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METHODOLOGY REPORT

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1. INTRODUCTION

The Innovation Indicator is a quantitative system to monitor Germany's performance in the context of innovation in an international comparison. The project is initiated by the Association of German Industry (BDI) in collaboration with Roland Berger Holding GmbH and conducted by a consortium consisting of Fraunhofer Institute for Systems and Innovation Research ISI and Center for European Economic Research (ZEW) with support of seitenplan media agency.

The Innovation Indicator uses a composite of a selected set of individual indicators to describe and analyse the performance of national economies in terms of their innovation activities. As in many indicator-based reports, the methodology, the data and the modelling have a crucial impact on the results and the discussion of the results. This present report is aiming at presenting and documenting our approach to select, to extract, to normalize, to aggregate and, finally, to calculate the Innovation Indicator composites. The Innovation Indicator reporting system is, first of all, designed to provide information and interpretation to decision makers in economy and politics. Therefore, the methodology and data is important as an instrument or a vehicle towards this goal. As the discussions and the interpretation are in the core of the reporting system, we decided to separate this methodology report from the final reports. This methodology report targets the scientific community as well as interested readers of the Innovation Indicator reports.

Our broad and principle approach uses the innovation systems heuristic as a starting. Traditionally, the innovation system heuristic has been used to identify relevant sub-systems, most relevant actors and the underlying factors and effects that should effectively be taken into account. New insights in innovation research suggest however that the core perspective should shift from actors to innovation system functions. We have followed these new insights, also because this allows the Innovation Indicator a further differentiation of dimensions of national innovation systems and a focus on aspects that are of particular relevance in the second decade of the 21st century, including digitalization and sustainability.

This methodology report is structured as follows. The next chapter of this report describes the conceptual background and the functions of particular interest in the Innovation Indicator monitoring system. Based on this approach we have selected a set of variables and indicators that operationalize these functions. To realize a thrifty and effective modelling, we have tested many variables and indicators. Several of them had proved to be of relevance in previous operationalisations of the Innovation Indicator in an econometric model that followed the logic of an innovation production function (input, throughput, output). In addition, we used statistical methods to reduce redundancy and to select only relevant indicators. Chapter 3 describes the data, the selection, normalisation and aggregation as well as the concrete construction of the composite indicators. Chapter 4 offers a validation check on the influence of individual indicators and in particular of weighting schemes on the rakings of the countries based on data for the year 2021.

2. THE CONCEPTUAL FRAMEWORK

Since its first publication in 2005, the Innovation Indicator has provided a systematic measurement concept for recording the innovative capacity of national economies. The strength of the measurement concept used is based, on the one hand, on empirical and methodological expertise in the construction of composite indicators. On the other hand, the Innovation Indicator always clearly emphasises the theoretical foundation of its measurement concept, which in the past was based on the concept of national innovation systems (NIS).[1] The NIS distinguishes between various subsystems whose design has a significant influence on the innovative capacity of an economy and focuses on its actors and their connections. These subsystems include the economy itself, with companies as the main actors; science, with its contributions to basic and applied research; society, with its corresponding attitudes towards innovation; the education system; and the state, which sets the legal and regulatory framework. In a national innovation system, these subsystems interact and thus determine the innovative capacity of national economies in different ways.

The NIS approach has a long tradition in innovation research and had proven to be a fruitful starting point for the empirical analysis of innovation processes at the national level in the past. This also reflects the fact that the approach has been continuously developed over the past decades to take account of changing framework conditions, e.g. new societal challenges or the emergence of new technologies. In particular, the system-centred NIS approach has increasingly been extended to include a functional perspective. This so-called functional NIS approach no longer focuses on capturing ex ante defined systems (science, economy, state, society, education) and their actors, but the way in which certain functions are fulfilled that are relevant to innovation systems. Building on the functional NIS approach, the new Innovation Indicator takes up these findings of innovation research and translates them into an operationalised measurement concept that maps central challenges and functions facing modern innovation systems.

The Innovation Indicator is a so-called composite indicator, which is composed of a number of individual indicators that are standardised and then aggregated to an index. In the past, the Innovation Indicator had adopted an "actor perspective" and captured the main actor groups in innovation systems through various indicators. The increasing technology competition in the course of geopolitical reorganisation as well as the central challenges of decarbonisation and digitalisation of the economy, science, state and society are to be understood as the background of the new Innovation Indicator.

