

Article

Analysis of the Potential of Palladium Market: Structural Transformation of Global Demand in the Context of the Energy Transition

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Abstract

The palladium market represents a critical role in supporting key industrial sectors and facilitating the energy transition, as it is widely used in the automotive industry, electronics, chemical manufacturing, and hydrogen energy. These sectors influence a steady demand amid tightening environmental regulations and the development of green technologies. The aim of this study is to assess the structural transformation of the global palladium market through 2030 and to project Russian palladium production for 2026–2028 amid the energy transition by applying economic-mathematical methods, including linear regression, the Grey forecasting model, exponential smoothing, and Autoregressive Integrated Moving Average (ARIMA) time-series modeling. Particular attention is paid to the analysis of factors influencing the dynamics of the global palladium market, including the electrification of transportation, the substitution of palladium with alternative materials, and changes in global supply chains. The simulation results showed that the exponential smoothing model possesses the highest predictive accuracy, enabling it to estimate future palladium production volumes. The market is undergoing a structural transformation: declining demand from the traditional automotive sector is partially offset by the development of new applications in hydrogen energy, electronics, and advanced materials, suggesting that technological improvements can compensate for the loss of conventional demand segments. The key findings are (1) exponential smoothing ($R^2 = 0.9812$) outperforms linear regression, Grey model, and ARIMA; (2) Russian palladium production is projected at 74–130 tonnes (2026), 63–141 tonnes (2027), and 54–150 tonnes (2028); and (3) the decline in automotive demand is partially offset by new applications. Our findings confirm the need for Russian producers to adapt their strategies to the structural transformation of global demand, deepen domestic processing, and develop new high-tech applications for palladium to maintain their competitive positions amid the energy transition.

Keywords: palladium; palladium industry; market dynamics; development prospects; trends; production; demand; consumption; forecasting

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1. Introduction

In the current context of global economic transformation and the energy transition, it is particularly important to analyze the development prospects of markets for strategic metals, including palladium, which represents a key role in meeting environmental standards due to its widespread use in automotive catalytic converters as well as in a number of high-tech industries.

In this study, we adopt the definition of “strategic metals” as critical raw materials that are essential for key industrial sectors, have high supply risk due to geographical concentration or geopolitical factors, and are difficult to substitute in the short term. Palladium meets all three criteria: it is indispensable for automotive catalytic converters, hydrogen energy, and electronics; its global production is highly concentrated in Russia (~40%) and South Africa (~36%); and substitution with alternative materials is technically limited and economically costly [1]. This strategic status makes the analysis of long-term market trends particularly relevant for both producing countries and importing economies.

For Russia, which controls approximately 40% of global palladium production (primarily through PJSC MMC Norilsk Nickel) and holds one of the world's largest resource bases for platinum group metals, the study of long-term market trends takes on strategic importance. Despite Russia's undisputed leadership in palladium extraction, the industry faces a profound structural problem that is often overlooked: a critical imbalance in the domestic value chain and a severe lack of deep processing. Its internal consumption and deep processing capabilities remain critically underdeveloped, accounting for less than 5% of total national output (roughly 5–7 tonnes annually) [2]. Consequently, the vast majority of the metal is exported in raw or semi-refined forms. This creates a strategic vulnerability: Russia controls the physical supply but captures only a fraction of the final added value, which is realized by foreign manufacturers. Furthermore, this heavy reliance on raw material exports makes the industry highly susceptible to external shocks, such as geopolitical sanctions, price volatility, and logistical disruptions. As the global energy transition threatens to reshape traditional demand patterns, assessing the long-term sustainability of this export-oriented model and identifying opportunities for deeper domestic processing become critically important research and policy challenges.

The energy transition is accompanied by growing demand for critical materials used in modern energy technologies, as well as increased risks of supply disruptions, including geopolitical tensions and sanctions (notably following 2022), logistical reconfigurations of global trade routes, pandemic-related production shutdowns (as observed in 2020), labor strikes in major producing regions, and the high geographical concentration of deposits in a limited number of countries, which are significantly impacting the markets for precious and platinum group metals, including palladium [3–5].

Energy transition aims to reduce carbon emissions and other substances and mitigate the effects of climate change [6]. The rapid adoption of sustainable technologies in the energy and transportation sectors is increasing demand for a range of critical mineral resources, including lithium, cobalt, graphite, rare earth elements, and platinum group metals, which are scarce and unevenly distributed worldwide [7,8].

This scarcity reflects not only limited geological endowments but also supply-side constraints, including the high geographic concentration of deposits (primarily in Russia and South Africa for palladium), underinvestment in new mining capacity, and the long lead times required to bring new deposits into production.

Improving the efficiency of existing technologies, developing new devices with higher performance and lower environmental impact, and advancing the energy transition through the wider deployment of renewable energy technologies are considered the main approaches [9].

Palladium is among the most significant platinum group metals (PGMs), playing a critical role in ensuring the functioning of key industries and in the implementation of energy transition processes. Its unique physical and chemical properties, including high catalytic activity, exceptional hydrogen permeability (absorbing up to 900 times its own volume of hydrogen), corrosion resistance, thermal stability, and good electrical conductivity—make it widely used in the automotive industry (catalytic converters), electronics (multilayer ceramic capacitors, contacts), chemical manufacturing (catalysts for hydrogenation and dehydrogenation), and hydrogen energy (purification membranes and fuel cell catalysts) [10,11].

Amid tightening environmental regulations and the development of green technologies, demand for palladium remains stable, though the structure of this demand is undergoing significant changes. Russia occupies a special place in the global palladium market: Public Joint Stock Company Mining and Metallurgical Company Norilsk Nickel (PJSC MMC Norilsk Nickel) accounts for approximately 40% of global palladium production, producing about 2762 thousand troy ounces (86 tonnes) in 2024 [12]. The country possesses one of the largest mineral resource bases for platinum group metals, which ensures its status as a key supplier to the global market. At the same time, domestic consumption of palladium remains limited due to the slow development of the processing and high-tech industries, which creates a dependence on export supplies and makes the industry vulnerable to external shocks.

Existing research on the palladium market is often fragmented and fails to account for the combined impact of various factors: the electrification of transportation (which reduces demand for traditional catalytic converters), the replacement of palladium with alternative materials, changes in logistics.

Changes in logistics refer to transformations in palladium supply chains caused by geopolitical tensions, sanctions, and shifts in global trade patterns. This includes not only changes in suppliers and consumers but also the reorganization of transportation and distribution routes. For example, following sanctions-related restrictions, part of the Russian palladium supply has been redirected through alternative trading hubs and intermediaries in Asia and the Middle East. In particular, China, Turkey, and the United Arab Emirates have gained importance as alternative transit and trading routes. Specific logistical shifts include the loss of “good delivery” status for Russian palladium on Western exchanges (LPPM), complicating sales through traditional financial channels; the redirection of Russian palladium exports from Western markets to Asian markets via eastern logistics hubs and through China as a transit node; and the increasing use of the Northern Sea Route as an alternative shipping corridor.

Beyond these supply-side logistical shifts, the demand side of the palladium market is also undergoing significant transformation, primarily driven by the accelerating adoption of electric vehicles. According to the International Energy Agency (IEA) Global EV Outlook 2025, the global electric vehicle fleet is projected to reach approximately 250 million units by 2030 [13]. According to BloombergNEF estimates, the global electric vehicle fleet could grow to approximately 700–800 million units by 2040 under a scenario of accelerated transportation electrification [14].

A comprehensive analysis of the interrelationships between these factors and their impact on market dynamics remains insufficiently developed. Moreover, there are no verified forecasting models that would assess future palladium production volumes amid structural shifts in supply and demand.

Although previous studies have examined individual aspects of the palladium market, several important gaps remain. In the first place, existing research predominantly focuses on either supply-side dynamics, recycling, or specific applications of palladium, while the combined effects of transportation electrification, substitution by alternative ma-

materials, and the emergence of new high-technology applications have received limited attention. In the second place, the literature presents contradictory conclusions regarding the future of palladium demand under the energy transition.

On the one hand, some studies predict a catastrophic structural decline in demand due to the rapid electrification of the automotive sector, arguing that the widespread adoption of electric vehicles (EVs) will eliminate the need for catalytic converters and render current primary production volumes excessive. On the other hand, other researchers argue for an inertial or adaptive scenario, emphasizing that the transition will take decades, tightening emission standards will increase palladium loading per internal combustion engine (ICE) vehicle, and new high-tech applications (such as hydrogen energy and electronics) will partially offset the loss of traditional automotive demand.

In the third place, insufficient attention has been paid to the implications of these structural changes for Russia as the world's largest palladium producer.

While the Russian mining and metallurgical industry produces approximately 84–86 tonnes of refined palladium annually (primarily as a byproduct of copper-nickel extraction), the vast majority of the metal, around 78–80 tonnes, is exported as raw material. This significant structural imbalance in the domestic value chain leaves the industry highly vulnerable to external market shocks.

Finally, few studies integrate qualitative analysis of market transformation with quantitative production forecasting. This study seeks to address these gaps through a comprehensive analytical framework that combines structural demand analysis and forecasting modeling.

The aim of this study is to assess the structural transformation of the global palladium market through 2030 and to project Russian palladium production for 2026–2028 amid the energy transition by applying economic-mathematical methods, including linear regression, the Grey forecasting model, exponential smoothing, and ARIMA time-series modeling.

The study addresses the following research questions:

RQ1: How will global palladium demand change through 2030 under the influence of transport electrification, substitution by alternative materials, and the emergence of new high-technology applications, and what implications will these changes have for the global palladium market?

RQ2: What are the projected volumes of Russian palladium production for the medium term (2026–2028), and which economic-mathematical model provides the highest forecasting accuracy under conditions of high market volatility?

RQ3: What factors will determine the long-term sustainability of the palladium market, and what strategic responses are required from major producers in the context of the energy transition?

To achieve this aim, the study pursues the following objectives:

- Identify and systematize the key factors affecting the development of the global palladium market, including transport electrification, material substitution, technological change, geopolitical developments, and shifts in global supply chains;
- Develop and compare alternative forecasting models (exponential smoothing, ARIMA, linear regression, and the Grey model) to predict Russian palladium production and evaluate their forecasting performance;
- Assess the expected evolution of global palladium demand through 2030, considering both declining demand from traditional automotive applications and emerging demand from hydrogen technologies, electronics, chemical catalysis, and other high-technology sectors;
- Analyze the implications of projected demand and production trends for the future balance of the global palladium market;

- Formulate practical recommendations for Russian palladium producers aimed at maintaining competitiveness and ensuring long-term market sustainability under the energy transition.

The study is structured into several interconnected stages, each of which logically follows from the previous one and ensures a sequential exploration of the aspects of the issue under study.

The first stage focuses on analyzing external and internal factors affecting the palladium market. In the context of this study, external factors are defined as global macroeconomic, geopolitical, and technological trends that shape overall market equilibrium but are beyond the control of individual national producers (global transport electrification, international environmental standards, and supply chain disruptions). Internal factors refer to industry-specific, corporate, and national conditions that determine the operational efficiency and competitive position of domestic producers (geological specifics of byproduct extraction, depth of domestic processing, corporate R&D programs, and state support).

The second stage involves economic-mathematical modeling of palladium production volumes based on time series data for the period from 2009 to 2023. Various forecasting methods (including exponential smoothing, trend models) are compared, their accuracy is assessed, and the selection of the most appropriate tool for medium-term forecasts is justified. The results of this stage serve as a quantitative basis for assessing the future availability of the metal.

