ISSN 1075-7007, Studies on Russian Economic Development, 2017, Vol. 28, No. 5, pp. 472–479. © Pleiades Publishing, Ltd., 2017.
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SCIENCE AND TECHNOLOGY

Scientific and Technological Development: Limitations and Opportunities

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Received November 29, 2013

Abstract—This paper considers the role of innovations and technologies in modern social and economic development. There is a discrepancy between the declarative goals contained in government documents on the role of science, technology, and the actual results achieved. It has been shown that in the tough external environment for Russia there is no alternative to the development and creation of domestic competitive technologies. In order to make full use of the scientific and technological potential that has been preserved in the country, it is first of all necessary to restore the full innovative cycle and stimulate the interest of Russian companies in national innovative solutions and competitive technologies. The responsible role of the state in reforming the domestic scientific sector, as well as in the harmonization of relations between the state, business, scientific community, and society as a whole has been emphasized.

DOI: 10.1134/S1075700717050094

Development based on innovation and continuous technological modernization of the economy enables the real diversification of the economy, while progressive (not declarative) import substitution is possible based only on competitive domestic technologies. A technological lag was one of the reasons for the economic crisis in the Soviet Union. Excessive pressure on resource-extracting industries resulted in its increased volumes of technological imperfections in manufacturing industries and production infrastructure [1–3].

The state of the sphere of technological development in Russia can be characterized as consistently low [4]. So, in 2010–2015, 800–1500 advanced production technologies (PPT) were created annually, 100000–200000 technologies were assimilated, technologies valuing less than $1 billion USD were exported, and technologies worth about $2 billion were imported.

The weakly positive dynamics for the creation and use technologies hardly affects the dynamics of economic development indicators. In 2010–2015, the share of innovative products was 5.0–6.5% (in leading countries, 15–20%); the retirement ratio of fixed assets is about 1%, while their degree of wear and tear is 45–50%; Russia's share in world exports of high-tech products is 0.4%; and the share of intensive factors in economic growth (peer review) is less than 10% of GDP growth.

A direct quantitative assessment of the level of technological development in the form of a universally recognized scalar is extremely difficult. An indirect assessment of the technology level based on the indicator vector is possible, including:

—qualitative characteristics of consumer properties;

—sales volume in domestic and world markets;

—industrial and technological potential of output of products, etc.

With these estimates, Russia is among the world's technological leaders in the space and aviation industries, nuclear industry, and production of weapons. The gas and oil industry, the chemical and petrochemical industry, the production of fertilizers, and ferrous and nonferrous metallurgy are close to technological leaders. In the Russian economy, utilities, road construction, deep processing of industrial and domestic waste, as well as technologies for managing and coordinating social and economic processes, are among the technological outsiders.

Patterns of technological development. The technological development of industry and the economy as a whole has its own regularities, inherent to both separate technologies and sets of technologies that form integral chains. Let us dwell in more detail on the system properties of technology and patterns of technological development.

Among them, first of all, it is necessary to highlight the presence of four mandatory components: the tech-

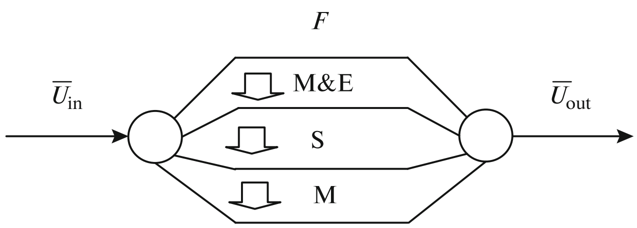

Fig. 1. Structure of integrated (organizational) technology: $\overline{U}_{in}$ is a vector of indicators at the input; $\overline{U}_{out}$ is vector of indicators at the output of technology; F is technology itself or the method; M&E is machines and equipment; S is staff who organized work; M is management system mechanism.

