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Austria 2025:

Looking Out For the Frontier(s)

Towards a New Framework For Frontier Measurement in Science, Technology and Innovation

Jürgen Janger, Agnes Kügler, Andreas Reinstaller, Fabian Unterlass

Research assistance: Kathrin Hofmann, Irene Langer, Peter Reschenhofer, Anna Strauss

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Abstract

Several strands of the innovation and growth literature use the notion technological or innovation frontier for performance assessment of countries and for policy recommendations as a function of the distance to these frontiers. We show that these concepts and measures are not easily interchangeable due to the lack of a common definition and a consensus on how to measure different kinds of frontier. We propose a consistent framework for the measurement of the scientific, technological, innovation and economic frontier, which also takes account of the impact of global value chains on innovation indicators. This can be used as a basis for empirical validation of the different claims of the literature using the frontier concept as well as for guiding performance comparison of countries and hence policies.

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Introduction

In a dictionary, the term "frontier" is defined as border, or as the land that forms the furthest extent of a country's settled regions[1]; in various strands of the literature related to science, technology, innovation, productivity and growth it has been used to denote the highest level of the variable of interest. In growth economics, the frontier relates to the highest level of productivity (see, e.g., D. Acemoglu, Aghion, & Zilibotti, 2006; OECD, 2015); in the technology gap approach, it relates to technology in- and output indicators (see, e.g., Jan Fagerberg, 1987); in evolutionary economics, the frontier is used to mark the highest limit of technological trajectories (see Dosi, 1982). In most of these contributions, the frontier is referred to as the "technological frontier". But perhaps the most common use of the term is in science, where it simply relates to the limit of our knowledge (see the famous report by Bush, 1945).

The "frontier" concept is highly relevant for science, technology and innovation policy, as policies can either push the frontier outward or shorten the distance to the frontier. In the growth literature, the appropriateness of policies depends on the distance to the frontier (Philippe Aghion & Howitt, 2006). Countries behind the frontier can benefit disproportionately from absorbing frontier technologies, catching up to those countries already at the frontier. The distance to the technological frontier is also related to the scope for further technological upgrading as a potential reaction by firms to low-cost competitors (see, e.g., the concept of quality ladders in Khandelwal (2010), or Bloom et al. (2011)).

In the innovation and policy literature generally, many contributions work with the term "frontier" to situate countries, sectors and firms in terms of relative performance and derive policy conclusions (see, e.g., Hobday et al., 2004; Koh and Wong, 2005). Innovation rankings such as the EU's European Innovation Scoreboard don't use the term explicitly, but are similar in spirit when they establish "innovation leaders", featuring the highest level of innovative performance and analysing convergence (Hollanders et al., 2016).

However, these contributions establish neither a common conceptual nor an empirical definition of the term "frontier". They use in particular the terms productivity, technological and innovation frontier interchangeably while far from always meaning the same kind of frontier. A wide variety of indicators is used to measure the frontier, usually without explaining and justifying the choice of the measure. Some papers use simply GDP per capita (Verspagen, 1991), some just assume the US to be at the frontier (Spolaore and Wacziarg, 2009), while others use productivity (labour productivity or total factor productivity TFP, see OECD 2015) or the summary scores of innovation rankings (Archibugi & Filippetti, 2011). Technology indicators (e.g., technology usage levels as in Comin et al. (2008a), or direct and

[1] See, e.g., dictionary.com. This is also the inspiration for Bush's, 1945, frontier of science term: "It has been basic United States policy that Government should foster the opening of new frontiers. It opened the seas to clipper ships and furnished land for pioneers. Although these frontiers have more or less disappeared, the frontier of science remains."

indirect (embodied) R&D intensity (e.g., Hölzl and Janger, 2014) have been applied to measure the frontier as well.

This severely limits the usefulness of the frontier concept, as policy conclusions may vary depending on the kind of frontier concept and measure used. All kinds of "best practice diffusion"-policy approaches need some kind of consensus on which frontier concept to use, and how to measure it to actually know where the frontier is; policy impact analysis or evaluation of policies is also severely affected by a lack of consensus on performance measures. Distance to the frontier indicates a potential for learning, and hence may point to the need for policy reform to support this kind of learning; when the frontier is not accurately measured, or when different frontier concepts are used, there is no sound basis on which to compare countries and draw conclusions for potential learning. If the main aim of frontier indicators is to reduce uncertainty for policy-making, then this uncertainty is currently very high.

This comes at a time when against the backdrop of slowing productivity and the prospect of "secular stagnation", there are signs of divergence in productivity and innovation performance between some countries, regions and firms (Archibugi and Filipetti, 2011, OECD, 2016). Proper frontier measurement is essential to identify the causes for this recent divergence and to put policies in place which are able to boost convergence to the frontier. A lot is at stake for the European Union, which is emphasising open markets for knowledge and research. Large performance gaps within the EU could lead either to quick catch up by the less performing regions, if learning from the frontier was easy; or to the most talented individuals and firms moving to the most attractive places, reinforcing disparities and locking in performance differences in STI, potentially preventing convergence of GDP per capita (Archibugi and Filipetti, 2011).

We contribute to the literature in three ways. First, we develop a conceptual framework for frontier measurement which distinguishes between the scientific, technological, innovation and economic frontier; second, based on a survey of frontier measures we choose selected ones to illustrate the framework and its potential usefulness for indicator development and STI policies. While the framework should be consistent, indicator choice is always open to debate and constrained by data availability. We outline which indicators are suitable to measure which kind of frontier, defining selection criteria for frontier indicators and showing that different measures of frontiers need not coincide at the country level, pointing to policy-relevant differences in drivers of different frontier concepts; third, we propose some new indicators to measure the innovation frontier, where there is currently the biggest debate on how to measure it accurately. In particular, we come up with a suggestion to reflect the impact of global value chains on innovation indicators, which is a central challenge to innovation indicators as global value chains affect the link between science and knowledge creation on the one hand and value creation on the other hand.

This should contribute to establishing a common conceptual basis for frontier measurement which can guide further research and enable consistency of results from different approaches by being clear on the concepts used. It can also help interpreting the results of various rankings by showing to which kind of frontier they relate to, which is particularly useful for policy coordination and country comparisons.

This paper is organised as follows: section 1 provides a review of the frontier concept in the literature. Section 2 builds our conceptual framework, followed by an empirical illustration in section 3. Section 4 concludes.

1. The "frontier" concept in the literature

"New frontiers of the mind are before us, and if they are pioneered with the same vision, boldness, and drive with which we have waged this war we can create a fuller and more fruitful employment and a fuller and more fruitful life." (Franklin D. Roosevelt in a letter to Vannevar Bush, as cited in Bush, 1945)

The frontier as limits of knowledge

Several strands of the literature related to science, technology, innovation and growth conceptualise a frontier and use it for further analysis[2]. Its most intuitive use has probably been in basic science, where it clearly denotes the limits of what we know, or the frontiers of knowledge (see the famous report by Bush, 1945: "Science, the endless frontier"). While early references to the scientific frontier did not include any frontier measures, nowadays comparison of scientific performance at the country level through bibliometric indicators is frequent (Albarrán et al., 2010; King, 2004).[3] It is not just identified in terms of publication counts, but in terms of the use of scientific results for further research which builds on them (scientific impact). The scientific frontier would hence be measured by the highest level of that performance in terms of citation counts. The "leading" country is usually identified with the US, in particular as regards highly cited journal articles. Other approaches build on the distribution of Nobel Prizes (Weinberg, 2009). Already Bush, 1945, viewed the advance of the frontier of science as determining the speed of advance of the "application" frontier (Rosenberg and Steinmueller, 2013), implicitly assuming a linear model of innovation.[4] The locus of the expansion of the frontiers of knowledge was seen within universities and basic research institutes, whereas industry and government research took care of the application of existing knowledge to practical problems.

The frontier as productivity and income levels

In the economic growth literature, the concept of frontier is used to denote the highest level of development, and to analyse effects of the distance to this frontier on growth rates, or on convergence perspectives through technology transfer or absorption of knowledge created in frontier countries (e.g. Kneller, 2005, Keller, 2004, Cameron et al., 2005, Lee, 2016)[5]. In

[2] Agwara, Auerswald, & Higginbotham (2013) also survey the "changing frontier". However, for them frontiers are actually the main drivers of what we call innovation frontier – e.g., the scientific frontier corresponds to the time after the second world war when science was supposedly the main driver of innovation. One problem with this analysis is that citations of patents to academic science were lower after the second world war than they are now.

[3] The frontier can be seen as the highest level of performance.

[4] "New products, new industries, and more jobs require continuous additions to knowledge of the laws of nature, and the application of that knowledge to practical purposes… This essential, new knowledge can be obtained only through basic scientific research. " (Bush, 1945, https://www.nsf.gov/od/lpa/nsf50/vbush1945.htm , Online Document without page numbers)

[5] In fact the whole technology transfer literature can be seen to rely on the concept of frontier which enables transfer.

general, this literature finds that the further behind the frontier, the faster a country can improve its productivity through technology transfer. The distance to the frontier, also called the "technology gap", is hence a measure of the potential for technology transfer, implying that perspectives for productivity growth will be judged differently according to the true measurement of the frontier.

The distance to the frontier is also seen to impact the effectiveness of growth policies. In particular the work building on Schumpeterian growth theory pursues the idea that "different types of policies or institutions appear to be growth-enhancing at different stages of development", Philippe Aghion, Akcigit, & Howitt (2013, p. 1); see also D. Acemoglu et al., (2006); Aghion and Howitt, (2006). E.g., competition has different effects on innovation activity depending on the distance to the frontier of firms, and strategies of firms at the frontier are more successful when they are geared towards innovation, while strategies of firms far from the frontier are better off pursuing imitation as a competitive strategy. Higher or research education has a higher effect on growth in countries or regions close to the frontier (Vandenbussche, Aghion, & Meghir, 2006). Effective policies are hence different in frontier and non-frontier countries, "because those policies and institutions that help a country to copy, adapt and implement leading-edge technologies are not necessarily the same as those that help it to make leading-edge innovations." (Philippe Aghion et al., 2013, p. 21)[6]

The frontier is called interchangeably technological or productivity frontier, or frontier on its own, and measured usually by some form of [total factor] productivity. Variants include the relation between national TFP to the TFP of the U.S., implicitly assuming the U.S. being the leading country (Vandenbussche et al., 2006; Ha et al., 2009), or identifying the country with the highest TFP in each point in time at the industry level (Daron Acemoglu, Aghion, & Zilibotti, 2006; Bogliacino & Cardona, 2014; Griffith, Redding, & Van Reenen, 2004; Kneller, 2005); and also GDP per capita (Philippe Aghion, Alesina, & Trebbi, 2007).

The frontier as capabilities

Related to this growth literature is the "technology gap"-approach which similarly hypothesizes that countries which are on a lower technological level (the "followers") than countries on the "innovation" frontier (the "leaders") can boost economic growth (Abramovitz, 1986; Gerschenkron, 1962) through imitation of the leading countries' technology; exploiting the technological gap to the frontier countries as a driver of growth depends on the abilities of countries to change its social, institutional and economic structures (Fagerberg, 1987). The difference with the neo-classical growth literature lies in the conception of technology ("know-how how to do things", Fagerberg, 1994, p. 1156) not as a freely available public good, but as something which is embedded in organizational and institutional structures and hence difficult to be applied in different settings without dedicated efforts at capacity-building, e.g. through R&D or education. National-level factors influence

[6] The discussion is not just relevant for developing vs advanced countries, as e.g., Aghion et al., (2005) use US states' distance to frontier for investigating how higher education relates to growth and find significant effects.

technological change, which led scholars to the concept of countries as "technological" systems, or as national innovation systems (Lundvall, 2010; Nelson, 1993).
This is also relevant for the measurement of the technological level, or the innovation frontier: instead of relying on productivity only, the technology gap approach uses indicators on the level of innovative activity, e.g. on the share of product innovations in output or on the prevalence of process innovation in production, which should be correlated with productivity: Product innovations can be sold at higher prices, while process innovations lead to higher productivity, so that countries with a high level of innovative activity tend to have higher GDP per capita. While imitation boosts growth behind the frontier, surpassing the frontier countries only works through boosting innovative activity.
Measures of innovative activity can be divided into "technology input" such as R&D expenditures and human resources and "technology output" measures, such as patents. Input measures are not only relevant for innovation, but also for imitation capacity, while outputs in the form of patents are supposed to be more directly indicative of innovative capacity. Also in this literature, the US is important as the supposed frontier country – e.g., Soete 1981, uses patenting in the US as an indicator of the highest technological level; to investigate the "gap", GDP per capita is also used, although on the assumption that it reflects technological sophistication rather than the capital-labour ratio as in the neoclassical growth theory (Fagerberg, 1987, 1994). A twist to the gap approach can be seen by Comin et al. (2008b), who choose an interesting approach using technology usage gaps to the U.S., where technological usage levels measure the innovation frontier. Countries usage lags of diverse technologies, from communication technologies to IT, are identified by the time lag to the last point in time the U.S. had the same usage level.

The social and institutional embeddedness of technology and the focus on capabilities in the technology gap literature is inspired by an evolutionary view of technical change (see Dosi and Nelson, 2010, for a recent survey). This literature adopts a micro- and procedural view of technological change which contrasts with the macro-view of the growth/gap literatures. Following Dosi, 1982, p. 154, "one can define as the "technological frontier" the highest level reached upon a technological path with respect to the relevant technological and economic dimensions", whereby technologies usually relate to specific technologies such as those needed for the production of an aircraft or a car and the economic dimension refers to product or process characteristics such as e.g. number of passengers to be carried, cost per passenger mile etc.
Advance on this path (also called "trajectory") is cumulative in character, building on tacit knowledge resulting from past trials and errors in innovation efforts by heterogeneous firms in competition with each other (rather than based on fully informed decisions). Cumulative advances largely based on tacit knowledge acquired in own trial and error imply that getting to the frontier is not easy and requires efforts (as in the gap literature above). The literature features a detailed discussion on the nature of technological knowledge and advance, and by implication on the nature of any technological frontier, rather than just calling the highest

level of productivity the technological frontier; e.g., technology is defined as "a human designed means for achieving a particular end" in both manufacturing and services (Dosi and Nelson, 2010, p. 55). Technologies and hence frontiers can be seen both as a practice (in terms of "recipes" or "routines" of firms, e.g. the set of instructions needed for producing a car) and as artifacts, the output "space" of practices, eg. the performance characteristics of the car itself. These practices differ across industries, so that frontiers are technology-specific rather than country-specific, although e.g. Dosi (1982) employs the frontier concept also for the country level. Routines are the building blocks of firms' competencies and capabilities. They are central to the evolutionary concept of technological change (and frontiers) and connect this literature to the innovation management literature on dynamic capabilities (see Helfat et al., 2009; Teece, 2010).

The evolutionary literature remains mostly silent on how exactly to measure the frontier of capabilities (the prevailing best practices) and performance characteristics of technologies. However, Dosi and Nelson (2010) criticize the substitution of measurement of technological practices in economics by the input-output relationships of production functions as they "blackbox" the actual capabilities required for innovative success; very different routines or capabilities may give rise to similar input-output relationships, while different input output relationships may be based on similar capabilities; phrased in another way, production efficiency in terms of inputs vs output is analytically separate from the technological routines or capabilities leading to this efficiency.

Other literatures build on the concept of capabilities, while proposing concrete measurements for what they view as the not necessarily identical "capability frontier". Similarly to the gap and evolutionary literatures, Furman et al., 2002, are motivated by the puzzling co-existence of cross-country innovation intensity differences with the assumption of technology flowing freely across borders in the neo-classical growth theory. They measure the technological frontier through the number of international patents granted by the USPTO per capita to OECD countries. Although they don't explicitly define the frontier, they see patents per capita as a measure of the impact of national innovative capacity[7]. This capacity is built on national-level institutional factors, borrowing from the concept of national innovation systems, and cluster- or firm-level factors as outlined in Porter's cluster approach, as well as linkages between these two. Furman et al., 2002, are explicitly using the production function approach, and output measures of the innovation process as indicators of capabilities, and the highest level of such measures indicates the "world's commercial technology frontier" (p. 909). International patents per capita are seen as providing a "useful benchmark to compare the relative ability of countries to produce innovations at the international frontier." (p. 929)

[7] Defined as a "country's potential—as both an economic and political entity— to produce a stream of commercially relevant innovations." (Furman et al., p. 905)

They distinguish innovative capability from scientific and technical capability (although they refer to the "technological" frontier, rather than the innovation frontier); and they see it as different from national productivity levels, which in their opinion results not only from innovation, but also many other factors, in clear contrast with the growth literature: They find only a nuanced relationship between productivity growth and innovative capacity, as well as little relationship between the stock of scientific articles and innovative capacity. There is a correlation between innovative capacity and GDP per capita, which is seen as an aggregate measure of technological sophistication, although they don't explain why they see GDP pc rather than TFP as referring to technological sophistication.
Because patents are only imperfect proxies for commercialised innovations, Furman et al., 2002, also use market shares in high-technology exports as an alternative indicator of the frontier, essentially yielding similar results. This builds fundamentally on the view of the evolutionary literature that emerging technological paradigms (radical innovations) as giving rise to new industries (see e.g., Dosi and Nelson, 2010), so that a high share of knowledge-intensive industries or exports is supposedly indicative of a country's innovative capacity or capability. As a result, for a long time, shares of knowledge-intensive or high-tech industries or exports have been used as indicators of innovation capabilities or outcomes (see Godin, 2004). Another paper using outcomes (economic effects of innovation rather than inventions) as a measure of innovation capabilities is Faber and Hesen, 2004, who analyse the relationship between patents and sales of product innovation as captured by the Community Innovation Survey, following a similar approach to Furman et al., 2002.

Of course, a vast literature uses patent indicators to analyse innovation (Nagaoka, Motohashi, & Goto, 2010); however, the theoretical underpinnings or what patents are supposed to show differs across articles. In general, patent measures can only capture the codified part of knowledge accumulation; tacit knowledge is probably even more important (see Dosi and Nelson, 2010, OECD, 2016), not least because it is costly to fully codify technology and hence large parts of it remain tacit. However, per definition, tacit knowledge can't be measured. Efforts to find proxies usually use R&D intensity measures as proxies for the accumulation of tacit knowledge. E.g., Hölzl and Janger, 2014, measure the technological frontier based on the direct and indirect R&D intensity of a country, with direct intensity relating to BERD as share of GDP and indirect intensity calculated on R&D embodied in capital goods used in the industries of a country, using input/output analysis ("a rough measure of the level of technological development of a country in terms of its capacity to generate new technologies and its ability to use foreign technologies", p. 710). They find that the distance to this technological frontier is correlated with the prevalence of innovation activity among firms (firms in countries close to the frontier are more likely to use innovation as a competitive strategy) and that barriers to innovation differ by distance to the frontier.
A different way to measure capabilities is proposed by the complexity- or product space-literature (Hidalgo & Hausmann, 2009; Hidalgo, Klinger, Barabási, & Hausmann, 2007; Reinstaller, et al., 2013; Reinstaller, 2013). The theory proposes that the productive structure of

countries is determined by the local availability of highly specific inputs, or capabilities, which can be thought of as specific building blocks of production. Capabilities are broadly defined and could be tangible inputs, such as bridges, ports and highways, or intangibles, such as norms, institutions, skills or the existence of particular social networks. In this theory, at any given point in time, countries are endowed with a set of capabilities, whereas products require specific capabilities. The sophistication of a product is related to the number of capabilities that the product requires; whereas the complexity of a country's economy is related to the set of capabilities it has locally available. The highest level of production of sophisticated products could then be seen as the frontier in capabilities (see also Agwara et al., 2013).