The third stage focuses on analyzing the structural transformation of palladium demand. The study examines the decline in consumption by the traditional automotive sector due to the growth of electric vehicles and stricter environmental standards and assesses the compensatory potential of new sectors. Quantitative parameters of the substitution of some sectors by others are identified.

The fourth stage focuses on assessing the long-term sustainability of the palladium market. It analyzes opportunities for diversifying the metal's end uses, including the development of high-tech applications. It examines the role of recycling (the anthropogenic cycle) as a factor in stabilizing the balance of supply and demand. Conditions are formulated under which the market will remain balanced even if traditional demand declines.

The fifth stage involves developing recommendations for Russian palladium producers, primarily for PJSC MMC Norilsk Nickel, taking into account the identified trends. The necessity of deepening domestic processing, developing domestic high-tech production and adapting export strategies to the changing global market conditions is justified. State support measures that help maintain Russia's competitive position amid the energy transition are evaluated.

The proposed research framework represents a systematic approach to analyzing the palladium market, combining factor analysis, forecasting modeling, an assessment of structural shifts in demand, and the development of practical recommendations. The sequential implementation of these stages allows not only for the identification of current trends but also for the formulation of scientifically grounded forecasts and strategic recommendations for the long-term development of Russia's palladium industry.

Scientific Novelty and Analytical Framework

While the forecasting methods employed in this study (ARIMA, regression, exponential smoothing) are established econometric tools rather than radically new algorithms, the scientific novelty of this research lies in its integrated analytical framework. Crucially, this framework moves beyond purely descriptive market analysis to provide a robust, data-driven predictive model applied to a uniquely complex market context.

A key methodological contribution is the rigorous empirical framework for model selection. We evaluate forecasting performance using multiple error and fit metrics to compare traditional exponential smoothing with autoregressive models such as ARIMA. The approach is designed to identify the most robust forecasting method for highly volatile and structurally shifting time series of strategic metals under conditions of uncertainty.

Conceptual Shift in the Demand Paradigm: the study introduces a forward-looking conceptual shift, evaluating palladium not merely as a metal facing decline due to automotive electrification, but as a critical enabler for emerging high-tech sectors. This is substantiated by the analysis of specific, upcoming industrial applications, such as palladium membranes for hydrogen energy and new alloys for glass fibre production (e.g., initiatives by the Palladium Technology Centre).

The scientific novelty of this study lies in several aspects. First, the work proposes an integrated analytical framework for assessing the structural transformation of the global palladium market under the energy transition. The overwhelming majority of empirical studies focus on forecasting palladium price dynamics using methods such as ARIMA, artificial neural networks, and other machine learning algorithms. By contrast, quantitative studies aimed at forecasting physical demand and consumption volumes are virtually absent [15,16]. Notably, the authors of price models themselves recognize that a major limitation of their approaches is the exclusion of macroeconomic and geopolitical factors, which reduces the relevance of their forecasts under conditions of uncertainty.

The value of our approach is not in the individual models themselves, but in their comparative validation, which provides an evidence-based justification for model selection under conditions of high uncertainty. This comparative validation is absent from the existing literature, where authors typically apply a single forecasting method without empirical justification for their choice.

We formulated three research hypotheses. The first hypothesis posits that simple adaptive modeling, specifically exponential smoothing, provides higher forecasting accuracy for volatile time series of strategic metal production compared to complex econometric models. The second hypothesis asserts that the structural transformation of the global palladium market up to 2030 will be inertial in nature, meaning that the decline in automotive demand will be partially offset by the growth of new high-tech applications. The third hypothesis examines whether Russian producers can maintain their competitive positions by deepening domestic processing and diversifying sales markets, a proposition that we evaluate through quantitative parameters of export flows and domestic consumption dynamics.

This study offers substantial strategic implications for the Russian palladium industry and policymakers. Data-driven forecast of production volumes through 2028 and a structural demand analysis through 2030, this research serves as a decision-support tool for corporate strategy and state regulation. Specifically, the study identifies specific high-growth sectors (e.g., hydrogen membranes, advanced glass fiber catalysts) where targeted R&D investments can offset the inevitable decline in automotive demand. The findings contribute to ensuring the technological sovereignty and long-term economic resilience of Russia's platinum group metals sector amid the global energy transition.

2. Materials and Methods

To achieve the objective of analyzing the current state, growth factors, and prospects of the palladium market, this study employs a comprehensive methodological framework that combines data systematization, comparative analysis, scenario-based demand assessment, and economic-mathematical modeling. The methodological approach is structured into four sequential stages: (1) data collection and systematization, (2) comparative and

factor analysis, (3) scenario-based assessment of structural shifts in demand, and (4) predictive modeling of production volumes.

2.1. Data Sources

The research database consists of publicly available data from the following sources:

Data on the main producers of palladium and their production indicators (Table 1) were compiled from Glaister and Mudd and the United States Geological Survey (USGS) Mineral Commodity Summaries.

Foreign trade statistics for Russian palladium exports were sourced from the World Integrated Trade Solution (WITS) and TradeMap databases (Table 2).

Data on the main applications of palladium and substitution possibilities (Table 3) and on key projects in the Russian palladium market (Table 4) were compiled from scientific literature, industry reports, and company announcements.

The time series data for palladium production in Russia from 2009 to 2023 (Table 5) were obtained from the State Report on the Status and Use of Mineral Resources of the Russian Federation. Results of the ADF stationarity test (Table 6), evaluation rules for ARIMA model selection (Table 7), ARIMA model parameters (Table 8), and forecast accuracy comparisons (Tables 9–11) were calculated by the authors using SPSS version 29.0 based on the State Report data. The forecasted palladium production ranges for 2026–2028 (Table 12) were derived from the exponential smoothing model applied to the 2009–2023 time series.

Global production and supply data were obtained from the United States Geological Survey (USGS) Mineral Commodity Summaries (Figure 1), Johnson Matthey PGM market reports (Figure 2), and the Annual report PJSC MMC Norilsk Nickel (Figure 3).

Figure 4, which presents the forecast for domestic palladium consumption in Russia (tons), was constructed by the authors based on the methodological approaches of Seo and Morimoto and Zhang et al., combined with historical consumption data Norilsk Nickel annual reports.

Figure 5, which shows trends in palladium production volumes in Russia from 2009 to 2023, was constructed by the authors based on data from the State Report on the Status and Use of Mineral Resources of the Russian Federation.

Figure 6, which presents the partial autocorrelation function (PACF) and Figure 7, which shows the autocorrelation function (ACF) plot of the model residuals, were generated by the authors using SPSS. Figure 8, which illustrates the construction of forecasting models (linear model, Grey forecasting model, exponential smoothing model, and ARIMA model), was constructed by the authors based on the modeling results calculated using SPSS.

2.2. Scenario Development and Assumptions

The analysis of structural shifts in demand is conducted using a scenario-based approach. Three groups of factors influencing the dynamics of the palladium market are examined: the electrification of transportation (decreasing demand from internal combustion engines), the substitution of palladium with alternative materials (primarily platinum), and the development of new applications.

Three scenarios were developed to assess the future evolution of the palladium market through 2030: pessimistic, baseline, and optimistic. Each scenario is defined by specific quantitative parameters for the key demand drivers, derived from a combination of literature sources, industry reports (Johnson Matthey PGM Market Report, World Platinum Investment Council (WPIC), IEA Global EV Outlook 2025, BloombergNEF Electric Vehicle Outlook), and our own estimates based on historical trends.

Pessimistic scenario: rapid penetration of electric vehicles, accelerated substitution of palladium by platinum in catalytic converters, slow development of hydrogen technologies, and increasing secondary supply from recycling. Under the pessimistic scenario, electric vehicles are assumed to capture 45–50% of global new car sales by 2030, corresponding to an EV fleet of 300–350 million units. Palladium substitution by platinum in gasoline catalysts occurs rapidly, reaching 75–80% replacement. The development of hydrogen energy applications remains slow, with limited commercialization. Recycling contribution to total palladium supply increases to 30–35%. Global new high-tech demand from hydrogen energy, electronics, and glass fibre sectors reaches only 10–15 tonnes annually by 2030.

Baseline scenario: moderate growth of electric vehicles, gradual substitution of palladium, stable industrial demand, and limited expansion of new applications. Under the baseline scenario, the global EV share in new car sales is projected at 35–40% by 2030, with the EV fleet reaching 250–300 million units. Substitution of palladium by platinum proceeds at a moderate pace, with 50–60% replacement. Hydrogen energy applications develop gradually through pilot projects and early adoption. Recycling contribution reaches 25–30% of total supply. Global new high-tech demand is estimated at 20–30 tonnes per year by 2030.

Optimistic scenario: slower decline in automotive demand, rapid growth of hydrogen energy technologies, electronics, advanced materials, and successful commercialization of new palladium-based products. Under the optimistic scenario, the global EV share in new car sales is limited to 25–30% by 2030, with an EV fleet of 180–220 million units. Substitution of palladium by platinum occurs slowly, at 30–40% replacement. Hydrogen energy technologies experience rapid growth and widespread deployment. Recycling contribution remains at 20–25%, reflecting slower growth in secondary supply. Global new high-tech demand reaches 35–45 tonnes annually by 2030.

The resulting scenarios were used to evaluate the possible trajectories of palladium consumption through 2030. In this study, «palladium consumption» refers to refined palladium—the metal that has been processed to marketable purity and is ready for use in catalytic converters, electronics, hydrogen technologies, and other industrial applications. This includes both primary refined production and secondary (recycled) material.

Data systematization and generalization are used to identify fundamental patterns in the evolution of the palladium market, including cyclical price fluctuations, long-term production and consumption trajectories, and the impact of external factors on industry dynamics.

A comparative analysis is used to compare the positions of Russia and other palladium-producing countries (South Africa, the United States, Canada, and Zimbabwe) as well as to assess the competitive advantages of PJSC MMC Norilsk Nickel within the global value chain.

2.3. Model Inputs and Variables

Economic-mathematical modeling is a key research method used to forecast palladium production volumes based on time series [17–20]. This study compares four forecasting models: linear regression, the Grey Model, the exponential smoothing model, and the ARIMA (Autoregressive Integrated Moving Average) model. These models were selected due to their different natures and their ability to account for various types of patterns in time series: linear trends, adaptation to recent changes, and autoregressive dependencies.

These models were selected to capture distinct patterns in the time series: linear regression serves as a baseline to identify long-term linear trends; the Grey model is designed for forecasting with limited data under high uncertainty; exponential smoothing

provides rapid adaptation to recent market fluctuations by assigning higher weights to the most recent observations; and ARIMA captures complex autoregressive dependencies in stationary time series. Together, these models allow us to compare simple adaptive approaches with more complex econometric methods and select the most appropriate tool for volatile strategic metal markets.

Before applying the ARIMA model to analyze and forecast palladium production, it is important to verify the stability of the time series. To do this, a stationarity test must be conducted. The test determines whether a unit root (a characteristic of a polynomial related to its roots) is present in the series, which in turn helps determine whether differencing is required to achieve stationarity. There are several methods for conducting this test, including the ADF test (Augmented Dickey–Fuller Test), the PP test (Phillips–Perron Test), the NP test (Ng–Perron Test), and others. In our study, we will use the ADF test to analyze trends in palladium production in Russia from 2009 to 2024.

The dependent variable for all four models is annual palladium production in Russia (tonnes), covering the period 2009–2023 (15 observations). The independent variables vary by model:

For linear regression, time (years 1 through 15, where year 1 = 2009, year 15 = 2023) serves as the single independent variable.

For the Grey model GM (1,1), the model uses the original time series values without transformation, applying the first-order accumulation generation operator to identify the underlying development trend.