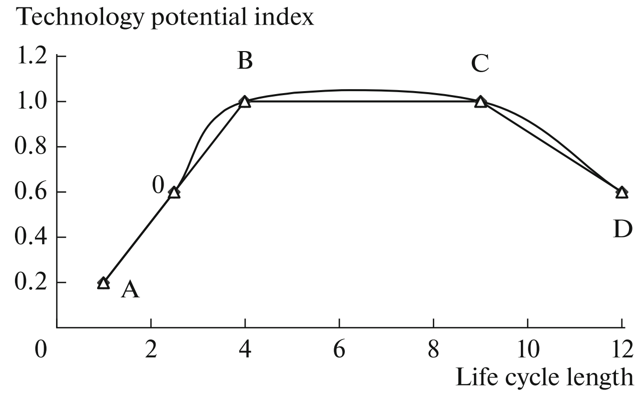

Fig. 2. Dynamics of the technology cycle potential index.

nology itself, machinery and equipment, organized labor, and the mechanism and systems of management. Their quantitative characteristic is the potential index measured by the relative value in the range of 0–1. The maximum potential equal to 1 is achieved at a theoretically possible level of perfection, which in turn is a scalar convolution of a set of indicators (productivity, consumer properties, product loss size, etc.). The organized technology answers the question: *What needs to be done (produced)?* The technology itself corresponds to the questions of "how?" and "in what way?" the goals outlined by the technology should be achieved. The machines and equipment involved answer the question "what?" The staff should answer the question "who?" and the mechanism and management system the question "why?" In combination, the use of organized technology presupposes an answer to the following complex questions: "What needs to be done?" "How?" "Using what?" "By whom?" "Why?" (Fig. 1).

The coordination of the potential of the four main components of the technology is such that, first, the coordination procedure starts with the technology itself, the implementation potential of which is primarily determined by the potential of machines and equipment. Then, the agreed-upon potential of technology, machines, and equipment is coordinated with the capacity of the maintenance staff, then with the mechanism and system for controlling the organized technology. The potential of technology varies according to the law of the trapezoid within its full life cycle (Fig. 2).

The initial segment (AB) of the trapezoid corresponds to the stage of matching and growth of the component potential to a level corresponding to the theoretically possible one. The next segment (BC) of the trapezoid characterizes the stage of the stable operation of the technology, and the segment (SD) characterizes the stage of completion of operation and subsequent utilization of the technology in the sector (VS).

Due to current and major repairs of machines and equipment, retraining of personnel and improvement of management systems, it is possible to keep the realized potential of the technology at a level close to the maximum. At the end of operation (SD), which stays at a consistently high level is impossible, and the real level of the technology potential will inevitably decline to the level of maintaining profitability.

The dynamics of the achievable potential of the technology obeys the S-shaped pattern of its improvement (see Fig. 2), which largely coincides with the trapezoidal law of variations in the potential of the full life cycle [5]. To simplify the calculations, instead of the S-shaped dependence, its linear approximation can be used. In the initial section, where the potential of the technology is consistently increasing, there is usually an inflection point 0, in which the accelerated build-up of the potential ends and the transition to a slowing down of its increase occurs. The patterns of the functioning of the aggregates of technologies, which form the chain of technologies, are largely based on the properties of individual technologies, and the characteristics of these sets have a set of vectors of indicators at the inputs of the chains and a set of vectors at the outputs of the technology chains.

It is necessary to note the multidimensionality and the vector nature of estimates of characteristics of technologies, which include indicators of output volumes, nomenclature (type) of products, their qualitative properties, cost parameters, product loss rates, environmental load, etc. To obtain integral estimates of the characteristics of technology chains, operations of summation of cost indicators and multiplication for quality indicators and calculation of network capacity are used [2].

The conjugacy of the related technologies and their chains implies mutual agreement (assignment, enhancement) between technology characteristics in order to increase the integral level of the potential and the vector of characteristics of the technology chain.

The possibilities for improving the integrated potential of technological chains, especially their qualitative characteristics, depend on the potential of their least perfect links. Therefore, predictive assess-

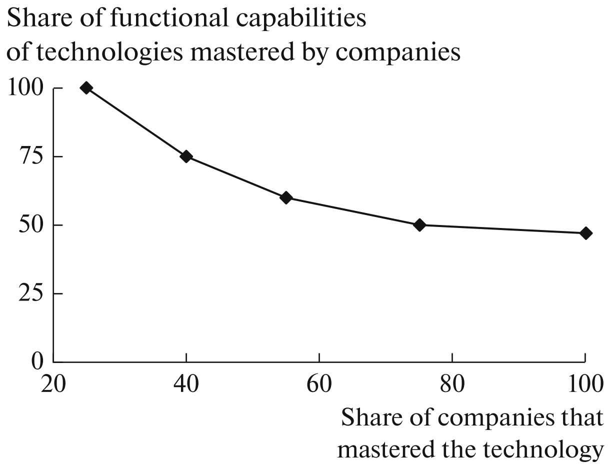

Fig. 3. Distribution of the potential of technologies mastered by companies.

ments of the improvement of the integrated potential must begin with a consistent improvement in the characteristics of the least advanced technologies. Ignoring this situation in the past led to the multi-orderliness of the domestic economy, when along with the technologies of the fifth technological order there were many technologies of the fourth and third orders [6].