Therefore, the new Innovation Indicator takes a slightly different perspective in order to capture better the change in innovation processes and the dynamics in the systems. It also makes it possible to take into account factors and technologies relevant to future innovation capacity. The

[1] See for example Lundvall, Bengt-Åke (Ed.) (1992): National Innovation Systems. Towards a theory of Innovation and Interactive Learning. London: Pinter; Edquist, C. (Ed.) (1997): Systems of Innovation - Technologies, Institutions and Organizations: Pinter, London, Washington.

concept of the new Innovation Indicator partly abandons the actor perspective and adopts a functional perspective instead. This means that it focuses more on the functions to be fulfilled within the innovation systems of the countries, instead of structuring the analyses along actors or actor groups forming the subsystems as before. On the one hand, this change is intended to adequately take into account more recent scientific findings in the field of innovation systems theory. On the other hand, the functional perspective enables a closer interlocking with current topics and discussions of innovation policy. A comparison of the performance of the countries with regard to these functions is thus the subject of the analyses carried out.

In the late 2000s, the criticism of the national innovation system as being too static or not taking into account the dynamics of a system led to a scientific discussion that focuses more on the functions rather than the actors. In a paper by Hekkert et al. (2007)[2], seven functions are proposed: 1) Entrepreneurial function, 2) Knowledge development, 3) Knowledge diffusion through networks, 4) Guidance of the search, 5) Market formation, 6) Resource mobilisation, and 7) Creation of legitimacy / counteract resistance to change. In a paper based on this, Bergek et al. (2008)[3] also propose seven categories of functions: 1) Knowledge development and diffusion, 2) Influence on the direction of search, 3) Entrepreneurial experimentation, 4) Market formation, 5) Legitimation, 6) Resource mobilisation, and 7) Development of positive externalities.

The functions discussed in the literature are initially very abstract and not all of them can be used in the same way for an empirical implementation in a composite indicator. The new innovation indicator therefore focuses on central functions in the systems that, in our view, essentially determine or depict innovative capacity and therefore uses indicators that are relevant to describe the innovative capacity of national economies, the orientation towards key technologies as well as indicators that are able to provide an assessment of the sustainability of the economy. This selection brings together some of the differentiated functions from the scientific literature or focuses on certain aspects of them. The following three functions are mapped, which bundle the functions mentioned in the literature (see the functions mentioned in the brackets), but also concretise them by our functions two (key technologies) and three (sustainability):

1. *Innovativeness* function, under which the sub-functions "knowledge development" and "knowledge diffusion and market activities" (knowledge diffusion, market formation, entrepreneurial function / experimentation, resource mobilisation) are combined.
2. *Developing future fields through key technologies* (guidance of the search / influence on the direction of search). A function that primarily addresses future innovation and competitiveness.
3. *Sustainable management* (development of positive externalities, legitimation). A function that not only generally addresses the avoidance of negative externalities or the creation of positive externalities, but also specifically addresses the ecological transformation of economic activity.

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[2] Hekkert, M. P.; Suurs, R. A. A.; Negro, S. O.; Kuhlmann, Stefan; Smits, R. E. H. M. (2007): Functions of innovation systems. A new approach for analysing technological change. In: Technological Forecasting & Social Change 74 (4), S. 413–432.

[3] Bergek, Anna; Jacobsson, Staffan; Carlsson, Bo; Lindmark, Sven; Rickne, Annika (2008): Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. In: Research Policy 37 (3), S. 407–429. DOI: 10.1016/j.respol.2007.12.003.

All three functions are empirically recorded and analysed as independent target functions.

The new Innovation Indicator takes into account how long-term oriented a country's positioning is. Firstly, this is achieved by analysing how well the individual economies perform in relation to significant key technologies. Secondly, the new Innovation Indicator takes into account how sustainable the economy and innovation processes are. For example, an economy may be successful in innovation in the present, but might face strong barriers to innovation in the long term. This might be the case, if it does not invest sufficiently in technologies that will be important in the future and that are innovation drivers across many sectors. Another case might occur, if the innovations do not comply with environmental and resource-related sustainability limits. In this sense, the methodological-conceptual innovations of the Innovation Indicator pursue the goal of opening up a more long-term perspective on the innovative capacity of individual economies.