For exponential smoothing, the smoothing parameter $\alpha = 0.9$ is predefined to maximize model sensitivity to recent market fluctuations, justified by the high volatility of the time series (as evidenced by sharp production declines in 2010 and 2021, and peaks in 2013 and 2020).

For ARIMA (1,1,0), the model order ($p = 1$, $d = 1$, $q = 0$) was determined by the Auto-correlation Function (ACF) and Partial Autocorrelation Function (PACF) analysis. Stationarity of the time series was confirmed by the Augmented Dickey–Fuller (ADF) test at a 5% significance level.

To assess the stationarity of the time series for the period 2009–2023, the augmented Dickey–Fuller (ADF) test is applied. The coefficient of determination (R^2) serves as a measure of model quality, allowing us to estimate the proportion of variation in the dependent variable explained by the model. Presents the forecast accuracy metrics (RMSE, MAE, MAPE) for all the models constructed. Additionally, confidence intervals for the forecasts are calculated based on Student's t -distribution, which allows for a quantitative assessment of the degree of uncertainty in the forecast estimates.

All model estimates were computed using SPSS (Statistical Package for the Social Sciences), which was used for the ADF test, ACF/PACF analysis, model parameter estimation, and forecast accuracy evaluation.

The proposed methodological approach constitutes a comprehensive system of analytical tools that combines economic and mathematical modeling, scenario analysis of structural shifts in demand, systematization of industry data, and graphical interpretation of results.

3. Results and Discussion

3.1. Russia's Role in Global Demand for Palladium

Palladium (Pd) occurs naturally in extremely small quantities, which poses risks to the stability of its future supply [21]. Pd is one of the rarest elements in the Earth's crust, with an average abundance of approximately 0.015 ppm (15 parts per billion, ppb) [22]. The richest deposits are associated with igneous rocks found in countries such as Canada, Russia, South Africa, the United States, and Zimbabwe [23,24]. However, the role of pal-

ladium extraction varies by region. For example, in Canada and Russia, it is primarily extracted as a byproduct of copper-nickel ore processing, particularly in the Sudbury and Norilsk mining and metallurgical complexes [25,26]. In South Africa, by contrast, it is the primary mining target, especially within the Bushveld Complex, which includes such reefs as the Meren, UG2, and Platreef [27]. In Zimbabwe, mining takes place in sulfide deposits, while in the United States, the only significant source is the Stillwater complex, where palladium is also extracted as a byproduct. Environmental issues associated with palladium mining include negative impacts on local water resources, forced resettlement of populations, and a decline in biodiversity [28].

Table 1 presents the producers indicators of the palladium market.

Table 1. Key producers on the palladium market: primary mining production data for 2024 [28,29].

Company	Key Assets (Deposits)	Regional Share of Palladium Production, % (2024)	Palladium Production in 2024, in Thousands of Ounces	Share of Global Palladium Production, %	Company Characteristics
PJSC MMC Norilsk Nickel (Russia)	Norilsk-Talnakhsky District	28.6	2762 thousand ounces (86 tons)	40%	The undisputed global leader in palladium production (~40% of global output).
Anglo American Platinum (South Africa)	Mogalakwena, Amandelbult, Twickenham, Union, and others (Bushveld Complex)	6.6	1249 thousand ounces (40 tons)	18%	The world leader in platinum. Headquartered in Johannesburg.
Impala Platinum (South Africa)	Impala Rustenburg, Impala Bafokeng, Marula, Two Rivers, Zimplats	7.2	1158 thousand ounces (36 tons)	18%	A diversified portfolio. Owns mines in South Africa, Zimbabwe, and Canada. High proportion of platinum.
Sibanye-Stillwater (South Africa/United States)	South Africa: Kroondal, Marikana, Rustenburg. United States: Stillwater, East Boulder (Montana)	12 7	1216 thousand ounces (38 tonnes) South Africa: 775 thousand ounces (24 tonnes) The United States: 441 thousand ounces (14 tonnes)	13%	The only major producer of palladium in the United States.
Northam Platinum (South Africa)	Zondereinde, Booyssendal, Eland	3.6	375 thousand ounces (11 tons)	4%	Independent South African producer focused on the PGM markets.
Impala Canada (Canada)	Lac des Iles Mine (Ontario)	2.4	242 thousand ounces (7.5 tons)	3%	The only operating primary palladium mine in Canada. PGMs are also recovered as by-products in the Sudbury Basin by Vale and Glencore.

The data presented indicates that global palladium production is highly concentrated among a limited number of vertically integrated companies, with the market geographically divided primarily between Russia and South Africa. The undisputed leader of the industry is PJSC MMC Norilsk Nickel, which controls about 40% of global output and

accounts for more than a quarter of the total production volume of the five largest players. In absolute terms, considering that total global palladium mine production currently averages around 210 tonnes annually, Norilsk Nickel's 40% market share equates to an extraction volume of approximately 84 tonnes, or 84,000 kg, per year [29].

South African companies (Anglo American Platinum, Impala Platinum, Sibanye-Stillwater, and Northam Platinum) collectively account for approximately 36% of the global palladium supply. In absolute terms, this regional output equates to about 75 tonnes, or 75,000 kg, annually [29]. However, their operations are closely correlated with the platinum market, as palladium is often mined as a byproduct. A notable feature of the market structure is the unique position of Sibanye-Stillwater, which, thanks to its assets in Montana, remains the only major palladium producer in the United States, thereby diversifying the industry's regional dependence.

Figure 1 shows global production of platinum and palladium, in kilograms.

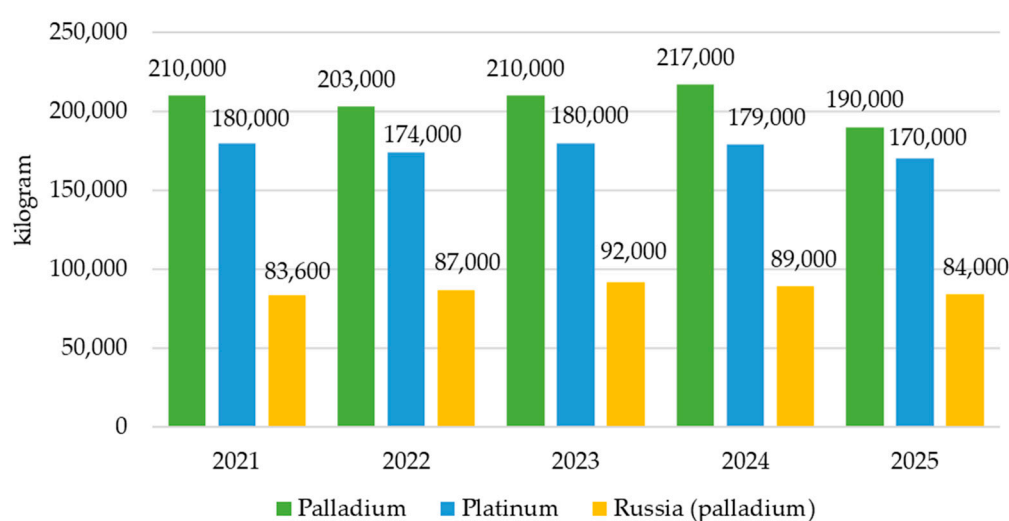


Figure 1. Global mine production of palladium and platinum in the period from 2021 to 2024, kg [29].

The observed decline in production volumes can be attributed to several interconnected factors. In South Africa, the world's dominant supplier of platinum-group metals, mining operations are confronted with depressed palladium prices, escalating costs associated with ultra-deep extraction, and chronic electricity shortages. In Russia, output has been constrained by deteriorating ore grades, reduced recovery rates, and geopolitical instability. Moreover, the automotive industry, which accounts for 80% of global palladium consumption, is experiencing a slowdown in vehicle manufacturing and an accelerating shift from palladium to platinum in catalytic converters, both of which have further suppressed demand and contributed to lower production levels across the sector.

The Russian palladium industry developed around large deposits of sulfide copper-nickel ores, primarily in the Norilsk industrial region and on the Kola Peninsula. A distinctive feature of production is that palladium is extracted primarily as a byproduct, which determines the cost structure and technological characteristics of production [30]. Russia and the Republic of South Africa account for about 80% of global palladium production, with Russia maintaining a leading position for many years. Russian legislation establishes the legal framework for regulating the precious metals industry, including palladium.

This metal plays a strategic role not only for the mining industry but also for the country's entire economy, serving as a major source of export revenue [31]. In the mid-2020s, the palladium market faced a fundamental challenge associated with the energy

transition, particularly the rapid electrification of transportation. Electric vehicles completely eliminate the use of palladium, as they do not require catalytic converters, and, consequently, the growth of their market share directly leads to the displacement of the corresponding demand segment. At the same time, it is important to note that this process is accompanied by another significant development: the dynamic substitution between palladium and platinum in gasoline engines, which is driven by their relative prices. During 2021–2024, when palladium prices exceeded those of platinum, automakers increasingly substituted palladium with platinum. However, as of 2025, this trend is reversing as platinum prices have risen above palladium levels. Russia accounts 40–45% of global palladium production (Figure 2).

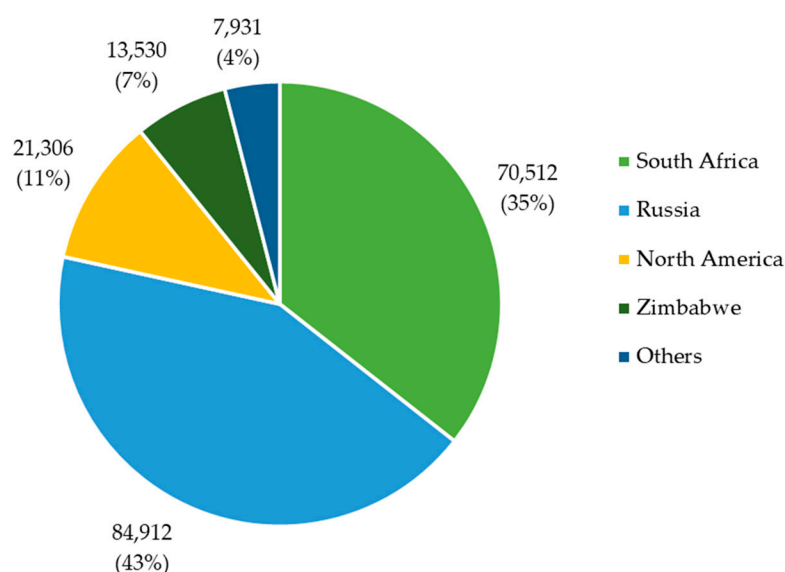


Figure 2. Palladium supply in 2025, in kilogram [32].

The key feature is that approximately 85 tons of palladium are produced annually in the Norilsk industrial region, where it is extracted as a byproduct of nickel and copper mining [33] (Figure 3).

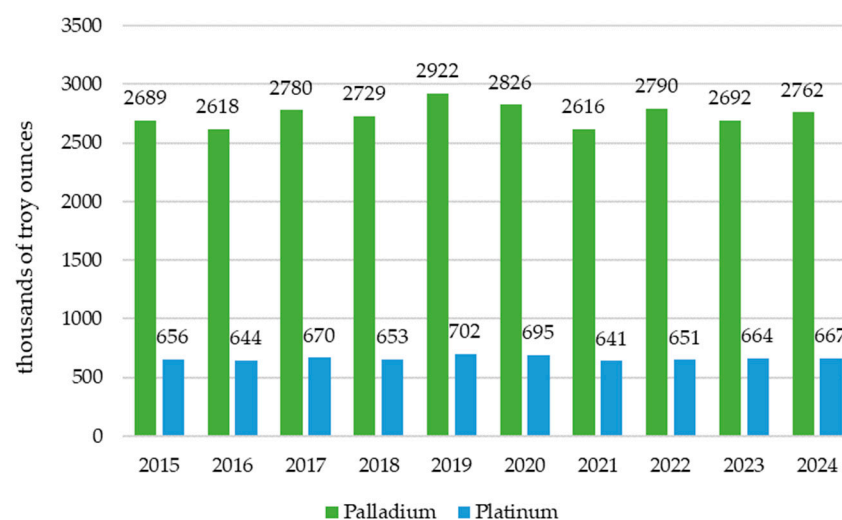


Figure 3. Nornickel's refined production of palladium and platinum from own mined feedstock, in thousands of troy ounces [33].