Finally, related to the artifact concept, indicators building on changing performance characteristics of product innovations (the characteristics in the output space) have been suggested by technometrics or literature-based approaches, which use information from technical and trade journals (Grupp, 1994; Coombs et al., 1996; Kleinknecht and Reijnen, 1993).

The frontier as highest level of efficiency

Prominently using the concept of "frontier" is the large literature trying to measure R&D and innovation efficiency through variants of DEA, stochastic frontier analysis, or distance function approaches. However, in this literature, the frontier relates to a relative statistical relationship between some inputs and some outputs; it does not denote an absolute concept in terms e.g. of high levels of technology (high levels of input or output), but a statistical measure of the highest level of outputs given inputs, or the lowest level of inputs given outputs. This means that a country can achieve high R&D efficiency when it does not use a lot of R&D spending to achieve a given level of patenting which may be far below the highest level of patents per capita. Examples in this literature include Hu et al., 2014; Wang and Huang, 2007. The outcomes of such analyses are efficiency scores. Moreover, directional distance functions allowing for different technologies, under which different groups of countries are operating, have been calculated to measure the distance to a metafrontier (Dong-hyun Oh and Jeong-dong Lee, 2010; Kounetas, 2015) on the basis of estimated total factor productivity.

The frontier as a composite of innovation indicators

Innovation country rankings such as the European Innovation Scoreboard (EIS) and the Global Innovation Index (GII) are imbued with the terminology of the growth convergence and technology gap literature. While they don't use the term frontier explicitly and rather employ the more general term innovation performance, they clearly see their measures as indicating the highest level of innovation performance, hence an innovation frontier; countries at the top are "leading" countries, while others are "followers", very much in the terminology of Abramovitz (1986) or Ames and Rosenberg (1963). The rankings usually divide innovation indicators in indictors on inputs as well as outputs and outcomes of innovation activities. Among the outputs and outcomes, measures include indicators on patents and high-tech exports, inputs include R&D and education spending as well as human resources, covering a wide variety of national factors influencing innovation. This is obviously inspired by the literature on national innovation systems also used by Furman et al., 2002. It is noteworthy though that usually all these indicators – both input and output/outcome – are grouped together in a composite indicator, which determines the country ranking. Innovation performance, and the frontier of it, is hence a mixture of input and output/outcome variables.

The innovation rankings use their measures to analyse convergence of countries to the frontier (the group of countries with the highest level of performance in in- and output indicators) in their own reports (e.g. Hollanders et al., 2016), but also the academic literature draws on them for convergence to the frontier analysis or efficiency frontier analysis (see e.g. Archibugi and Filippetti, 2011; Halkos and Tzeremes, 2013). The former use the summary innovation index of the EIS to analyse what they call convergence in innovation capabilities and build their theoretical grounding on the growth and gap literatures outlined at the beginning of section 2.

Summary – making sense of the literature

As the survey of the different strands of literature has shown, while the notion of frontier in science is rather straightforward as the limits of knowledge, there are a wide variety of meanings attached to the concepts of technological or innovation frontier (the frontier in "application"):

- a pure economic performance concept, denoting a macro-frontier in terms of productivity and income levels
- a frontier in technological and innovation capabilities
- a frontier as the composite of in- and output innovation indicators
- a frontier in efficiency

Frontier approaches differ, e.g., by the view on whether technology flows freely across borders (so that reaching the frontier depends on lifting barriers to technological diffusion) to the view that producing innovative goods and services requires high levels of technological capabilities which can only be built slowly and cumulatively over time, both through education and R&D efforts by firms working on practical problems.[8] The empirical implementation of frontier measures is equally confusing, ranging from technological or knowledge-related measures properly speaking such as patents, or R&D spending, the novelty of innovations, to economy-wide productivity measures such as labour productivity or GDP per capita, and composite indicators consisting of many indicators related to

[8] A remark by (Caselli and II, 2006, p. 510) is illustrative here: "We conclude this discussion by noting that our framework implicitly defines a world technology frontier. This can be thought of as the "highest" frontier, or the frontier of a country that faces no barriers. … it reflects the current state of human technical knowledge.")

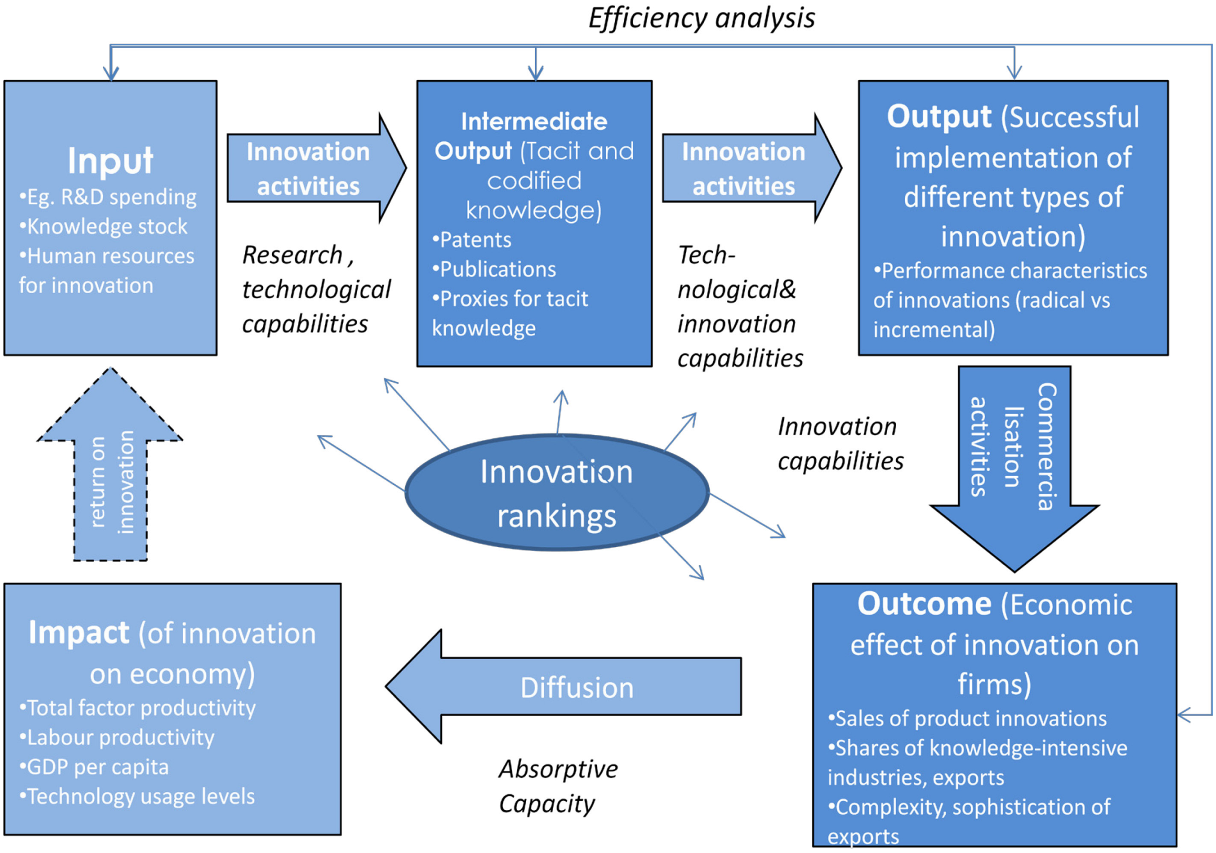
education, R&D and innovation. While these are certainly related, the precise nature of the relationship often remains unclear. It is however clear that productivity measures reflect more than gaps in technology, such as resource availability or the quality of infrastructure.

How to reconcile these various concepts of frontier? We use the conceptual framework of the innovation production function pioneered by Griliches, 1990, which has also inspired the concept of a logic chart in the evaluation literature (McLaughlin and Jordan, 1999), a tool to single out areas for performance measurement; in general, input-output frameworks are guiding indicator construction (Godin, 2007). In this framework, inputs or resources such as the stock of scientific knowledge or R&D spending are used in innovation activities to first, if successful, produce tacit or codified knowledge (in terms of patents or publications); in a next step, this knowledge may be turned into innovations (outputs), i.e. significantly changed goods, services or production processes. The economic effects of these outputs are called outcomes. Diffusing throughout the wider economy leads to economy-wide benefits in terms of productivity or GDP per capita ("impact"). Figure 1 shows such an approach and localizes the various frontier concepts and measures discussed above. Such a framework allows for identifying frontier concepts with various levels of innovation inputs, outputs, outcomes and impacts.

This approach works for innovation in firms; for firms, scientific output is an input, but for the sake of concise presentation we here show publications as an intermediate output, not least because researchers in firms also publish.

The technological frontier of the evolutionary literature or the literature derived from that on innovation capabilities clearly focuses on intermediate or innovation outputs and outcomes, encompassing patents, but also concepts such as incremental and radical innovation (performance characteristics of the output space) and high-tech exports. Also the technology gap literature addresses these levels of the framework. The technological frontier of the growth literature is clearly associated with economy-wide innovation impacts, and capabilities include not only technological creation, but also absorptive capacity to adopt innovations produced somewhere else; moreover, this includes many economy-level factors influencing diffusion and absorption. Efficiency frontiers are also possible, by relating various measures of inputs vs. outputs and outcomes. Innovation rankings provide measures of nearly all building blocks.

Figure 1: Synthesising frontier concepts and measures: Frontiers in…



Source: Authors.

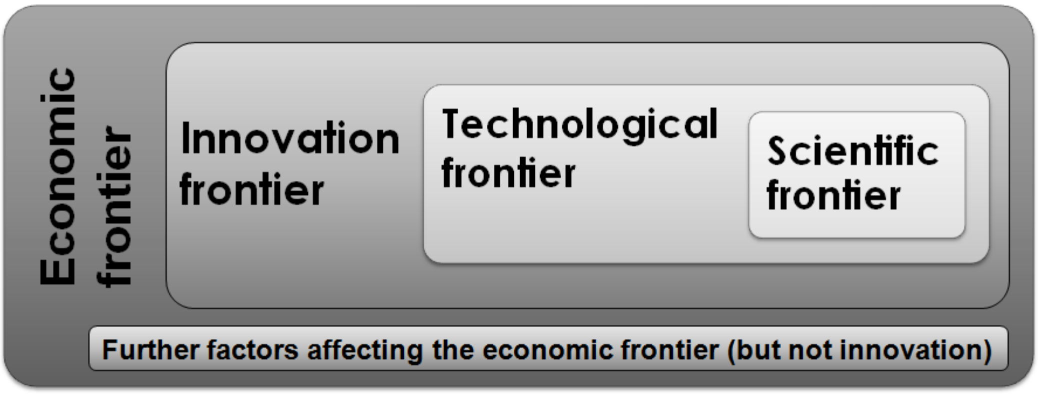
This framework is able to accommodate different literatures using different concepts and measures of the various frontiers; it can connect the dots between concepts such as the rate of innovative activity, incremental vs radical innovation, high-tech industry shares, etc. Table 1 in the annex provides an overview of frontier papers and the various measures they use based on the classification above.

2. A conceptual frontier framework

Based on this review, we propose a new conceptual framework which differentiates frontiers in the domains of science, technology, innovation and the wider economy. We conceptualise the scientific frontier as the highest level of capability to expand the limits of scientific knowledge. The technological frontier is the highest level of the capability to produce innovation outputs, such as new goods with significantly changed characteristics. This includes intermediate outputs such as tacit or codified technological knowledge, so that the technological frontier also comprises inventive capability. The technological frontier is about novelty.

The innovation frontier is the highest level of capability to turn innovation outputs into economic benefits, e.g. value added generated by new products, or cost savings by new production processes (hence, innovation outcomes); and finally the economic frontier as the highest level in transforming economic inputs (not necessarily science, technology and innovation-related) into economic output generally (hence including innovation impacts); we prefer the term "economic frontier" within our framework to the term "productivity frontier", as productivity analysis can be done for all domains.

Figure 2: Interdependencies of the frontiers



Source: Authors.

For the domains of science, technology and innovation (STI) the frontier concept is hence clearly related to capabilities as opposed to endowments; for the economic frontier other factors can also play a role (such as natural endowments, the quality of the transport infrastructure, or non-STI related capabilities, such as managerial competence). Our framework applies in principle to units at all potential levels of disaggregation – global, country, regional, sectoral/field, organisational and individual level. It is clear that a global frontier will tend to run across countries rather than identify with individual countries; for the global economic frontier at the firm level, the OECD (2015) clearly shows that it runs through global firms situated in different countries.[9] The same will hold true, e.g., for science, where the global frontier in a narrowly defined field may not even run through top basic research institutions, but rather across a couple of individuals who define the frontier in their field. For this paper however, we focus on the national frontiers, as we focus on indicators for STI with a view for informing policies, which are often designed at the national level. While we will focus on country averages for the sake of simplicity, micro-data (e.g. firm data for economic data, or data on inventors and academics at the individual level) would allow for a more fine-grained analysis of capabilities: looking at the distribution of micro-units around the average allows for judging, e.g., whether average capabilities are the result of a few top units, whereas the main part of the distribution is lagging behind; or whether they result from good average capabilities across the population, without showing top performance.

Our conceptual definition of the frontiers in STI relates to units' capabilities to contribute more to the frontier *relative to their size*. This is also often not made clear in the literature – e.g., at the country level, which countries contribute most to pushing out the frontier in total vs. which are the most capable in pushing out the frontier relative to their size?[10] In principle, every firm or research institution that publishes an article in an internationally recognised journal or is granted a patent at a major international patent office contributes to the global frontier as it adds by definition to the stock of globally available scientific or technological knowledge. In our framework, this would not be sufficient for being "at the frontier", what is required is being close to the highest level of frontier contribution relative to size: countries need to publish a high amount of publications relative to their size. Clearly, the policy relevance of the "distance to the frontier"-approach hinges on this.

We also don't look at past contributions to the frontier, e.g. at the stock of publications or patents, but at the yearly flow of such contributions. Being at the frontier means producing the highest yearly increments to the existing stock (relative to size), irrespective of the stock (of course, stocks in each country are going to influence the capability to contribute to the frontier, but this belongs to a discussion of what drives capabilities, rather than what they are and how to measure them).

Our framework is potentially useful to guide theoretical and empirical work using frontier concepts, such as growth and innovation economics, as well as indicator development, convergence analysis and STI policy. A more consistent assessment of countries' distance to the various frontiers can make performance benchmarking and convergence analysis more robust. In terms of indicator development, the framework can serve as a basis for moving

[9] Although the robustness of firm micro data to investigate the economic frontier remains an issue for debate, as industry level price indices are used for computing firm-level productivity growth. As a result, it is not clear whether productivity differences mirror actual productivity performance or differences in price levels (OECD, 2016).

[10] Total shares in publications and patent applications by countries would give different answers to the question "Which country is closest to the actual global frontier?" by comparison with publications and patent statistics controlling for country size. If one is interested rather in the worldwide rate of change, in the pace of advance of the frontier itself (to examine, e.g., questions of secular stagnation), then the sum of all country contributions would have to be considered (and of course big advanced countries contribute more to the movement of the frontier).

towards the next generation of data and indicators – as a base for consensus finding on indicators which appropriately measure the frontier and the role of international bodies in data harmonisation. Moreover, separately framing the scientific, technology and the innovation frontier allows for an analysis of whether scientific and technological knowledge creation are related to the creation of value added, and hence also allow for taking account of the increasing role of global value chains in international production and how they affect frontiers in STI. It can also help innovation rankings' choices on which indicators to include.

In terms of policy, a systematic frontier framework can serve as a consistent basis both for further policy research and policy assessment, informing science, technology and innovation policy priorities, but also wider economic policy ones: Distinguishing between different frontiers allows for a sharper analysis of the drivers of getting closer to the frontier or of pushing outward the frontier: at each stage – starting from science – additional factors come into play to determine the capability to contribute to the respective frontier (ranging from more STI-system specific policies to including more economy-wide framework conditions), which can sharpen the focus of analysis and choice of explanatory variables in econometric analysis. E.g., if a country is at the frontier in science and technology, but not economy-wise, then clearly non-STI related factors must be at work to explain the distance to the economic frontier. In addition, e.g., often science policy elements such as basic research funding are used to explain movements towards the economic frontier; this is necessarily very indirect and policy analysis may be more precise when science policy elements are first investigated for their contribution to explain the distance to the scientific frontier before they are associated with the economic frontier.

In principle, such frontier measures can also be interpreted as performance indicators of their respective domains, so that they could be used to inform efficiency analysis as outlined in section 1; however, the efficiency frontier created by such an analysis informs not on the highest levels of scientific, technological capabilities etc., but on the efficiency with which the respective levels of each country are attained. ***Estimating efficiency frontiers has to be distinguished from capability frontiers.*** E.g., countries might work absolutely efficient with respect to the generation of innovation output given a specific amount of inputs, which is reflected by high efficiency scores close to one. Yet, high efficiency scores do not directly imply being among the most innovative countries. In the efficiency literature the frontier is defined by the most efficient countries, independent of their actual level of innovation output. In contrast, we are looking for those countries with the highest level of innovation capability irrespective of the efficiency with which this capability has been reached.

The framework also allows for measuring in principle how fast the frontiers move relative to each other, e.g. in terms of the yearly increments to the stock of patents and citable documents (see for the measurement of the speed of scientific and technological change e.g., Rotolo, Hicks, & Martin (2015).[11] However, for this the sum of increments across all countries needs to be assessed, rather than scale-normalised increments per country. This can inform the discussion on secular stagnation, or on the OECD's (2015) results of global frontier firms racing ahead of other firms: when the science and technology frontier is moving outward more quickly than the economic frontier, then it may not be a problem of STI-opportunities exhausted, but rather a problem of economic factors holding back smaller firms, such as a lack of demand and financial constraints preventing them from adopting frontier technologies and innovations.

[11] E.g., the rate of technological change can be interpreted as the movement or the expansion of the technological frontier (a common way to discern technological opportunity is a fast rate of growth of patents in an area).

3. Frontier measurement: an illustration and empirical analysis

We choose measures based on our review of the literature, on their fit with our frontier concepts and on their suitability to be used for country-level indicators accurately reflecting yearly changing levels. The indicators have to be reproducible and available for several countries, and thus cannot be based on unique, country-specific datasets. To control for size, we use population size for the science and technology frontiers; in the domain of innovation we use shares of industries rather than total output of these industries, or shares of exports. We argue that the quantity and the quality of the capability to contribute to the frontier should be differentiated. E.g., in science and technology, the number of publications or patent-applications per unit can be contrasted with their average quality as measured by citations, which can also be seen as the average contribution to the expansion of the frontier. Table 1 gives a review of the chosen indicators grouped by the different frontier concepts. While most of these indicators can be constructed or are available for both OECD and non-OECD countries, for this paper we focus on the EU-28, the USA, Japan, Korea, China and Switzerland. A detailed description of the data sources as well as a table including all indicator values used in the analysis is provided in the Appendix.

