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Review

Prospects for the Development of the Russian Rare-Earth Metal Industry in View of the Global Energy Transition—A Review

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Abstract: Global energy transition trends are reflected not only in oil and gas market dynamics, but also in the development of related sectors. They influence the demand for various types of metals and minerals. It is well-known that clean technologies require far more metals than their counterparts relying on fossil fuels. Nowadays, rare-earth metals (REMs) have become part and parcel of green technologies as they are widely used in wind turbine generators, motors for electric vehicles, and permanent magnet generators, and there are no materials to substitute them. Consequently, growth in demand for this group of metals can be projected in the near future. The topic discussed is particularly relevant for Russia. On the one hand, current trends associated with the global energy transition affect the country's economy, which largely depends on hydrocarbon exports. On the other hand, Russia possesses huge REM reserves, which may take the country on a low-carbon development path. However, they are not being exploited. The aim of this study is to investigate the prospects for the development of Russia's rare-earth metal industry in view of the global energy transition. The study is based on an extensive list of references. The methods applied include content analysis, strategic management methods and instruments, as well as planning and forecasting. The article presents a comprehensive analysis of the global energy sector's development, identifies the relationship between the REM market and modern green technologies, and elaborates the conceptual framework for the development of the REM industry in the context of the latest global tendencies. It also contains a critical analysis of the current trends in the Russian energy sector and the plans to develop the industry of green technologies, forecasts future trends in metal consumption within based on existing plans, and makes conclusions on future prospects for the development of the REM industry in Russia.

Keywords: energy transition; rare-earth metals; low-carbon development; clean technologies; green economy; demand; critical materials

Citation: Cherepovitsyn, A.; Solovyova, V. Prospects for the Development of the Russian Rare-Earth Metal Industry in View of the Global Energy Transition—A Review. *Energies* **2022**, *15*, 387. https://doi.org/10.3390/en15010387

Academic Editor: Krzysztof Galos

Received: 27 November 2021
Accepted: 1 January 2022
Published: 5 January 2022

1. Introduction

Modern economic conditions are characterized by high rates of development, entailing increasing uncertainty in terms of strategic decision-making. Priorities change, while market dynamics and such processes as the internationalization and globalization of global economic systems are intensifying. Recent events related to the global COVID-19 pandemic have also influenced the perceptions of how the world will be structured. Markets for raw materials are also undergoing transformations: demand patterns, needs, the structure of the critical materials market, the applications of some minerals, and their role for the global economy are gradually changing [1–3].

The global energy sector is gradually transforming in favor of the use of alternative energy sources, which is indicated by not only the opinion of the scientific community, but also statistics showing an increase in the share of renewable energy sources in the pattern of primary energy consumption [4,5].

New trends associated with the energy transition are also creating new challenges. Researchers all over the world are discussing issues related to how to make this transition, what tools to use, and how to create the necessary institutional conditions, with a particularly large number of studies being devoted to the question of what resources and materials will be needed to make a transition to low-carbon development and commitment in the context of climate change mitigation [6–8]. All the results of these studies boil down to the fact that one of the integral components of the energy transition will be metals, and, in particular, rare-earth metals, which are actively used in the creation of clean technologies due to their unique properties [9–14]. Today, the properties of rare-earth metals, the conditions of the global REM market (market monopoly), the difficulties of implementing REM projects, and the problems of their being inefficient under the current conditions are widely studied [15–17].

A large and growing body of literature has investigated the role of rare-earth metals in the modern economy and assessed their contribution to scientific and technological progress [18–20]. They are considered to be critical and strategic types of raw materials, sometimes being called "vitamins of modern society" [16,19,21]. It is discussed in the publicistic works that in the future the competition for access to these metals will be comparable to the competition in the global oil and gas market [22,23]. The comparison with the oil market in this context is not accidental. Estimates of the future development of the rare-earth metal industry are increasingly interconnected with the trends in the global energy sector, the structural parameters of which are constantly changing.

Rare-earth elements (REEs) are classified as critically important types of raw materials by many countries of the world (Japan, the USA, Australia, European countries, etc.) [24–26]. Of greatest interest in the context of this research are studies in which the degree of criticality of rare-earth metals is studied from the standpoint of their contribution to the green energy sector. An example is a study conducted in 2013 by the U.S. Department of Energy in order to determine the required raw material potential for sustainable development of areas related to green energy. Two key indicators were calculated: significance for green energy and supply risk. When analyzing the former, such indicators as the demand for green technologies and the possibility of replacing certain raw materials were taken into account. Supply risk was assessed based on the political, social, and economic factors existing in the world. According to the results obtained, the highest level of critical importance is possessed by such rare-earth elements as dysprosium, neodymium, terbium, europium, and yttrium, which are characterized by both high importance for the development of green energy (namely production of components for electric vehicles and wind turbines) and a high probability of supply risks [27].

A number of scientific works have developed predictive estimates of future needs in REMs, taking into account the emerging trends in the field of low-carbon development [11–12,28–29]. It can be noted that, despite the difference in the applied methods and approaches to calculating the volume of demand, research results show that the demand for these metals in the future will increase. Another issue is that not all experts see the intensification of the use of rare-earth metals as a process that brings only advantages. Those who also discuss disadvantages critically assess how an increase in metal extraction and processing can affect the environment and whether an energy transition based on technologies containing dirty metals can reduce environmental damage, hydrocarbon emissions, and the emissions of other harmful substances [30].

Paradoxically, rare-earth metals, on the one hand, contribute to the achievement of the global sustainable development goals (SDGs)—Agenda 2030, and, on the other hand, their extraction and processing can produce a negative impact on environmental parameters [31,32]. In Russian literature, the issue of the SD in case of REM industry has not been reflected either in scientific sources or in government strategies and programs. However, in foreign sources, this topic has been widely discussed [32]. Thus, McLellan et al. reflects the relationship between the stages of production of REM products and social, as well as environmental parameters [33]. In a study by Liang et al. a whole system of factors has been developed, which are necessary for analysis in assessing the sustainability of REM projects. They include social, environmental, economic factors, current technological and logical capabilities of production and processing of REM products [34]. Nevertheless, this only stimulates interest in this topic, dividing the scientific community into those who believe in the power of rare-earth metals in the context of the energy transition and those who prove the opposite effect from their use.

In one way or another, today's global energy transition trends affect the economies of all countries of the world, regardless of what kind of contribution a particular state makes to the solution of global environmental problems: the structure of the energy mix is changing, new requirements for technologies are being formed, and so forth. The emphasis in this study is placed on Russia, a country which both has a significant resource potential and strives to shift the focus of its economy from raw materials to low-carbon development and green principles. Despite the relevance of the research topic under consideration for the country, very little research has been devoted to the study of the problem of resource provision for an energy transition. There is a problem of REM deficiency in the country, which is widely covered in Russian scientific and publicistic papers [35–37]. There is an opinion that the development of national high-tech industries is impossible without providing domestic industries with the required REEs [38]. In works by Russian researchers, even an attempt was made to correlate the trend of growing demand for rare-earth metals with the shift of the domestic industry to a «green» development [39].

The aim of the study is to investigate the prospects for the development of the Russian rare-earth metal industry in view of the global energy transition. The hypothesis of the study is that the current trends in the global energy sector have a direct impact on the development of the rare-earth metal industry and may become a driver for the revitalization of rare-earth metal production in Russia.

The main objectives of the study are the following:

- To analyze the relationship between the transformation of the global energy sector and rare-earth metals;
- To determine why rare-earth metals are considered to be critical in the transformation of the energy sector; and
- To investigate in what ways the current trends associated with the global energy transition affect Russia and what potential impact they can have on the prospects for the development of the domestic REM industry in the future (taking into account the current state of the national industry).

2. Materials and Methods

The research is mostly analytical and conceptual; the analysis and the conceptualization presented are qualitative. Systematization and decomposition techniques along with the methods of comparative and situational analysis were used. The common methods to planning and forecasting were applied. Figure 1 shows an algorithm of the research.