The main reasons for the slow decision-making, and often the refusal to use innovative solutions, new technologies, and modernization of industrial enterprises, are the staff's interests in maintaining the existing technologies that provide them with local benefits; the need for partial or complete shutdown of production, which threatens the loss of revenue and possibly the loss of the market; doubts about the prospects of the technologies chosen and not quite reliable estimates of the calculation of the economic benefits of modernization; the possibility of reducing the number of personnel and the loss of part of jobs; etc.

The search for methods of forming technologies was limited to an orientation toward the well-known laws of mechanics, physics, and chemistry, and, at the beginning of the 21st century, the developed technologies have become more complex due to the combination of possible directions, and their general design has become known as *info-nano-cogno-bio* [2]. This design assumes the possibility of using information technology (info-); creation of technological processes at the nanoscale (nano); adaptability, i.e., the ability to choose the best mode depending on external conditions (cogno-); and the possibility of using the processes inherent to biological systems (bio-).

Since the beginning of the 21st century, especially in the engineering industry of developed countries, the tendency to recycle has gradually started to form, which consists of ensuring the use of these materials and methods of processing that allow the use of details and parts of equipment and machinery based on efficient recycling technologies. This trend, which is aimed at ensuring the conditions for the complete utilization of packaging materials, also takes place in the case of using biodegradable materials. The opportunities for a wider distribution of the recycling trend largely depend on the consideration of the conditions of recycling technologies in the development and design of new materials.

Between the chains of technologies for extracting resources, their processing, which converts them into machines, equipment, devices, and appliances, as well as their use in the production of end products and the creation of an industrial infrastructure, there are reciprocal links that allow the current potentials of the degree of readiness of the products of the previous stage to be redistributed to effective use at the next. Thus, in the extraction of hydrocarbons and solid minerals, the high purification of primary resources (oil, gas, and condensate) from impurities is important before transportation, storage, and delivery to consumers. For recoverable minerals, it is important to separate their useful part from rock and impurities to the fullest, while the manufacture of machinery and equipment requires high-quality materials and their respective assortment to reduce losses during processing.

The scale of development of new technologies obeys a stable pattern characterized by a shifted hyperbola (Fig. 3). It is known that only a relatively small number of companies and enterprises are able to fully utilize all of the functional capabilities of technology. For various reasons (human resource, technological, organizational), most companies only partially use all possibilities of technology. This situation occurs for power-generating plants and technologies, the actual efficiency of which varies within ±10%; new medical technologies (tomographs, X-ray machines, etc.), as well as methods of performing complex operations (on the heart, kidneys, etc.) are only successfully implemented in a small number of centers, etc. The transition from technologies being used for the next generation technologies of higher level introduces new and more stringent requirements for the machines and equipment used, personnel, mechanisms, and control systems.

The plan to skip any technology generation that has not previously been developed by an industry will not always accelerate the development of the most advanced technologies and often only leads to an increase in the costs and timing of developing new-generation technologies. The proposals by some experts to abandon the consistent development of technologies and immediately move to mastering the best imported technologies (and thus to eliminate the long-term technological backlog accumulated in Russia) by domestic industry is not always acceptable. Keeping imported technologies in the operational state requires considerable expenses accrued in replacing elements and components of technologies that lost their potential, which are also possible based on imports, since the domestic innovative system is not capable of the immediate innovative support of advanced technologies. Therefore, it is advisable to combine the import of technologies with the support of the development of domestic technologies in the leading areas of economic development that correspond to national goals [9].

An important property of technology is the competitiveness of its potential, that is, the ability to maintain competitive advantages over similar competitive technologies within a certain period of the life cycle that are sufficient to maintain its cost-effective operation with the necessary profits [8].