Table 1: List of indicators used to illustrate the frontier framework

Frontier domain	Indicator	Measure	Source	Variable name
Economic frontier	GDP per capita	GDP per capita, PPP (current international $)	World Bank	GDP
	Labour productivity	GDP per total annual hours, PPP, current international $	World Bank, TED	LP
	Multi-factor productivity	TFP level at current PPPs, USA=1	Penn World Tables	TFP
Innovation frontier	Structural change	Share of sectors with medium-high/high innovation intensity (in % of total VA in manufacturing)	SBS, STAN, WIFO	SII
	Structural upgrading ("Innovation quality")	Industry purged business expenditures on R&D (BERD)	STAN, ANBERD, Eurostat, WIFO	BERD
	Structural upgrading	Share of high-quality segment in total exports	BACI (HS 6, 1992), WIFO	EQ
	Structural change & upgrading	Country sophistication	BACI (HS 6, 1992), WIFO	Csoph
Technological frontier	Patent quantity	Patent applications per 1,000 population	PATSTAT, WIFO	PA
	Patent quantity & quality	Triadic patent applications per 1,000 population	PATSTAT, WIFO	TPA
	Patent quality	Number of patents receiving more than 5 citations per 1,000 population	PATSTAT, WIFO	Pcit
Scientific frontier	Publication quantity	Number of citable documents per capita	SCImago	PUB
	Publication quality	Number publications in the top 10°% of journals per 1,000 population	SciVal Elsevier, OECD	TopPub

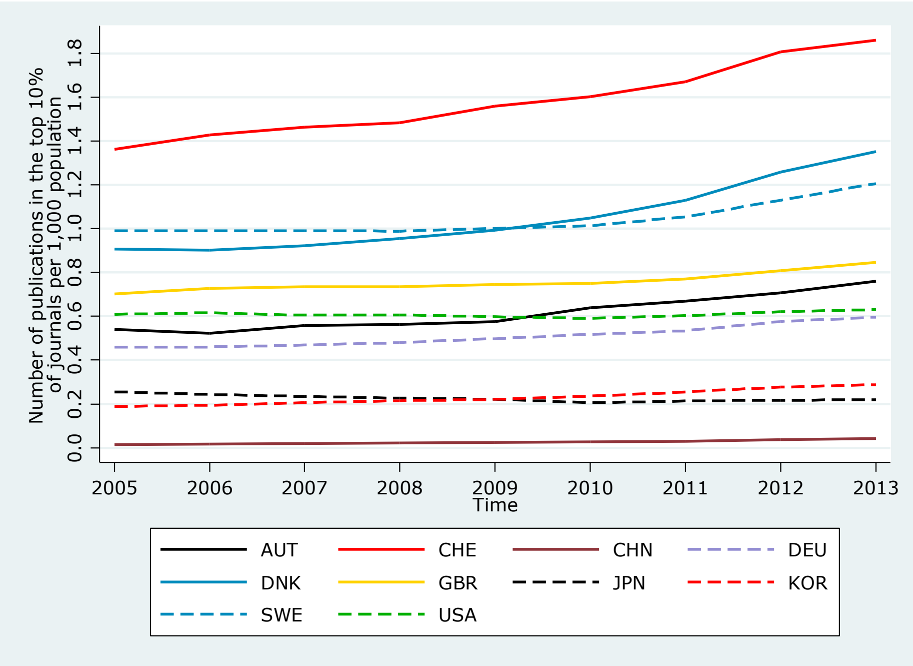
3.1 Scientific frontier

We measure the scientific frontier by using the quantity and the quality of scientific journal articles. Specifically, we choose the number of citable documents per capita provided by SCImago as a quantity indicator for the capability to contribute to the frontier of scientific knowledge. With respect to the quality of the contribution to the expansion of scientific knowledge we use the number of top-10% most cited publications in each scientific field per 1,000 of the population. Many other, similar bibliometric indicators are possible, with drawbacks and advantages. We propose these two to illustrate our concept; we don't see them as perfect frontier measures.

Besides data availability, the advantage of using publication data is the feasible disjunction between quality and quantity aspects. Figure 3 and Figure 4 illustrate the importance to include both aspects in a careful analysis of potential contributions to the scientific frontier on a country level. Even though the country rankings might be quite similar, there is a difference between those figures with respect to the time trends. Whereas the quantity measure "total number of publications" remained stable or even declined in the most recent years for the scientific leaders, the quality measure "number of publications in top journals" steadily increases, pointing to divergence rather than convergence. The leading nations with respect to total publication output as well as publication quality, like Switzerland, Denmark or Sweden, concentrate on high quality publications and accept a decline in total publication output in return.

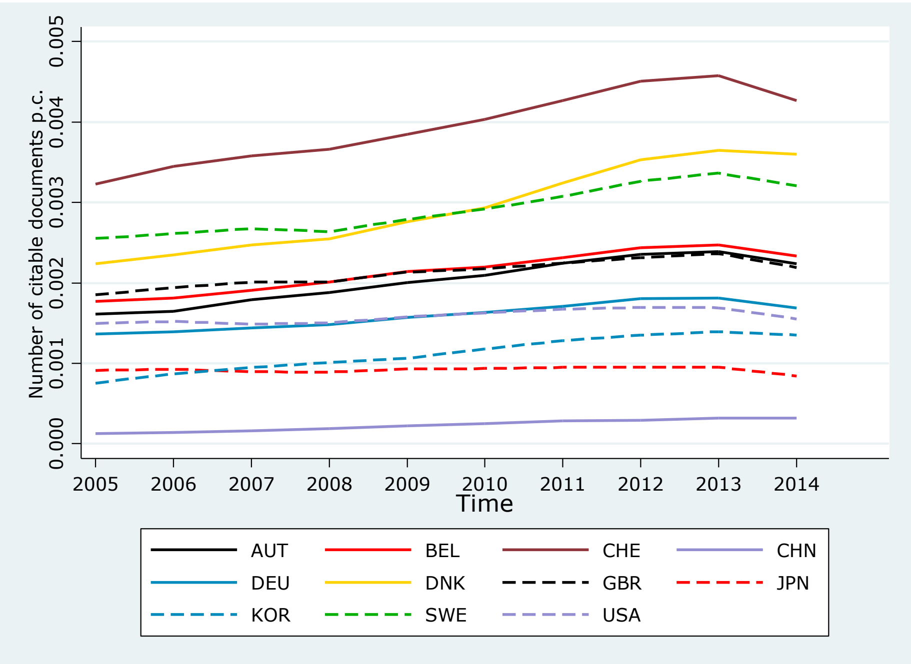
In contrast, South Korea's per capita publication output has constantly increased and almost caught up with Germany and the U.S., but a corresponding increase in population-adjusted highly-cited publications cannot be observed. Scientific knowledge production does not just build on codified knowledge as evidenced by publications; on the contrary, tacit knowledge plays an important role. Many contributions to the sociology of science show that research results only become "usable" once they are actually applied and used for further research in labs, so that people really understand what is going on (see, e.g., Knorr-Cetina, 1981). Tacit knowledge in science could only be proxied through, e.g., basic research expenditures, or research expenditures in higher education institutions.

Figure 3: Number of publications in the top 10% of journals per 1,000 population



Source: SciVal Elsevier, OECD.

Figure 4: Number of citable documents



Source: SCImago.

3.2 Technological frontier

To measure the technological frontier, a variety of indicators is in principle possible: indicators of codified technological knowledge[12] (patents as intermediate outputs of innovation activity) or indicators of the novelty of product innovations. For the latter, object-based approaches are possible (the technometric literature, see section 1) and subject-based ones (asking firms about the novelty of their innovations, as practiced by the CIS). However, both approaches are currently unsuitable for a reliable country-level measurement of the technological frontier (see Janger et al., 2017, for a discussion).[13] Hence we focus on patent data which are commonly used in the literature to measure technological output. A patent has to reflect a novelty, i.e. a movement of the technological frontier, so that patents are often used to measure the rate of technological change.

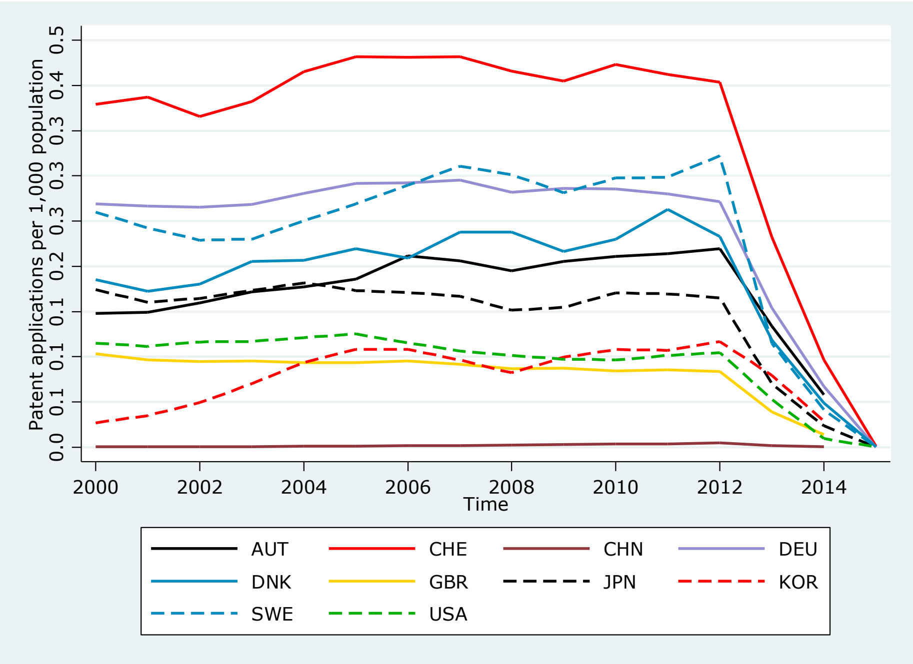
We choose three different patent based indicators. First, capturing the quantity aspect, we use the population-adjusted aggregate number of patent applications at the EPO. This indicator reproduces a country's patent propensity. Figure 5 illustrates the difference in the number of patent applications for a group of countries within the last 15 years. The sharp fall of patent applications since 2012 results from the time span between application and publication and is reinforced by the use of priority dates instead of publications dates. Therefore, these data points need to be interpreted carefully or even excluded from the analysis. However, it can easily be seen that Switzerland has by far the highest patent application rate, followed by Germany and Sweden. Of course, patent indicators are not pure indicators of technological knowledge, with many caveats applying (see Janger et al., 2017, for a recent discussion).

We use the population-adjusted number of patent applications that receive more than five citations by subsequent patents as a second indicator for the technological frontier to capture the quality level of the contribution to the technological frontier as well. Indeed, highly cited patents can be assumed to be more influential and possibly more groundbreaking than patents that are barely quoted (Albert, Avery, Narin, & McAllister, 1991; Hall et al., 2005; Trajtenberg, 1990). However, some inventions might be ahead of the times and thus it could take a while before their impact becomes manifest in citations. Hence, we do not determine a specific citation span but count all forward citations during the whole observation period.

[12] Steinmueller, 2010 distinguishes scientific from technological knowledge by its mode of production and by its openness: scientific knowledge is knowledge produced for open disclosure with the aim of achieving recognition as the originator (scientific priority) while technological knowledge is produced with the aim of capturing some form of exclusive rights to its use (with exclusivity protected by patents or other means, such as secrecy).

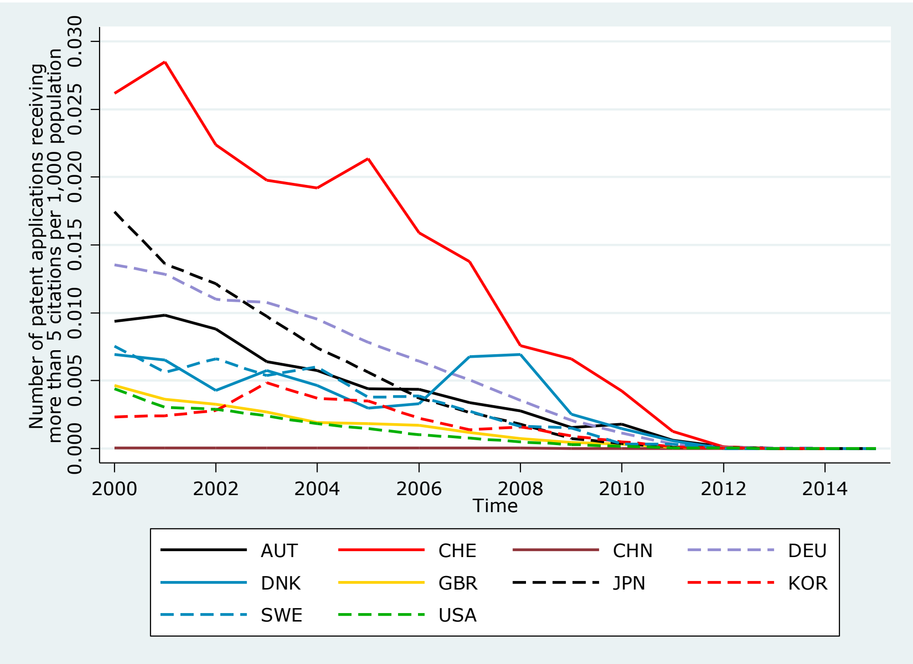
[13] Basically, subjective assessment of novelty by firms leads to puzzling cross-country results, while constructing technometric indicators is too cumbersome for entire countries.

Figure 5: Number of patent applications per 1,000 population



Source: PATSTAT, Spring 2016, WIFO.

Figure 6: Number of patent applications receiving more than 5 citations per 1,000 population

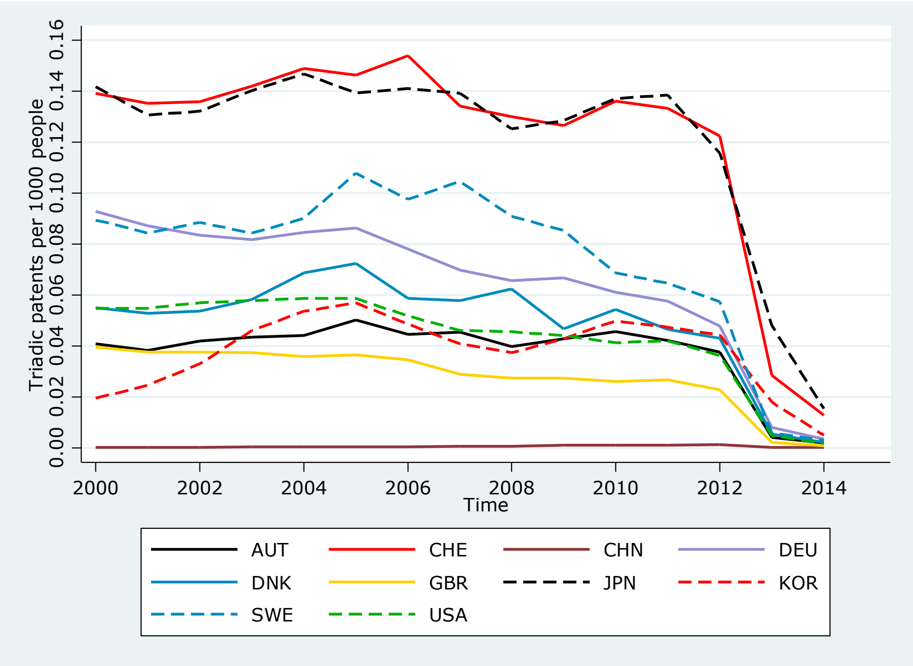


Source: PATSTAT, Spring 2016, WIFO.

Naturally, the number of highly-cited patents shown in Figure 6 is decreasing as more and more citations are accumulated over time. Again, Switzerland is the leading country regarding patent citations, even though Denmark has increased its citation rate within the last years tremendously. In contrast, Japan, that was the second leading country with respect to patent citation rates at the beginning of the 2000s, has been outperformed by Denmark and Germany.

Third, we use the population-adjusted number of triadic patent filings. On the one hand, this indicator detects high quality patents in the view of the fact that only patents that are considered as commercially highly significant might be filed at the EPO, the USPTO and the JPO at the same time. Because every patent application at each patent office is connected to certain costs (administrative costs as well as nonrecurring fees and annuity fees) it is plausible to assume that only patents with a promising future in terms of being turned into successful innovations are filed at all three patent offices (Cerulli, 2014). Another advantage refers to the fact that patent indicators based on the information of only one specific patent office often suffer from a "home" bias, i.e. domestic enterprises rather tend to file patents at their home country's patent office instead of foreign patent offices (Dernis & Khan, 2004). Figure 7 shows that with respect to the number of triadic patent applications Japan and Switzerland are far ahead of other countries. Regarding all three population adjusted patent indicators, Switzerland seems to be the leading country over the last 15 years. For similar reasons as in the case of simple patent application count data, a sudden decrease in triadic patent applications can be observed and therefore information of the most recent years should not be included in the analysis.

Figure 7: Number of triadic patent applications per 1,000 population



Source: PATSTAT, Spring 2016, WIFO.

However, with respect to the requirements of our framework, a clear lack of measures can be seen with regard to the quantity and quality of innovations. All patent based indicators reflect inventions and lack the ability to fully capture product, service, process and organisational innovations. Patent intensity also highly differs across industries and thus reflect national industry structures (Cohen, Nelson, & Walsh, 2000). The use of patent citations or triadic patents cannot fully bypass these problems. However, with respect to country specific patent behaviour induced by social norms, indicators aimed at high-quality or commercially significant patents might be less biased than indicators based on simple patent counts. Also tacit knowledge, which is probably even more important in application than in science, could only be proxied through R&D spending by firms or by applied research and development expenditures. In summary, our measures of the technological frontier are however clearly technology- or invention-related, rather than using an economic concept such as TFP which is often used in the growth literature as a proxy for the technological frontier. TFP has several drawbacks as a measure of the technological frontier as we define it. First, it includes the effect of all factors influencing GDP and productivity, not just science and technology related ones. Second, TFP can't be observed unlike publications or patents, it is fundamentally the result of a complicated calculation based on many assumptions, with difficulties involved particularly with the measurement of the capital stock which often makes it difficult to compare levels of TFP across countries, which is however needed to compare performance or frontier level. Third, due to its nature as a residual, it is sensitive to cyclical effects (capacity utilisation).[14] Yearly changes in productivity growth should as a consequence not be interpreted as "shifts in disembodied technology" (Schreyer and Pilat, 2001, p. 160).

3.3 Innovation frontier

There is probably most discussion on how to measure the innovation frontier, or innovation outcomes (Freeman & Soete, 2009). The CIS indicator on sales of innovative products suffers from the same problem of subjective assessment of novelty discussed above. To measure the innovation frontier, we draw on recent contributions (see Janger et al., 2017) that innovation outcomes must either be reflected in structural change towards knowledge-intensive sectors or structural upgrading within sectors towards more knowledge-intensive segments of a sector ("climbing up the quality ladder"). While indicators of the share of high-tech industries or exports have been widely used, lacking from the literature so far was a measurement of this important upgrading component. This can be seen to reflect movement along a technological trajectory as conceptualised by an evolutionary view on innovation, while structural change reflects the emergence of new trajectories.

To cover economies' structural change we choose an indicator based on the value added share of sectors with medium-high or high innovation intensity in total value added (Peneder, 2002, 2010). In contrast, structural upgrading is reflected by two indicators, a measure of business R&D intensity corrected for industrial structure as well as by the share of the high-quality segment in total exports (manufacturing only).