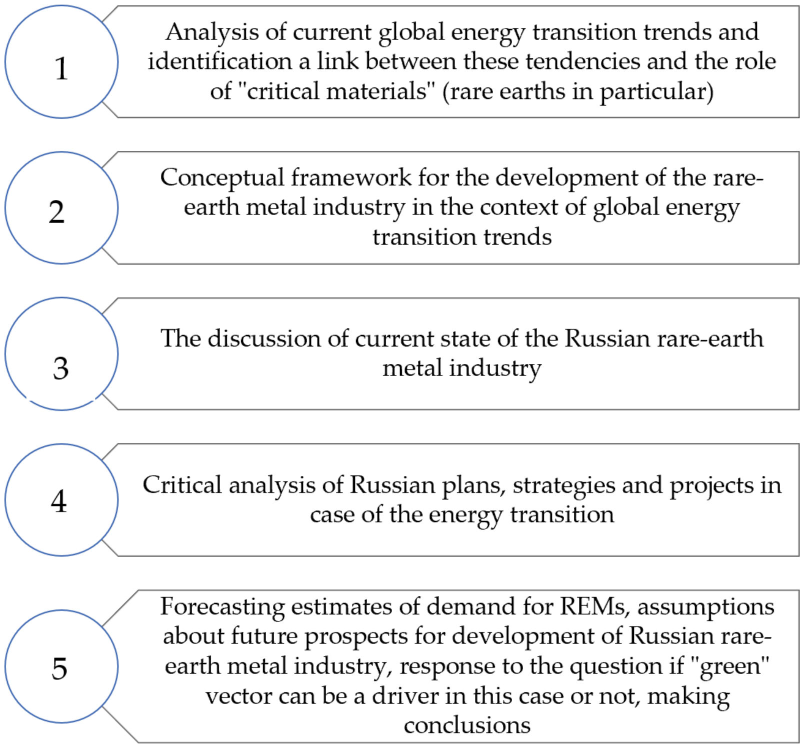

Figure 1. Algorithm of the research.

The study is based on an extensive list of references. A content analysis was carried out of academic literature and industry reports devoted to both the latest trends in the development of the energy sector and the economy of rare-earth elements. The main emphasis in this study is placed on the relationship between the energy sector and the REM market in order to determine whether the demand for metals and, in particular, for rare-earth metals can be influenced by progressive transformations in the global energy sector or not.

Despite the fact that the topic discussed in this research is rather important and relevant, in Russian academic and journalistic literature there are no studies devoted to analyzing the prospects for the national REM industry in a view of the global energy transition. Therefore, a foundation of this research is primarily foreign scientific articles, research, as well as international reports, outlooks, forecasting estimates, and statistical data of the authority agencies—DNV GL, IRENA, IEA, and so forth [5,6].

We attempt to encompass the main trends and issues related to the topic discussed and to move consistently from the world's experience toward Russian «unexplored reality» to answer the questions raised in the research. To get insight into the Russian intentions related to the energy transition trends, we provide a critical analysis of the current situation, as well as observe governmental plans, strategies, programs and agendas. The data about the production of «green» technologies are rather fragmented and unsystematic. To achieve a common vision about current plans and intentions, and to collect quantitative data about particular technologies (discussed in the research) to provide reliable forecasting estimates, plenty of sources were involved, including both scientific and journalistic.

2.1. Global Trends in the Energy Sector and Criticality of Rare-Earth Metals

Currently, processes related to the global energy transition are becoming more intensive [1,40]. There is a range of different approaches to defining the term "energy transition" (Figure 2). This study discusses energy transition as a shift in emphasis from the use of energy that is mainly derived from such carbon-based fuels as coal and oil to the use of energy from such low-carbon sources as natural gas and renewables. One of the important trends taken into considerationin in this case is the fact that the demand for and applications of green technologies (wind turbines, electric vehicles, etc.) are expanding.

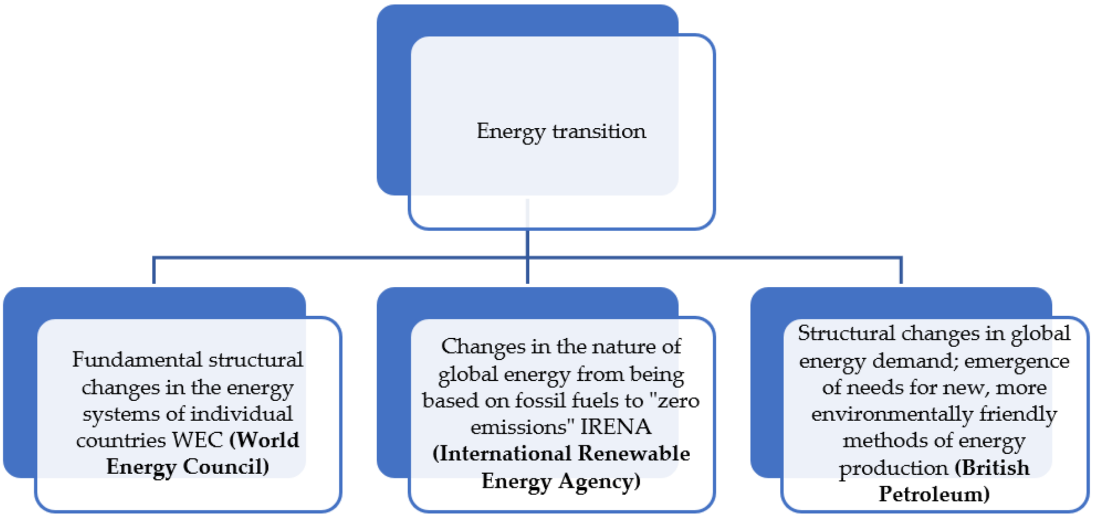

Figure 2. Approaches to defining «energy transition». Source: compiled by the authors based on [5,41–42].

The role of fossil fuels in the pattern of demand for energy sources has begun to be gradually redefined. In 2019, the share of oil, coal, and natural gas in the global energy mix decreased by 6.1, 3.7, and 14.8% compared to 2018, respectively, and the growth in energy consumption in the world was provided only by alternative energy sources [5,43]. According to BP scenarios reflected in The Energy Outlook, the structure of the energy balance will radically change by 2050 in favor of the prevailing share of renewable energy sources (Table 1) [44].

Table 1. Shares of primary energy (current and future trends).

Primary Energy by Fuel	Shares of Primary Energy in 2010–2019, %				Shares of Primary Energy in 2050 (by Different Scenarios)						Main Future Trend
					Rapid		Net Zero		BAU		
	2010	2015	2018	2019	Shares in 2050, %	Change 2019–2050, %	Shares in 2050, %	Change 2019–2050, %	Shares in 2050, %	Change 2019–2050, %	
Oil	32	32	33	31	14	−54.84	6.8	−78.06	24	−22.58	decline
Natural gas	21	22	24	23	21	−8.70	13	−43.48	26	13.04	stability
Coal	28	28	27	26	3.9	−85.00	1.9	−92.69	17	−34.62	decline
Nuclear	6	5	4.2	5	7	40.00	9.1	82.00	4.2	−16.00	stability
Hydro	5	5	6.5	4	9.1	127.50	9.9	147.50	7.1	77.50	increase
Renewables	8	9	4.7	10	44	340.00	59	490.00	22	120.00	increase

Source: compiled by the authors based on [44].

According to the World Energy Council (WEC), the sharp decline in demand for traditional energy sources in 2020 has been a driver for reallocating capital in favor of digital solutions and environmental sustainability [41]. The Moody's rating agency named COVID-19 as one of the main reasons for the accelerated transition to green energy. This fact was linked with the revision of corporate policies in the sectors connected with hydrocarbons, changes in consumer behavior in key energy markets, and adopting measures aimed at promoting the recovery of the global economy, with the environmental component being taken into account [40].

According to DNV GL Energy Transition Outlook 2020, the share of oil and coal in the global energy mix will gradually decrease [4]. At the same time, the shares of solar and wind energy production will significantly increase. According to the same report (DNV GL Energy Transition Outlook 2020), electric vehicles are expected to reach 100% of global car sales by 2040. In view of this, it can be stated that new trends will create a demand for green technologies.

Figure 3 presents information on changes in oil prices and the volume of investments in the global energy transition. It is worth noting that there is an inverse relationship between these parameters [45,46]. Despite the current problems that arose in the global oil and gas industry and the general decline in the development of global economic systems, it can be noted that investments in energy transformation processes only increased, and amounted to $330 billion (an increase of 11% compared to 2014). In the same period, the main provisions of the Paris Agreement were approved. By 2020, the volume of investments in the global energy transition reached $501.3 billion, growing by 9% compared to 2019 and by 113% compared to 2010 [46].