In 2025, Russia accounts for the largest share of palladium supply (43%), as it is a key player in the global market for this metal. South Africa ranks second with a 36% share, also exerting a significant influence on global supplies. North America accounts for 11% of supply, while Zimbabwe's contribution is 7%. Other countries account for a relatively small share (4%) [33]. The palladium market is characterized by a high concentration of production in a few countries, primarily Russia and South Africa.

Between 2015 and 2024, palladium production volumes in Russia remain significantly higher than those of platinum and, overall, show relative stability with minor fluctuations. Palladium production peaks in 2019, followed by a slight decline, particularly noticeable in 2021, though volumes partially recover in subsequent years. Platinum production is also characterized by stability, fluctuating within a narrower range, with a peak in 2019 and a moderate decline in 2021 [33].

In Russia, palladium is found predominantly in the sulfide copper-nickel ores of the Norilsk region and the Kola Peninsula [34,35]. According to the World Platinum Investment Council (WPIC), Russia will produce approximately 84.1 metric tons of the metal in 2026, and this volume will remain stable through 2030 [36]. By comparison, its main competitor, South Africa, will reduce production to 73.3 metric tons in 2026 [36]. Trade unions play a significant role in South Africa, and strikes in the mining sector occur fairly regularly, posing risks to the stability of platinum metal supplies. For example, in January 2014, a prolonged strike lasting about five months led to the loss of over 1 million ounces of production and caused a decline in global platinum production of approximately 40% (the economic losses to the industry were estimated at approximately \$2 billion) [37]. This incident revealed a number of systemic problems in the industry, including low wages, poor working conditions, and high rates of workplace injuries and fatalities.

The bulk of production is provided by PJSC MMC Norilsk Nickel, for which palladium is a byproduct of copper-nickel ore processing. The continued tight market conditions are exacerbated by a steady decline in production outside Russia. In the United States, Canada, South Africa, and Zimbabwe, palladium production is stagnating as existing deposits are depleted. The situation is exacerbated by the fact that not a single major new asset has come online in these countries over the past decade. Power outages at mining operations are adding further pressure. By the end of 2025, the financial reports of leading international companies in the sector (Sibanye-Stillwater and Impala Platinum) are expected to reflect a further decline in production volumes.

Russia is actively working to develop its own price indices and trading instruments that are independent of Western ones. Starting 23 March 2026, the Moscow Exchange will begin calculating palladium fixings (PLDFIXME) based on exchange trading in rubles. Palladium trading has commenced on the Moscow Exchange, providing investors with new opportunities to diversify their portfolios and gain direct access to the platinum group metals market. These instruments allow for a rapid response to market changes and the ability to capitalize on the potential for price growth in platinum and palladium. In addition, to attract a wide range of investors and increase liquidity, trading in cash-settled mini-futures on palladium (code PLDM) was launched on the derivatives market on 10 March 2026; these contracts are 10 times cheaper than standard contracts. The contract is a cash-settled palladium futures with a lot of 0.1 troy ounce (2 pennyweights), quoted in USD per troy ounce [38].

An important area of development for the Russian palladium market is the optimization of logistics and supply chains (Table 2). The reorientation of export flows toward new markets is one of the key effects of import substitution, driven by changes in the external economic environment. Russia is actively redirecting palladium supplies from traditional Western markets to Asian countries, particularly China, India, and Japan. This restructuring will reduce dependence on intermediaries, increase the added value of

products, improve inventory management, and lower transportation and financial risks. In addition, efficient logistics contribute to more stable palladium supplies amid fluctuations in global demand and prices.

Table 2. Exports of Russian palladium in unwrought or powder form (HS code 71102100) by destination country in 2024 [39,40].

Application Area	Transaction Amount: \$1000	Share of Russian Exports, %	Quantity, kg	Explanation
United States	877.76	27.3	27.599	The main buyer of Russian palladium
China	625.67	16.6	16.852	A large market, especially for industrial use
European Union	393.49	11.5	11.695	Primarily for the jewelry and automotive industries
Hong Kong, China	390.46	12.3	12.459	Transit market, resale to China and other countries
Japan	380.11	11.9	12.095	Used in electronics and catalytic converters
Armenia	252.93	8.49	8.573	A small regional market
Italy	201.89	6.3	6.416	The jewelry industry and technology
Germany	179	5.23	5.280	Industrial applications and automobile manufacturing
Switzerland	199	0.01	6	For processing and resale, financial and investment market
Mean (average)	388.92	11.07	11.89	-
Standard deviation	231.50	7.76	6.99	-

Russian palladium exports are heavily concentrated in a few key markets, with the United States leading the way, accounting for the largest share of shipments in terms of both value and volume. China and the United States import more than 50% of platinum, palladium, and rhodium, so competition for these minerals may intensify if processing technologies do not advance [41].

Disruptions to traditional trade routes, particularly after 2022, forced Russia to redirect its palladium exports to countries that had not joined the sanctions, primarily to China. The creation of these new logistics chains is associated with increased costs, risks, and time expenditures [42]. Moreover, this has led to the formation of two parallel markets: a legal, restricted market, and a shadow or gray market characterized by high costs and risks. The lack of access to legitimate supply channels to global markets makes the physical delivery of Russian palladium virtually impossible.

Despite sanctions pressure and external restrictions, PJSC MMC Norilsk Nickel and other Russian companies continue to maintain high levels of palladium production and shipments. By the end of 2024, palladium exports from Russia had increased by approximately 1.8% to 2.75 million ounces (about 85.5 tons), demonstrating the industry's resili-

ence to external shocks. Under these circumstances, the flexibility of export policy and companies' ability to adapt quickly to the changing structure of the global precious metals market take on particular importance [43].

Between 2020 and 2024, domestic palladium consumption in Russia remained relatively stable, fluctuating between 5.8 and 6.3 tons per year (Figure 4). The pessimistic scenario assumes a gradual decline in domestic consumption from 6.2 tons in 2025 to 3.5 tons by 2030, which may be attributed to reduced demand from traditional consumer sectors (automotive, dentistry), an increased export focus among producers, or the substitution of palladium with other materials in industrial processes.

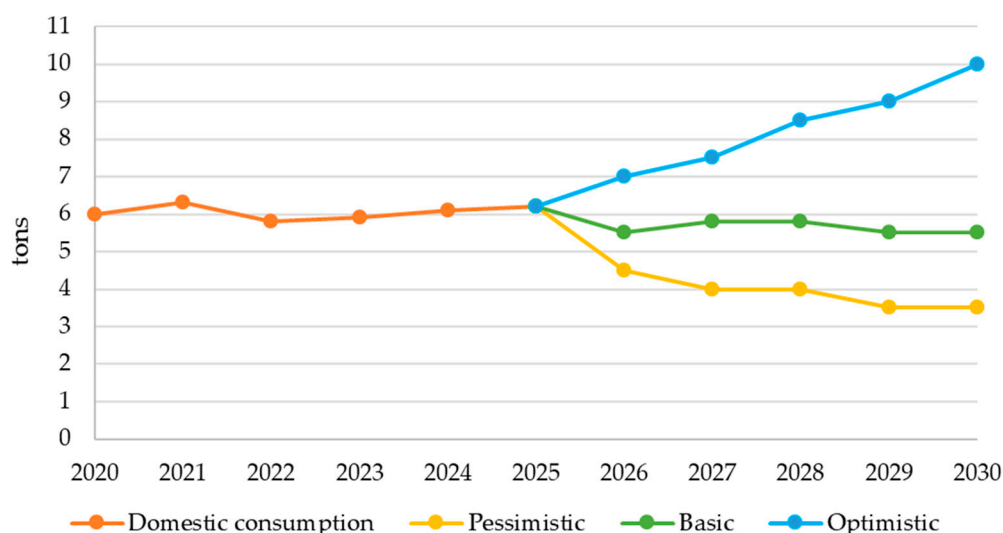


Figure 4. Forecast for domestic palladium consumption in Russia, tons [33,44,45].

The baseline scenario demonstrates a high degree of stability: consumption fluctuates within a narrow range of 5.5–5.8 tons throughout the entire forecast period. This scenario assumes that the current structure of domestic demand will remain unchanged without significant shocks or disruptive changes, which is consistent with the economy's inertial development.

The optimistic scenario shows the most dynamic growth: palladium consumption is projected to rise from 6.2 tons in 2025 to 10 tons by 2030, representing an increase of more than 60% over the five-year period. Such a trajectory is possible with the successful implementation of import substitution programs and the expansion of domestic palladium processing instead of exporting raw materials.

The domestic Russian palladium market remains relatively underdeveloped and does not have a significant impact on the industry's overall dynamics. Domestic consumption accounts for less than 5% of total production, which in absolute terms corresponds to approximately 100,00–120,000 ounces per year. Even with the active development of the chemical industry and import substitution programs, this figure is unlikely to exceed 200,000–250,000 ounces (6.2–7.8 tons per year) by 2030.

3.2. New Promising Applications for Palladium in High-Tech Industries

Energy transition is accompanied by a significant increase in demand for raw materials, including critical materials necessary for the production and operation of energy technologies such as energy storage systems, hydrogen fuel cells, and renewable energy sources, which heightens dependence on the resilience of their supply chains [46,47]. Russia is one of the largest producers of critical minerals, accounting for approximately 13% of global nickel production, 7% of copper, 5% of zinc, and over 40% of palladium [48].

Control over its supply is a matter not only of economic benefit but also of technological independence, especially in the context of global decarbonization and the struggle for access to resources for high-tech industries (defense, electronics) [49,50]. The palladium shortage is largely due to its geographical concentration in South Africa and Russia, and the high energy intensity of its production has led to palladium being recognized as a strategically important raw material on a global scale [51].

The growth in demand for palladium is driven by its widespread use across various industrial sectors. From a demand perspective, palladium is traditionally used in the automotive industry, where it is a component of catalytic converters [52]. Tighter environmental standards in various countries are driving an increase in the palladium content of such devices, which supports demand for the metal in the long term [53]. However, the structure of palladium demand is gradually transforming. About 80% of global demand for palladium comes from the automotive industry, primarily for use in internal combustion engines, but the development of electric vehicles is gradually leading to a decline in this share [54]. In addition, palladium is used in electronics for the production of microchips, capacitors, and contacts, as well as in the chemical industry as a catalyst for various reactions. These factors contribute to maintaining a high level of demand for this metal on the global market.

Table 3 presents the main applications of palladium and the possibility of replacing it with other metals.

Table 3. Main applications of palladium [32,55,56].

