221	−4.176	0.762
$MacStrengthi_{2000-2010}$	17	0.452	1.555	−2.095	2.970
$InstWeaki_{2005-2010}$	17	−0.966	1.394	−4.600	1.456

Source: Own estimations based on USPTO data patents of nanotechnology classes; The World Bank Indicators; *The Global Competitiveness Report*; *United Nations Development Programme, PNUD.*

developed an econometrical estimate, keeping in mind the limitations on testing β convergence in the nanotechnology sector across countries.

In order to find the best estimate of the model (best linear unbiased estimators (BLUE), we tested two procedures to confirm the significance of the variables and proceed to eliminate those that disrupt the robustness of the model. The first consisted of estimating the model with all the proposed variables and making the necessary adjustments. In the second, based on Rogers (2003), the model was adjusted, testing with 14 regressions which associate $lnPatNano_{0,i}$ with another independent variable (replacing a different independent variable in each regression) in relation to the dependent variable. Finally, the results of the first adjusted estimate and the second based on Rogers (2003) were compared, and we identified which significant variables coincided (see Table A1).

These results allowed us to rule out variables related to countries' technological capabilities: human capital growth rate of $country_i$ ($Hk_{i2000-2010}$), relative technological level growth rate of $country_i$ ($TechHeight_{i2000-2010}$), and the technological absorption capability growth rate ($TechAbsCapF_{i2000-2010}$) and variables of social capabilities except institutional weakness ($InstWeak_{i2005-2010}$). All kinds of new investments that enable the development of capabilities in new technologies need a stable environment without corruption or institutional weakness. However this indicator does not consider relevance in nanotechnologies, perhaps because for many countries it is in an initial step to measuring impact.

Econometrical results and discussion of findings[13]

The findings of our estimates suggest that the variable which directly confirms the process of β-convergence is $lnPatNano_{0,i}$. In other words, the initial state of the level of nanotechnology patents granted ($lnPatNano_{0,i}$) is $\beta < 0$ (−10.8) and is a statistically significant variable (p-value 0.00). Thus, the average percentage change from the initial level of the number of nanotechnology patents granted to the group of countries is a factor which drives the process of convergence across countries in this sector. One of the four variables of technology and innovation in the nanotechnology sector, the growth of cumulative technological knowledge in nanotechnology ($AtechNano_{i2000-2010}$) is statistically significant (*p-value* 0.00), and the value of the parameter indicates that it positively influences the $lnPatNano_{0,i}$. This favorable effect coincides with that anticipated in the hypothesis: greater growth of cumulative knowledge in nanotechnology helps foment convergence and catch-up of countries toward the leader. Romer (1990) observes that the rate at which researchers discover new ideas depends on existing technological knowledge.

In turn, the links between scientific activity and inventive activity growth rate in this technological sector ($ScTecLinkNano_{i2000-2010}$) also influence the process of conditional convergence (*p-value* 0.03), as we expected, but the growth rate for inventive capabilities of researchers in nanotechnology in the period studied ($SizeRT_{i2000-2010}$) does not contribute positively to it, despite showing a positive coefficient. This result suggests that inventive capabilities appear to be relatively limited and are still not sufficient to boost inventiveness in this technology sector, creating the conditions for a convergent tendency, although specialized literature has acknowledged that larger teams have greater inventive productivity. Findings quoted in scientific articles on patents are used as input to develop inventive activity, theoretically contributing to the conditional convergence process.

The behavior of the variable of social capabilities, institutional weakness ($InstWeaki_{2005-2010}$), is not statistically significant (*p-value* 0.14). Nor is the expected hypothesis confirmed, since with less institutional weakness ($InstWeaki_{2005-2010}$), measured by the average annual growth of the corruption index, conditions may improve for inventive activity in nanotechnology in countries, and therefore for a conditional convergent process. Perhaps it would be more appropriate to consider another kind of institutional variable in the model.

The fact that the study includes only 17 countries may be a contributing factor in the statistical insignificance of some variables. This probably can be corrected by increasing the number of countries and with it the number of observations. However, in this study we limited ourselves to countries that

Table 3. Regression estimated coefficients of the convergence model.