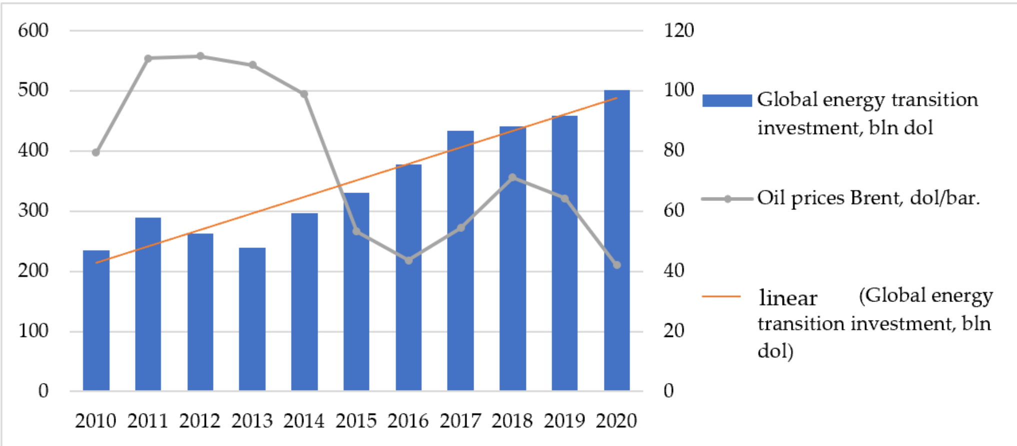

Figure 3. Changes in oil prices and total investments in the global energy transition. Source: compiled by the authors based on [45,46].

It can be stated that the processes associated with the energy transition can be witnessed all over the world: the production of green technologies is intensifying, plans are being made to reduce the negative impact on the environment, and it is planned to improve energy and resource efficiency. At the same time, it should be understood what exactly lies behind these transformations and how they can affect the future development of global markets, particularly those for metals.

The main drivers for the implementation of the global energy transition are considered to be such factors as government regulation and the availability of technology [47]. The former is directly related to legal regulation, institutional conditions, funding opportunities for special programs and projects, and so forth. The latter is associated with the availability of materials without which the creation of progressive technologies is simply not possible. It is known that environmentally friendly technologies require much more metals for their production than their counterparts that rely on fossil fuels [48]

There is an opinion that the global energy transition may cause a depletion of the key resources of the earth, which will only be accelerated by the plans to use metals more intensively [49]. This is relevant not only for rare-earth metals. Minerals such as nickel, copper, cobalt, lithium, and natural graphite are also among the materials widely used in the green industry. However, due to their availability, there is no concern over their supply being unsustainable [50].

Rare-earth metals are known for their high electrical conductivity, lightness, and strong magnetic properties. All this makes REMs an integral part of clean energy. These metals are successfully applied as raw materials for the production of permanent magnets, which are widely used in generators for wind turbines and engines for electric vehicles [14–17]. Zhou et al. (2017) provided information on the average consumption of individual elements in manufacturing various green technologies [11]. To produce wind turbines, significant amounts of such elements as neodymium and dysprosium are required; for the production of fluorescent lamps, smaller amounts of elements are required, but their range is bigger and includes lanthanum, cerium, europium, yttrium, neodymium, and terbium [13]. According to IRENA estimates, there is five times more metals and minerals (lithium, nickel, cobalt, zinc, rare-earth metals, etc.) in electric vehicles compared to conventional cars (173 kg per unit versus 34 kg) [51]. For the production of one wind turbine, more than 30 kg of these valuable components is required [18].

Despite all the difficulties in obtaining rare-earth metals that are associated with the geological features of deposits and the complexity of processes required to produce value-added products using REMs (required in the production of modern «green» technologies—oxides, magnets, etc.), there are currently no substitutes that could replace these metals [18]. The heightened interest in the search for so-called alternative materials was caused by the rare-earth metals crisis that covered the period 2010–2011 [52–54].

According to the Technology Metals Research, prior to the crisis, magnets used in wind turbines cost $80,000 per unit. Under the influence of the rapid rise in prices for rare-earth metals in 2011, similar products began to cost $500,000 and more (an increase of more than 520%) [18]. As the pricing environment stabilized, global wind turbine companies began to rethink their supply chain strategies. A number of companies completely abandoned the use of rare-earth components in their products. For example, Siemens eliminated dysprosium from the production of turbines, and the well-known General Electrics switched to "old" transmission technologies to eliminate possible risks of a failure in the supply of rare-earth metals in the future [18].

In the United States, special studies are being carried out, the purpose of which is to reduce the dependency of the national economy on neodymium-dysprosium magnets and to switch to using its own resources. Since the United States does not have significant reserves of dysprosium, there is only one way out, which is to replace this element with another with similar properties. Cerium—the most common element from the group of rare-earth metals—is being tested as a substitute. However, it does not have the same strong magnetic properties as dysprosium and neodymium do. Therefore, the magnets that are planned to be produced in the future will, a priori, be inferior to their competitors in terms of characteristics [18].

While some companies are striving to abandon the use of REMs in order to neutralize possible losses from geopolitical risks, others, on the contrary, express their readiness to use them. For example, the largest oil and gas companies begin to show interest in new, or transition materials. According to a BP survey, rare-earths, along with cobalt, natural graphite, and lithium, are "key minerals" for the energy transition. BP collects data on rare-earths stock and production dynamics in order to predict available sources of supply in the future [5].

In 2021, Norway, one of the leaders in the global oil and gas industry, announced its intention to reorient from deep-sea oil and gas production to deep-water mining of metals, in particular rare-earth metals. The reason for this is the growing demand for such green technologies as electric vehicles, solar power plants, and wind turbines. Japan and China are developing similar plans. The United Nations International Seabed Authority (ISA), which regulates seabed mining in international waters, has approved 30 exploration contracts with China [55,56].

Rare-earths are expected to play an increasing role in the world's resistance to global warming in the long term, and for good reason. According to forecasts by the International Energy Agency (IEA), in order to limit global warming to 2 °C, renewable energy should generate half of the electricity on the planet in 20 years. In one of the most likely scenarios, IEA makes the assumption that solar and wind energy will have to jointly generate more than 6000 TWh, which is more than six times the demand that existed at the turn of 2013–2015. Moreover, manufacturers of electric vehicles must increase production volumes by 80% annually [18].

Of interest are studies carried out by the Massachusetts University of Technology, according to which for a full transition to green technologies (wind turbines, electric vehicles) over the next 25 years, it will be necessary to increase the production of neodymium by 700% and that of dysprosium by 2600% [18]. The problem is that the rate of annual growth in the production of these metals does not exceed 6–8%. Alonso et al. predicts that 2035 demand for dysprosium will be over 2500% the supply of its metal in 2010 [57].

Studies by the U.S. Department of Energy and the European Union confirm the thesis that the world will soon face the problem of a shortage of necessary materials to implement the planned environmental changes. The report "Securing Materials for Emerging Technologies" (APS Physics) states that the lack of required materials can significantly "slow down the introduction of alternative advanced energy technologies" [58]. This means that without strengthening the supply chain of REMs and other metals, the world will be forced to abandon its plans for the energy transition in favor of preserving the dominant role of fossil fuels [59].

An interesting fact is that, on the one hand, rare-earths are needed to produce a number of progressive «green» technologies, but, on the other hand, to manufacture REM products innovative mining, refining and processing technologies are needed. Therefore, a growing demand for electric vehicles, wind turbines, and so forth will orderly stimulate a development of novel technologies for REMs' extraction. Taking into consideration the current market «balance of power», the technologies implemented have to be advanced.

2.2. Conceptual Framework for the Development of the Rare-Earth Metal Industry in the Context of Global Energy Transition Trends

Based on the tendencies, trends and forecasts discussed, the conceptual framework for the development of the rare-earth metal industry in the context of global energy transition has been formed. Clearly, a need for «green» technologies and REMs in the modern economics are linked.

In this study the demand for rare-earth metals is classified as derived demand. This kind of demand for a resource is driven by the demand for the goods that are produced using this resource. Resource demand:

(A) Increases in the event of an increase in demand for finished products; and
(B) Decreases if there is a decrease in demand for finished products created with the help of this type of resources.

Figure 4 reflects the conceptual foundations for the development of the rare-earth metal industry in the context of global energy transition trends.