Every industry produces goods and services on a quality ladder, e.g. a three gear steel bicycle versus a 21 gear carbon bicycle. An indicator on export quality divides an industry's total exports in three parts by unit value (price segments; see Janger et al., 2012). It then shows how much of the exports of a country in a particular industry is in the high quality (high price) segment. Averaging and weighting over all industries gives a country value for the quality of exports, which is based on actual product quality, rather than based on international averaging of knowledge-intensive goods, as in the case of structural change indicators. The indicator we use is the share of high-quality segment in total exports. By

[14] See Schreyer & Pilat (2001, p. 157f): "Multi-factor productivity growth is often interpreted as an indicator of technological progress. This is not entirely correct for three reasons: i) technological change does not necessarily translate into MFP growth; ii) MFP growth is not necessarily caused by technological change; and iii) MFP may understate the eventual importance of productivity change in stimulating the growth of output. These three factors are discussed below. … Just as some technological change does not correspond to MFP growth, some MFP growth is not caused by technological change alone… Even where the residual reflects part or all of technological change, several other factors will also bear on measured MFP. Such factors include adjustment costs, economies of scale, cyclical effects, inefficiencies and measurement errors. This is confirmed by econometric studies that link MFP growth to technology variables, in particular research and development and patents or those that explicitly control for adjustment costs or allow for non-constant returns to scale. Research and development expenditure, for example, tends to show a statistically significant relation to productivity growth, but only explains a relatively small part of the overall annual movements in MFP. This indicates the presence of other factors. Measures of MFP are thus better interpreted as measures of improvements in overall efficiency than as pure expressions of technical change."

concentrating on high-priced products we capture the quality aspect of the innovation frontier since it can be assumed that within products higher unit values are connected to higher quality.

The measure correcting business R&D intensity for industrial specialisation of countries is based on the observation that there are huge differences between industries regarding the prevailing technological regime (conditions of appropriability, technological opportunity and knowledge cumulativeness) which lead to big differences in how much R&D is necessary for international competitiveness (Peneder, 2010; Reinstaller and Unterlass, 2011). Average business R&D intensities mask these sectoral differences; correcting for them allows for an unbiased view how R&D intensive a country is given its industrial specialisation. Structural change indicators (shares of high-tech industries) are distorted by the international fragmentation of value chains (knowledge creation in one country, commercialisation or production in another). Combining them with the R&D intensity measure corrected for sectoral specialisation enables to see in which part of the value chain countries are (more vs. less knowledge-intensive), hence shedding light on the "upgrading" component of the innovation frontier (See Janger et al., 2017, for a detailed discussion).[15] Separately framing the technology and the innovation frontier, and conceptualising two dimensions of the innovation frontier – change and upgrading – allows for investigating innovation in times of GVC; our upgrading, or quality indicators, are able to remove some of the bias incurred through the increasing organisation of production in GVC.

Figure 8 to Figure 11 illustrate the indicators for measuring the innovation frontier. The calculation of shares of innovation-intensive sectors as well as the BERD intensity corrected for industrial structure require detailed industry-level data[16]. Unfortunately, using data from both Eurostat SBS and OECD STAN leads to only a limited country sample for restricted time periods. Because of the lack of data, China is not considered in Figure 8 and Figure 9. Although these data issues argue against the use of indicators based on sector shares, the assessment of a country's position with regard to the innovation frontier should account for prevailing industrial structures and their development over time. The differentiation between within industry upgrading and structural change allows for capturing the two crucial dimensions of innovation outcomes at the sectoral level (see Janger et al., 2017). Upgrading has been shown to be a major feature of firms' innovation activities.

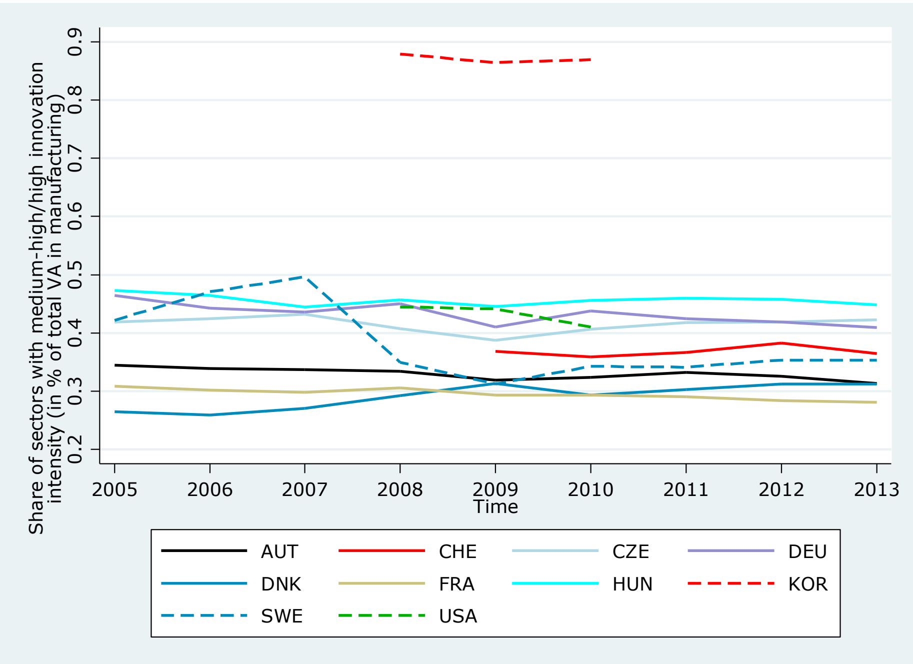
Hungary is one of the best examples to emphasize the necessity to incorporate both shares of knowledge-intensive industries as well as the upgrading of industries in the analysis. Regarding industry structures with high innovation intensity South Korea is ranked first place, followed by Hungary, the U.S. and Germany (Figure 8). The high share of innovation-intensive industries in Hungary partly reflects the embeddedness of Hungary's manufacturing sectors in a global

[15] This is just one possible interpretation or use of the indicator. It could also be seen as more reflecting tacit knowledge created in firms relevant for the technological frontier.

[16] NACE at 3-digit-level is necessary to identify research-intensive sectors, the innovation intensity and BERD corrected for sectoral specialization are based on NACE 2-digit data.

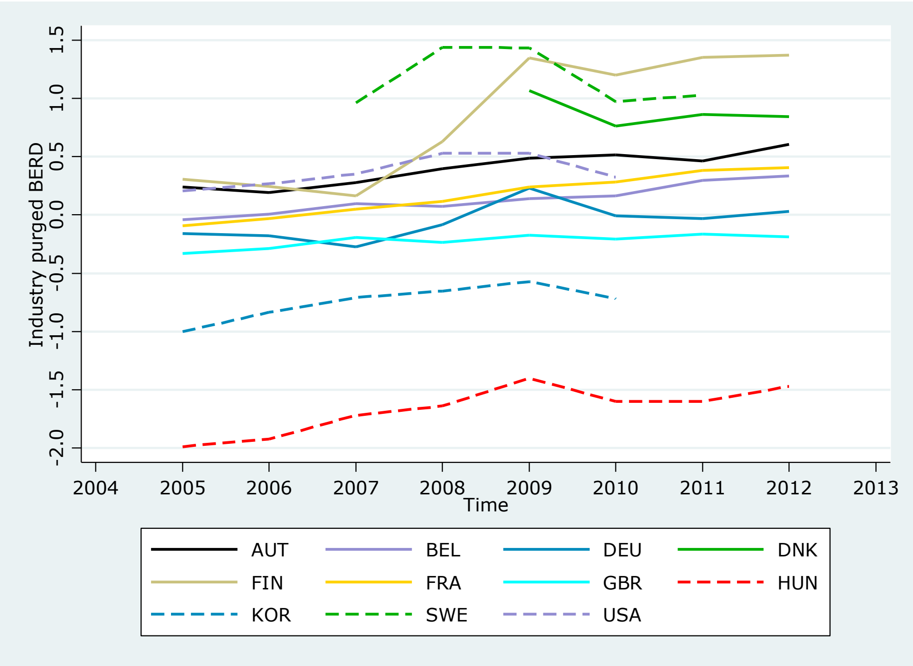
value chain, particularly with respect the automotive and chemical industry as a result of concentrated foreign direct investment (Kiss, 2007; Lengyel & Cadil, 2009). In contrast, Hungary is far from being among the leading countries considering the within industry quality aspect displayed by the industry-purged BERD intensity (Figure 9). Given the auspicious industry structure this result indicates that most of the manufacturing companies classified into high or medium-high innovative sectors in Hungary do not invest in R&D to an extent that would be expected from such industries. This is in line with research on the automotive industry in Eastern-Central Europe (ECE) showing that the concentration of automotive R&D remains concentrated in Western Europe close to the headquarters' location, though the relevance of passenger car assembly is increasing in ECE (Pavlínek, 2012; Pavlínek & Ženka, 2011).

Figure 8: Share of sectors with medium-high/high innovation intensity (in % of VA in manufacturing)



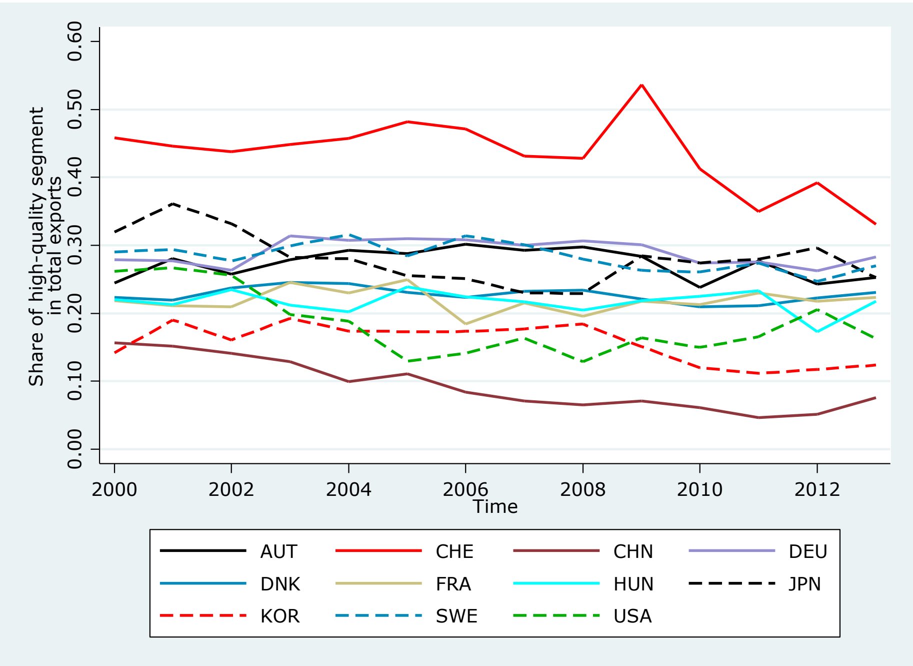
Source: SBS, STAN, WIFO.

Figure 9: Industry purged business expenditures on R&D (BERD) intensity



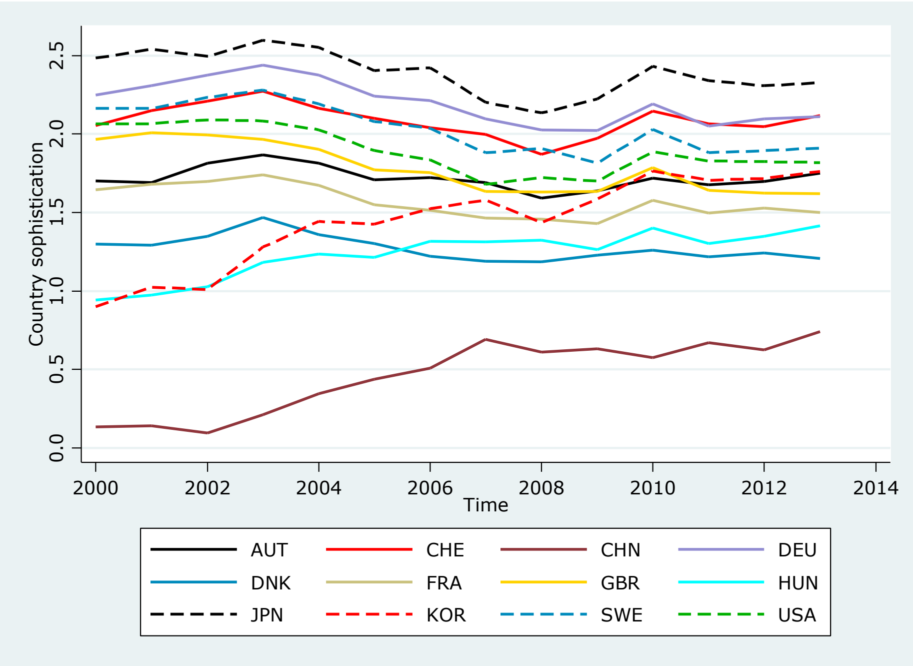
Source: STAN, ANBERD, Eurostat, WIFO.

Figure 10: Share of high-quality segment in total exports



Source: BACI (HS 6, 1992), WIFO.

Figure 11: Country sophistication



Source: BACI (HS 6, 1992), WIFO.

Due to the restricted data availability, we consider as an alternative approach to measure the innovation frontier the product space- or complexity-literature. Here, data is available for every country that exports , however for manufacturing only (we hence gain in countries, but lose in terms of the size of the economy). The productive structure of countries is conceptualized to be determined by the local availability of capabilities termed "sophistication" and measured by network algorithms applied to export data, combining quantity and quality aspects of frontier contribution in one measure, as it relates both to how many different products a country makes and how difficult they are to make (see, e.g., Hidalgo & Hausmann, 2009; Hidalgo, Klinger, Barabási, & Hausmann, 2007; A. Reinstaller, Werner, Johannes, & Christian, 2013; Andreas Reinstaller, 2013). In terms of country ranking, a similar picture is obtained, with Japan at the top, followed by Germany and Switzerland.

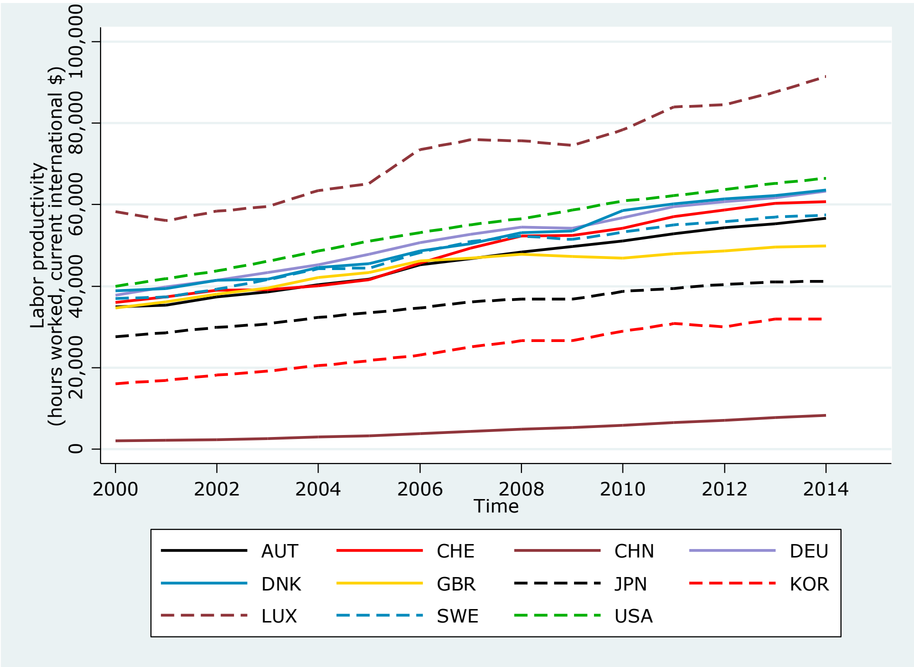
3.4 Economic frontier

We choose the classic indicators GDP per capita, labour productivity per hours worked and TFP provided by the World Bank, the Total Economy Database (TED) and the Penn World Tables to measure the level in transforming inputs (not necessarily STI-related) into general economic output. These indicators are shown in Figure 12 to Figure 14. Again, the country ranks are different from those regarding the scientific, technological or the innovation frontier. Clearly, considering not only STI-related performance but rather the general economic performance the U.S. ranks among the world's top performers. Its productivity, irrespective of measuring it by LP or TFP, has been highest for most of the last 15 years. Regarding per capita GDP the U.S. has just been overtaken by Switzerland from 2009 onwards. This observation definitely supports our approach to strictly differentiate between STI- based frontiers and their measurement and general economic performance measures (see Table 2).

Countries at the economic frontier such as Luxemburg or Norway are not necessarily at the top in STI-related frontiers, pointing to wider influences such as e.g. natural endowments (Norway) or the share of foreign workers (Luxembourg), even with respect to TFP. This adds to the problematic of using TFP as a measure of the technological frontier as often done in the literature, as the level of TFP is barely suitable as an indicator of yearly changing levels (see the discussion above).[17] While many studies find a significant correlation between R&D expenditures and productivity growth, they usually explain only a small part of productivity growth (Schreyer-Pilat, 2001), highlighting the role of other factors. TFP measures are hence a better indication of overall efficiency gains than of technological change or innovation activity. Using the terms productivity and technological (in our framework, innovation) frontier interchangeably does not seem to be warranted. Furthermore, the US is not always the leading frontier country, so that research should not simply assume the US to be the leading country.

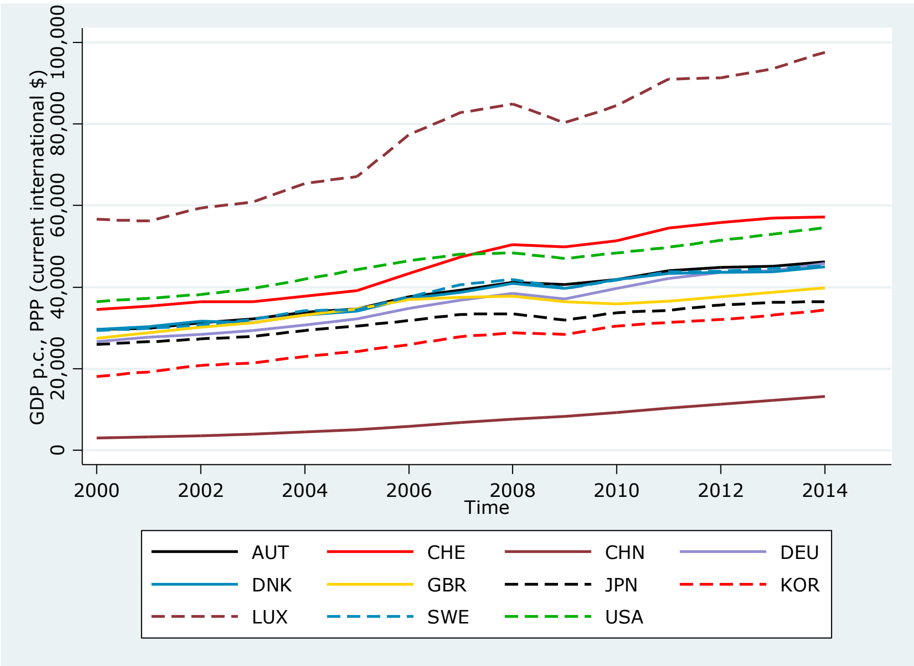
[17] Keller 2004: "In contrast to R&D and patents, TFP is a derived measure of technology, as it is computed from data on inputs and output. This introduces measurement error and perhaps biases, because the appropriate data on inputs and outputs is rarely, if ever, available."…" Other factors might thus contaminate the use of TFP as a measure of technological efficiency, which ultimately goes back to the concern that TFP is constructed as a residual, and may potentially capture a host of spurious influences"

Figure 12: Labour productivity (per hours worked, current international $)



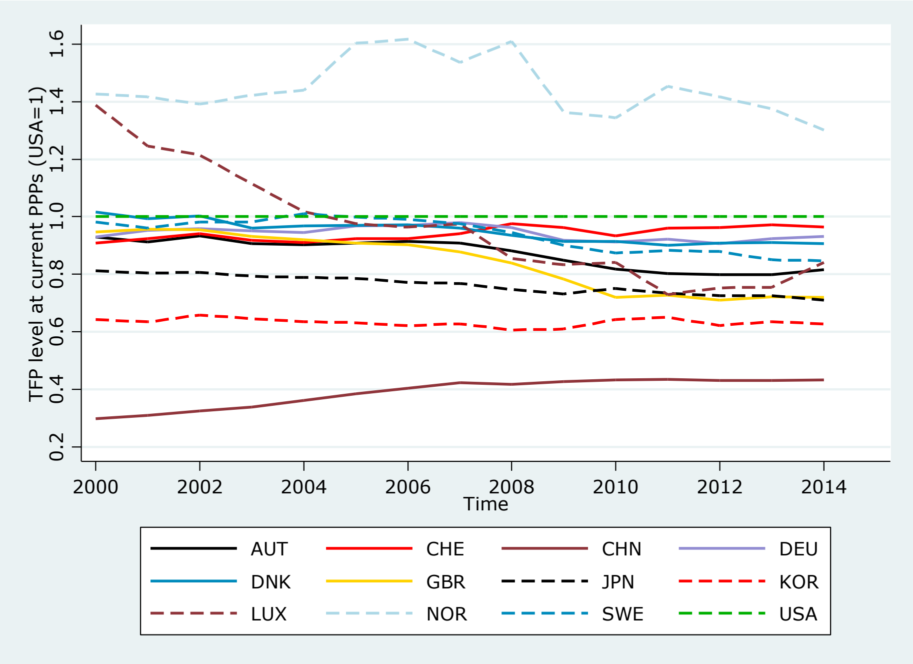
Source: World Bank, TED.