PatNanoi2000–2010	Coefficient	Robust Std.Err.	t	P > t(P = values)	(95% Conf. Interval)	
lnPatNano0,i (2000)	−10.81	2.30	−4.69	0.00	−15.88	−5.74
$AtechNano_{i2000–2010}$	0.24	0.05	4.67	0.00	0.13	0.35
$ScTecLinkNano_{2000–2010}$	0.30	0.12	2.50	0.03	0.04	0.56
$SizeRTNanoi_{2000–2010}$	0.02	0.37	0.05	0.97	−0.79	0.82
$InstWeaki_{2005–2010}$	−2.91	1.85	−1.57	0.14	−6.99	1.16
Cons.	−14.15	6.51	−2.17	0.05	−28.48	0.17

Source: Own estimate. $R^2 = 0.48$.

report patents in nanotechnology granted systematically over the entire period. Even with that limitation, the estimate of the model shows evidence that supports the hypothesis of conditional convergence.

By the fact that more countries could be involved in the nanotechnology paradigm, including more R&D expenditure, researchers, and different actors, the beta convergence could show more significant statistical findings (Table 3).

Based on these estimates, we can anticipate that countries lagging behind yet striving for convergence toward the United States, the nanotechnology leader, through substantial growth of innovation under this new technological paradigm, need to promote the growth of accumulation of technological knowledge in the sector, links with the academic and scientific sectors, and inventive capabilities in nanotechnology.

The results of the model partially confirm the hypothesis of authors like Gerschenkron (1962), Nelson and Phelps (1966), and Abramovitz (1986). Probably because the paradigm is still incipient, some of the proposed variables were not statistically significant and had no impact on the convergence process.

Conclusions

Studies of technological convergence have enormous relevance, because they help to analyze factors, which may help less advanced countries achieve tendencies of convergence toward leader countries. In such processes, the objective is to contribute substantially to boosting economic and social performance in those countries.

In the new technological paradigm of nanotechnology, certain countries are on the leading edge of R&D, and also of innovation, with significant advantages in the mass application of nanomaterial products, and all the nano sectors. The United States is the clear leader, followed at a considerable distance by Japan, Korea, Taiwan, and China. Other industrialized and emerging countries make efforts in these areas to make their own inroads into this new area of innovation.

The different econometric estimates and tests of robustness have helped us arrive at a final formulation of a reliable model. Thus, our research hypothesis of conditional convergence and catch-up across countries in the nanotechnology sector in the long term seems to be partially confirmed. But we have tested that the $\beta < 0$ is conditioned to the innovation and technological capabilities in the sector and for the particular country and social capabilities. The variables accounting for the technological absorption capabilities were not considered in this model after the different tests carried out.

In particular, our study findings allow us to corroborate that convergence in this new technological paradigm across countries will occur in the long term to the extent that less advanced countries report higher rates of growth of innovation in nanotechnology than the leading country, contingent on their making substantial gains in accumulating technological knowledge, researchers' inventive capabilities, and links between scientific activity and inventive activity, and in inverse relation to the increase in institutional weakness.

The results suggest that it is possible for less technologically developed countries to close the gaps in this new technological paradigm conditioned to statistically significant technological capabilities, as we have analyzed.

The availability of more countries and therefore more observations, as well as improving the proxy indicators, will enable us to test the β convergence model methodology more adequately. The current empirical evidence used in this work provides the foundation for conducting future research on this pending issue.

In short, we suggest that we are currently at an incipient stage of the conditional convergence process. We still do not know whether developing countries will arrive at an equilibrium level lower than that of developed countries; however, it will be an important step forward for them.