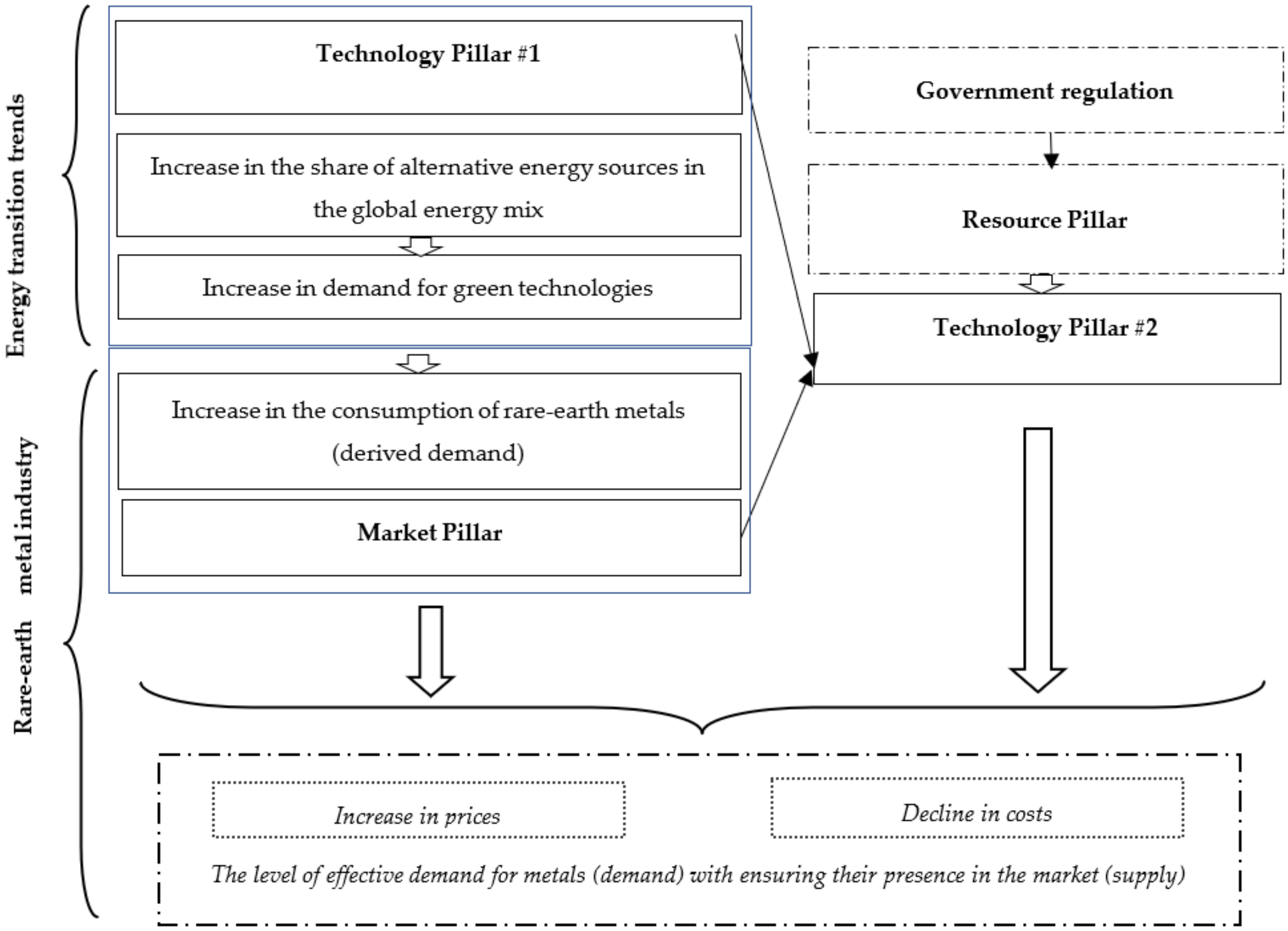

Figure 4. Conceptual framework for the development of the rare-earth metal industry in the context of global energy transition trends.

Based on the presented conceptual framework, the study is based on the following assumptions:

(1) Global energy transition trends are associated with the intensification of the use of green technologies (Technology Pillar #1).
(2) The level of demand for green technologies will affect the consumption of rare-earth metals and, accordingly, the situation in the rare-earth metal market, where an increase in demand will lead to an increase in prices, especially for heavy group of metals which are more demanded (Market Pillar).
(3) Positive changes in the market stimulate the development of technologies for the extraction and processing of rare-earth metals (Technology Pillar #2), thereby acting as a driver pushing the development of the industry that consists of two basic components, which are government regulation and access to raw materials (Resource Pillar).

Technology Pillar #1 and Market Pillar shape demand factors. Technology Pillar #2, Resource Pillar, and government regulation influence REM supply. The cumulative impact of the factors associated with technology and the market will become the framework for transforming the economic foundations for the development of REM initiatives in the context of rising prices and falling costs. Table 2 provides a more detailed description of the above factors.

Table 2. Description of the pillars shown (Figure 3).

Pillars	Meaning	Description	Factor
Technology Pillar #1 (T1)	Development of technologies ensuring growth in demand for rare-earth metals	Rare-earth metals are essential for the creation of green technologies. Under the influence of global energy transition trends, the scale of application of these technologies will grow.	Demand factor
Market Pillar (M)	Changing market trends	Upward changes in demand and prices (favorable conditions for the manufacturer)	Demand factor
Technology Pillar #2 (T2)	Development of technologies that ensure a reduction in the cost of producing rare-earth metals	Development of innovative technologies for the extraction and processing of rare-earth metals in order to obtain products with high added value; without a demand for rare-earth metals, the creation and implementation of such science-intensive and capital-intensive technologies has no practical sense.	Supply factor
Resource Pillar (R)	Supply of raw materials for the production of finished products	The availability of resources is one of the determining factors affecting the level of criticality of rare-earth metals.	Supply factor
Government regulation (G)	Current policy in the development of the potential of the mineral resources sector	Resource management and support measures	Supply factor

Based on the assumptions presented above, we state that the demand for rare-earth metals is elastic in relation to the demand for green technologies. To assess the future demand for rare-earth metals in Russia factoring in the plans for the production of green technologies, it is proposed to use the following formula:

$$De = Ci1 * Ve1 + Ci2 * Ve2 + \cdots + Cin * Ven \quad (1)$$

Where *De* is the demand for REM products caused by the production of a specific green technology; *Ci* is the average consumption of a specific rare-earth element in producing the technology under consideration; and *Ve* is the volume of production of this type of green technologies. To find the total increase (ΔD) in demand for REMs caused by producing green technologies in a specific period, the following calculation needs to be performed:

$$\Delta D = De1 + De2 + \cdots De n \quad (2)$$

In order to determine whether global energy transition trends can act as a driver for the development of the rare-earth metal industry, it is necessary to know whether the country has a plan for fostering production and expanding the use of green technologies that cannot be produced without using REM components. In view of this, it is necessary to answer a number of questions:

(1) Does the country have plans for an energy transition?
(2) Does it plan to use modern green technologies (construct new production facilities)?
(3) How can these trends affect the development of the Russian rare-earth metal industry (taking into account the current state of industrial development)?

In the context of the topic under consideration, it is advisable to turn to specific green technologies that contain rare-earth elements. To forecast future demand for metals caused by growth in the production of environmentally friendly technologies, the previously mentioned scientific article (Zhou et al., 2017) considered such types of technologies as electric vehicles, wind generators, nickel-metal hydride batteries, catalytic converters, and different types of lamps (LED, LFL, CFL) [11]. As the key objects for this study, we chose two types of technologies that are classified as environmentally friendly and require the largest number of REMs per unit: (a) electric vehicles; (b) wind turbines.

3. Results

3.1. The Russian REM Industry: In Search of New Development Drivers

Russia, which possesses significant reserves of rare-earth metals, may not consider the factor of resource availability as critical in contrast to European countries, Japan, and South Korea [60–62]. Another issue is that at the moment, REM deposits in the country are not actually being developed, which is due to a number of systemic problems at the level of the national industry—a low level of adoption of multipurpose resource use practices, issues associated with the replenishment of mineral deposits, imperfection of current institutional and economic mechanisms, technological limits, and lack of production capacities to manufacture high value-added products, to name a few [63–69].

The Lovozero deposit remains the only source of rare-earth elements despite the fact that the country ranks fourth in terms of REM reserves in the world [62]. The future potential in the context of the REM industry is associated with new projects. However, even despite the availability of technologies, new projects are not being implemented. Table 3 contains information about the most promising Russian projects for the development of rare-earth metals and their basic data (products, investments, and estimated launch dates) [62,70].

Table 3. The key characteristics of prospective REM projects in Russia.