Limitations of technological development. The low level of domestic scientific and technological potential is associated with the breakdown of branch science, chronic underfunding of science, aging of human resources, the departure of many specialists abroad, and the opposition of officials to the development of the Russian Academy of Sciences. The created domestic technologies are not complex and are not transferred to the customer on a turn-key basis; rather, they require additional work and additional costs for their development. There are no long investments at low interest to finance innovative and investment projects. The formed innovative and investment projects are developed and inefficiently implemented with significant deviations from targets, technical and economic indicators, and cost and time estimates.

The reorganization of the innovation sphere is urgent, as there are not enough structures, scientific centers, or institutions in the country that predict, research, design, and create complex technologies that are positively perceived by the domestic economy. When developing projects and assessing their effectiveness, it is necessary to take into account not only the economic effect, but also the burden on the environment, since socially friendly ecology is expensive. These costs must be assumed by both business and society as a whole. In innovative development, creation of advanced technologies, and modernization of the economy, the elimination of contradictions and the establishment of concerted actions by the government, the business elite, the scientific community, and society as a whole play a significant role.

Limitations of imports of advanced technology from the United States and EU countries (as an important part of the economic war against the Soviet Union) have existed for a long time, and the Jackson–Vanik amendment adopted by the US Congress in the 1970s established these restrictions at the legislative level. In the conditions of isolation of the Soviet economy from the supply of advanced imported technologies, the country was forced to independently create, master and use domestic innovative solutions and technologies. While in the field of defense and armament, the domestic innovative and industrial potential turned out to be sufficient to ensure parity with the United States and NATO countries, this potential was not sufficient for the harmonious development of the civilian sector of the economy. Its backlog from the needs of society determined the causes of the crisis and the subsequent collapse of the USSR.

Despite the cancellation of the Jackson–Vanik amendment at the beginning of the 21st century, restrictions on imports of technology by leading countries to Russia in the interests of the competitive advantages of the United States under various pretexts remained after its abolition. An example is the refusal to sell shares in the car company Opel to Russia and others. It is hardly possible to hope for a change in the economic policies of the leading countries and complete abolition of restrictions on imports of advanced technologies to Russia in the short and medium terms.

In this situation, the full use of the national innovation potential is necessary to create and master Russian technologies. It is possible and necessary to cooperate with countries that are not dependent on sanctions, both in the organization of scientific and technological programs and exploratory research projects, and in the exchange of ready-to-use technologies with partner countries (BRICS, SCO, etc.). Execution of the increased load by the domestic innovation environment is impossible without its radical reforming, the variants of which were considered in [1, 3, 8]. The main conditions for reform are:

—the restoration of the full innovation cycle;

—maintaining the potential of fundamental research carried out by the Russian Academy of Sciences;

—reformation of the potential of applied research of the Russian Academy of Sciences and its increase through the creation of joint structures with universities and companies;

—increasing the funding of local structures that implement programs to create new technologies in accordance with the goals of national development.

The listed system properties of technologies and the laws of technological development are extremely important in forecasting and system design both at the macro and meso levels. Imperfection of domestic technologies and their lagging behind the level of foreign technologies largely depends on the inconsistency of the levels of technology components and their integration into related technology chains. The lack of systematic coherence of technologies largely explains the lag in the labor productivity of Russian companies and companies operating in Russia with foreign participation.

The current state of development of the economy and the business environment has a significant direct and indirect negative impact on the development of the innovation sector and technological modernization. Many of the relations and patterns that have developed in the pseudo-market economy of Russia

Table 1. Commodity structure of the import-to-export ratio in the Russian Federation

Product	Import/export		
	2001–2005	2006–2010	2011–2015
Food and agricultural raw materials (except for textile)	3.96	3.54	2.37
Mineral products	0.03	0.02	0.02
Chemical industry products, rubber	1.06	1.35	1.50
Tanning raw materials, furs and fur products	0.78	2.61	3.06
Wood and pulp and paper products	0.40	0.52	0.54
Textiles, textile products, and footwear	3.06	11.59	17.48
Metals, precious stones, and their products	0.17	0.29	0.38
Machinery, equipment, and vehicles	2.11	4.87	5.09
Total:	0.41	0.54	0.57

Source: Work [4].

contradict those that take place in the developed market economy of developed countries. Thus, the constantly high level of inflation in Russia is significantly influenced by the constantly growing tariffs of natural monopolies, and many regional markets are controlled by local monopolists. At the same time, the rise in prices for traditional goods and services is often accompanied by a decrease in their quality.