Figure 13: Gross domestic product, per capita, PPP (current international $))



Source: World Bank.

Figure 14: Total factor productivity (current international $, U.S. = 1)



Source: Penn World Tables.

Table 2: Countries leading in the various frontier measures, 2010

Frontier domain	Indicator	Abbr.	Leading country	Rank of USA	Quantity	Quality
Economic frontier	GDP p.c., PPP (current international $)	GDP	Luxembourg	4		
	Labor productivity (hours worked, current international $)	LP	Luxembourg	4		
	TFP level at current PPPs (USA=1)	TFP	Norway	3		
Innovation frontier	Share of sectors with medium-high/high innovation intensity (in % of total VA in manufacturing)	SII	South Korea	4	x	
	Country sophistication	Csoph	Japan	6	x	x
	Industry purged BERD	BERD	Finland	5		x
	Share of high-quality segment in total exports	EQ	Ireland	20		x
Technological frontier	Patent applications per 1.000 population	PA	Switzerland	14	x	
	Triadic patent applications per 1.000 population	TPA	Japan	11	x	
	Number of patents receiving more than 5 ciations, per 1.000 population	Pcit	Switzerland	18		x
Scientific frontier	Number of citable documents p.c.	PLB	Switzerland	14	x	
	Number of scientific publications among the top 10% p.c.	TopPub	Switzerland	11		x

Source: See Table 1.

3.5 Analysis of indicators

We test the relationships between various frontier measures using cluster and factor analysis, to investigate whether there are stable country groups across the frontiers (whether several countries share similar frontier contribution capabilities) and to check for common dimensions among the indicators. We also compare innovation and technology frontier measures at the country level with measures at the sectoral level, as far as possible, to show whether frontier measures at the country level are suitably reflecting underlying sectoral heterogeneity.

Factor analysis for a compact representation of the countries' position on the frontiers

First, we use factor analysis for each indicator set of the four frontiers to reduce the number of indicators to one latent variable per frontier set. This provides a convenient way to combine information of several sources and allows for a compact representation of countries' position on the different frontiers. For each frontier we obtain one latent variable on the basis of the respective frontier's indicators. The factor loadings are presented in Table 3; they show how much the individual indicators influence the factors and accordingly how much variation of individual indicators can be reflected by the factors.

Table 3: Factor loadings and uniqueness variances

Frontier	Variable	Factor	Uniqueness
Scientific	PLB	0.9729	0.0534
	TopPub	0.9729	0.0534
Technological	PA	0.9363	0.1234
	TPA	0.8735	0.237
	Pcit	0.7572	0.4267
Innovation	SII	0.3647	0.867
	BERD	0.5882	0.654
	Csoph	0.8085	0.3463
	EQ	0.6465	0.582
Economic	GDP	0.9258	0.1428
	LP	0.9858	0.0282
	TFP	0.8731	0.2377

Source: See Table 1.

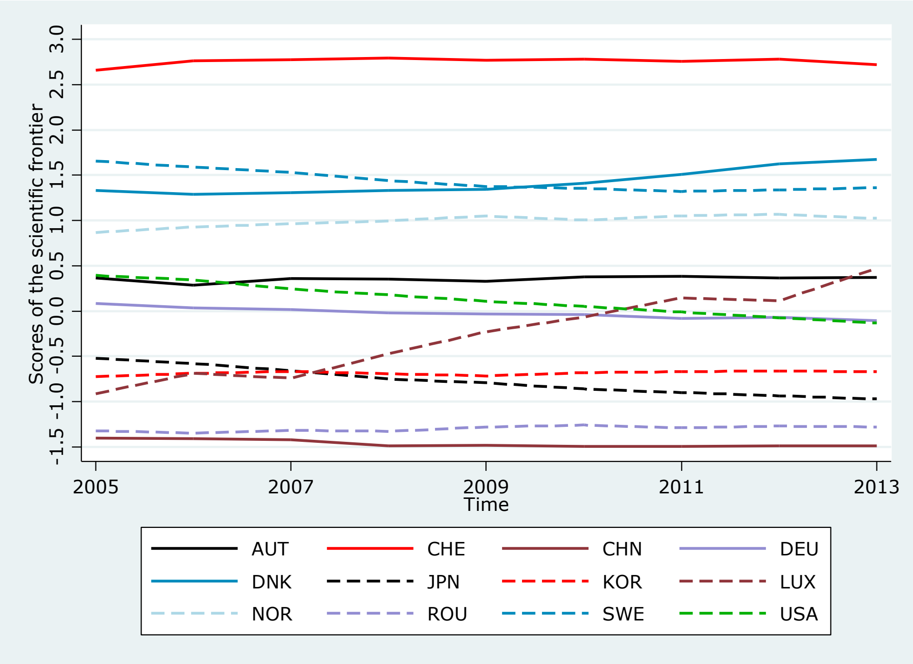
In case of the scientific frontier the factor loadings are equally large with respect to the number of publications in the top 10% of journals and the number of citable documents, meaning that both indicators seem to be statistically important to measure the frontier in science. A higher factor loading is associated with the number of patent applications than with triadic patent applications or the number of applications receiving more than five citations. Regarding the innovation frontier factor, the highest loadings are associated with country sophistication and the share of the high-quality segment in total exports, while the share of innovation-intensive sectors and the industry purged BERD intensity are associated with variances that are highly 'unique' to them and cannot be accounted for by other variables in the factor analysis. Thus, the resulting latent variable is mainly driven by country sophistication and the share of the high-quality segment in total exports. Finally, the factor analysis including the indicators dedicated to the economic frontier results in particularly high loading for labour productivity and p.c. GDP.

The consolidated frontier: results from the factor analysis

The estimated latent variables based on the factor loadings are presented in Figure 15 to Figure 18. Starting with the latent variable of the scientific frontier we find that Switzerland is on top, followed by Denmark and Sweden. Considering the clear and similar country ranking of the two underlying indicators this result comes as no surprise. The countries' latent factor scores regarding the technological frontier can be explained by the high load on patent applications. Again, Switzerland is the leading country, Sweden and Germany come second and third place alternating with one another. Mainly due to its high rate of triadic patent applications Japan is also well placed.

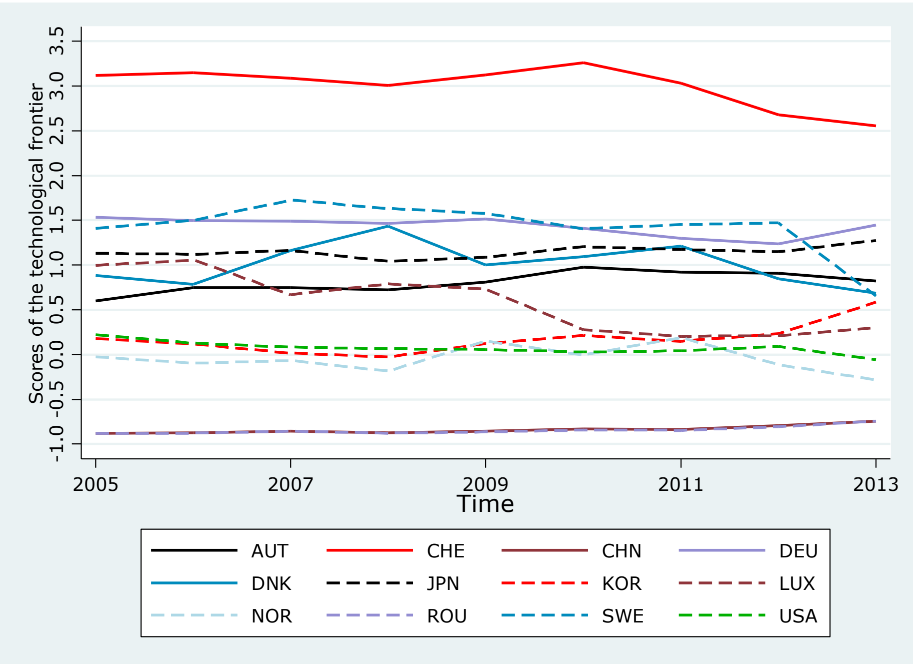
The latent variables scores of the innovation frontier are based on country sophistication, the high-quality segment in exports of complex products, industry purged BERD intensity and the share of innovation-intensive sectors, where the last variable measures structural change and the second and third are associated with structural upgrading. Since we do not have industry-level data for all non-European countries for every year, the latent variable cannot be calculated for all countries in all periods. Looking at the latent variable scores Germany and Sweden are clearly leading.

Figure 15: Latent variable scores from factor analysis based on scientific frontier indicators



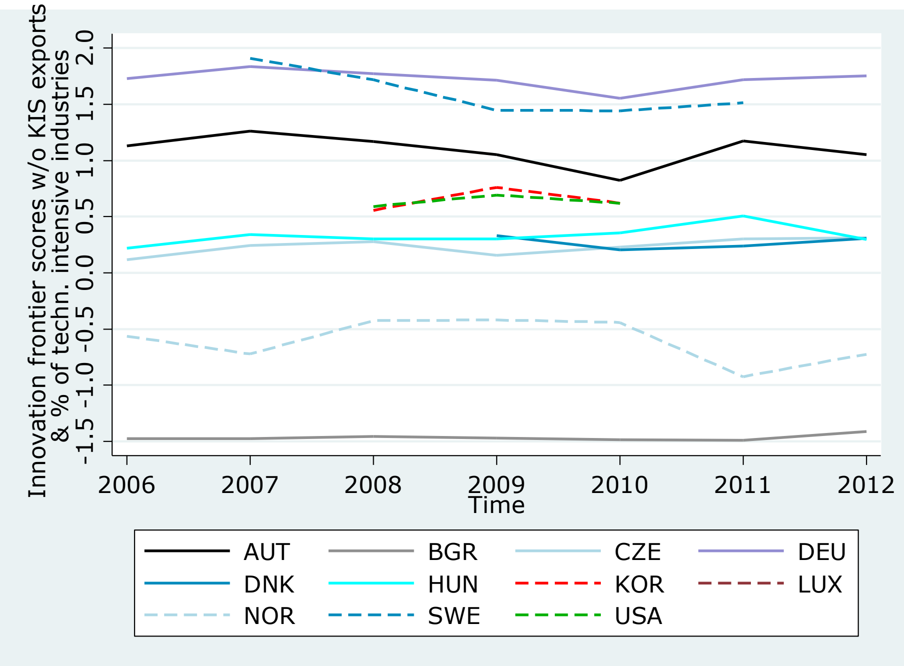
Source: For data sources for the calculation of the frontiers see Table 1.

Figure 16: Latent variable scores from factor analysis based on technological frontier indicators



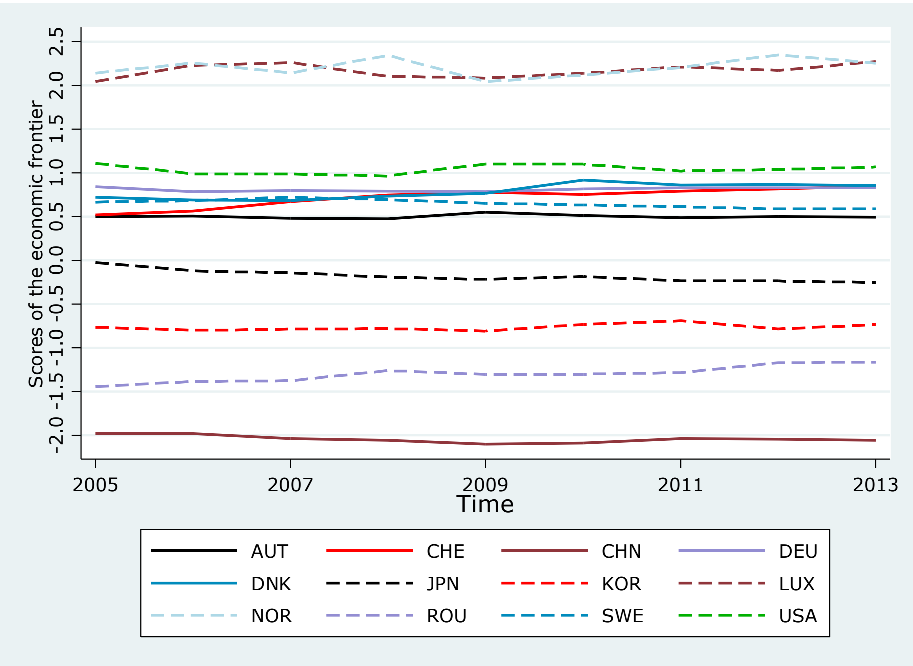
Source: For data sources for the calculation of the frontiers see Table 1.

Figure 17: Latent variable scores from factor analysis based on innovation frontier indicators



Source: For data sources for the calculation of the frontiers see Table 1.

Figure 18: Latent variable scores from factor analysis based on economic frontier indicators



Source: For data sources for the calculation of the frontiers see Table 1.

Luxembourg and Norway constitute the leading countries regarding the economic frontier. Besides those frontrunners a group of economically well-situated countries is closely grouped together, above all the U.S. but also Switzerland, Sweden, Denmark and Germany. Note that the overall economic performance measured by the respective latent variable scores need not necessarily mirror the country rankings of the innovation frontier. For instance, Norway might be characterized by average innovation-related capabilities and the same holds for its inventive capability based on patent-related indicators. However, Norway is clearly close to the frontier with respect to its overall economic performance and its capability to expand the limits of scientific knowledge is close to Denmark and Sweden as well. This example supports our claim to differentiate between different types of frontiers, as there are probably different drivers at work and as a result different policy measures would be required to boost a country's position regarding one particular frontier.

Generally, considering the definitions of the four frontiers the resulting four frontier scores are rather reasonable. Surely, as suggested by our theoretical framework these frontier scores are correlated with each other and interdependent. In particular, as shown in Figure 19, the rank correlation between the innovation frontier and the technological frontier is high. The same applies for the rank correlation between the scientific frontier and the technological frontier, which is intuitive as there should be a connection between scientific knowledge and a country's inventive capability. Interestingly, a rather high rank correlation between the scientific frontier scores and the economic frontier can be observed, that gives a strong hint at the importance of a country's established scientific knowledge base. The lower correlation between the economic and the innovation frontier is possibly due to the fact that the innovation frontier comprises both the structural change and upgrading dimensions; in particular in the structural change dimension, countries with lower GDP per head or labour productivity, such as Hungary and South Korea, achieve very good scores due to a high share of knowledge-intensive sectors. Further research will aim at disentangling these two dimensions of the innovation frontier.

Figure 19: Rank correlation matrix of the latent variables scores of the four frontiers

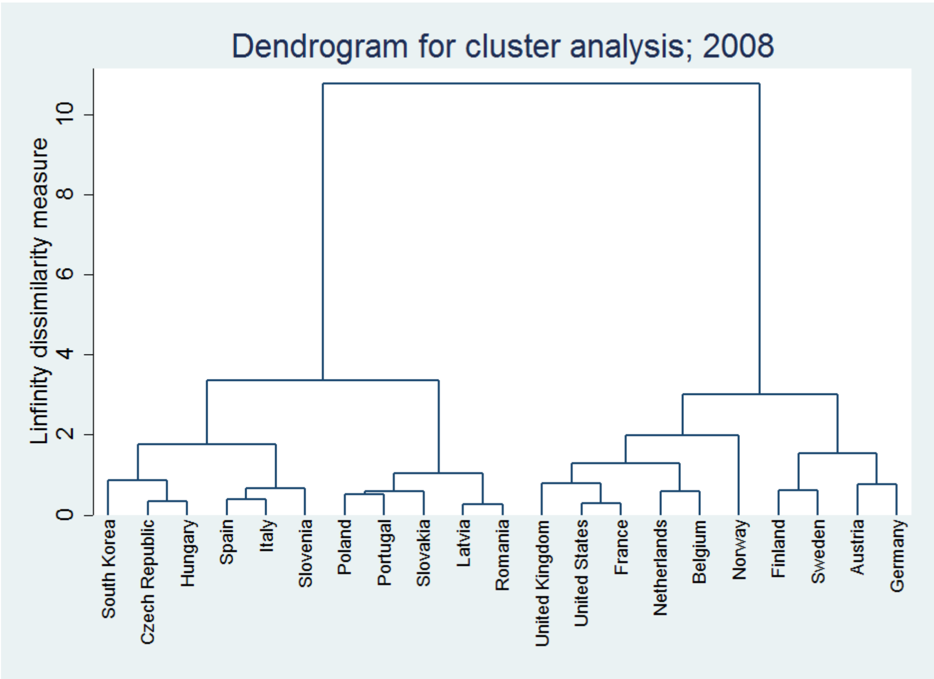
	Rank w.r.t. scientific frontier scores	Rank w.r.t. technological frontier scores	Rank w.r.t. innovation frontier scores	Rank w.r.t. economic frontier scores
Rank w.r.t. scientific frontier scores	1			
Rank w.r.t. technological frontier scores	0.841	1		
Rank w.r.t. innovation frontier scores	0.667	0.811	1	
Rank w.r.t. economic frontier scores	0.840	0.800	0.601	1

Source: For data sources for the calculation of the frontiers see Table 1.