Deposit/Company	Products	Annual Production Capacity for Rare-Earth Metals	Investments Required	Estimated Implementation Time
Tomtor Deposit/IST Group	REEs, ferroniobium, didymium	2.4 thousand tons of REEs	RUB 53 billion	2025–2026
Zashikhinskoye Deposit/Technoinvest Alliance	Ferroniobium, niobium, tantalum, zirconium, rare-earth metals	240 tons of concentrates of REE oxides	RUB 27.6 billion	2024–2025
Afrikanda Deposit /SGK Arkmineral LLC	Niobium, tantalum, titanium dioxide, rare-earth metals	400 tons of mixed REE concentrate	About RUB 70 billion (taking into account the cost of technology)	2020–2039
Seligdar Deposit	Apatite concentrate, rare-earth metals	100 tons of REE concentrate	RUB 46 billion	No data available

Source: compiled by the authors based on [62,70].

According to 2018 data, the level of Russia's dependency on the supply of rare-earth metals was 81% [71]. In 2019, the growth in consumption of REMs was accompanied by an increase in imports reaching 1260 tons (in terms of oxides). At the same time, the domestic market for rare-earth metals is incomparable with markets in China, the USA, and Japan in terms of capacity and consumption. This is viewed as an obstacle to the development of the national rare-earth metal industry due to the lack of effective incentives that can give impetus to the implementation of market approaches.

The country's high import dependency on the supply of rare-earth metals and their compounds jeopardizes chances for developing domestic high-tech industries and improving the economic security of the country under the conditions of increased geopolitical risks and the absence of effective mechanisms for boosting the development of manufacturing capacities required for extracting the necessary elements [36,38].

In modern conditions, solving the problems of providing the economy and industry with the necessary rare-earth elements is a challenge greatly affecting the country's scientific and technological progress in such sectors as green energy, low-carbon development, and so forth [72]. Speaking of potential growth, the question immediately arises as to whether the Russian economy will be able to provide a sufficient level of demand for rare-earth metals. Despite the global upward trend in the demand for these metals, the Russian market can be classified as poorly developed. While the growth rate of the global REM market is estimated at 10–13%, the same indicator for the national market is only 3–5% [73]. In global REM production, the share of Russia does not exceed 1.1% [60].

REM consumption figures in Russia can be called insignificant, despite the fact that the role of high-tech industries is becoming increasingly important for the sustainable development of the Russian economy, especially in the context of the government's intentions to develop on par with other economically developed countries and move along with the fifth and sixth waves of innovation [38].

As of 2020, the consumption of rare-earth products did not exceed 1400 tons of TREO. However, as it was established earlier, the demand for rare-earth metals in the world is growing, with one of the factors being the pressure of emerging green trends [56–58]. Here, the question arises as to whether this is valid for Russia.

3.2. Global Energy Transition Trends: The Case of Russia

For the Russian economy, which is exclusively focused on raw materials, the departure from the model based on the sale of hydrocarbon resources should be accompanied by a transition to a low-carbon type of development [74,75]. Plans, scenarios, and strategies based on such a development model have become widespread all over the world, and they are becoming adopted in Russia, albeit not on a wide scale [76].

The trends discussed in the first section of the article gave impetus to discussing paths towards energy transition that the country can take [77–79]. There is such a concept as the oil curse (sometimes called "oil needle"), which is characteristic of the Russian economy. However, in the context of the current and projected trends, it becomes unclear how the country can maintain its advantages as a producer of hydrocarbons if they lose their positions in the global market [47,75]. Not only are the prices changing, but also the attitude of investors and consumers (ESG concept) [80]. All this shape a fundamentally new environment in which the existing national economic model may turn out to be unviable.

The first initiatives related to the transition to alternative energy sources in Russia emerged back in 2009, which was associated with the adoption of a government decree defining the priority directions of state policy in the field of developing renewable energy sources. It was planned that by 2015, the scale of the introduction of clean energy technologies would increase significantly, and the share of alternative sources in the national energy mix would reach at least 4.5%. In 2013, special rules were developed for determining the price of capacity for facilities using renewable energy sources in the wholesale market, which allowed the country to join the existing system of capacity supply agreements (CSA) [47,81].

At the One Hundred Years of Energy International Forum, Petr Bobylev, Director of the Competition, Energy Efficiency and Ecology Department of the Russian Ministry of

Economic Development, said that Russia was building its own energy system, focusing on the strategic goal associated with the transition to low-carbon energy. At the same time, as it was clarified, the country was trying to avoid the "mistakes" of the accelerated transition witnessed in the EU and the United States. Therefore, one should not expect from Russia a rapid pace of development in this direction.

According to IRENA, Russia's installed renewable energy amounted to 55,000 MW in 2019, demonstrating an increase of 10% from the year before. When compared with other countries, these figures seem insignificant. For example, China has a capacity of 759 thousand MW of renewable power (according to 2019 data). As for Russia, most renewable energy is produced by hydroelectric power plants that were built back in the Soviet era. An overwhelming majority of investments (about 90%) in renewable energy are channeled into solar panels and wind turbines. As of 2019, more than 1.7 GW of renewable energy capacity was commissioned in Russia, most of which is accounted for by solar generation. However, wind power facilities are also being actively built [42].

On 23 September 2019, Russia ratified the Paris Agreement. The experience of other countries indicates that it is necessary to develop plans to be able to fulfill long-term commitments under this agreement. In particular, for a successful transition to a low-carbon type of development, necessary facilities need to be created [82]. In January 2020, the Government of the Russian Federation approved the National Action Plan for the first stage of adaptation to climate change for the period up to 2025.

In April 2020, against the background of a high level of instability in the global energy sector, the Energy Strategy of the Russian Federation for the period up to 2035 was approved, according to which the main goal of modern energy development in the country is to move its resource-based energy sector towards a resource-innovative path [83]. However, it is not clarified how it should be done. It is unclear whether the transition to a resource-innovative energy sector is equivalent to the priorities that countries set themselves in the framework of the global energy transition. In Russian scientific literature, there are different understandings of this term. Some associate it with an increase in investment in the energy sector, the creation of new jobs, and the transition to the production of finished products with higher value added while others interpret it as a synonym of low-carbon development. The said strategy identifies reducing the negative impact of the energy sector on the environment and adapting to climate change as its key goals. At the same time, an increase in coal production is predicted, which goes against these goals [83-84]. Figure 5 shows forecasts for coal and oil production in Russia until 2035.

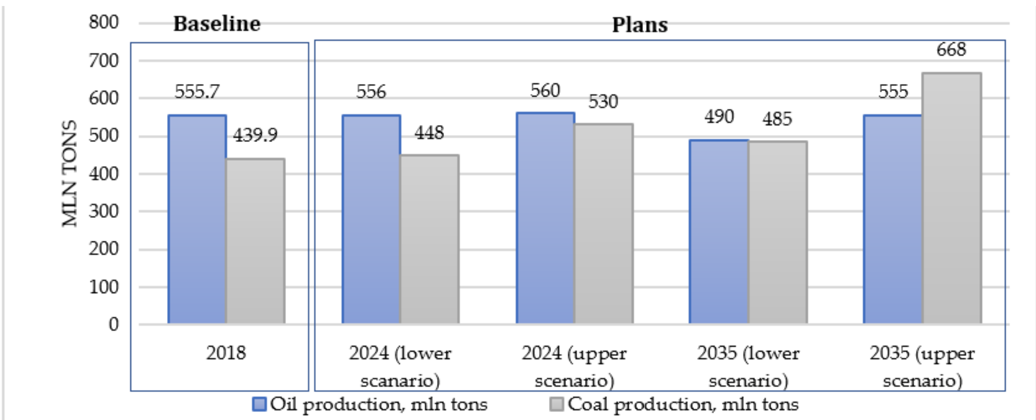

Figure 5. Oil and coal production scenarios according to the Energy Strategy of the Russian Federation for the period up to 2035. Source: compiled by the authors based on [83,84].

The figure presents so-called lower and upper production scenarios. The former involves the development of the national energy sector while ensuring sustainability and energy security of the country. It is based on the assumption that the growth rate of the national economy will be moderate in the context of a conservative forecast regarding global demand and prices for energy sources. As for the upper scenario, it implies a high rate of economic growth. It assumes that prices for energy sources will grow while the external and internal conditions influencing the energy sector will be favorable (macroeconomic stability, low inflation) [83,84]. However, as mentioned earlier, forecasts by international analytical agencies regarding future oil prices suggest the opposite.

Despite the fact that energy transition trends are not reflected in the scenarios described above, the Energy Strategy of the Russian Federation for the period up to 2035 considers the following to be breakthrough technologies for the development of the national energy sector [83]:

- Renewable energy sources and energy storage;
- Hybrid vehicles and electric vehicles, including cars;
- Hydrogen fuel;
- Unmanned vehicles and intelligent transport systems; and
- Network technologies in the electric power industry.