3. THE CONSTRUCTION OF THE INDICATORS

The procedure of the construction of a composite indicator is straightforward. We follow the steps commonly used for composite indicators and documented in the relevant literature.[4] After the selection of the individual indicators and the data collection, the next step is the concrete calculation of the composite indicator. The main stages are, next to data selection, the normalisation of the individual indicators so that they become dimensionless and can be averaged, and the aggregation. The aggregation procedure defines the weighting scheme and further treatment that then culminates in the calculation of the final index values as the (weighted) average of the individual indicators.

3.1 Selection of countries

Within the framework of the Innovation Indicator, a selection of 35 countries is analysed comparatively. The countries included are, on the one hand, the established industrial nations, which have a high orientation towards innovation and generally maintain an intensive exchange of knowledge- and technology-intensive goods and services on the world markets in addition. On the other hand, emerging countries are also included in the group of economies studied. In this context, these also include the emerging countries - especially the BRICS, which are interesting for international comparison in the Innovation Indicator not only because of their dynamism or expected dynamism, but also because of their size.

3.2 Selection of indicators

The basic idea of the innovation production function, i.e. a process perspective on innovations, was retained. As with the indicators for the other functions of the innovation system, all indicators for sustainability are checked for their regular availability, their country coverage, their meaningfulness with regard to the target function, and for overlap (redundancy) with other possible indicators. The final list of indicators to be collected annually is compiled according to the empirical findings and was designed with them aim of conciseness.

3.2.1 Innovativeness

The "Innovativeness" function of the new Innovation Indicator presents a new approach to measuring the innovation capacity of 35 countries. The indicator aims to map how innovations are

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4 Siehe bspw. Nardo, M.; Saisana, M.; Saltelli, A.; Tarantola, S.; Hoffmann, A.; Giovanni, E. (2005): Handbook on Constructing Composite Indicators: Methodology and User Guide, OECD Statistics Working Paper STD/DOC(2005)3, Paris: OECD.

generated, introduced and productively used and to make the results comparable. To this end, 23 individual indicators measure four sub-processes:

- the creation of new knowledge relevant to innovation,
- the diffusion of this knowledge,
- the transformation of knowledge into marketable innovations, and
- the achievement of economic returns from these innovations.

The indicator selection combines measures of a country's current innovation performance, which is based on past investments, with measures of activities that pay into a country's future innovation capacity. In particular, the innovation indicator thus takes into account those factors that will gain in importance for innovation performance. These include, for example, the international orientation of the innovation system and the interaction between science and business.

Table 1: Indicators in the function "innovativeness"

INDICATOR	SOURCE
PhDs (ISCED 6) in STEM subjects as a share of population	OECD Education at a Glance (EAG)
Tertiary graduates as a proportion of highly educated employees aged 55+	ILOSTAT
Share of employees with tertiary education in all employees	ILOSTAT
Annual expenditure on education (tertiary level incl. R&D) per student	OECD Education at a Glance (EAG)
Venture capital used for early stage in relation to gross domestic product	OECD Enterprise Statistics
Share of international co-patents in all applications for transnational patents	EPO - PATSTAT
Share of value added in high technology in total value added	OECD - STAN
Gross domestic product (GDP) per capita of the population	World Bank
Transnational patent applications per capita	EPO - PATSTAT
Value added per capita (in PPP-$) in manufacturing (ISIC Rev. 4 B-F)	World Bank
Balance of trade in high technologies	UN - COMTRADE
Share of business-financed university R&D expenditure	OECD - MSTI
Business R&D expenditure as a share of GDP	OECD - MSTI
Government-funded business R&D expenditure as a share of GDP	OECD - MSTI
Number of scientific and technical articles in relation to population	Elsevier - Scopus
Average number of citations per scientific and technical publication	Elsevier - Scopus
Number of patents from public research per inhabitant	EPO - PATSTAT
Share of R&D expenditure in public research institutions and universities in GDP	OECD - MSTI

INDICATOR	SOURCE
Share of a country in the 10% most cited scientific and technical publications	Elsevier - Scopus
Trademark applications at EUIPO per inhabitant	EUIPO / RISIS-ISI-TM
Co-patents science-economy per inhabitant (only available for EU)	EPO - PATSTAT
Co-publications science-economy per capita	Elsevier - Scopus
Number of job vacancies (EU and USA only)	Eurostat and US Bureau of Labor Statistics

Source: Own representation.