3.6 Cluster analysis

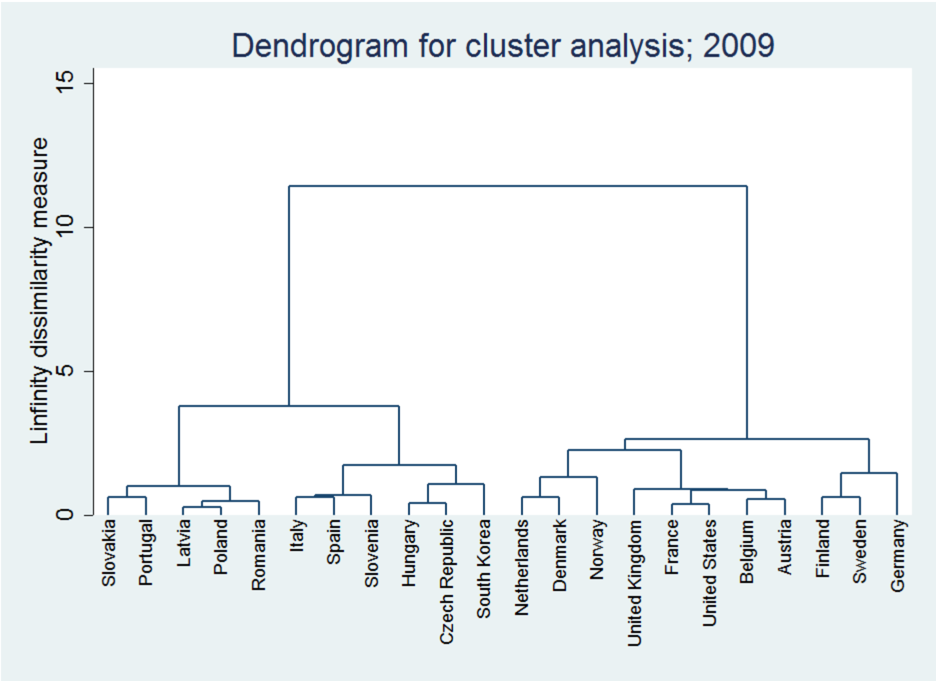
In a next step we cluster countries by using the four latent variable scores of the frontiers for the years between 2008 and 2010 in which all variables are available. We cluster the data in each year separately. As we do not have a priori information about the number of clusters required we use a hierarchical cluster method. We choose Ward's method (minimum variance method) based on the sum of squares criterion because of its tendency to avoid clusters containing single individuals. On the base of dendrograms (Figure 20 to Figure 22) we choose to group the countries into four different groups. The country members of the different groups are shown in Table 4.

Figure 20: Dendrogram, four latent frontier variables, 2008



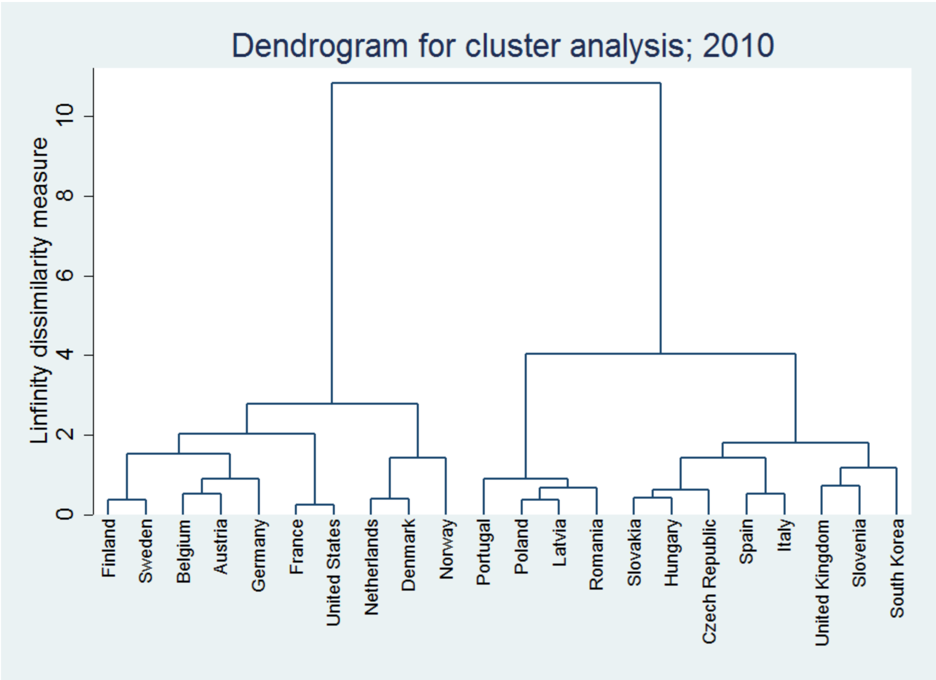
Source: WIFO-calculation.

Figure 21: Dendrogram, four latent frontier variables, 2009



Source: WIFO-calculation.

Figure 22: Dendrogram, four latent frontier variables, 2010



Source: WIFO-calculation.

Table 4: Country groups based on Ward cluster analysis between 2008 and 2010

Year	Group 1	Group 2	Group 3	Group 4
2008	Austria Finland Germany Sweden	Belgium France Netherlands Norway United Kingdom United States	Czech Republic Hungary Italy Slovenia South Korea Spain	Latvia Poland Portugal Romania Slovakia
2009	Finland Germany Sweden	Austria Belgium Denmark France Netherlands Norway United Kingdom United States	Czech Republic Hungary Italy Slovenia South Korea Spain	Latvia Poland Portugal Romania Slovakia
2010	Austria Belgium Finland France Germany Sweden United States	Denmark Netherlands Norway	Czech Republic Hungary Italy Slovenia South Korea Spain Slovakia United Kingdom	Latvia Poland Portugal Romania

Source: WIFO-calculation.

The four country groups can be described by using the (z-standardized) variables measuring the four frontiers (see Figure 20). Obviously, regarding their characteristics the basic content of each group does not significantly vary over time, i.e. the cluster analysis provides four groups that are similar and comparable with respect to their measured features in each of the three years. The first group of countries is associated with outstanding performance regarding all indicators included. Members of the first group are all-rounders, but particularly characterised by strong national manufacturing bases. These countries do not only contribute to extending the global stock of knowledge by the high quantity and quality of their academic publications, but also master being inventive and apply knowledge to some practical use, which is indicated by exceptionally high patent statistics. In addition, their industrial structure, regarding both knowledge-intensity across and within sectors, is exemplary. Germany, Sweden and Finland are constant member states of this group between 2008 and 2010.

However, the economic performance of the first group's members is outperformed by the second group of countries, the globalisers. In this group are the most productive countries measured by labour and total factor productivity with exceptional per capita income, though, their technological achievements are lower than those of the first group. Furthermore, they lack innovation-intensive sectors as well as high shares of high-quality exports of complex goods. Member countries of the second group are characterized by a high degree of internationalization with science-based production abroad. Constant members of this group are Norway and the Netherlands.

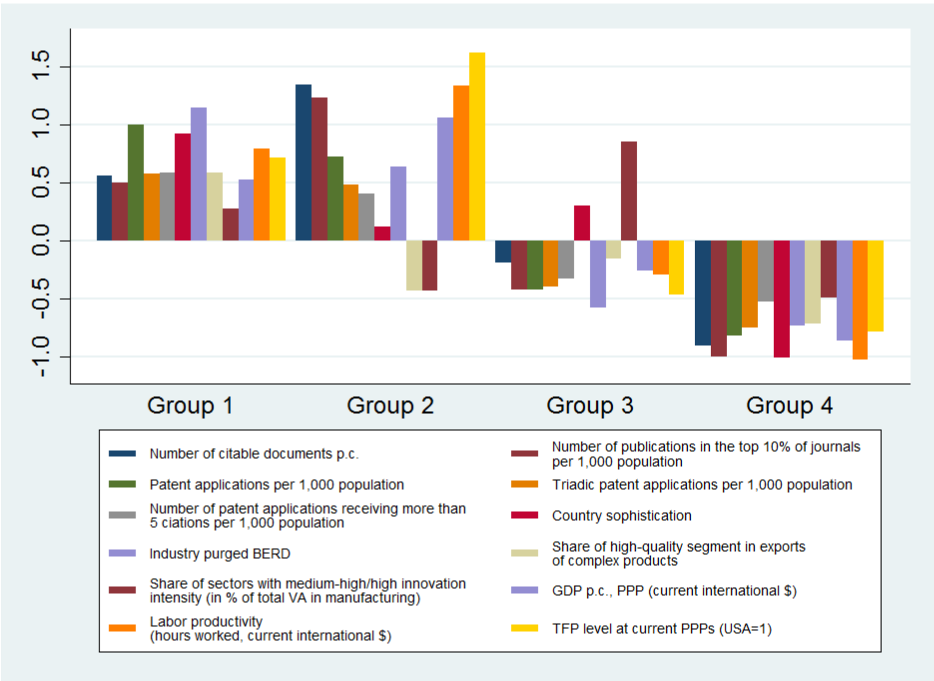
In contrast, the third group is outstanding with regard to a high share of innovation-intensive sectors only. Their values of country sophistication are above-average as well. However, all other indicators give a rather poor account. Members of this group are value-chain integrators. Amongst others Hungary, South Korea and the Czech Republic are members of this group. The characteristics describe countries that might be well-embedded in the global value chain but rather hosting fabricators than researchers and developers; an impression supported by the former analysis on the level of individual indicators. Though not yet at the highest level of frontier contribution, these countries can resort to and build on available industrial infrastructure; a trump card probably important for future development.
The fourth group consists of countries that lag behind the other country groups irrespective of what frontier indicator is examined. Neither their patent statistics, their scientific publications nor their industry structure or their general economic performance are close to the frontier. This group mainly consists of Eastern European countries such as Poland and Romania, but also Latvia and Portugal.

Transition between groups
Within the short period of three years there is not a lot of transition between the four groups (Table 4). One exception is the U.K. Till 2009 the U.K is grouped together with Belgium, the U.S. and France based on the latent variables identifying the four different frontiers. However, in 2010 the U.K. is grouped together with Slovenia, the Czech Republic, Hungary and South Korea. Its sluggish contribution to the scientific and innovation frontier but mainly its economic slowdown, particularly with respect to TFP, might explain that the similarity of the U.K.'s frontier indicators with the frontier indicators of the third country group is increasing. In addition, all patent based indicators of the U.K. are above sample average, but clearly below the patent application rates of the group of leading countries.
In contrast, Belgium, France and the U.S. successfully relocate to group 1 in 2010. France managed to enhance its capability to transform science and technology into innovations indicated by an increase of the innovation frontier indicator in 2010. Mainly, this results from a continuously upgrading process reflected by the rise in industry purged BERD intensity and a period characterized by an increased level of country sophistication. Similarly Belgium enhanced its industrial structure which is mirrored by a continuous increase in BERD as well as by a level shift of high-quality exports (QE) from 2009 onwards. Also Austria managed to switch back to group 1 due to increasing publication quality (TopBub), slightly increased patent quality (TPA, Pcit) in 2010.
However, looking at Figure 25, three countries form the hard core of the first group, namely Germany, that is characterized by an excellent industry structure, high-quality products as well as excellent technological capabilities and Finland and Sweden, two all-round leading countries with respect to the scientific, the technological and the innovation frontier.

To summarize, the cluster analysis using our four frontier indicators results in a novel and intuitive grouping of countries which takes into account different sources of capabilities for STI and the economy, and also accurately reflects the international fragmentation of production. Weaknesses with respect to scientific capabilities result from other factors and ask for different policy measures than shortcomings regarding the ability to transform knowledge and technology into innovations.

We also show that some innovation frontier measures – in particular shares of knowledge-intensive sectors in manufacturing, which are widely used in innovation rankings such as the Innovation Union Scoreboard - are affected by global value chain developments. Countries highly integrated in global value chains such as Hungary (see OECD, 2015) or South Korea actually perform very well in terms of the share of sectors classified as knowledge-intensive, even though they are not at the frontier in science and technology. This is because they specialize in the less innovation-intensive segments of these sectors, focusing on production rather than innovation. We have developed a measure of business R&D intensity which should be concluded in any frontier analysis as it corrects for industrial structure effects (Andreas Reinstaller & Unterlass, 2012) and is able to highlight such GVC effects.

Figure 23: Characteristics (standardized) of country groups, 2010



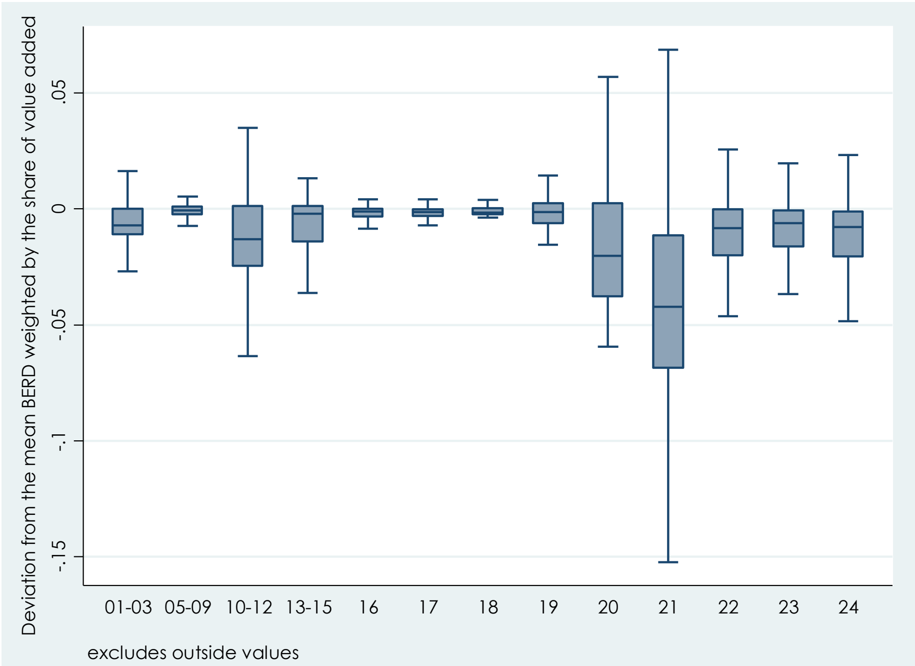
Source: For data sources see Table 1.

3.7 Industry level analysis

To make sure that our proposed aggregate indicators provide a good overview of a country's performance and sectoral heterogeneity is well reflected, we take a closer look at industry structure. Whenever applicable the used indicators are broken down into industry levels to check whether country frontiers are based on a little or a lot of sectoral heterogeneity. Particularly, we take a close look at those industries characterized by large variations between countries to identify those industries influencing the aggregate level most. To a certain extent this approach ascertains that the presented overall country performance is not only driven by some measurement artifacts. Above all, we are interested in verifying the robustness of the suggested indicators describing the quality and quantity aspect of the innovation frontier as these indicators are still less popular than others.

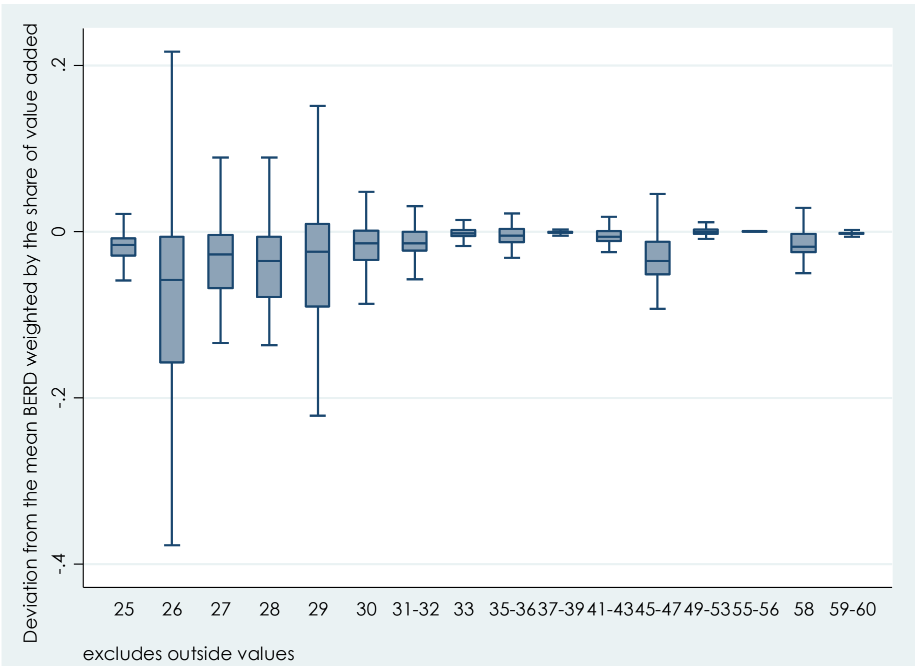
Figure 24 to Figure 26 show the variation of the value added weighted difference between a country's business R&D intensity and the mean business R&D intensity over all countries per industry between 2005 and 2015. Apparently, the highest variance between countries with respect to the industry purged BERD intensity can be found in some service sectors. In particular, this holds true for highly innovation-intensive industries like scientific research and development (NACE 72) or computer programming, consultancy and related activities and information service activities (NACE 62-63). Besides, also in the manufacture of computer, electronic and optical products (NACE 26) a long (interquartile) range is observed. In all of these industries particularly Finland, Sweden and Denmark, but also Austria represent positive outliers, reflected in high aggregate values at country level. However, most of these huge deviations between countries result from different classifications of these service sectors. Although this might bias the results on the industry level, on aggregate the different classification cancel out and do not influence the value of the country-level indicator.

Figure 24: Deviation from the mean business R&D intensity weighted by the share of value added in total production, 2005 to 2012, boxplots by industries, NACE 1 to 24



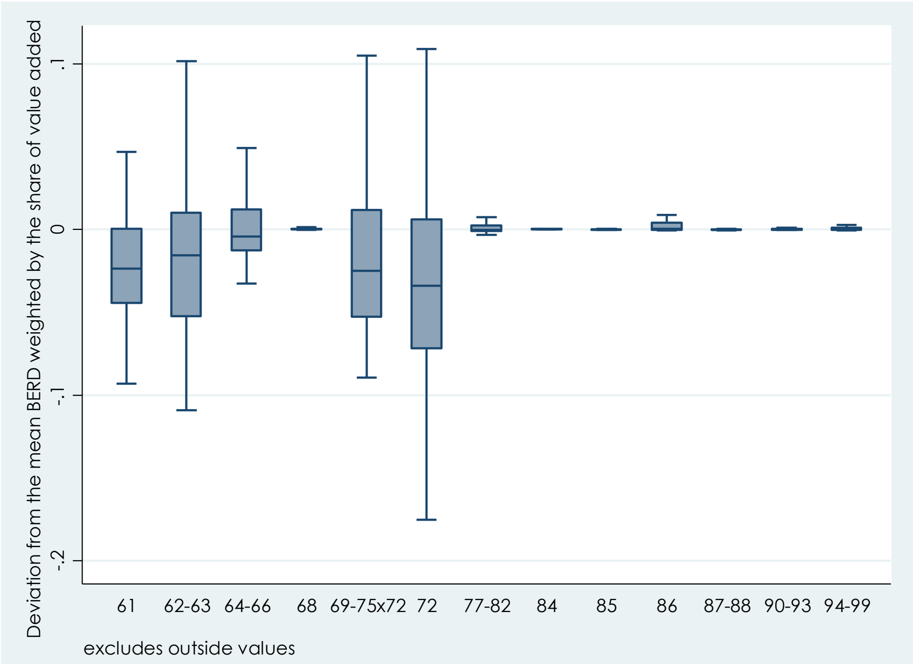
Source: Eurostat, Structural Business Statistics, OECD STAN, OECD ANBERD, WIFO-calculation.

Figure 25: Deviation from the mean business R&D intensity weighted by the share of value added in total production, boxplots by industries, NACE 25 to 60



Source: Eurostat, Structural Business Statistics, OECD STAN, OECD ANBERD, WIFO-calculation.

Figure 26: Deviation from the mean business R&D intensity weighted by the share of value added in total production, boxplots by industries, NACE 61 to 99



Source: Eurostat, Structural Business Statistics, OECD STAN, OECD ANBERD, WIFO-calculation.

The indicator "sophistication" at NACE 3-digit level reveals that some industries are characterized by large variations between countries. Examples are the manufacture of magnetic and optical media (268), the manufacture of electronic components and boards (261), the manufacture of motor vehicles (291) and the manufacture of other chemical products (205). Since the year 2000, Austria is almost always the leading country with respect to the diversity and complexity of products manufactured in the branch of magnetic and optical media. Hungary has shown a steeply increasing sophistication index in this industry since the mid-2000s too.