At the same time, it is emphasized that scaling-up these technologies will entail significant technological and organizational changes in the management and operation of electric power systems. It is also noted that these technologies will become the foundation for Russia's transition to green energy. However, the strategy itself does not provide any specific plans regarding these technologies in terms of the timing of implementation, their output, or consumption, which creates uncertainty as to when exactly the transition mechanisms will be launched in Russia and whether they will be launched at all.

The National Security Strategy of the Russian Federation, which was adopted in July 2021, indicates that two key factors should become priorities in the context of the transformation of the global economy: (1) human capital and (2) environment. The development of low-carbon energy is viewed as one of the key goals of ensuring the country's economic security [85].

It can be concluded that Russia has plans to transform the national energy sector. After all, the need for the development of clean energy technologies is reflected in the Energy Strategy of the Russian Federation for the period up to 2035, a legal document [83]. However, can it be argued that real steps are being taken in this direction?

3.3. The Way to Green Technologies and Forecasting Demand for Rare-Earth Metals

According to the Energy Transition Index 2020, Russia ranks 80th out of 115 countries with a score of 50.5% (which is 1% higher than in 2019) [86]. For comparison, Sweden tops the ranking with a score of 74.2%. Russia's energy transition readiness is estimated at 39% (it did not change from 2019 to 2020). This indicator is based on the analysis of institutional and economic conditions, contribution to the energy transition, the volume of investments, the pattern of the energy mix, and the legal regulation of this area. Also, energy system performance is assessed based on such criteria as energy security, sustainable development, and economic growth. In 2020, Russia's system performance was estimated at 63%, an improvement of 3.3% compared to 2019. Based on these indicators, we can conclude that the Russian economy demonstrates some shifts towards the energy transition, but in comparison with other countries, the pace of movement is not very high.

3.3.1. Electric Vehicles

As for specific green technologies, it should be noted that Russia still does not have its own production of electric vehicles. The internal market for electric vehicles is constrained by many factors associated with both the high cost of environmentally friendly vehicles and the lack of the necessary infrastructure [87,88]. All electric vehicles sold in Russia are imported, which makes it is surprising that despite the current crisis, sales of new electric vehicles in the country by the end of 2020 increased by 95% compared to 2019.

The Strategy for the Development of the Automotive Industry in the Russian Federation for the period up to 2025 notes that REMs, along with composite materials and electronic components, are irreplaceable materials for the creation of domestic production [89]. Obviously, as the volume of production of electric vehicles expands, the demand for key components will also increase.

Russia plans to introduce facilities for the production of electric vehicles, which is confirmed by the Concept for the Development of Electric Transportation adopted in 2021. While information about the prospects for creating facilities for the production of electric vehicles used to be fragmentary, now all developments in this direction are becoming systematic. This segment is currently showing some positive results. In 2018, 2383 electric vehicles were sold, including new and used models (0.14% of the total domestic passenger car market). According to PwC forecasts, sales of electric cars in the country will increase in the period from 2019 to 2025 with an average annual growth rate of up to 30% resulting from government support measures [90]. All this will ultimately stimulate the creation of production facilities for the manufacturing of electric vehicles.

The Table 4 provides information on the key models of electric vehicles that are planned to be launched on the market in Russia in some future. An interesting fact is that the ZETTA model, which was designed by Russian scientists, does not require rare-earth elements [91]. Manufacturers replaced electric motors with wheel motors that do not need the use of rare-earth metals. It can be stated that domestic manufacturers, along with European researchers, are looking for material substitutes in order to (a) reduce production costs and (b) minimize the risks of supply disruption.

Table 4. Types of electric vehicles in Russia (preparations for launching production are in progress).

Name	Estimated Costs	Needs for REMs
ZETTA (Zero Emission Terra Transport Asset)	550 thousand rubles	REMs are not used (this explains the relatively low cost of the proposed vehicles)
GAZelle e-NN	NA	The first cars will be equipped with Chinese motors and batteries. But over time, manufacturers plan to switch to REM components of domestic production.
Cama-1 (St. Petersburg Polytechnic University)	About 1 million rubles	Requirements for rare-earth metals were not disclosed

Source: compiled by the authors based on [91,92].

In accordance with the Concept for the Development of Electric Transportation, the first facilities for the production of electric vehicles in Russia should be launched already in 2022 (with an annual production of 5000 electric vehicles). By 2025, this value will grow to 50,000 units (10 times more than in 2022), reaching 217,000 units by 2030. Figure 6a shows the projected REM consumption in the implementation of the plans announced by the state for the production of electric vehicles.

If we take into account that the projected production volumes (according to the Concept for the Development of Electric Transportation) include electric vehicles produced by ZETTA that do not require components made of rare-earth elements, the demand for metals will be as follows (see Figure 6b). According to production plans, in the first years of production, the volume of production will not exceed 3000 units, and the maximum capacity will be 15,000 units.

The main REM components in the production of electric vehicles are neodymium and dysprosium oxides, which belong to the heavy group of metals [11]. Their peculiarity is their relatively high cost and relatively low availability (the balance problem). A total of 86% of the required rare-earth metals are neodymium oxides, and 14% are dysprosium oxides.

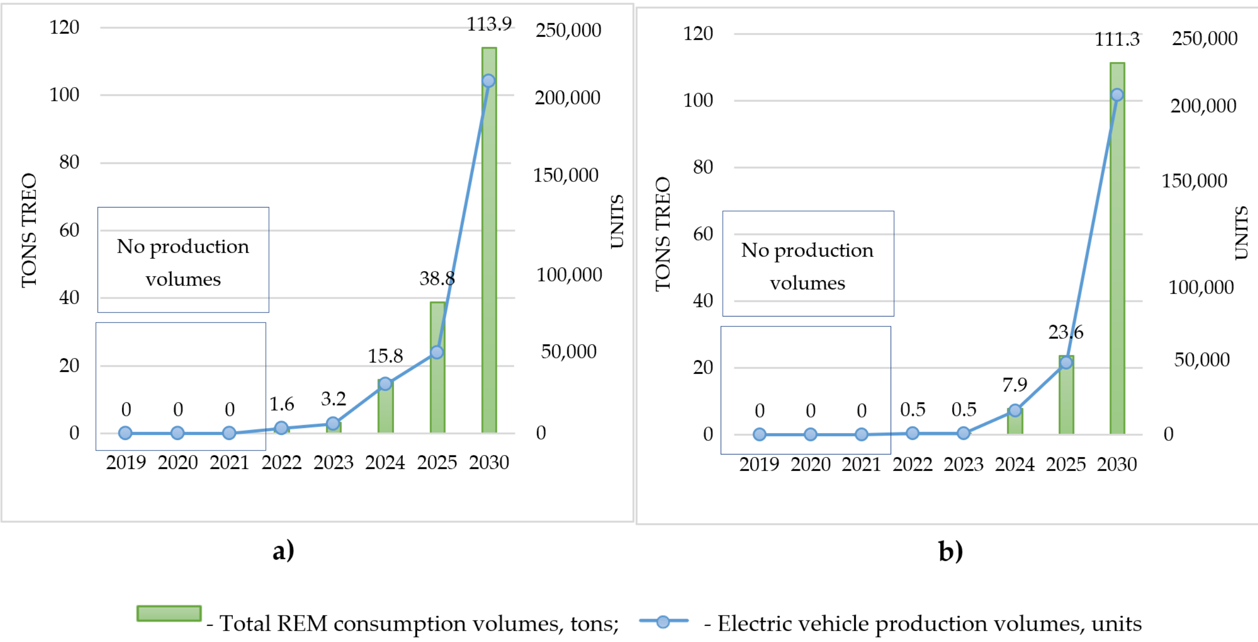

Figure 6. Forecasted REM consumption (**a**) in the implementation of the plans announced by the state for the production of electric vehicles; (**b**) in the implementation of the plans announced by the state for the production of electric vehicles without taking into account the ZETTA electric vehicle that does not require REMs.

3.3.2. Wind Turbines

The capacity of the Russian wind energy market is small and amounts to no more than 1% in the global market. It is believed that Russia is the only major economy in the world in which wind energy is only beginning to take its first steps [93,94].

The main obstacle to the development of wind energy in Russia is the insignificant volume of the domestic market guaranteed by the government support program, which is due to the absence of a climate and environmental agenda in the country. At the same time, global energy trends cannot help but influence the national market. The introduction of carbon border tax by the European Union raises concerns not only at the level of the corporate sector, but also at the government level. The availability of the necessary competencies and capacities in the field of wind energy can reduce the economic losses that Russian exporters are likely to bear from the introduction of this type of tax [93,94].