Direction	Applications	Substitutability
Automotive catalytic converters	Three-way catalytic converters (TWC) for gasoline and diesel engines	Partial replacement with platinum or rhodium, but limited by effectiveness and cost. Replacement in diesel engines is technically challenging
Chemical industry	Production of fine and basic chemicals (hydrogenation and dehydrogenation catalysts).	Partial with base metals (Ni, Cu)
Pharmaceuticals	Synthesis of pharmaceutical compounds	Cu/Ni catalysts possible
Jewelry industry	Platinum alloys (white gold, jewelry), palladium inlays	Substitution with other metals (nickel, silver) is possible
Dentistry	Dental alloys (for crowns and bridges)	Partially replaceable (beryllium, chromium-cobalt alloys)
Petrochemicals	Catalysts for reforming, hydrogenation, and cracking	Partial replacement with platinum or nickel
The Glass Industry	Glass fiber production. Crucibles and nozzles for drawing glass fiber	Partial replacement with platinum, but at a higher cost
Electronics	MLCCs, Pd-Ag pastes, hard drives, mobile devices	Partial with Ni or Ag (reduces quality/solderability)
Energy	Catalysts for hydrogen (PEMFC) and alcohol (DAFC) fuel cells, membranes for hydrogen purification	Partial substitution is possible (platinum alloys, low content)
Defense and Aerospace Industry	Catalysts for specialized equipment, life support systems, aerospace and shipbuilding, rocket engines	Replacement options are extremely limited. Potential substitutes include platinum, rhodium, iridium, and selected nickel-based superalloys
Water Treatment	Catalysts for the treatment of exhaust gases and industrial effluents	Partial substitution with other platinum group metals is possible
Hydrogen Energy	Catalysts on the anode/cathode, palladium membranes for hydrogen purification	Partial replacement with non-platinum catalysts

Scientific research	Electrochemistry, laboratory equipment, precision alloys	Limited (palladium can be replaced by platinum, gold, titanium, graphite, or nickel-based materials depending on the application)
Additive technologies	3D printing, powders for printing high-load components in the aerospace and medical industries	It depends on alternative alloys; palladium's unique properties are critical
Medicine	Instruments, implants, markers (palladium alloys)	Partially replaceable (tantalum, gold)

Scientific research points to the emergence of new applications for palladium. In addition to the automotive sector, palladium is widely used as an industrial catalyst in various chemical processes, including nitric acid production, as well as in oil refining, petrochemicals, and pharmaceuticals. Its demand is driven by unique physicochemical properties, such as high thermal and corrosion resistance [57].

Hydrogen energy, fuel cells, and water purification technologies are of particular importance. Membranes based on palladium alloys provide high permeability and selectivity due to the catalytic properties of palladium [58].

Palladium demonstrates high efficiency in catalytic processes and can be used in the oxidation, hydrogenation, and decomposition of complex compounds. Experimental developments, including the creation of new palladium-based composite materials, confirm its potential in the energy sector of the future. A decline in demand from traditional industries may be partially offset by growth in new segments.

As part of the implementation of the new national project «Bioeconomy», additional opportunities are opening up for the development of Russian enterprises engaged in the extraction, processing, and application of palladium and other metals [59]. The effective utilization of scientific developments by domestic research teams will enable the introduction of modern production technologies and the enhancement of product value added. At the same time, it is necessary to intensify cooperation with universities and specialized educational institutions, and to create specialized training programs and classes, which will ensure the training of qualified personnel to support the industry's sustainable development and enhance its competitiveness in the international market.

PJSC MMC Norilsk Nickel, the world's largest supplier of palladium, and Krastsvetmet, one of the world's largest producers of precious metals and products made from them, presented a new technology for palladium alloy spinnerets in Shanghai, which will help glass fiber manufacturers significantly reduce equipment ownership and maintenance costs. Company actively drives demand for palladium by combining production and operational efficiency improvements with market expansion through new technologies and materials [60]. A prime example of this strategy is the Palladium Technology Center, which develops, tests, and brings innovative palladium-based materials to market. The company plans to introduce 100 new palladium-based materials by 2030, including advanced alloys for glass fiber production, catalytic materials for chemical synthesis, and innovative solutions for hydrogen energy, water treatment, and electronics applications, of which 25 have already been created. Product development is conducted in collaboration with leading Russian scientific organizations, and support from the Moscow Innovation Cluster helps accelerate project implementation. Plans are underway to open a state-of-the-art laboratory within the cluster, where specialists will study the properties and synthesis of materials based on platinum group metals.

The Palladium Technology Center has successfully conducted industrial trials of palladium current leads for glass fiber production in China and is now moving to scale up the solution across the entire industry. At the same time, the center is launching industrial trials of a base palladium alloy for bushings in China. Chinese companies have already

purchased 20,000 ounces of palladium in 2025 for glass fiber projects. In addition, the center is developing initiatives in related segments of the glass industry, including the production of optical, display, and technical glass. Given the need to expand most applications of platinum group metals to address modern environmental and technological challenges, demand for them will grow steadily in the long term [61].

3.3. Opportunities in the Russian Palladium Market

The outlook for the Russian palladium market remains generally moderately positive. Domestic demand is expected to show steady growth through 2030, with an average annual growth rate (CAGR) of approximately 7–8% [62].

At the same time, the greatest growth potential lies in the chemical industry, while the automotive sector is gradually losing its dominant position, indicating a structural transformation of palladium demand. In the long term, sustainable development is possible provided that the applications of palladium are diversified and domestic processing is deepened, which will increase economic efficiency and reduce dependence on external factors.

There is growing interest in recovering palladium from secondary sources, such as spent catalysts, used equipment, electronic waste, and membrane-electrode assemblies, since the platinum group metal content in such materials is often higher than in natural ores [63]. Palladium recycling is of great importance from both an economic and an environmental standpoint [64,65]. According to the European Commission's study on critical raw materials, the global EOL-RIR for palladium is approximately 14% [66]. This indicator measures the contribution of recycled palladium from end-of-life products to the total material demand. However, it is important to note that the actual share of secondary palladium in global supply is significantly higher, approximately 30–34%. In 2024, global palladium demand was approximately 290 tons, with mining production accounting for about 190 tons and secondary recovery from recycling providing approximately 90–100 tons.

It reduces dependence on ore mining, which is complex and costly, and also reduces the amount of industrial waste [67,68]. The platinum group metal content in spent automotive catalysts reaches 1000–3000 g/t, which is thousands of times higher than the average platinum group metal content in ores (0.796 g/t) [69]. Palladium is almost entirely recyclable: depending on the type of product, 95 to 98% of the contained metal can be recovered and reused after the end of its service life [70].

However, while recycling plays a crucial role in reducing primary mining pressure and industrial waste, it cannot fully meet the growing global demand for palladium, particularly as new applications in hydrogen energy, electronics, and chemical catalysis expand. Therefore, a balanced approach—combining primary mining, investment in recycling capacity, and development of circular economy models—is essential for long-term supply security.

The primary source of palladium for recycling is spent automotive catalysts, as they contain significant amounts of this metal, which is used to neutralize harmful emissions [71,72]. It is estimated that recycling 2 Mg (megagrams, equivalent to 2 metric tons) of spent automotive catalysts can prevent the extraction of 150 kg of ore containing platinum group metals [73,74]. Palladium is also recovered from electronic components, old jewelry, and industrial waste. In recent years, numerous methods for recycling platinum-containing end-of-life products have been actively developed, driven by the desire to create a more environmentally sustainable circular economy [75]. Such approaches aim to reduce energy consumption and minimize the generation of hazardous liquid and gaseous waste. Due to the much higher concentration compared to mined ores, recycling also helps significantly reduce the environmental impact of metal supply chains, particularly regarding

climate impact [76]. In addition to its environmental value, the high cost of platinum group metals makes their recycling economically attractive [77].

The launch of the Chernogorsk Mining and Processing Plant in the Krasnoyarsk region is scheduled for the second half of 2026. This project will be pivotal for palladium and platinum production in Russia, establishing the country's second major metal production hub. The first phase of the facility is designed to process 7–9 million tons of copper-nickel ore per year, which will strengthen Russia's position in the global market [78]. The project's implementation is of strategic importance to the industry: it will create new jobs, attract investment to the region, reduce dependence on imported equipment, and ensure a stable supply of critical metals.

The Chernogorsk Mining and Processing Plant (Krasnoyarsk region) is the most significant new project in the industry. The launch of the plant's first phase is scheduled for the second half of 2026. The design capacity of the first phase is 7 million tons of ore per year. This will create Russia's second-largest center for palladium and platinum production. Total investment in the project (since 2020) will reach 215.3 billion rubles, and 1600 new jobs will be created [79]. The project is included in the regional metallurgy development program and benefits from government support in the form of stable tax conditions. The launch of the Chernogorsk deposit will ensure moderate production growth in Russia in 2026.

On the supply side, key efforts are focused on maintaining stable metal output, reducing operational risks, and improving the environmental sustainability of production. The management of mining companies has announced investment programs aimed at modernizing metallurgical facilities and optimizing production processes, which is crucial given the potential for logistical disruptions and shifts in demand transformation.

At the same time, there is a growing focus on recycling secondary raw materials and recovering palladium from spent catalytic converters. While recycling volumes have increased in recent years, secondary supply alone has been insufficient to meet the rapidly growing global demand. According to Johnson Matthey and World Platinum Investment Council data, the global palladium market experienced a structural deficit from 2019 to 2022, with demand consistently exceeding supply. Secondary recycling, which accounts for approximately 30% of total supply, has helped mitigate this deficit and stabilize prices.

For the Russian industry, the development of domestic infrastructure for the processing and production of semi-finished products and high-value-added goods will be critical for enhancing stability and profitability amid fluctuations in global prices.

The most promising sector for palladium is hydrogen energy. The metal's unique property is its ability to absorb hydrogen in a volume 900 times greater than its own [80]. This makes it indispensable for the development of fuel cells, hydrogen storage systems, and hydrogen purification systems. China has already launched its first high-power hydrogen turbine, and Middle Eastern countries (Saudi Arabia, Oman, Qatar) have far-reaching plans to develop this industry. Vladimir Potanin, President of PJSC MMC Norilsk Nickel, has proposed establishing a new exchange in the Middle East for trading platinum group metals, which could combine Russia's resources with the region's ambitions in the hydrogen sector.

Table 4 lists key projects currently underway in the Russian palladium market.

Table 4. Initiatives in the palladium market [81–83].

Project Title	Initiator/Company	the Essence of the Project	Key Parameters and Values	Status and Timelines
Chernogorsk Mining and Processing Plant (Phase 1)	«Russian Platinum»	The establishment of a second palladium and platinum production center in Russia	Capacity: 7 million tons of ore per year. Investment: 215.3 billion rubles. Jobs: 1600. Ore reserves: 131 million tons con-	Launch: second half of 2026. Final preparations are underway.

		based on the Chernogorsk deposit.	taining palladium, platinum, rhodium, and gold.	
Chernogorsk Mining and Processing Plant (Phase II)	«Russian Platinum»	Development of the Norilsk-1 field to expand capacity following the launch of the first phase.	Increase the complex's total capacity to 14 million tons of ore per year. The project is scheduled to run through 2077.	To be determined once the first phase is fully operational.
Palladium Technology Center (Project «Palladium»)	PJSC MMC Norilsk Nickel	A research and development center dedicated to the development and implementation of new palladium-based materials.	Goal: to develop 100 new materials by 2030. The portfolio already includes 25 products	Effective as of 2025. Expansion is planned.
Development of new catalysts for polymers	Institute of Petrochemical Synthesis; Institute of Organoelement Compounds	Development of fundamentally new types of palladium catalysts for high-tech industries.	Eleven new catalysts have been developed.	Completed R&D (research and development) phase. Potential for industrial application.
Launch of palladium mini-futures trading	Moscow Exchange	Creating an accessible financial instrument for retail investors and hedgers.	Contract code: PLDM. Lot size: 0.1 troy ounce. This has attracted a wide range of retail investors to the palladium market	Launch: March 10, 2026
Initiative to establish a platinum group metals exchange in the Middle East	PJSC MMC Norilsk Nickel	Establishment of an international commodities exchange for trading palladium, platinum, and other metals.	Specific parameters not yet disclosed (project at conceptual stage). Partner regions under consideration: Saudi Arabia, Oman, and Qatar.	It is currently in the discussion and conceptualization phase.