Notes

1. For an extensive discussion about technological revolutions and technological-economic paradigms, see Pérez (2010).
2. When we talk about knowledge convergence, we make allusion to confluence in the cognitive and technological scopes and in human activity (Roco and Bainbridge 2013).
3. In this sense, they discovered that at the company level and in most sectors, investments and patents correlate positively with both the probability of being an exporter and the capacity to acquire and increase export market shares.
4. It means that the meta-system is linked to the term meta-knowledge, which associates the interdisciplinary research and scientific domains of nanotechnologies with the previous new paradigms (New Paradigms of Meta-System Engineering (1999-2004), The ENEA Server web pages, http://erg4146.casaccia.enea.it/wwwerg267.)
5. See Guzmán and Toledo (2009), for the discussion of the methodology used to search nanotechnology patents at the USPTO.
6. The world market for nano products had 25% AAGR between 2000 and 2010, up from 30 billion dollars to 200 billion dollars, where 40% belongs to the United States, especially in nanostructures. This market could increase to 1 trillion dollars, where the US could contribute as much as 800 billion dollars (Roco 2011).
7. We explain the sample methodology in the next section about our empirical research.
8. If we consider other intellectual property offices like the European Patent Office –EPO– or the Japanese Patent Office, the distribution might be different, but the United States would most assuredly retain its leadership.
9. We are considering the abilities to learn from frontier knowledge and to generate novelties in nanotechnology.
10. The size of the sample was estimated, following Anderson, Sweeney, and Williams (2008) as: $n = \frac{Z_\alpha^2 Npq}{i^2(N-1)+Z_\alpha^2 pq}$. Where: ***N*** is the size of the population considered (18,467 patents); *Z* is the value related to the Gauss distribution, $Z_{\alpha=0.05} = 1.96$; ***p*** is the expected prevalence of the parameter to evaluate. If it is unknown we assume: ***p***=0.5; ***q*** is taken as: *q*=1-*p*; *i* and means the expected error. In this case it is 5%, therefore, *i*=0.05. Now, by estimating we have *n*=17687.6868 / 47.0004, so, *n*= 376.33 and round it, we have *n*=376 patents. (Anderson, Sweeney, and Williams 2008).
11. Human capital by country, spending on research, and development by country as a percentage of GDP (World Bank Indicators); the human development index by country (United Nations Development Program (UNDP), the global competitiveness index by country, the level of technology by country, the efficiency level of public institutions by country, and the level of macroeconomic stability by country (Klauss 2011).
12. The data for Israel were not available in the World Bank statistics.
13. A first analysis was made in Guzmán, Acatitla, and Brown (2018). We have obtained different results because a new variables estimation was made.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Appendix

Table A1. Factors affecting the new technological knowledge in Nanotechnology β Convergence across countries.

Variables/ Regressions	1 *lnPatNano0,i* (2000)	2 *CINanoi* 2000–2010	3 *R&D/GDPi* 2000–2010	4 *TechHeighti* 2000–2010	5 *AtechNano* i2000–2010	6 *ScTecLinkNano* 2000–2010	7 *DHIi* 2000–2010	8 *SizeRTNanoi* 2000–2010	9 *IPEi* 2000–2010	10 $Hki_{2000–2010}$	11 *ProdCompi* 2000–2010	12 *TechAbsCapFi* 2000–2010	13 *MacStrengthi* 2000–2010	14 *InstWeaki* 2005–2010
lnPatNano0,i (2000)	−5.722 [0.044]	−5.257 [0.067]	−5.426 [0.07]	−5.149 [0.092]	−6.114 [0.029]	−5.413 [0.042]	−5.758 [0.06]	−6.110 [0.06]	−5.498 [0.069]	−5.580 [0.044]	−5.976 [0.052]	−5.470 [0.068]	−5.731 [0.067]	−5.000 [0.079]
$CINanoi_{2000–2010}$		0.4759 [0.3]												
$R\&D/GDPi_{2000–2010}$			1.1730 [0.238]											
$TechHeighti_{2000–2010}$				−1.4342 [0.509]										
$AtechNano_{i2000–2010}$					0.1638 [0.010]									
$ScTecLinkNano_{2000–2010}$						0.1556 [0.2]								
$DHIi_{2000–2010}$							−3.2080 [0.743]							
$SizeRTNanoi_{2000–2010}$								0.2194 [0.56]						
$IPEi_{2000–2010}$									0.8555458 [0.75]					
$Hki_{2000–2010}$										−3.049 [0.225]				
$ProdCompi_{2000–2010}$											0.1311 [0.969]			
$TechAbsCapFi_{2000–2010}$												0.226 [0.14]		
$MacStrengthi_{2000–2010}$													−0.020263 [0.993]	
$InstWeaki_{2005–2010}$														−4.086 [0.135]

Source: Own estimations, based in Rogers Model (2003).
*The estimate was made using the robust standard errors method, with the aim of getting unbiased standard errors and avoiding heteroscedasticity.