It is believed that it is the global challenges that can become the impetus for the development of the wind energy market in Russia. According to IEA, in 2020, renewable energy sources accounted for about 90% of the total volume of newly installed capacities. During the year, 200 GW of new green generation was added globally, with 65 GW being accounted for by wind farms (an increase of 8% compared to 2019) [95].

The analysis showed that Russia has plans to commission new wind energy capacities, which are reflected in the Order of the Government of the Russian Federation of January 8, 2009 No. 1-r titled “On Approval of the Main Directions of State Policy in the Field of Increasing the Energy Efficiency of Electric Power Generated on the Basis of Renewable Energy Sources for the Period up to 2035”. However, when comparing the real and planned indicators, it turned out that in the period from 2015 to 2017, the announced plans were not fulfilled. It was planned to commission 51, 50, and 90 MW of energy capacity in 2015, 2016, and 2017, respectively. The failure to meet these plans can be associated with two key factors:

(1) Excessive requirements for equipment localization;
(2) Sharp change in the ruble exchange rate in 2014.

Consequently, the approved plans began to be implemented only in 2018. Figure 7 shows data comparing the planned and real values for the commissioning of new wind power capacity in Russia with an assessment of the needs for dysprosium and neodymium (based on average values).

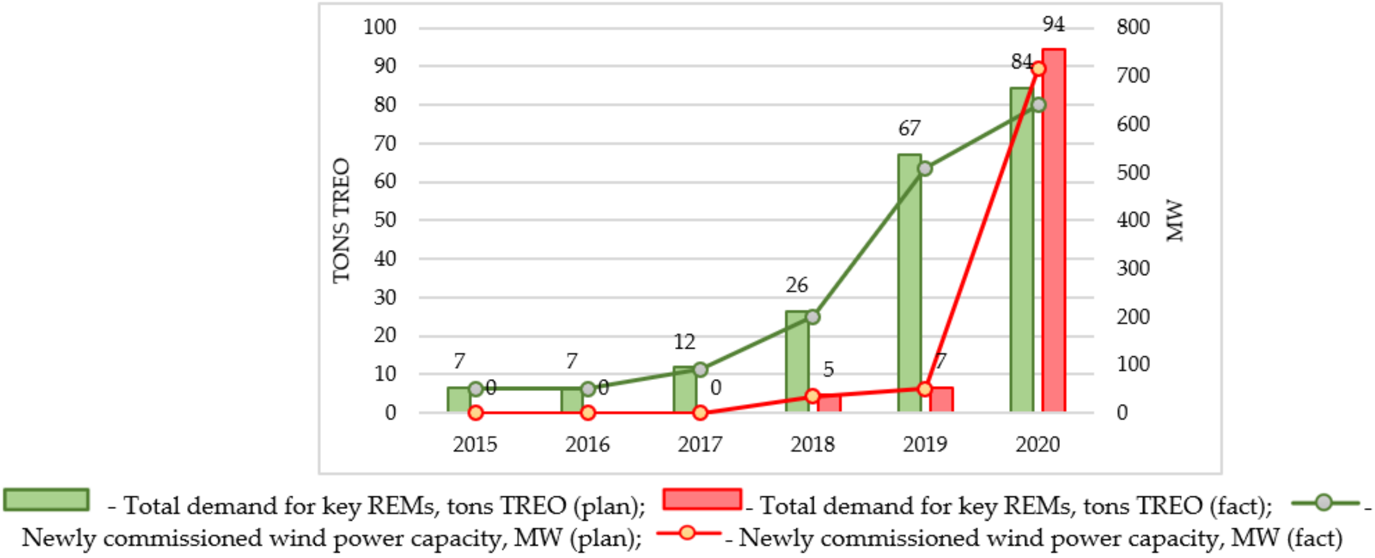

Figure 7. Comparison of planned and actual indicators of wind production capacities in Russia with an assessment of potential requirements for rare-earth materials.

Figure 8 shows the total demand for key REMs in the planned and real commissioning of wind power capacity. Based on the data obtained, it can be seen that in 2020, the planned demand for rare-earth metals was 92% lower than the real demand. At the beginning of 2021, wind farms with a total capacity of about 1 GW operated in Russia, 700 MW of which were commissioned in 2020 despite the existing difficulties and restrictions caused by the COVID-19 pandemic. According to the approved plans, 530, 532.7, and 228.75 MW will be commissioned in 2020, 2023, and 2024, respectively. Based on the data above, the forecasts presented in the figure were made. By 2024, the total demand for REM products will amount to 500 tons of TREO.

The demand pattern for specific types of rare-earth metals is similar to that for the production of electric vehicles: up to 90% are neodymium oxides and less than 10% are dysprosium oxides.

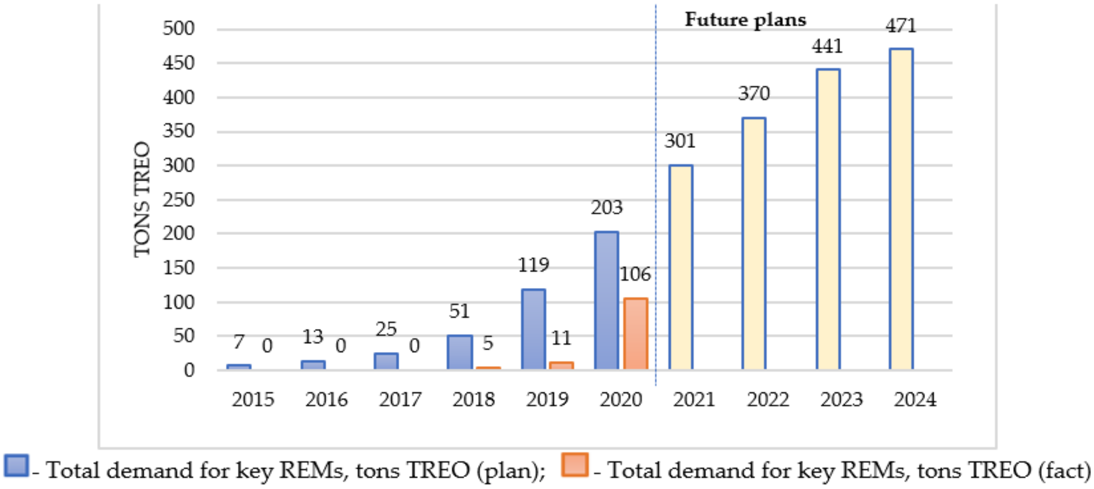

Figure 8. Total demand for key REMs (cumulative total).

3.4. Prospects for the Development of Russia's REM Industry in View of Current Trends

According to the previously presented conceptual framework for the development of the rare-earth metal industry, the prospects will largely be determined by the future demand for advanced technologies, including green ones, which influence trends in the global energy transition. Today, the total demand on the national rare-earth metal market varies from 1200 to 1400 tons of TREO, more than 85% of which is imported from other countries (China, the United Arab Emirates, Estonia, etc.).

It was revealed that there is yet no demand for rare-earth metals to be used in electric vehicle production since there is currently no such industry in Russia. As for the wind power sector, the current demand does not exceed 100 tons of TREO, which is no more than 5–7% of the country's total needs. However, the approved plans indicate that the creation of new production facilities in Russia is not only possible, but will also be implemented in practice in the medium term.

Table 5 presents the results of the analysis of the prospects for the development of the rare-earth metal industry in Russia in the context of the production of green technologies. In addition to the key factors (T1, T2, and M), government regulation and resource availability are also included. In the context of Russia, we believe that additional factors will not become an obstacle to the implementation of the plans for the development of the industry due to (a) the availability of rare-earth metal reserves and (b) the readiness of the government to support the development of the industry: initiatives have been launched, tax measures are being introduced, and there are opportunities to use modern support mechanisms.

Table 5. Analysis of the prospects for the development of the rare-earth metal industry in Russia in the context of green technology production.