The manufactured motor vehicles present a similar picture. Hungary and Austria are dominating, although Great Britain and Sweden are slowly catching up. However, with respect to the manufacture of bodies of motor vehicles Switzerland and Japan are leading.

The core capabilities in the manufacture of electronic components and boards are clearly centered in Great Britain, the U.S., Germany and Japan, whereas Austria's performance is mediocre only. In contrast to the flagging performance during the 2000s, South Korea's sophistication index has risen at a tearing pace between 2010 and 2013.

In the manufacture of other chemical products regarding diversity and the complexity of products Japan is dominating but South Korea and Denmark are close on its heels.

The variance of the patent based indicators on the industry level sheds light on how much the ability to contribute to the technological frontier in specific fields differs between countries. In particular the manufacture of computer, electronic and optical products (C26), the manufacture of machinery and equipment (C28), the manufacture of chemicals and chemical products (C20) and the manufacture of basic pharmaceutical products and pharmaceutical preparations (C21) show a huge variety in terms of patent applications between countries. Regarding the population adjusted number of patent applications receiving more than 5 citations, the industries with the highest degree of variation are concentrated around the manufacturing of machinery and electronic products (C26, C27, C28).

It has already been noticed that, on aggregate, Switzerland is far beyond other countries with respect to the calculated technological frontier measure. The large gap between Switzerland and other countries is particularly true for the mentioned industries characterized by large variations. It comes as no surprise that from 2009 to 2013 the pharmaceutical industry's share in the total value added of the manufacturing sector ranges between 17°% and 19°% in Switzerland. In comparison, the average of the EU-28 is about 5°%. Clearly, considering the pharmaceutical industry Switzerland is the global market leader, which is also reflected in a high level of exports, that has been almost unaffected by the financial crises (Fuentes, Ramskogler, & Antoinette, 2011). The high quality of Switzerland's pharmaceutical industry structure is also reflected in persistently high prices of complex products within this branch. Over the last 20 years Switzerland's performance has been constantly high. Interestingly, Sweden's export prices of complex pharmaceutical products and complex pharmaceutical preparations suddenly dropped around 2009 and have not recovered yet to its original level. Finland experienced a decrease in export prices of complex pharmaceutical products in 2011 as well, although the decline was not as intense and has not persisted.

With respect to patent activities in manufacturing of computer, electronic and optical products, Switzerland is also highly ranked but Sweden and Finland reign supreme. Not surprisingly, Germany is characterized by notably high patent activities in manufacturing of machinery and equipment and chemicals and chemical products.

Overall, there is a substantial amount of heterogeneity, with some countries in some industries better than countries which lead on average. This has already been observed by Abramovitz (1986): "The flow of knowledge from leader to followers is, of course, the very essence of the catch-up hypothesis. As the technological gaps narrow, however, the direction changes. Countries that are still a distance behind the leader in average productivity may move into the lead in particular branches and become sources of new knowledge for older leaders. As they are surpassed in particular fields, old leaders can make gains by borrowing as well as by generating new knowledge. In this respect the growth potential of old leaders is enhanced as the pursuit draws closer. Moreover, competitive pressure can be a stimulus to research and innovation as well as an excuse for protection."

4. Conclusions

Based on the observation of a lack of consensus on the nature and the measurement of frontiers in science, technology, innovation and the economy, this paper proposes a consistent framework for frontier identification and measurement. We conceptualise frontiers as the highest level of scale-normalised capability to contribute to scientific knowledge creation (scientific frontier), technological knowledge creation (technological frontier), to turn scientific and technological knowledge into value added or tangible economic benefits (innovation frontier) and to turning all kinds of inputs (not just STI-related) into value added (economic frontier). We propose indicators to measure these frontiers at the country level, in particular differentiating between structural change and upgrading as two dimensions of the innovation frontier. Our framework can guide theoretical and empirical work in growth and innovation economics but also inform indicator development and policy analysis. E.g., our approach allows for shedding light on the impact of global value chains on innovation performance by separation frontiers in knowledge and value creation and by not just looking at shares of knowledge-intensive sectors, but also at within sector upgrading.

In terms of empirical results, the cluster analysis using our four frontier indicators results in a novel and intuitive grouping of countries which takes into account different sources of capabilities for STI and the economy, and also accurately reflects the international fragmentation of production. Moreover, we clearly show that using TFP as a proxy for the technological frontier does not seem to be warranted as clearly TFP levels are not just driven by STI factors. This also implies that using the US as a leading country by assumption as done in many papers should be reconsidered.

Further research can add additional or come up with better indicators – while our framework should be consistent on a conceptual basis, indicator construction is usually constrained by data availability. Taken the indicators as given, further work could investigate the drivers of the various frontiers and how the distance to the frontier affects these drivers. Convergence analysis could examine the speed of closing the gap to the frontiers, or the extent of divergence in case of top countries racing ahead, also shedding light on issues of secular stagnation. Moreover, results of current innovation rankings which usually include all three frontier areas could be compared to our results.

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Appendix

Data Sources

Scientific Frontier

The data regarding scientific knowledge are provided by the OECD and drawn from the SciVal Elsevier database. The journal ranking refers to the Scientific Journal Ranking (SJR) and the country is determined by the authors' institutional affiliation (OECD, 2014).

Technological Frontier

The patent indicators are based upon the last release of the PATSTAT database in spring 2016. A patent is attached to the country connected to the home address of the inventor[18]. To have a proxy of the inventive capability of countries rather than the productivity of the EPO, we refer to patent applications (rather than to patent grants). One advantage of using applications rather than grants is that because the granting process could take several years we would have to consider a nonnegligible time lag between the innovation and the patent granting.

Additionally, we do not consider publication dates but priority dates. If a patent application was filed at another patent office in the first place and at the EPO only subsequently, the date of the first application is used rather than the application date at the EPO. This ensures being as close as possible to the actual moment of invention. However, it has to be considered that all pending EPO patent applications are published 18 months after the priority date. In addition, if the patent had been filed at another patent office before the time span between the priority date and the publication date would be even longer. As a result the patent application data for the most recent years are not fully consolidated and subject to a continuous updating process by PATSTAT.

[18] In case of several inventors rooted in different countries the patent application is allocated equally to their respective home countries.

Complementary tables and graphs

Table 5: Frontier measures in the literature

Author/s	Title	Year	The frontier is measured by …
Scientific frontier			
Della Malva, Carree	The spatial distribution of innovation: evidence on the role of academic quality for seven European countries	2013	the frontier of inputs: highest research quality; the frontier of outputs: highest number of high-tech patents
Technological frontier			
Patents			
Furman, Porter, Stern	The determinants of national innovative capacity	2002	(the highest number of) international patents p.c., where international patens are patents granted to inventors from a particular country other than United States by the USPTO in a given year. For United States, PATENTS is equal to the number of patents granted to corporate or government establishments (this excludes individual inventors)
Basuchoudhary, Reksulak	Losing the edge at the final frontier: a relative decline in scientific inputs and its consequences	2007	(highest level of) patent applications by residents and non-residents
Cerulli	The impact of technological capabilities on invention: an investigation based on country responsiveness scores	2014	(the highest) inventive responsiveness
Fu, Yang	Exploring the cross-country gap in patenting: A Stochastic Fronteri Approach	2009	the estimated patent production function
Innovation frontier			
R&D indicators			
Hu, Yang, Chen	R&D efficiency and the national innovation system: an international comparison using the distance function approach	2014	the estimated R&D production function
Wang, Huang	Relative efficiency of R&D activities: A cross-country study accounting for environmental factors in the DEA approach	2007	the calculated R&D production frontier, i.e. efficiency scores with value one
Hölzl, Janger	Distance to the frontier and the perception of innovation barriers across European countries	2014	the leading country cluster based on direct and indirect BERD intensity and levels of GDP as a proxy for TFPs following Reinstaller and Unterlass (2011)
Innovation indicators			
Comin, Hobijn, Rovito	Technology usage lags	2008	U.S. usage level of real GDP per capita and of several technologies (electricity, IT, communication technologies, etc.)
RCA			
Winston Smith	Follow me to the innovation frontier? Leaders, laggards, and the different effects of imports and exports on technological innovation	2014	the highest relative industry strength (RCA) following Balassa (1979)
Economic frontier			
TFP			
Acemoglu, Aghion, Zilibotti	Distance to Frontier, selection, and Economic Growth	2006	the highest TFP in industry i at time t in the sample
Vandenbussche, Aghion, Meghir	Growth, distance to frontier and composition of human capital	2006	TFP in the United States
Bogliacino, Cardona	Capabilities and investment in R&D: An analysis on European data	2014	the highest TFP in each sector at each time point
Griffith, Redding, Van Reenen	Mapping the two faces of R&D: productivity growth in a panel of OECD industries	2004	the country with the highest value of TFP relative to the geometric mean in each industry j at time t
Ha, Kim, Lee	Optimal Structure of Technology Adoption and Creation: Basic versus Development Research in Relation to the Distance from the Technological Frontier	2009	TFP in the United States
Kneller	Frontier Technology, Absorptive Capacity and Distance	2005	the highest TFP in industry i at time t in the sample

Author/s	Title	Year	The frontier is measured by …
Westmore	Policy incentives for private innovation and maximising the returns	2013	
Danquah, Quattara	Productivity growth, human capital and distance to frontier in sub-saharan africa	2014	the calculated production frontier, i.e. efficiency scores with value one
Mahadevan	A frontier approach to measuring total factor productivity growth in Singapore's services sector	2002	the estimated production function
Berghall	Has Finland advanced from an investment to an innovation-driven stage?	2014	the estimated production function
Oh, Lee	A metafrontier approach for measuring Malmquist productivity index	2010	the metafrontier enveloping different production possibility sets of homogeneous country groups is defined by a metafrontier Malmquist Index.
Kounetas	Heterogeneous technologies, strategic groups and environmental efficiency technology gaps for European countries	2015	the metatechnology ratios w.r.t. different technology frontier scenarios
LP			
Timmer, Los	Localized Innovation and Productivity Growth in Asia: An Intrtemporal DEA Approach	2005	the calculated production frontier, i.e. efficiency scores with value one
López-Pueyo, Mancebón	Innovation, accumulation and assimilation: Three sources of productivity growth in ICT industries	2010	the calculated production frontier, i.e. efficiency scores with value one
Amable, Demmou, Ledezma	Product market regulation, innovation and distance to frontier	2010	the country-industry couple with the highest LP at time t
Bogliacino, Pianta	Engines of growth. Innovation and productivity in industry groups	2011	the country in which sector i has the highest LP
Genetic distance			
Spolaore, Wacziarg	Long-Term Barriers to the International Diffusion of Innovations	2011	allele frequencies across a set number of genes in the United States
Spolaore, Wacziarg	Diffusion of development	2009	allele frequencies across a set number of genes in the United States
Ang, Kumar	Financial development and barriers to the cross-border diffusion of financial innovation	2013	allele frequencies across a set number of genes in the United States
Mixtures			
Archibugi, Filippetti	Is the economic crisis impairing convergence in innovation performance across Europe?	2011	the ranking of the Summary Innovation Index (SII)
Halkos, Tzeremes	Modelling the effect of national culture on countries' innovation performances: A conditional full frontier approach	2013	the calculated innovation production frontier based on composite indices of the EIS 2007, efficiency scores with value one
Verspagen	The spatial hierarchy of technological change and economic development in Europe	2010	the leading regional country cluster based on several indicators related to education, growth, employment, patent, market concentration etc.
Hölzl, Friesenbichler	High-growth firms, innovation and the distance to the frontier	2010	the leading regional country cluster following Verspagen (2010)
Ghazinoory, Riahi, Azar, Miremadi	Measuring innovation performance of developing regions: learning and catch-up in provinces of Iran	2014	the leading set of countries based on the catch-up index, the learning index and the R&D efforts

Table 6: Correlation matrix between the different indicators used, by frontier, 2010

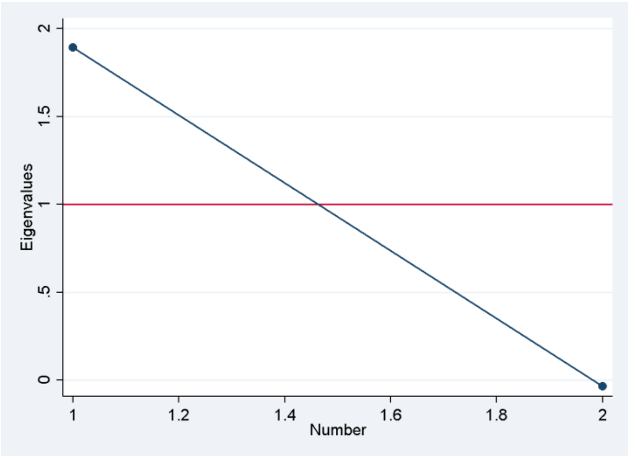
Economic frontier	**GDP**	**LP**	**TFP**	**SII**	**BERD**	**Csoph**	**EQ**	**PA**	**TPA**	**Pcit**	**PUB**	**TopPub**
GDP p.c., PPP (current international $)	1.00											
Labour productivity (hours worked, current international $)	0.96	1.00										
TFP level at current PPPs (USA=1)	0.85	0.87	1.00									
Innovation frontier												
Share of sectors with medium-high/high innovation intensity (in % of total manufacturing and services VA)	-0.20	-0.25	-0.30	1.00								
Industry purged BERD	0.68	0.67	0.48	-0.17	1.00							
Country sophistication	0.46	0.47	0.29	0.41	0.42	1.00						
Share of high-quality segment in exports of complex products	0.38	0.39	0.30	0.07	0.52	0.52	1.00					
Technological frontier												
Patent applications per 1.000 population	0.64	0.65	0.50	0.09	0.80	0.69	0.71	1.00				
Triadic patent applications per 1.000 population	0.60	0.62	0.52	0.16	0.74	0.67	0.63	0.93	1.00			
Number of patents receiving more than 5 ciations per 1.000 population	0.25	0.29	0.39	0.18	0.33	0.45	0.52	0.57	0.61	1.00		
Scientific frontier												
Number of citable documents p.c.	0.81	0.79	0.57	-0.16	0.77	0.49	0.42	0.69	0.60	0.21	1.00	
Number of scientific publications among the top 10 p.c.%	0.84	0.83	0.65	-0.18	0.81	0.50	0.50	0.77	0.74	0.32	0.94	1.00

Source: For data sources see Table 1.

Factor Analysis

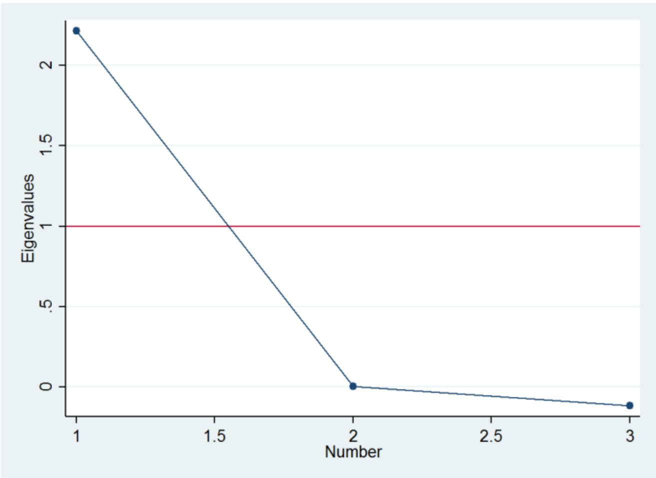
The various indicators have been z-standardized before conducting the factor analyses. The resulting four factor analyses suppose the use of one factor for each set of variables. Following the Kaiser rule we concentrate on factors with eigenvalues above one. The screen plots of the four factor analyses can be found in figure 27 to 30. Besides economic reasoning the inclusion of all variables in the factor analysis is supported by the Kaiser-Meyer-Olkin measure of sampling adequacy. For most variables the Kaiser-Meyer-Olkin measure of sampling adequacy has values strictly above 0.6, and for no variable included it has values below 0.5. The Kaiser-Meyer-Olkin criterion justifies the generall use of factor analysis.

Figure 27: Scree plot of eigenvalues (scientific frontier)



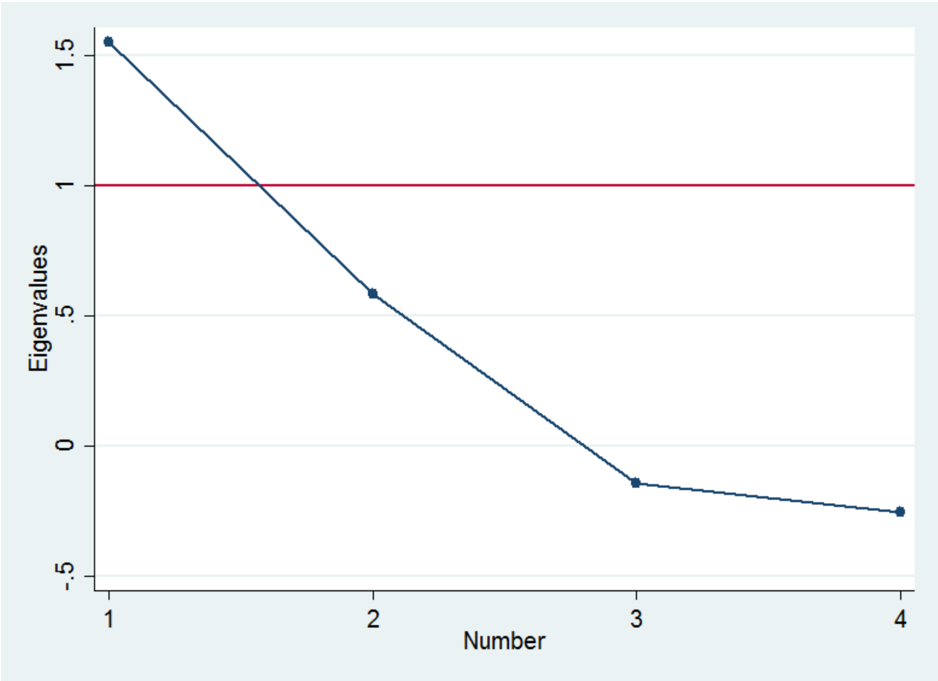
Source: WIFO-calculation.

Figure 28: Scree plot of eigenvalues (technical frontier)



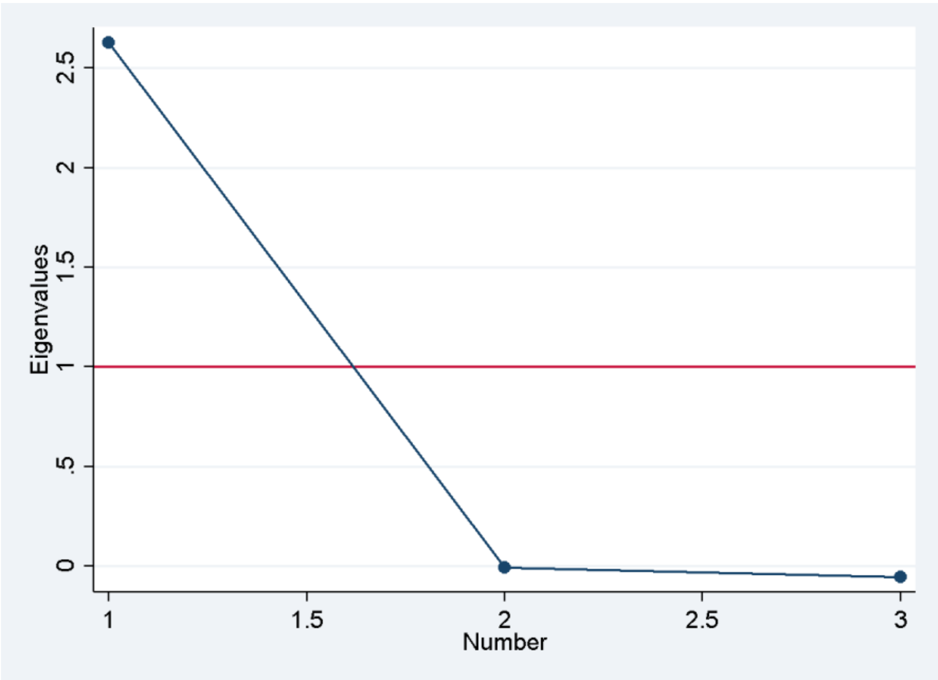
Source: WIFO-calculation.