3.2.2 Developing future fields through key technologies

The function "Developing future fields through key technologies" focuses on the ability of an economy to independently produce innovations in certain, generally defined technology areas and to use the economic development potentials that arise from them. This approach is thus based on a long-term, technology-oriented competitive perspective. The concept of key enabling technologies essentially involves a focus on technologies or technological paradigms that are relevant to a wide range of applications.

With a view to the key technologies, seven technological areas are mapped that we consider particularly relevant for future competitiveness, not least because they are prerequisites for technological developments in other technology areas and a variety of economic sectors:

- Digital hardware
- Digital networking
- New production technologies
- Energy technologies
- New materials and advanced materials
- Biotechnology
- Circular economy

The selection of data sources or individual indicators takes place empirically and follows the methodological approach previously followed in the Innovation Indicator. The coverage of the countries (see section 3.1), the regular availability of the data and, above all, a low redundancy of the individual indicators decide on the inclusion or exclusion of the indicators.

Table 2: Indicators in the function "Developing future fields through key technologies"

INDICATOR	SOURCE
Scientific publications of a country in a field as a share in total publications of a country	Elsevier - Scopus
Scientific publications of a country in a field as a share of worldwide publications in that field	Elsevier - Scopus
Transnational patent applications	EPO - PATSTAT
Transnational patent applications	EPO - PATSTAT
Balance of trade (exports minus imports)	UN - COMTRADE
Balance of trade (exports minus imports)	UN - COMTRADE
Trademark applications	EUIPO / RISIS-ISI-TM
Trademark applications	EUIPO / RISIS-ISI-TM
Venture capital as a share of GDP (in PPP$)	data.europa.eu - venture capital investments
Venture capital as a share of GDP (in PPP$)	data.europa.eu - venture capital investments
Computer-implemented inventions as a share of all inventions in the field	EPO - PATSTAT

Source: Own representation.

3.2.3 Sustainable economy

This competitive perspective is expanded to include the function "sustainable management", which primarily aims to comply with planetary boundaries. This function is concerned with the question of whether existing production and innovation processes are organised sustainably and what scientific and technological prerequisites exist in the countries to support the transformations of the economy and society. Both perspectives - that on key technologies and that on sustainability - complement each other. For example, it is possible that an economy is a leader in the provision of energy technologies and can also derive economic benefits from this, while at the same time its own production and innovation processes are not organised in a sufficiently sustainable manner. In this sense, the sustainability indicator in the Innovation Indicator provides a measurement concept for the extent to which national economies can maintain their production structures in the long term, even within a sustainable economic paradigm.

The definition of this function should focus on economic or economically replicable sustainability processes or products. Classic environmental protection itself, oriented towards the sub-areas of the environment (soil, water, air), or recycling as a process are not explicitly included. Instead, processes and technologies that explicitly address a sustainability aspect are taken into account. The focus is thus on sustainability technologies - these include renewable energy technologies, climate protection technologies, energy and resource efficiency technologies, technologies for pollutant separation and/or prevention (e.g. filter systems) or recycling technologies. In order to take into account the demand side for sustainability technologies, characteristic values for attitudes and behaviour are also included.

The selected indicators are standardised (see section 3.3) and averaged with all individual indicators of the target function "sustainable management" to calculate the final sustainability index.

Table 3: Indicators in the function "Sustainable management"

INDICATOR	SOURCE
Share of R&D expenditures in key energy fields (renewables and energy efficiency) in total public R&D expenditure	IEA Energy data
Green early-stage investments	Eurostat and OECD Environment
Public R&D support for environment and energy	OECD MSTI
Environmentally friendly attitudes of the population	World Value Survey
Environmentally relevant publications per inhabitant	Elsevier - Scopus
Balance of trade in sustainable goods as a share of GDP	UN - COMTRADE
Development of environmental innovation in enterprises as a share of all innovations	OECD Green Growth Indicators
OECD Environmental policy stringency index	OECD EPS
Environmental patents per capita	EPO - PATSTAT
ISO 14001 certifications per inhabitant	ISO survey
Environmental taxes as a share of GDP	OECD Green Growth Indicators

Source: Own representation.

3.3 Normalisation

Normalisation is necessary to make the individual indicators independent of their respective units so that they can subsequently be offset against each other. It has proven useful to align the indicators with a constant and reliable benchmark group of innovation-oriented countries instead of including all countries under consideration in the benchmark group. The main reason for this is that it makes the calculations independent of the data availability of individual countries and the possible addition of further countries. For each of the selected individual indicators, sixteen countries form the benchmark (see below). Their index values each define the range from zero (minimum value) and one hundred (maximum value).