The Russian palladium market could follow several possible scenarios. In the conservative scenario, continued strong export orientation and moderate demand for catalysts will sustain current production and export volumes. In the technological scenario, the active adoption of palladium in hydrogen projects, electronics, and new catalysts will offset the decline in automotive demand and increase value added through domestic processing. Practical steps that could expand the sector's potential include developing local value-added processing chains, investing in research and development (R&D) on new palladium alloys and membranes, stimulating secondary raw material markets, and implementing targeted public-private programs for the commercialization of palladium-based technologies [84,85]. Supporting exports of new high-tech products and diversifying sales geographies (especially into Asian markets) are critically important [86].

The Russian palladium market will develop through 2030 amid a complex set of factors, dominated by stable supply and a structural decline in traditional demand. Low production costs ensure stable output and maintain Russia's share of the global market, while the transformation of the automotive industry driven by the energy transition, including transport electrification, reduced metal intensity, and substitution with platinum is leading to a surplus and downward pressure on prices. New applications for palladium, primarily in hydrogen energy, have growth potential; however, their contribution in the coming years remains limited and is unable to fully offset the decline in demand from the automotive industry.

As a result, the market is entering a phase of structural transformation, in which the key factor for sustainability is the ability of producers to adapt to changing conditions and diversify the applications of the metal. By coordinating the interests of the state, research centers, and business, Russia can maintain its leading role in the global palladium market

and mitigate the potential negative effects of the energy transition, particularly the electrification of the transportation sector.

3.4. Developing Predictive Models for Palladium Production in Russia

Figure 5 presents the time series of Russian palladium production from 2009 to 2024.

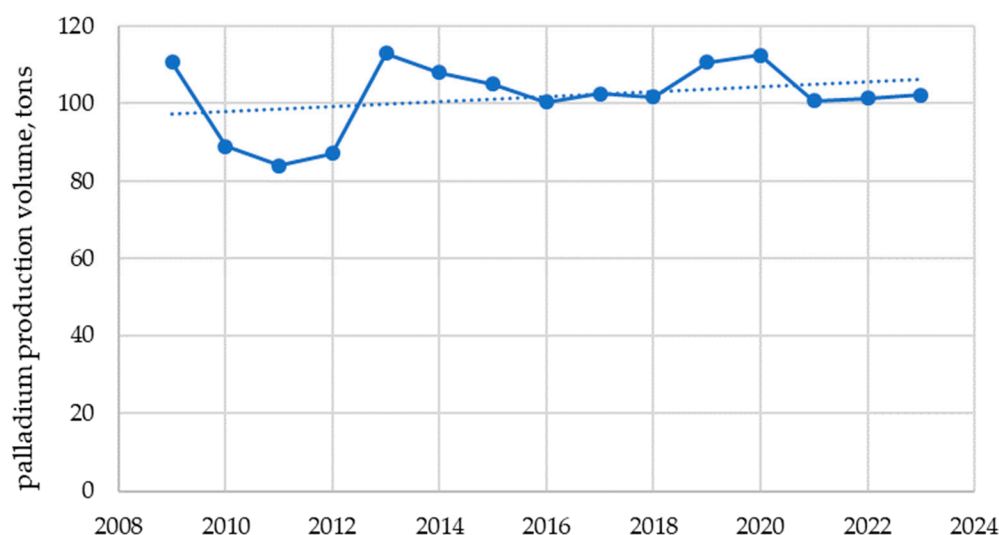


Figure 5. Trends in palladium production volumes in Russia from 2009 to 2024, in tons (solid line: actual data; dashed line: linear regression trend) [87].

Using SPSS (Statistical Package for the Social Sciences), an Augmented Dickey–Fuller (ADF) test was conducted on annual palladium production data for Russia covering the period 2009–2024. The results, presented in Table 5, indicate that the null hypothesis of a unit root can be rejected ($p < 0.001$), confirming the stationarity of the time series. The ADF statistic was compared with the critical values at the 1%, 5%, and 10% significance levels, further supporting this conclusion. Based on the Akaike Information Criterion (AIC), the first-order differencing model exhibited the lowest value and was therefore selected as the optimal specification for subsequent ARIMA modeling.

Table 5. ADF tests on data regarding palladium production capacity from 2009 to 2023. Compiled by the authors.

Option	d	v	p-Value	AIC
Production capacity	0	−3.519	0.0075	111.58
	1	−3.992	0.0019	106.77
	2	−3.383	0.0016	106.57

When constructing an AR model, the difference order d should be set to 1; that is, an ARIMA ($p, 1, q$) model should be used for the analysis, where the specific orders p and q should be determined by combining this information with other data, such as the autocorrelation function (ACF) and partial autocorrelation function (PACF).

The order (p, q) is determined by the partial autocorrelation function (PACF) of the sample series and the autocorrelation function (ACF), and the results (Figures 6 and 7) were calculated based on the data presented above.

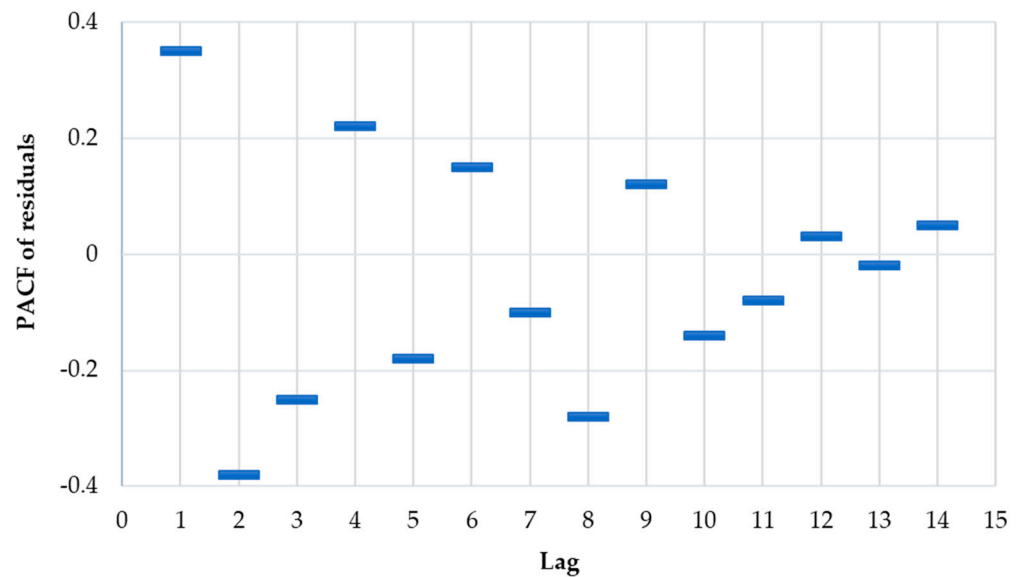


Figure 6. Partial autocorrelation function (PACF) for finite difference data. Compiled by the authors.

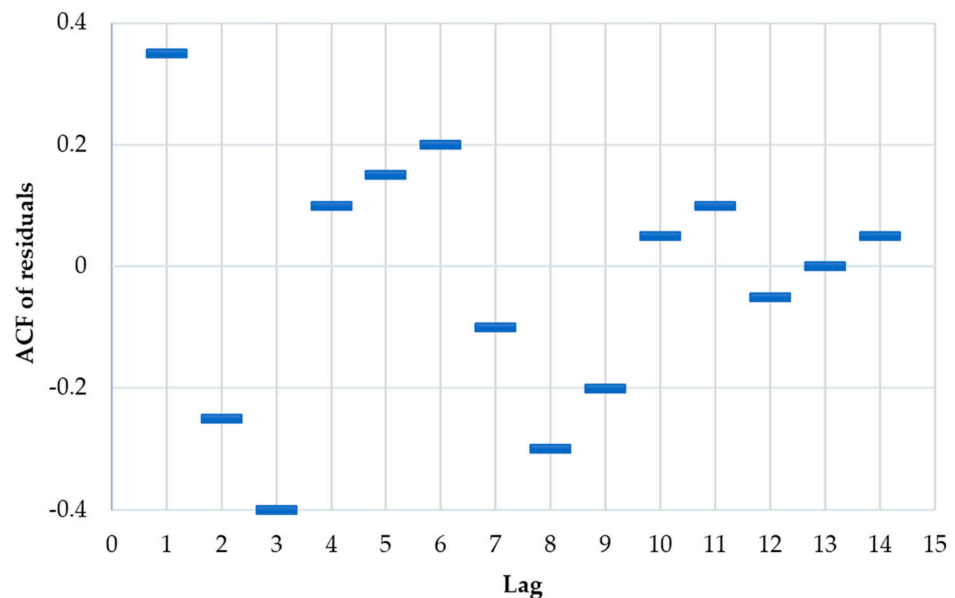


Figure 7. Autocorrelation function (ACF) plot of the model residuals. Compiled by the authors.

The ACF and PACF plots are analyzed for compliance with the decision rule given in Table 6: if the ACF or PACF plots are equal to 0 or close to 0 after the corresponding p- and q- orders, they are considered truncated; if they do not reach 0 after a certain step but decay exponentially or in the form of a sinusoidal wave, they are considered to have tails. The autoregression order is $q = 1$, and the moving average order is $q = 0$. The model parameters are defined as ARIMA (1,1,0).

Table 6. Evaluation rules for steps p and q. Compiled by the authors.

Modeling	ACF	PACF
AR (p)	Fade to 0 (geometric or oscillating)	p-truncation after the exponent
MA (q)	Fade to 0 (geometric or oscillating)	Fade to 0 (geometric or oscillating)

ARMA (p, q)	Decay to 0 after approximately q (geometric or oscillatory)	Decay to 0 after the pth order (geometric or oscillatory)
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In conjunction with the AIC information criterion, we use SPSS to automatically generate and compare several alternative models, which allows us to select the optimal model based on the results obtained.

Table 7 presents the parameters of the ARIMA (1,1,0) model

Table 7. Parameters of the ARIMA (1,1,0) model. Compiled by the authors.

Parameter	Designation	Coefficients	Standard Error	t-Statistic	p-Value
Constanta	106.4732942	8.810866122	12.08431643	1.92134E-08	106.4732942
AR parameter	0.047511852	0.089125787	−0.5330876	0.602967517	0.047511852

The specific form of the ARIMA model is expressed as the following formulas:

$$x_t = 106.473 - 0.0475x_{t-1} \quad (1)$$

Table 8 presents Russia's annual palladium production from mineral deposits for the period 2009–2023.

Table 8. Russia's annual palladium production from mineral deposits, 2009–2023, in tons [87].

Years	Palladium Production from Mineral Deposits, Tons	Growth Rate, %
2009	110.7	-
2010	89.0	−19.60
2011	84.1	−5.51
2012	87.1	3.57
2013	113.0	29.74
2014	108.0	−4.42
2015	105.0	−2.78
2016	100.4	−4.38
2017	102.6	2.19
2018	101.7	−0.88
2019	110.7	8.85
2020	112.5	1.63
2021	100.8	−10.40
2022	101.4	0.60
2023	102.3	0.89

In this study, four predictive models were used to analyze palladium production over a specific period and forecast future trends. Table 9 and Figure 8 present the results of palladium production forecasts based on these models and compare the error values. The table presents the forecast values, actual palladium data, and corresponding errors. By comparing the data, one can assess the accuracy and applicability of the various models, which will enable more informed decision-making in the future.

Table 9. Comparison of the results of the predictive model. Compiled by the authors.