Figure 29: Scree plot of eigenvalues (innovation frontier)



Source: WIFO-calculation.

Figure 30: Scree plot for eigenvalues (economic frontier)

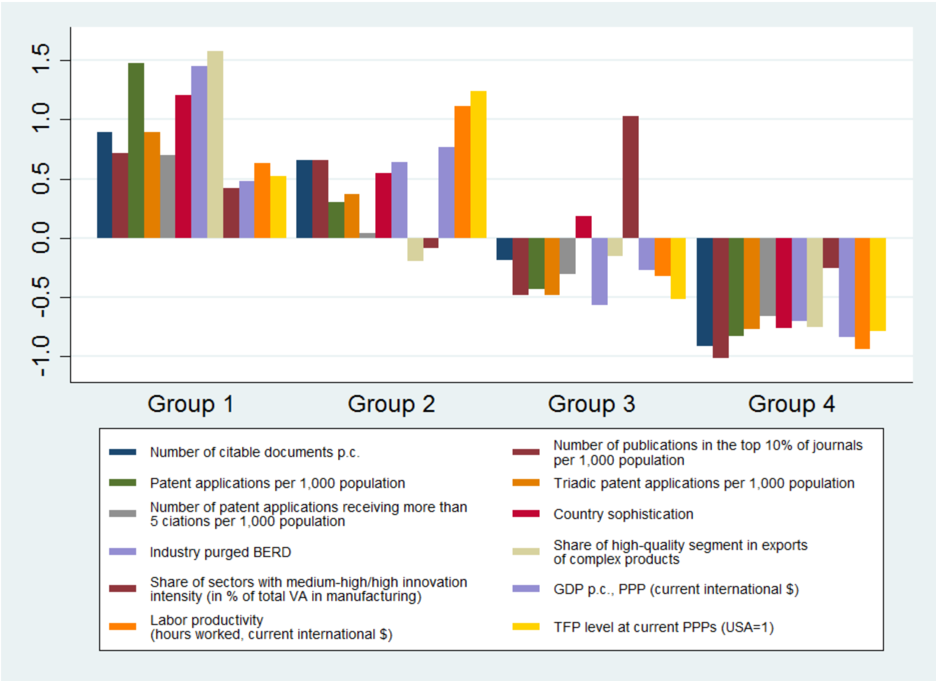


Source: WIFO-calculation.

Figure 31: Latent frontier variables (z-standardized) per country between 2008 and 2010

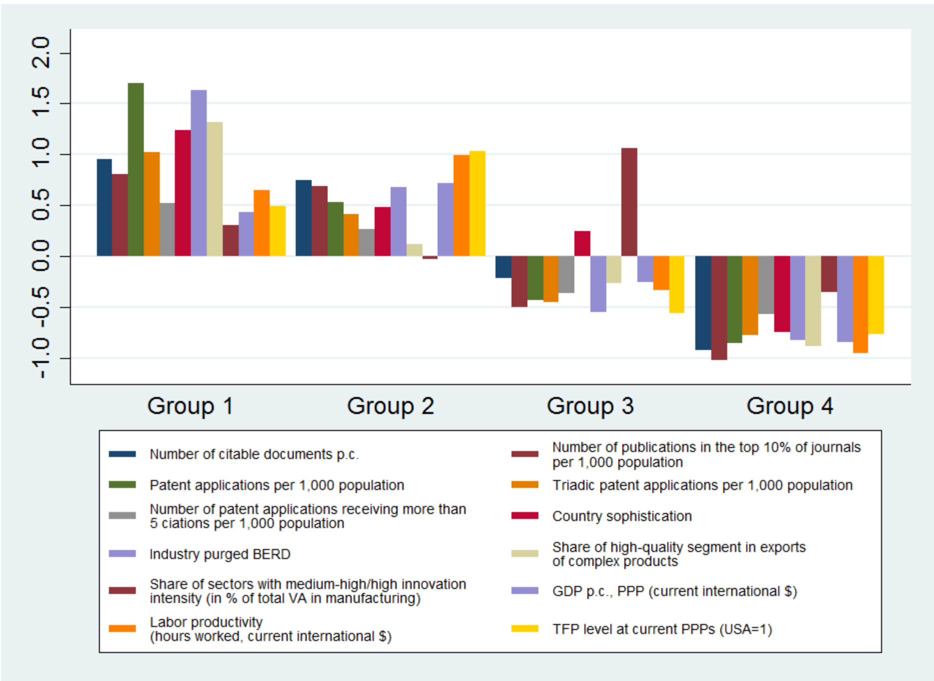
Source: For data sources for the calculation of the frontiers see Table 1.

Figure 32: Characteristics (standardized) of country groups, 2008



Source: For data sources for the calculation of the frontiers see Table 1.

Figure 33: Characteristics (standardized) of country groups, 2009



Source: For data sources for the calculation of the frontiers see Table 1.

Calculation of indicators used

Calculation of indicators

BERD corrected for industrial structure

Aggregated intensity of business enterprise expenditure on research and development adjusted by specific industry structures can be defined as the sum of all industry specific deviations weighted by their value added share in a country's total value creation and provides a better tool for country-level analyses than industry-dependent R&D intensities (Andreas Reinstaller & Unterlass, 2012; Sandven & Smith, 1998).

Besides the bilateral export values the BACI Dataset (Gaulier & Zignago, 2010) provides also quantity information for each product line (HS6). By dividing these export values with the corresponding quantity unit values are obtained[19]. For each year and each target market (country) these unit values are sorted. The trade flows that belong to the upper 25% of the unit values are classified as high quality exports.

It is well known that direct international comparison of R&D investments has limited informative value as this indicator is strongly influenced by the countries' specific industrial structures (Cincera & Veugelers, 2013; de la Potterie, 2008; Andreas Reinstaller & Unterlass, 2011). Low levels of the share of business enterprise expenditure on research and development (BERD) in total value added would suggest low levels of innovation activities. To improve competitiveness such countries would try to increase their R&D investments.

Therefore, it is reasonable to assume that countries historically engaged in research intensive industries, like manufacture of machinery or pharmaceutical products, are characterized by a higher share of R&D investments in total production than countries focusing on industries related to lower research intensity ((Moncada-Paternò-Castello, Ciupagea, Smith, Tübke, & Tubbs, 2010)).

Product space

The network algorithm is based on the observation that while most of the economically developed countries exhibit a high export diversification they are primarily exporting products that are only exported by few countries, i.e. only few countries experience comparative advantages with respect to these products. The complexity measure of countries' exports (and hence their capabilities) will be higher, the more products they export with a revealed comparative advantage (RCA) and the fewer countries export these products. A detailed description of the calculation is in the box below.

To exploit this Hidalgo & Hausmann (2009) construct a network in which products are linked to countries. In a first step the degree of diversification of a country is calculated by summing up the number of products in which the country is a significant exporter. An exporting country is

[19] To exclude measurement errors the unit values are filtered. We are using the filtering method proposed by (Gaulier, Martin, Méjean, & Zignago, 2008) for the price index calculation.

significant if the country has a revealed comparative advantage (RCA) with respect to a product. The larger the sum the more diversified a country will be. In the same way the characteristics of each product can be calculated by counting all significant exporter countries to get a measure for the "ubiquity" or exclusivity of a product. The fewer countries are exporting a product the more exclusive (or less ubiquitous) it is. As a result a direct characterization of each country and each product can be obtained.

The Method of Reflections (Hidalgo & Hausmann, 2009)

$k_{c,0} = \sum_p M_{c,p}$ … *diversification*

$k_{p,0} = \sum_c M_{c,p}$… *ubiquity*

$M_{c,p}$ denotes the country product matrix that contains ones for all country-product combinations in which the country *c* is a significant exporter of product *p*, otherwise zeros.

Iterations:

$k_{c,n} = \frac{1}{k_{c,0}} \sum_p M_{c,p}\, k_{p,n-1}$ for $n \geq 1$

$k_{p,n} = \frac{1}{k_{p,0}} \sum_c M_{c,p}\, k_{c,n-1}$ for $n \geq 1$

As long as the number of rank changes decreases, iterations are repeated. In case of stability in ranks the algorithm stops. The country sophistication is obtained by standardizing $k_{c,n}$. The product complexity respectively by standardizing $k_{p,n}$.

However, as countries and products are embedded in a network it is also possible to exploit information on countries exporting similar products and to classify countries accordingly by using a method of reflections (see Box). Hence, in the next step each product will be characterized by the diversification of the countries exporting it with comparative advantage, and each country will be characterized by the average "ubiquity" of the products it is exporting. In the country-product network the direct neighbours of countries are other countries exporting the same product. With respect to the product dimension the products' direct neighbours are other products exported by the same countries. Moving through the network of connections that are two, three or four steps away provide an increasingly precise indicator for the capabilities of economies in the sample.

Limitations of indicators commonly used

Change vs upgrading

This is important for policy implications, particularly in view of challenges with respect to smart specialisation and prospective movements of demand. Structural upgrading has the potential to improve a country's position in the global value chain and its development by creating possibilities for enhancing value (Gereffi, Humphrey, & Sturgeon, 2005; Henderson, Dicken, Hess, Coe, & Yeung, 2002; Humphrey & Schmitz, 2000, 2002). Therefore both the quality and the quantity aspect need to be considered in the analysis and a distinguished measurement of the two dimensions is only provided by these indicators.

Patent indicators

The techological frontier comprises the capability to produce tacit or codified technological knowledge. This also includes a nation's inventive capability or the application of knowledge to some practical use. The identification of the technological frontier by the use of patent statistics seems plausible since patents express one of the final stages of the innovation process, in most cases connected to the intention to transform abstract ideas to functioning devices. In the literature patent related indicators, such as the number of patent applications or grants per country (Basuchoudhary and Reksulak, 2007; Della Malva and Carree, 2013; Fu and Yang, 2009); (Basuchoudhary and Reksulak, 2007) has been often used to measure this kind of innovative capability. The applications/grants of international or triadic patents, which are patents filed at the European Patent Office (EPO), the United States Patent and Trademark Office (USPTO) and the Japan Patent Office (JPO) at the same time by the same applicant, is quite popular as well (e.g. (Cerulli, 2014)). Moreover, patent citations have been used to reflect the quality of granted patents ((Hall et al., 2005; Jaffe et al., 1993; Sterzi, 2013; Trajtenberg, 1990)).

A great advantage of using patent data is the high level of detail and the accessibility provided by the three largest patent offices. In addition, such measures provide a good image of the emergence of technical innovations (aside from software related innovations[20]).

However, patent statistics incorporate some pitfalls as well. First, taking only the number patent applications filed at the USPTO (EPO) would lead to a bias in favour (to the disadvantage) of the U.S.. Therefore, (Furman et al., 2002), only used the number of patents granted by the USPTO to inventors from a particular country other than United States in a given year. Such patents are bound to higher costs. The authors argue that this is the reason why international patents represent commercially significant patents only. Clearly, the same would hold for triadic patents. Therefore, international patents in the spirit of (Furman et al., 2002), or triadic patents indicate rather the quality of applied/granted patents than the mere quantity. Second, during the last years of observation aggregate forward citation[21] rates decreases drastically for all countries, since the number of citations reaches its peak only some years after the patent was granted. Thus, using patent citation counts to measure the

[20] The European Patent Convention (EPC) excludes computer programs as such in article 52(2)(c) and (3) and the U.S. patent law refuses to patent abstract ideas generally ((The European Patent Convention (EPC), 2015); (The United States Patent and Trademark Office (USPTO), 2015)). Therefore, lots of patents engaging software have been rejected by the patent offices.

[21] The number of forward citations of a patent is calculated by all subsequent patents that had cited the patent in their applications within a given time period. In contrast, the term backward citations refers to the number of patents cited in a patent's own application.

technological frontier means to forgo most current years[22]. Moreover, the speed of being cited can differ between groups of patents, e.g. depending on the technological fields (Lanjouw and Schankerman, 2004) or on the patent's owner structure (Sterzi, 2013). Third, to aggregate patent applications on the national level requires the assignment of inventors to specific countries, which can be difficult for groups consisting of inventors from different countries. Finally, general weaknesses of the current patent systems might affect the real power of patent based measures. To which extent patents really reflect the fringe of technological knowledge or rather the ability to defend market entrance is uncertain due to the strategic use of patents, e.g. the targeted use of patent trolls by incumbents (Bessen et al., 2011; Fischer and Henkel, 2012); (Boldrin and Levine, 2013).

The willingness to patent is influenced by cultural and social norms as well as by national patent protection rights and tax systems (Jaffe & Lerner, 2004); (Allred & Park, 2007). In addition, different industry structures are reflected in patent application statistics since small and medium sized enterprises (SMEs) show a lower patent propensity than large firms (Holgersson, 2013). Simple patent application counts also seem to be related to the innovation input side, which is reflected in their high correlation with R&D expenditures (Griliches, 2007). Moreover, while interpreting this indicator the strategic use of patents to attract venture capital and potential investors should be considered as well ((Holgersson, 2013)). Thus, a reliable analysis should not be based on patent counts only.

Innovation frontier

The last stage of the innovation process is defined by the capability to transform science and technology into real innovations. New products emerge in the market and generate economic value added. Also, non-R&D based innovative activity has been successfully accomplished. The measurement of the innovation frontier is challenging as, on the one hand, appropriate indicators should differentiate themselves from the scientific and technological frontier, and, on the other hand, need not represent general economic features that are not directly related to a nation's innovation capability.

Alternative indicators for the innovation frontier

Observed trade patterns can be used to reveal comparative advantages (Balassa, 1979) and measure international competitiveness. (Winston Smith, 2014), use revealed comparative advantages (RCA) based on export data to identify those high-tech industries with the highest relative industry strength. Of course, the calculation of more aggregated RCA, e.g. for the manufacturing sector, on national level is possible as well. The identification of the innovation frontier by RCA might work as long as quality and quantity aspects are not

[22] Sometimes, to compare forward citations of different patents, a specific citation span is determined that includes e.g. all forward citations within five years of the patent application date ((Lanjouw and Schankerman, 2004)).

needed to be distinguished. RCA do not generally reflect a country's industrial upgrading process or the quality of its industrial structure, because high RCA scores might e.g. just result from sources of natural recourses. (Laursen, 1998), points out that RCA is rather a measure of international specialization than a measure of performance or competitiveness. "The values of the measure imply that regardless of how poorly (or strongly) a country is performing, by definition a country will be specialized in something, and therefore will always have high values of RCA/RSCA [revealed symmetric competitive advantage] for some sectors of the economy and low values for other sectors" ((Laursen, 1998), p.101). Because of the high availability of trade data, the clear computation and for want of better alternatives, indices based on export values are widely-spread and commonly accepted in the literature. Alternative competitiveness indicators using export values might be afflicted with similar problems as well, but to a limited extent. Therefore, there might be more appropriate ways to measure the competitiveness of countries' industry structures and their upgrading processes. In conclusion, the literature has not yet come up with totally convincing indicators directly measuring the innovation frontier fitting in our intellectual frontier framework; a gap we intend to close.

Economic frontier

One can find a long history of the use of total factor productivity (TFP) to measure country's innovation capability. The growth literature has been trying to figure out the degree to which output growth results from technological changes ("productivity") or capital formation. However, TFP is basically a residual concept emerging from the estimation of production functions. In most cases, for the estimation of the production function on a national level capital stock and labor force are used as inputs and GDP serves as output factor. Everything not explained by the two input factors affects the Solow residual, i.e. the TFP. Thus, restricting TFP to technological change and neglecting all other factors that are relevant for GDP growth but not captured by the national labor and capital stock (changes in the institutional organization of production, etc.) might be myopic. Contrariwise, technological change induced by R&D expenditures would only be incorporated in the Solow residual if R&D spending was not included in the two input factors. That implies either TFP overestimates or underestimates technological change. Moreover, long discussions about the appropriateness of GDP as a measure of output and its consequences on the calculated TFP as well as about the needed assumptions regarding returns to scale and marginal cost pricing should pose questions on the trustworthy interpretability of TFP as an indicator of technological progress[23].
Within our framework of frontier concepts, the economic frontier is associated with the economy wide output that is generated using all input factors, not only those related to STI. Therefore, the measurement of the economic frontier requires more general indicators. The

[23] See (Hulten, 2001), for a detailed summary of critical contributions to TFP and its interpretation in the literature.

mentioned considerations about the correct interpretation of TFP lead to the conclusion that studies using TFP to measure (the distance to) the frontier would be best classified into the branch of literature regarding the economic frontier.
However, in the last decade most of the frontier related work based on TFP developed in the spirit of the efficiency literature and focus on change of productivity indices rather than on TFP levels, which are even more prone to misspecification ((Berghall, 2014; Danquah and Ouattara, 2014; Dong-hyun Oh and Jeong-dong Lee, 2010; Kounetas, 2015; Mahadevan, 2002)). The idea goes back to (Caves et al., 1982), who showed that productivity changes can be measured by the use of distance functions. Malmquist productivity index changes between two periods can be derived by the application of data envelopment analysis (DEA) or stochastic frontier analysis (SFA) and separated in efficiency changes and technical changes.
Some authors also use the relation between national TFP to the TFP of the U.S., implicitly assuming the U.S. being the leading country, to identify the distance to the economic frontier ((Vandenbussche et al., 2006); (Ha et al., 2009)). A more subtle approach is to determine the frontier by identifying the country with the highest TFP in each point in time at the industry level ((Daron Acemoglu et al., 2006; Bogliacino and Cardona, 2014; Griffith et al., 2004; Kneller, 2005)).
Besides TFP changes in labor productivity (LP), either measured by value added per labor input ((Amable et al., 2010; Bogliacino and Cardona, 2014)) or calculated by the use of distance function approaches similar to TFP ((Lopez-Pueyo and Mancebon, 2010; Timmer and Los, 2005)), is commonly used in the growth literature. Again, the focus is on relative productivity growth rather than productivity levels.

A rather isolated branch of literature deals with the application of genetic distance measures to reflect countries' positions in relation to the leading country ((Ang and Kumar, 2014; Spolaore and Wacziarg, 2013, 2011, 2009)). The frontier measure bases upon allele frequencies across a set number of genes of the leading country's population. However, in most cases the leading country is assumed to be the U.S. without further explanations[24], which is fairly unsatisfactory when one is looking for the frontier or rather for appropriate measures for identifying it. Genetic distance is interpreted "as an overall measure of differences in the whole set of intergenerationally transmitted characteristics" ((Spolaore and Wacziarg, 2009), p.480). This implies that relative genetic distance measures notably incorporate cultural barriers and, thus affect the innovation transmission between the leading country and the rest of the world, but it does not help to identify the leading country itself.

[24] In addition to the U.S. (Spolaore and Wacziarg, 2011), also use the U.K. as a reference country for the calculation of relative genetic distances.