The fixed set of benchmark countries is used to normalise all individual indicator values to a unitless interval. The selection of countries for the benchmark group follows various criteria that are intended to ensure that the benchmarks are comparable over time, reliable and sufficiently varied. The first criterion for the selection is therefore the regular availability of data for (as far as possible) all indicators. The second criterion relates to the size of the countries, i.e. large and also smaller economies should be included. Thirdly, the most innovative countries should be represented, but also less innovative or even weak countries, so that the spectrum of the values of the individual indicators is as wide as possible. The countries in the benchmark group should have stable values or stable trends so that the values do not change too much from year to year in order to ensure the stability of the benchmark over time. If the benchmark were to change massively every year, the values of the individual countries would also change, possibly even without a de facto change in their own original values. Therefore, catching-up countries or even emerging markets are not represented in the benchmark group.

In the new Innovation Indicator, the criteria led to the inclusion of the following countries in the benchmark group: Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Ireland, Japan, Poland, Spain, Sweden, Switzerland, the United Kingdom and the USA.

The values of all other countries are aligned with this, whereby countries that perform worse than the worst or better than the best country in the benchmark group are set to minimum value of -50 or maximum value of +150 respectively. For the total aggregation and the graphical representation, these values are put in the range from zero to +100, but for the calculation of the averages they enter with the range between -50 and +150.

3.4 Aggregation

The aggregation of the individual indicators is crucial for the respective result of the indices. In the Innovation Indicator, all values are considered with the same weight, i.e. there is no additional weighting of the individual indicators in the calculation. Within the three objective functions, the respective overall indicators are thus calculated as equally weighted averages from the respective individual indicators. The reason for the equal weighting is, on the one hand, easier communication and comprehensibility. On the other hand, both the theoretical-conceptual framework and the empirically guided selection of the individual indicators ensure that only indicators relevant to the respective function are taken into account and that at the same time there are no redundant indicators in the set, so that there is also no indirect weighting through the multiple mapping of a dimension by means of several indicators that measure the same thing.

4. ROBUSTNESS CHECKS

4.1 Monte-Carlo-Simulation of the Robustness of the Rankings

Like other statistical quantities, also composite indicators are subject to uncertainty. These may arise from regular sampling variation or from modelling uncertainties. Following the works documenting that specific importance of the weighting scheme,[5] we have subjected the three composite indicators in the new Innovation Indicator to rigorous statistical testing of the robustness of the rankings with respect to random deviations from the equal weighting scheme. Specifically, we conducted a Monte-Carlo-simulation of the rankings under randomly sampled weights. The employed procedure is as follows:

1) Draw a random vector of weights $w = (w_1, \dots, w_k)$ corresponding to the k individual indicators, where each individual weight is independently drawn from standard uniform distribution, i.e. $w_i \sim U(0,1)$.

2) Calculate a normalized weighting vector as follows $\tilde{w} = (w_1/\sum w_i, \dots, w_k/\sum w_i)$