Years	Actual Figure, in Tons	Linear Model, Tons	Error Message	Grey's Forecasting Model, Tons	Error Message	Exponential Smoothing, Tons	Error Message	ARIMA, Tons	Error Message
2009	110.70	97.55	13.15	110.70	0.00	110.70	0.00	110.70	0.00
2010	89.00	98.19	−9.19	94.76	−5.76	91.17	−2.17	89.00	0.00

2011	84.10	98.82	-14.72	95.73	-11.63	84.81	-0.71	88.45	-4.35
2012	87.10	99.46	-12.36	96.71	-9.61	86.87	0.23	83.98	3.12
2013	113.00	100.10	12.90	97.70	15.30	110.39	2.61	87.18	25.82
2014	108.00	100.74	7.26	98.70	9.30	108.24	-0.24	113.66	-5.66
2015	105.00	101.38	3.62	99.71	5.29	105.32	-0.32	107.87	-2.87
2016	100.40	102.02	-1.62	100.74	-0.34	100.89	-0.49	104.92	-4.52
2017	102.60	102.66	0.06	101.77	0.83	102.43	0.17	102.8	2.32
2018	101.70	103.29	-1.59	102.81	-1.11	101.77	-0.07	102.66	-0.96
2019	110.70	103.93	6.77	103.86	6.84	109.81	0.89	101.68	9.02
2020	112.5	104.57	7.93	104.93	7.57	112.23	0.27	110.93	1.57
2021	100.80	105.21	-4.41	106.00	-5.20	101.94	-1.14	112.55	-11.75
2022	101.40	105.85	-4.45	107.09	-5.69	101.45	-0.05	105.0	0.90
2023	102.30	106.49	-4.19	108.18	-5.88	102.222	0.00	101.42	0.88

Figure 8 illustrates the process of building predictive models.

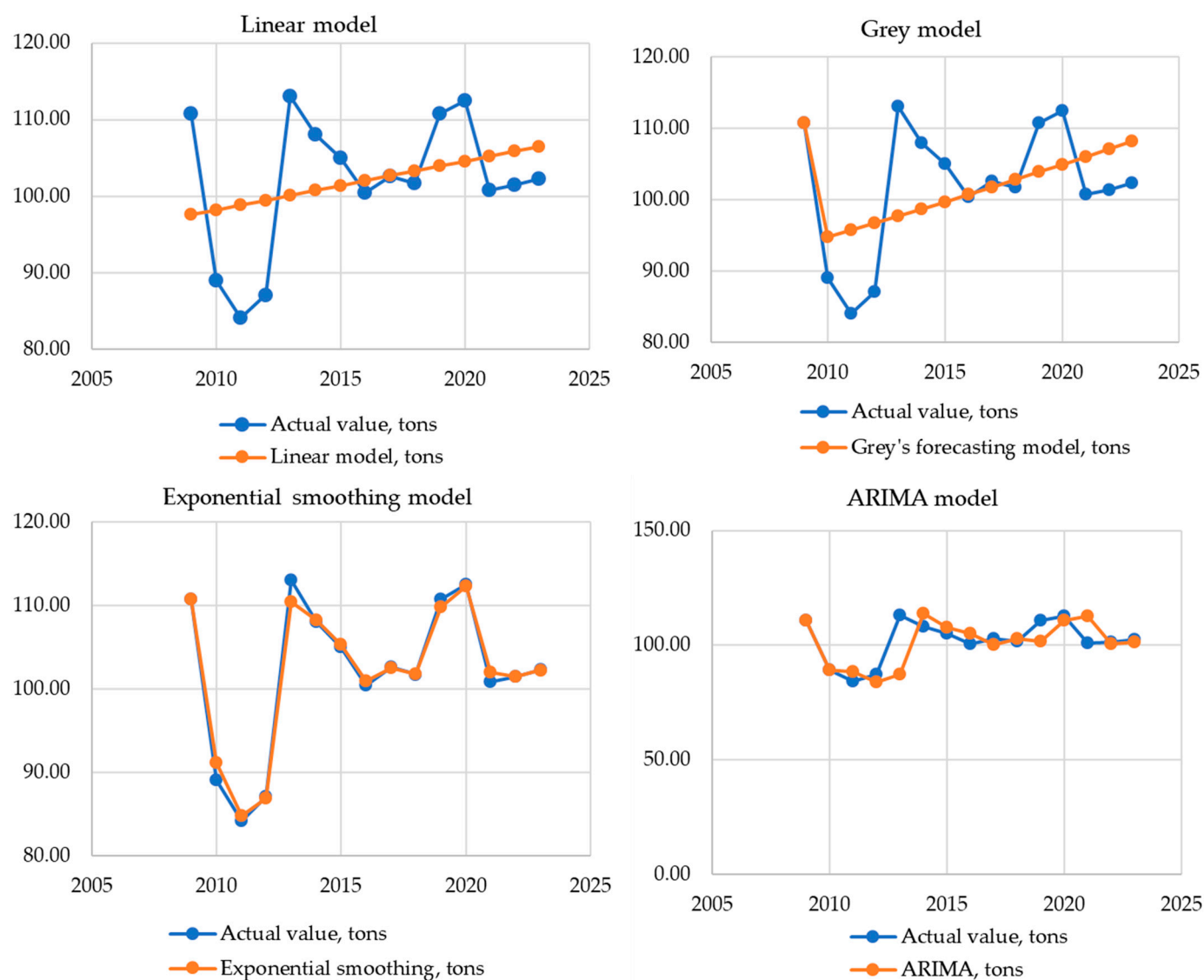


Figure 8. Construction of forecasting models: linear model; grey forecasting model; exponential smoothing model; ARIMA model. Compiled by the authors.

To evaluate the quality of the models, coefficients of determination were calculated and are presented in the form of formulas:

$$r^2 = 1 - \frac{s_y^2}{s_1^2} \quad (2)$$

The standard value is expressed as follows:

$$s_y^2 = \frac{\sum_{i=1}^n (y_i - y_t)^2}{(n - m)} \quad (3)$$

The total deviation is expressed as follows:

$$s_1^2 = \frac{\sum_{i=1}^n (y_i - y_t)^2}{(n - m)} \quad (4)$$

Table 10 presents the coefficients of determination for all the models constructed.

Table 10. Summary Table of the Coefficient of Determination. Compiled by the authors.

Forecasting Model	Coefficient of Determination
Linear regression model	0.0100
Grey forecasting model	0.0856
Exponential smoothing model	0.9812
ARIMA model	0.1376

The coefficient of determination takes values in the range $0 < R^2 < 1$ and characterizes the proportion of variation in the dependent variable explained by the selected model. The closer the value of the coefficient of determination is to one, the higher the quality of the approximation and the predictive power of the model. In applied economic research, it is generally accepted that an acceptable model should have a coefficient of determination of at least 0.5, while models with an R^2 value greater than 0.8 are considered to be of sufficiently high quality [88]. An R^2 value of 1 indicates the presence of a perfect functional relationship between the variables.

According to the results presented in the table, the linear regression model ($R^2 = 0.0100$), the gray forecasting model ($R^2 = 0.0856$), and the ARIMA model ($R^2 = 0.1376$) are characterized by extremely low values of the coefficient of determination, which indicates their low objective and predictive ability with respect to the considered time series of palladium production. These models do not reach the threshold value of $R^2 = 0.5$ and therefore cannot be considered acceptable for forecasting purposes.

At the same time, the exponential smoothing forecast model yields a coefficient of determination of $R^2 = 0.9812$, which significantly exceeds the threshold of 0.8 and indicates a high-quality approximation of the actual data. This leads to the conclusion that the exponential smoothing model is the most appropriate and robust for forecasting palladium production.

Therefore, in further calculations and when constructing forecasts for the 2024–2026 period in this study, it is advisable to use the exponential smoothing forecasting model.

Table 11 presents the forecast accuracy metrics for all the models constructed.

Table 11. Comparison of forecast accuracy metrics for palladium production models. Compiled by the authors.

Model	RMSE (Tons)	MAE (Tons)	MAPE (%)
Linear regression model	8.29	6.95	6.98
Grey forecasting model	7.35	6.02	6.01
Exponential smoothing model	0.99	0.63	0.63
ARIMA model	8.11	4.92	4.68

Exponential smoothing clearly outperforms the other models, with RMSE, MAE, and MAPE an order of magnitude smaller than those of the linear trend, Grey, or ARIMA models. The high smoothing parameter ($\alpha = 0.9$) allows the model to adapt very quickly to abrupt changes in the series (e.g., the peaks in 2013 and 2020, and the drop in 2022). As a result, the forecast errors are minimal (mostly within ± 2 tons) and the MAPE is only 0.63%, indicating almost perfect in-sample fit.

The result obtained using a forecasting model for palladium production is not a single, definitive value but carries a certain degree of uncertainty. Confidence intervals can quantify this uncertainty. Interval forecasting is a prediction of the future in which a specific interval (confidence interval) is indicated, that is, a range of values of the forecasted indicator. Below is the formula for calculating confidence intervals:

$$\Delta = \pm t_{\alpha} s_{\pi} \quad (5)$$

where s_{π} is the standard deviation of the forecast, calculated using the following equation:

$$s_{\pi} = s_y \sqrt{1 + \frac{1}{n} + \frac{(t_k - t^-)^2}{\sum (t_i - t^-)^2}} \quad (6)$$

where s_y is the mean squared error (MSE), which is calculated using the formula:

n —number of measurements;

m —the number of model parameters;

t_{α} —the significance level of Student's t -test (with a 5% significance level) is the most important factor.

The number of degrees of freedom is 13; according to Student's t -distribution table, $t_{\alpha} = 2.16$.

The projected range of palladium production from 2026 to 2028 was calculated as shown in Table 12.

Table 12. Palladium production forecast for the period from 2026 to 2028. Compiled by the authors.

Years	Forecast, Tons
2026	74.31–129.91
2027	62.61–141.23
2028	53.58–149.88

4. Discussion

Forecasting palladium demand under conditions of global energy transition is fraught with fundamental uncertainty. Two opposing perspectives have emerged in the academic literature regarding the future of the palladium market in the context of mass electric vehicle (EV) adoption.

Position 1: Structural decline in palladium demand (pessimistic scenario).

Hughes et al. [89] emphasize that electric vehicles require virtually no palladium, unlike internal combustion engine vehicles (ICEVs), where the loading reaches 5–10 g per catalytic converter. The authors predict that the long-term transition to electric mobility will fundamentally alter demand profiles, rendering current production volumes excessive. MacDonald et al. [90] complement this view with an analysis of supply chain resilience. They note that although hydrogen fuel cells may create new demand, they are predominantly oriented towards platinum and iridium, not palladium. The reduction in the ICEV fleet will generate a structural surplus of primary palladium, necessitating a radical

restructuring of the mining sector and making the development of new high-cost deposits economically unviable. According to Johnson Matthey, lower production of gasoline vehicles is predicted to cut automotive palladium demand by 5% in 2025, and the palladium market is expected to move into balance after 13 years of structural deficit [32].

Position 2: Demand preservation and adaptation (optimistic/inertial scenario).

Proponents of the alternative view point out that the complete phase-out of ICEVs will take decades, while tightening environmental regulations will continue to support palladium demand. Kim [91], in a study of palladium material flows, demonstrates that demand is rigidly determined by emission standards. Even with stagnant total vehicle sales, stricter limits on harmful emissions (CO, NO_x, hydrocarbons) require higher catalytic converter loadings. Moreover, palladium actively substitutes for more expensive platinum in gasoline catalysts, sustaining its industrial relevance. Omrani et al. [92] empirically confirm the trend of platinum-to-palladium substitution in modern catalysts. Their analysis shows that palladium content in new vehicle models is not decreasing but rather being redistributed. The authors also note that the long vehicle lifespan (15–20 years) means the existing ICEV fleet will require maintenance and catalyst replacement, providing stable baseline demand.