Influence of technological potential on the development prospects of the domestic economy. The relatively low level of the quality of domestic products in the early 1990s and its inconsistency with the standards of the EU countries and developed countries, as well as the desire to prevent Russian export industrial goods (machinery, equipment, airliners, helicopters, cars, etc.) from their markets significantly limited the export opportunities of the country. The obsolete technologies of the Soviet period and the lack of state support for enterprises producing export goods led to a sharp decline in the production potential of many machine-building enterprises, some of which under these conditions were forced to cease to exist (NPO Processing Centers in Ivanovo, S. Ordzhonikidze Machine-Tool Construction NPO, and others). In the early 2000s, tens of thousands of enterprises were closed in Russia. Only the products of oilmen, gas workers, and metallurgists were readily accepted on world markets. Foreign consumers of Russian raw materials were not embarrassed by the not quite high quality of exported products, which was compensated by price discounts, while Western countries also made good money bringing the raw materials to the standards required for consumers using the cryogenic technologies for separation of propane, ethane, and butane from natural gas, modern technologies for purifying oil and condensate from sulfur, etc.

If the technological imperfection of domestic extractive industries did not lead to a sharp decline in the country's export potential, then for the processing and manufacturing industries, the low level of technologies capable of producing obsolete products of poor quality and with large losses of raw materials (metal, electricity, etc.) proved to be a decisive factor in reducing the level of exports. Since 2000, the growth of imports of chemical products, machinery, and equipment, as well as food imports (table 1) has gradually emerged.

The dynamics of the import-to-export ratio has three characteristic stages, i.e., 2001–2005, i.e., the beginning of development of imports of products and technologies; 2006–2010, i.e., the achievement of small volumes of imports; and 2011–2015, i.e., a decrease in the growth of imports and an increase in exports of Russian products. It is estimated that the import of construction materials used by machine builders was about 50% of the total amount of materials used, and the share of imported control and measuring equipment, for example in the oil and gas industries, was close to 90%.

A significant (more than double) depreciation of the ruble and a decline in world prices for hydrocarbons significantly influenced the dynamics of exports and imports. In 2001–2015, the following trends in the ratio of import-export consistently formed:

1. The share of food products in the structure of exports was growing.

2. The share of mineral resources in Russian exports was consistently declining.

3. In general, the share of exports of timber and pulp and paper products was stable.

4. The share of exports of metals, precious stones, and their products was increasing.

5. The share of imports of machinery, equipment, and vehicles decreased and their exports increased.

The impossibility in Russia at the beginning of the 21st century of ensuring the production of modern airliners with digital avionics, navigation aids, and economical engines caused a decline in production and even the complete cessation of their production. The ability to weld ship hulls in the absence of domestic components and ship control means did not save Russian shipbuilding from the landing aground. Steps have only been taken in recent years to overcome the disintegration of the potential for producing high-tech components for aircraft and shipbuilding and organizing their import substitution.

Many experts and managers of various levels in recent years have regularly announced the need to change the economic model. The mandatory properties of the new model include the need for diversification in the direction of increasing the growth of gross added value, primarily due to the high technology sectors of the economy, reducing dependence on the commodity sectors of the economy, and increasing the economy's resilience to external challenges and price fluctuations in world markets.

These mandatory properties of the new economy model were considered at the beginning of the 21st century in the works of the Institute for Economic Forecasting of the Russian Academy of Sciences and were taken into account in the justification of the resource-innovation development strategy [1–3, 8]. The essence of the proposed development strategy was the need to consistently curtail the growth rate of exports of raw materials (oil, natural gas, roundwood, rough diamonds, etc.) and to build up the capacity of processing industries by increasing the volume of extractive industries and increasing the export of processed products. At the same time, according to the projected estimates, the cost of export products could increase many times as follows: refined products could increase by 2–2.5 times, the gas chemistry could increase by 5–7 times, timber processing could increase by 3–5 times, and processed diamonds could increase by 6–10 times, etc.