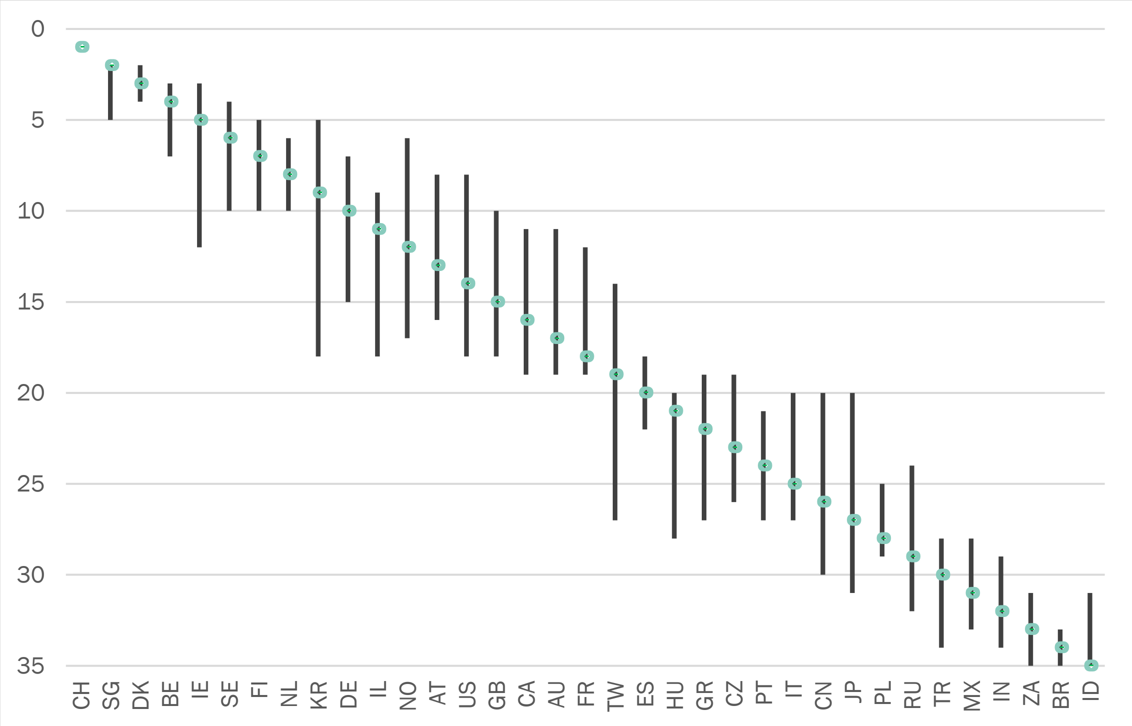
3) For each country, calculate the new simulated composite indicator and the corresponding rankings with the simulated normalized weights.

4) Repeat steps 1) to 3) often (1000 in our case) and use the simulated distribution of rankings to calculate the 95%-variation intervals based on the 2.5% and 97.5%-quantiles of the rankings for each country.

The resulting variation intervals give an indication how robustness the ranking is with respect random deviations from the equal weighting scheme. The results for the three indicators of the Innovation Indicator can be found in the following three figures.

[5] Grupp, H., & Schubert, T. (2010). Review and new evidence on composite innovation indicators for evaluating national performance. *Research Policy*, *39*(1), 67-78.

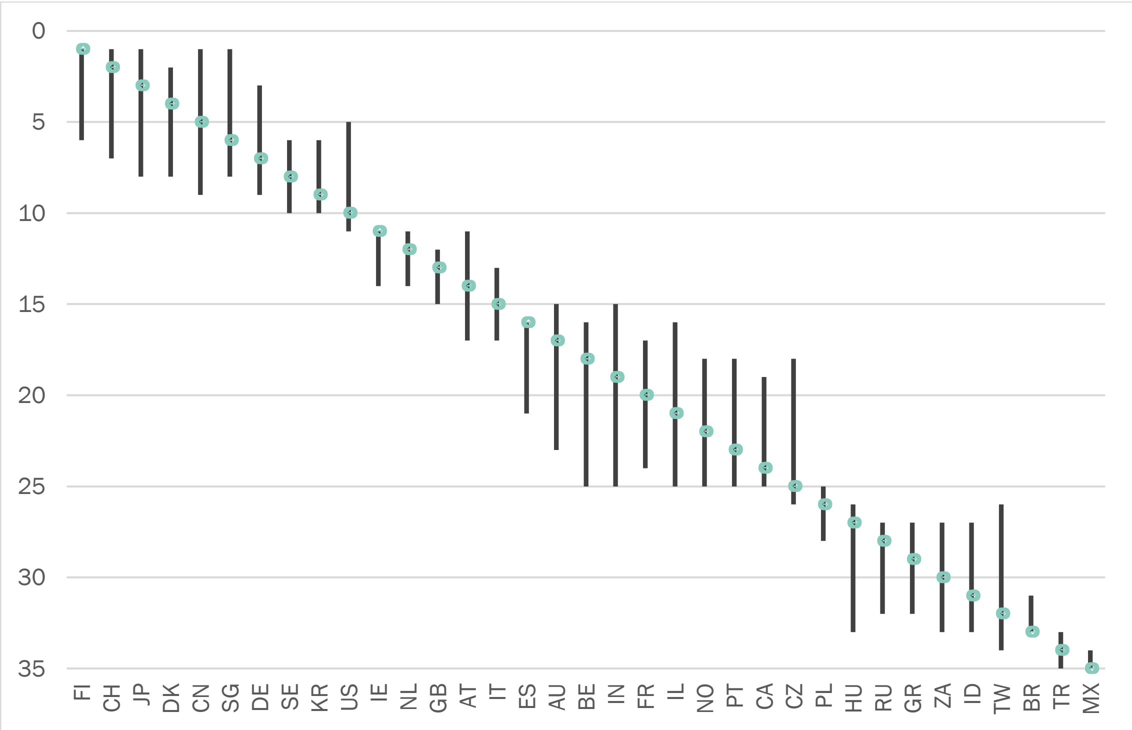
Figure 1: Range (Monte-Carlo-Simulation) of possible rankings per country: innovativeness