Pillars	Factors	
	Present	
	Electric vehicles	Wind turbines
Technology Pillar #1 (T1)	No production	There are production capacities; a plan for the introduction of new capacities has been developed and approved
Market Pillar (M)	No demand for REMs from this sector	The annual demand for rare-earth metals does not exceed 100 tons of TREO

Technology Pillar #2 (T2)	Lack of incentives to develop technologies for obtaining REM products	Technologies for producing neodymium and dysprosium oxides (heavy group of metals)
Future (2021 to 2030)		
	Electric vehicles	Wind turbines
Technology Pillar #1 (T1)	The launch of the first production facilities is planned by 2022 with subsequent growth in production volumes	Further implementation of the developed plan for the introduction of new wind power capacities until 2024
Market Pillar (M)	By 2025, the annual demand for rare-earth metals will amount to 7–15 tons of TREO (depending on the models launched into production). By 2030, the demand for REM products will exceed 100 tons of TREO per year	The annual demand for rare-earth metals will vary between 60 and 70 tons of TREO. By 2024, the total demand for REM products will reach 470 tons of TREO
Technology Pillar #2 (T2)	Technologies for producing neodymium and dysprosium oxides (heavy group of metals)	Technologies for producing neodymium and dysprosium oxides (heavy group of metals)
Additional factors		
Government regulation	Government initiatives are aimed at intensifying the development of the national industry of rare-earth metals (fiscal mechanisms are being implemented; there are opportunities to attract additional funding to REM projects)	
Resource Pillar	Russia possesses significant REM reserves, ranking fourth in the world	

Figure 9 shows the forecasts of how the demand for REM products in Russia may change in the implementation of plans for the production of electric vehicles and the commissioning of new wind power capacities in 2020–2024.

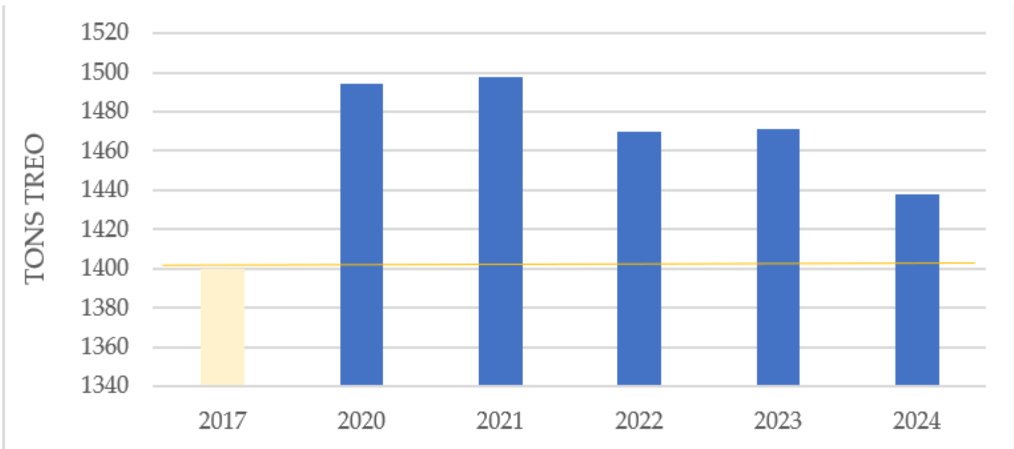

Figure 9. Forecasts for the increase in demand compared to the baseline indicator (if the plans associated with wind farms and electric vehicles are fulfilled), tons TREO.

4. Discussion

The issues of cross-sectoral development are especially relevant today. Transition trends in the global energy sector are reflected in one way or another in the economy, technology, and the structure of the world. In European countries and the U.S., which have a clear position on green trends, the issues of the critical importance of the materials required to keep up with these trends have been discussed for a long time. The U.S. is looking for ways to meet the country's needs for the necessary raw materials, developing matrices for identifying technologies that will be in highest demand due to the transition to renewable energy sources, and so forth. This study focused on rare-earth metals. This group of metals differs in many respects from others, which is associated with the specifics of the production of these metals. For many countries, they are indeed critical, since their supply is virtually entirely dependent on China. However, the significance of these valuable materials in the case of global energy transition trends is becoming increasingly more obvious, as was determined in this research.

In this research, prospects for REM industry's development were interrelated with the «green» sector. The main assumption was that an increasing demand for eco-friendly technologies will cause a systematic growth of needs for rare earths and the volumes of their consumption. Obviously, these changes may influence REM market tendencies, especially in the case of the most sought-after metals—dysprosium, neodymium, among other. This fact, in turn, might stimulate the development of REM industry, as to achieve necessary high value-added products, not only is mining required, but also processing, refining, and so forth. REM projects are well-known for their knowledge- and capital-intensity. However, we assumed that technologies for REMs extraction and processing will be developed under the pressure of new trends and novel needs. Such factors as governmental regulation and resource potential are also important, but in this research, they were discussed superficially.

The conceptual framework presented in this research is generalized, qualitative, and mostly analytical. The main shortcomings are related to a lack of quantitative indicators and relations to calculate how demand for particular technology may influence the need of certain types of REMs and, eventually, market parameters. We also did not take into account a variety of additional factors which may influence demand for REMs and its formation.

Despite the relevance of the research topic, as mentioned before, there are no scientific studies in Russia devoted to predicting the demand for metals, in particular REMs, in the context of global energy transition trends. This study showed that for the country, the issue of the development of the rare-earth metal sector has been, and still remains controversial. On the one hand, the government is taking measures to develop the national industry; on the other hand, there are no market incentives that can have facilitate this process. In view of this, the question is whether new trends in renewable energy sources and green technologies can act as a driver. To answer this question, predictive estimates were made on the basis of plans approved in Russia for the production of two key technologies requiring the use of rare-earth metals.

The study made assumptions about the average consumption of certain types of rare-earth metals used in the production of green technologies. Not all of these technologies, but only the key ones were considered that form the greatest demand for rare-earth metals, namely, wind-generators and electric vehicles.

It is interesting that while Russia has significant resources, manufacturers of green products are trying to abandon the use of rare-earth elements, considering them too expensive and not readily available. Taking into account the fact that other countries have not yet found materials that could replace these elements in terms of their properties, there is a question of what characteristics the technologies planned for release will have and whether domestic producers will be able to compete with foreign counterparts.

Based on the results of the study, we can conclude that as of today, the green sector of the economy cannot be called a key driver capable of influencing the prospects and incentives for the development of the rare-earth metal industry in Russia. Forecasts for the future demand for rare-earth metals are not comparable with global indicators.

5. Conclusions

Within the framework of this study, current trends in the development of the global energy sector were analyzed, the relationship between the market for rare-earth metals and modern green technologies was determined, and a conceptual framework for the development of the rare-earth metal industry in the context of global energy transition trends was created. A critical analysis of the trends in the Russian energy sector and plans for the development of the green technology industry was carried out, predictive estimates of the future consumption of metals within the framework of the existing plans were made, and conclusions on the future prospects for the development of the REM industry in Russia were formulated.

Based on the results obtained, the following conclusions can be drawn:

1. Global energy transition trends are shaping new development paths for the metal industry in general and the industry of rare-earth metals in particular. Obviously, REMs contribute to the 2030 Agenda as they are part and parcel of the current and future energy sector. It was established that the COVID-19 pandemic only contributed to the transition to renewable energy sources, causing a decrease in demand for traditional energy sources and bigger price volatility in this sector. To produce green technologies, more metals are required, which creates greater demand. In the context of current trends, rare-earth metals have become critical elements for many countries, which is associated with two key factors: (1) high demand, which is partly accounted for by the green technology sector, (2) increased supply risks and limited access to rare-earth metals (monopoly in the global market).
2. It can be concluded that Russia has plans to transform its energy sector. The need for the development of clean energy technologies is reflected at the government level in the Energy Strategy of the Russian Federation for the period up to 2035, a fundamental legal document. Nevertheless, the steps to create green technologies, in particular electric vehicles and wind turbines can be called modest in comparison with the measures taken on a global scale.
3. Forecasts show that there will be no significant growth in the demand for rare-earth metals due to the implementation of plans for the production of green technologies. If these plans are put into practice, the annual growth will not exceed 7% of the current demand. In view of this, answering the question posed at the beginning of the study, we conclude that although global energy transition trends affect the functioning of the energy market and the economy of Russia, they cannot serve as a driver for the progressive development of the national REM industry. The resulting increase in demand can be covered by imports of products, which does not require additional investments in the development of industries with high added value, including the production of neodymium and dysprosium oxides, which are key components in wind turbines.
4. At the same time, assessing the resource potential of Russia in the context of critical materials, we can conclude that the country can make a contribution to support global energy transition trends, competing with China. However, the question of whether the global energy market and new trends will be able to become an impetus for the creation of facilities in Russia to manufacture products requiring rare-earth metals remains to be answered.

Author Contributions: Conceptualization, A.C.; methodology, A.C.; validation, A.C., V.S.; resources, V.S.; data curation, V.S.; visualization, V.S.; supervision, A.C. All authors have read and agreed to the published version of the manuscript.

Funding: The research was performed at the expense of the subsidy for the state assignment in the field of scientific activity for 2021 № FSRW-2020-0014.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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