According to the calculations carried out with the possibility of investment growth due to some of the funds received from the export of resources, as well as the use of these funds for the innovative modernization of reprocessing and processing industries, estimates of GDP growth dynamics (doubling in less than 10 years) and a sequential increase in GVA for national economic complexes were obtained [1]. However, many mining companies in the early 21st century were not interested in the development of their technological potential and capacities of reprocessing industries. Interest in this development emerged after the financial crisis of 2008, when the role of the resource component in the prospects for the growth of the world economy was identified. At the same time, the economy began to form trends and intentions of companies at the state level to assist the development of the aircraft industry, shipbuilding, machine tools, pharmaceuticals, etc.

The sharp drop in world prices for hydrocarbons, sanctions imposed by the European Union and the United States for the supply of defense technology, and the possibility of obtaining short-term loans have forced Russia to solve the problems of import substitution and food and technological security. In order to ensure sustainable social and economic development of the country, resistant to external challenges, it is necessary to harmoniously develop the basic sectors of the economy, including extraction, recycling, processing, and final consumption, as well as production infrastructure. Over the past almost 20 years, the structural ratio for the volume of GVA between these sectors has been consistently changing. The distribution in the form of a falling hill in the late 1990s was transformed into a pit shape at the end of the 2010s, which began to straighten out by 2015 (Fig. 4).

It should be emphasized that the distribution of GVA by sector in the United States in the late 1990s had a shape of a convex hill, which, due to the increasing volume of shale hydrocarbon production by 2010, turned into a hill with a shelf. The distribution of GVA similar to the US was observed for the leading EU countries and Japan [3]. To ensure sustainable development, the distribution of GVA for Russia should have a shape close to horizontal, but convex in the middle of the full technological cycle. At the same time, in the long term, there should be a redistribution of export shares between the complexes of industries, when only 25% of the extracted resources should be exported, up to 40% of the processed raw materials and 30% of processed products (engineering, electronics, measuring instruments) can be exported, as well as in the production of final consumption goods, services, and industrial infrastructure the share of exports may be 20%.

Measures to overcome the limitations of technological development. The main measures to support and build up the domestic potential of innovation and technological development first of all include the restoration of a complete innovation and technological cycle, which was partially destroyed in the transition from planned to market mechanisms of economic management. This destruction primarily concerned the most important link in this cycle, i.e., branch science. The loss of this link was compensated for by private applied research institutes and state scientific centers, as well as by the Russian Academy of Sciences. This redistribution of functions within a full innovation-technological cycle could not fully compensate for the loss of potential in the applied research and development sector. In addition, this sector was deprived of a significant share of financial resources, which led to a reduction in the scope, quality level, and timing of innovative solutions, as well as the degree of completeness of innovations. These conditions, as well as the noncomplex character of the technologies transferred to domestic customers in the situation of full openness of domestic markets for imports, only enhanced the decrease in the potential of applied technologies and research-and-development products. These measures have greatly contributed to the strengthening of the

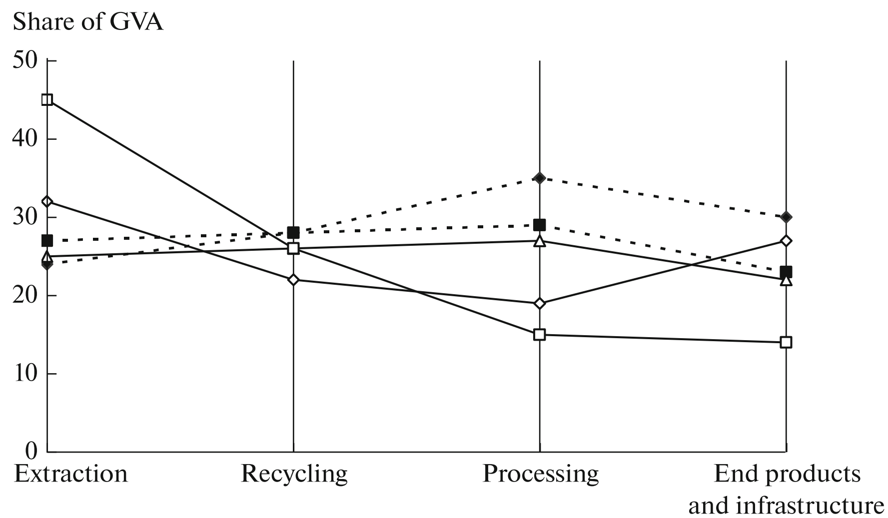

Fig. 4. Scheme of distribution of GVA for main sectors (complexes) of the economy of the Russian Federation and United States: –◆– US 2010; –■– US 2000; –◇– RF 2010; –□– RF 2000; –△– RF 2020.

immunity of domestic innovative solutions, as well as to a reduction in the purchases of Russian companies and the amount of funding for applied research and development.