Source: Innovation Indicator 2023

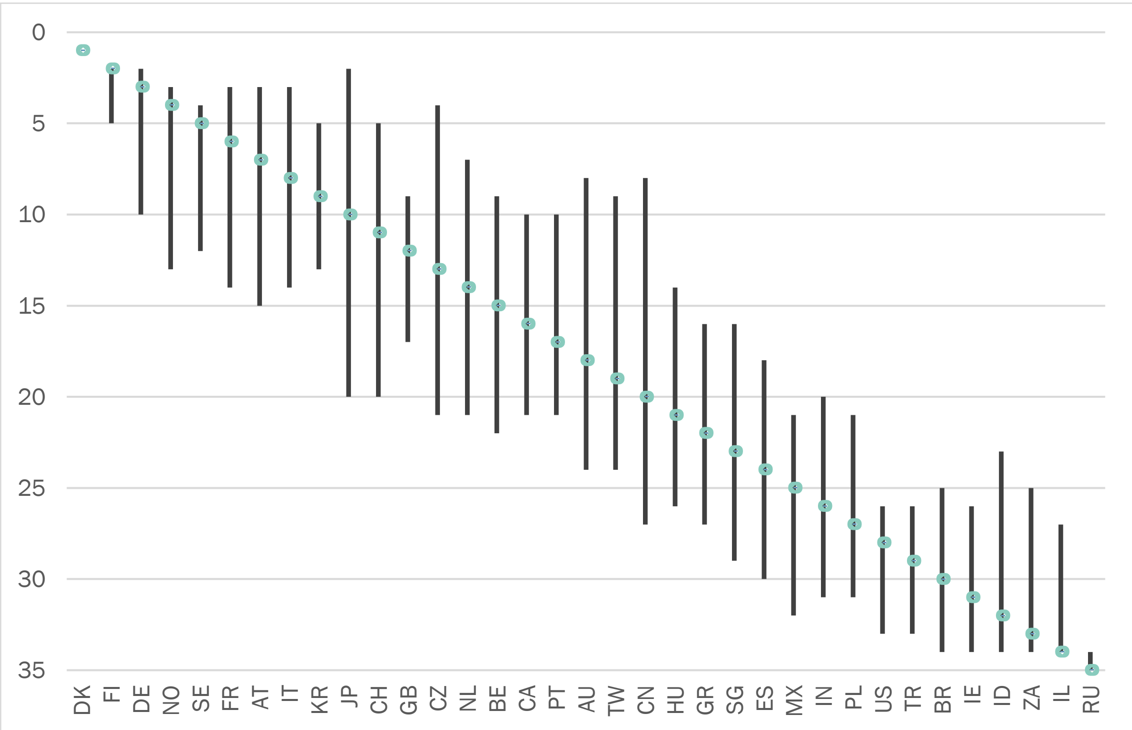
Overall, the findings suggest that the uncertainties of the specific rankings are non-negligible, in particular in the middle part of the ranking. In the baseline indicator ("Innovationen hervorbringen"), Germany would for example be ranked between place 7 and 15 in 95% of the cases when weights are random adjusted under the standard uniform distribution. Other countries are relatively stable. Switzerland is always first. Denmark will be ranked between place 2 and 4. South Africa would remain among the last countries even under randomized ranking. This implies, that while the Innovation Indicator rankings display variation due to modelling uncertainty, they also contain information about the country rankings that are robust to changes in the modelling assumptions. This conclusion holds also for the indicator about "Key Enabling Technologies" and "Sustainability".

Figure 2: Range (Monte-Carlo-Simulation) of possible rankings per country: key technologies



Source: Innovation Indicator 2023

Figure 3: Range (Monte-Carlo-Simulation) of possible rankings per country: sustainability



Source: Innovation Indicator 2023