Our position. In this study, we support the second (inertial) scenario as the most relevant for the medium-term forecasting horizon (up to 2030), but with an important caveat regarding long-term risks. In our view, even under the most aggressive EV adoption scenarios, the share of electric vehicles in the global fleet will not exceed 20–30% by 2030, and the full replacement of the vehicle fleet will take 15–20 years (the average vehicle lifespan). During this period, ICEVs and hybrids will continue to require palladium-based catalysts.

Tightening environmental regulations force automakers to increase the palladium content in catalytic converters to reduce emissions of nitrogen oxides and hydrocarbons. This factor partially compensates for the reduction in the number of new internal combustion engine vehicles. There is also a trend towards substituting more expensive platinum with palladium in gasoline catalysts, which further supports demand for palladium. The decline in demand from the automotive sector can be partially offset by the growth of new high-tech applications of palladium, such as membranes for hydrogen energy, catalysts for fuel cells, glass fibre production, and multilayer ceramic capacitors in electronics.

Empirical justification for our choice comes from comparative modelling of the Russian palladium production time series (2009–2023). Among the four models considered (linear trend, Grey model, exponential smoothing, and ARIMA), exponential smoothing with parameter $\alpha = 0.9$ demonstrated the highest accuracy: RMSE = 0.99 tonnes, MAE = 0.63 tonnes, MAPE = 0.63%. Such high adaptability to recent changes indicates that the short- and medium-term dynamics of palladium are largely driven by inertial factors—established production capacities, long-term contracts, and current environmental regulations, which have not yet shown a sharp break.

Nevertheless, we acknowledge that after 2030–2035, as the EV market saturates and new generations of palladium-free catalysts potentially emerge, primary palladium demand may enter a phase of structural decline. Our conclusion regarding the inertial scenario is limited to the horizon up to 2030 and does not account for hypothetical technological breakthroughs.

4.1. Justification of Model Selection

Linear regression serves as a baseline method for identifying long-term linear trends. Its inclusion allows us to assess the degree of linearity in the dynamics of the series and to evaluate how much more complex models outperform this simplest approach. An em-

pirical justification for using linear regression to forecast palladium prices is presented in [93], where the author conducts a regression analysis of palladium price forecasting.

The Grey model is chosen for working with time series under conditions of high uncertainty and limited data, which is typical for many economic indicators. It was specifically developed for modelling systems with partially known information and has already demonstrated its effectiveness for forecasting palladium prices. The suitability of applying this model for palladium price prediction is substantiated in [94].

Exponential smoothing belongs to the class of adaptive models that assign greater weight to more recent observations. This makes it indispensable for time series subject to abrupt changes (e.g., the production decline in 2020 and 2022). The selected high smoothing parameter ($\alpha = 0.9$) ensures maximum sensitivity of the model to the latest market fluctuations. The rationale for applying exponential smoothing methods to metal price forecasting is provided in [95].

The ARIMA model is a classical econometric approach that requires the series to be rendered stationary. Its inclusion enables a comparison between simple adaptive methods (such as exponential smoothing) and a more complex parametric model that captures regression dependencies in the data [96].

The practical implications include providing mining companies, investors, and policymakers with a validated, tool for medium-term planning. Future research should focus on incorporating exogenous variables (platinum-palladium price spreads, the pace of tightening emission standards, EV subsidy volumes), developing hybrid models that combine exponential smoothing with machine learning for enhanced robustness to structural breaks, and conducting scenario-based long-term projections using Monte Carlo methods.

Given that approximately 80% of global palladium demand originates from the automotive industry, where the metal is primarily used in catalytic converters for internal combustion engines, the gradual displacement of ICEVs by electric vehicles will inevitably lead to a long-term decline in demand within this segment [32].

However, in our view, this process will be neither rapid nor linear. The complete replacement of the global vehicle fleet will take at least 15–20 years (the average vehicle lifespan), and even under aggressive scenarios, the share of electric vehicles in the global fleet is unlikely to exceed 20–30% by 2030. During this transition period, palladium demand will be supported by three main factors: tightening emission regulations, which require higher catalytic converter loadings; the substitution of more expensive platinum by palladium in gasoline catalysts; and the need to service and replace catalysts in the existing vehicle fleet. We therefore foresee a gradual structural transformation of the market: automotive demand will decline, but this will be partially offset by increased palladium consumption in hybrid vehicles, as well as in new high-tech sectors such as hydrogen energy, electronics, and the glass industry.

The palladium market is entering a phase of prolonged structural transformation, but not a catastrophic collapse. Contrary to widespread fears that demand for palladium will soon disappear due to the electrification of transportation, the results show that the decline in consumption in the gasoline internal combustion engine (ICE) segment will occur gradually and will be partially offset by the growing use of palladium in hybrid vehicles, as well as in new high-tech sectors. The long-term sustainability of the market directly depends on the successful diversification of demand, that is, on reducing dependence on the automotive industry and developing alternative applications. Palladium's unique physical and chemical properties, particularly its selective permeability to hydrogen and high catalytic activity, make the metal highly sought after for "green" technologies. This is precisely why the development of hydrogen energy, where palladium is used in membranes for hydrogen purification and in fuel cell catalysts, is viewed as the most promising

growth area, although its contribution to global consumption over the next ten years will remain limited and will not exceed 10–15% of total demand.

However, the development of this segment in Russia is hampered by the lack of an effective collection infrastructure, particularly in remote regions. Therefore, in the coming years, the contribution of secondary palladium to total supply is unlikely to exceed 15–20%, which is insufficient to fully offset a potential decline in primary production.

This study suggests that the palladium market will not decline, but will undergo a radical transformation. The success of Russian producers will depend not so much on production volumes as on their ability to adapt to diversifying demand, develop new high-tech applications for the metal, and reduce dependence on raw material exports. The forecasts and scenario analysis presented in this study provide a quantitative basis for making such strategic decisions. However, the continuing high level of uncertainty associated with geopolitical factors and the pace of technological change requires regular revision of these forecasts and further refinement of the models.

Our contribution is threefold. We empirically demonstrate that exponential smoothing ($R^2 = 0.9812$) significantly outperforms ARIMA ($R^2 = 0.1376$) for volatile strategic metal time series, providing a validated baseline for forecasting under uncertainty. We introduce a conceptual shift in evaluating palladium as a critical enabler for emerging high-tech sectors. We also present the comprehensive assessment of Russian palladium market adaptation strategies under dual pressure from the energy transition and geopolitical shifts, including quantitative export flow analysis and scenario-based projections through 2030.

4.2. Limitations of the Study

The forecasting horizon is limited to 2030, since structural transformation of the palladium market is more likely after 2035 due to electric vehicle adoption and shifts in global supply chains. The models do not account for technological breakthroughs, such as palladium-free catalytic systems. Data quality depends on official statistics, which may be published with delays or in aggregated form. Geopolitical uncertainty remains a major exogenous factor, as sanctions, logistics reconfiguration, and import substitution policies can rapidly alter supply and demand. Consequently, this study focuses on probability ranges and qualitative adaptation scenarios rather than a single point forecast.

5. Conclusions

This study developed and compared four forecasting models for palladium production in Russia: linear regression, the Grey model, exponential smoothing, and ARIMA. The exponential smoothing model with a smoothing parameter $\alpha = 0.9$ demonstrated the highest approximation quality (coefficient of determination $R^2 = 0.9812$) and the lowest forecast errors—root mean square error of 0.99 tons, mean absolute error of 0.63 tons, and mean absolute percentage error of 0.63%. Linear regression, the Grey model, and ARIMA yielded R^2 values below 0.14, confirming their unsuitability for forecasting volatile time series of strategic metals under structural shifts. Based on the exponential smoothing model, interval forecasts for 2026–2028 were obtained: in 2026, palladium production in Russia will range from 74.3 to 129.9 tons (median value 102.1 tons), in 2027 from 62.6 to 141.2 tons, and in 2028 from 53.6 to 149.9 tons. The widening of the confidence interval by 2028 reflects rapidly increasing uncertainty driven by geopolitical and technological factors, which must be considered in the strategic planning of mining enterprises.

The analysis of structural transformation in global palladium demand shows that by 2030 the share of the automotive sector will decline from the current 80% to 65–70%, with an absolute reduction in demand from internal combustion engines estimated at 15–20 tons per year. At the same time, new high-tech applications: hydrogen energy (palladium

membranes for hydrogen purification, fuel cell catalysts), glass fibre production (palladium spinnerets and bushings), multilayer ceramic capacitors, and fine chemical synthesis catalysts—will be able to compensate for no more than 10–15% of this decline by 2030. Under the optimistic scenario, domestic palladium consumption in Russia could grow from 6.2 tons in 2025 to 10 tons by 2030, requiring an annual increase of 8–10—three times faster than under the inertial scenario.

Based on the quantitative estimates obtained, specific recommendations for Russian producers, primarily PJSC MMC Norilsk Nickel, are formulated. By 2028, it is advisable to increase the share of high-value-added products (spinnerets, palladium membranes, catalysts) in the export structure from the current less than 5% to 20%. It is recommended to complete industrial trials of at least three new palladium alloys for the glass fibre industry by 2027 and to conclude long-term contracts with five to seven Chinese manufacturing plants. Furthermore, a pilot industrial line for palladium recovery from spent automotive catalysts with a capacity of at least 2 tons per year should be launched by 2028 in cooperation with Krastsvetmet, which would reduce dependence on primary mining and lower the environmental burden.

The study's findings confirm that the long-term sustainability of the Russian palladium market depends on the industry's ability to adapt to structural shifts in global demand. The key conditions for maintaining a competitive position in the long term are: deepening domestic processing of raw materials with a focus on producing high-value-added products; developing a research and development base to commercialize new applications of palladium in hydrogen energy and electronics; diversifying export markets while strengthening partnerships in Asian markets; and promoting the development of secondary processing infrastructure to reduce dependence on primary mining and minimize environmental impact. Implementing these measures as part of a coordinated government and corporate strategy will enable Russia not only to maintain its leadership in global palladium production but also to transform its raw material advantage into technological leadership in segments of the «green economy».

The study explicitly tested three hypotheses formulated in the introduction. First, the hypothesis that exponential smoothing provides higher forecasting accuracy than complex econometric models for volatile strategic metal time series is confirmed ($R^2 = 0.9812$ vs. 0.1376 for ARIMA). Second, the hypothesis that the structural transformation of the palladium market will be inertial up to 2030, with declining automotive demand partially offset by new high-tech applications, is partially confirmed—the offset is only 10–15%, insufficient for full compensation. Third, the hypothesis that Russian producers can maintain competitive positions through deeper domestic processing and market diversification is confirmed, but only under the condition that the proposed specific measures are implemented within the 2026–2028 window.

To mitigate price volatility and geopolitical risks, Russian producers are advised to utilize the recently launched palladium mini-futures on the Moscow Exchange (ticker PLDM, lot size 0.1 troy ounce), which provide a cost-effective hedging instrument for smaller batches. This is particularly relevant given that transaction costs for re-exported palladium through third countries have increased by 12–15% according to TradeMap data.

Future research should focus on three key areas: (1) developing multivariate forecasting models that integrate palladium price dynamics, exchange rates, and industrial production indices as exogenous variables; (2) constructing a detailed econometric model of palladium demand by application sector with a horizon to 2040; and (3) analyzing the impact of potential platinum-palladium substitution in automotive catalysts on long-term market equilibrium.

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