The restoration of the interest of domestic companies in Russia's innovative solutions and technologies was largely facilitated by sanctions banning the supply of Western technologies to Russia, as well as the measures taken in 2014 by the Russian government to support Russian companies with import substitution. These measures were largely systemic in nature and included both financial subsidies for obtaining loans at preferential prices and guarantees of supporting the markets for products developed and created by companies under import substitution. All of this allows us to hope for the growth of interest of Russian companies in domestic innovations and technologies, which will also be expressed in the formation of forecasts and tasks for research and development.

Another important link in the full innovation-technological cycle is the Russian Academy of Sciences, the authority and leading role of which in the creation of advanced production technologies is recognized by both the world scientific community and state statistics [4]. In recent years, the Russian Academy of Sciences has repeatedly been subjected to biased accusations of non-competitiveness of its innovative solutions and the nonintroduction of Russian Academy of Sciences-created technologies by Russian companies.

At the same time, the strategy of scientific and technological development rightly emphasizes the growing role in the technological development of the fundamental research sector, the main potential of which is concentrated in the Russian Academy of Sciences. Meanwhile, the increasing complexity of scientific search in connection with external challenges and threats, as well as the orientation towards the national goals of the Russian Federation, require the reform of the entire innovation sphere, including the Russian Academy of Sciences.

One of the directions of reform consists of creating a network of mobile, temporary innovative structures involved in the implementation of projects on terms of financing based on grants and targeted orders based on the potential of the Russian Academy of Sciences and universities. In this scheme of organization, coordinators and scientific managers of projects carry out the invitation, selection, and management of project executors.

The basic foundation for supporting the reforms of the innovation sphere and restoring the potential of a full innovation-technological cycle can be a social agreement between the Russian Academy of Sciences, universities, the Government of the Russian Federation, domestic companies, and the Russian Union of Industrialists and Entrepreneurs (RSPP). At the same time, reforming of the Russian Academy of Sciences is impossible without its direct participation. The Government of the Russian Federation coordinates the interaction of the Russian Academy of Sciences and the universities in restoring direct relationships between science and industry (companies) with the support of the Russian Union of Industrialists and Entrepreneurs.

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Different ways of implementing the technological development of Russia's economy are possible. The direction that emerged in the early 21st century was based on the import of innovative solutions and technologies. Imported technologies were not always among the world leaders, but most of them were superior to domestic technologies; most importantly, they were supplied on a turn-key basis and on financial terms acceptable to the Russian side. The volume of imported technologies and products was significant and, in 2012 alone, amounted to about $200 billion USD [4]. Deliveries of imported machinery and equipment tied domestic consumers to the need to purchase spare parts and consumables from the seller, the cost of which was significant during their full life cycle, which inevitably led to an increase in domestic prices for products created. This violated the original estimates of the expected effect of technology imports.

The second direction is the development of the preserved domestic potential for creating innovations and new technologies. In the opinion of many government experts, this problem arose unexpectedly after a sharp fall in the prices of oil and natural resources, as well as the imposition of sanctions by the European Union and United States on the supply of new technologies and long-term loans for leading Russian companies. These same experts believe that way to solve this problem is via import substitution and the development of domestic potential. A quick and complete solution to this problem is impossible without its own innovations and technologies. In any case, it is important to use the preserved domestic innovation potential and develop it taking into account national goals and external and internal challenges. In any variant of the developed strategy of scientific and technological development, it is also necessary to use the third direction: harmoniously and fully take into account imports and the own potential for the development of the domestic economy.

ACKNOWLEDGMENTS

This article is based on research carried out with financial support of the grant from Russian Science Foundation (project no. 14-38-00009). Program-objective management of integrated development of the Arctic zone of the Russian Federation. Peter the Great St. Petersburg Polytechnic University.

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Translated by K. Lazarev