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# OIL AND GAS COMPANIES ON THE PATHWAY TO CARBON NEUTRALITY: THE ROLE OF RARE-EARTH ELEMENTS

**K. P. Danilin*, N. V. Romasheva, A. A. Cherepovitsyna**

*Luzin Institute for Economic Studies - Subdivision of the Federal Research Centre, Kola Science Centre of the Russian Academy of Sciences, Apatity, Russia*

A B S T R A C T

The cost of sustainable development and achieving carbon neutrality has increasingly become a focus of research. Rare-earth elements are considered critically important to the green economy, as reducing carbon dioxide emissions is challenging without their involvement. This article analyzes various pathways for oil and gas companies to achieve carbon neutrality, with a specific focus on the demand for rare-earth elements. A classification of the primary pathways to carbon neutrality available to oil and gas companies is presented, along with a qualitative assessment of their associated rare-earth elements demand. Reports from leading global and Russian oil and gas companies (by market capitalization) were reviewed to identify the strategies they employ. All pathways to carbon neutrality for oil and gas companies was also classified in terms of rare-earth elements demand for its implementation. However, it was found that calculating the direct demand for rare-earth elements is feasible for wind power projects. Consequently, this study provides calculations of rare-earth elements demand for wind power projects implementation by international (11049.3 tons) and Russian (54 tons) oil and gas companies. Information about these projects and their rated capacity was taken from company reports and other open sources. Additionally, the carbon footprint associated with the mining and processing of the required rare-earth elements for these projects was calculated. For international companies, the carbon footprint is 211196.32 tons of carbon dioxide equivalent, while for Russian oil and gas companies, it is 1033.13 tons of carbon dioxide equivalent.

**Keywords:** REE; pathways to carbon neutrality; greenhouse gas emissions; oil and gas companies; carbon footprint; wind power.

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## 1. Introduction

The problem of greenhouse gas (GHG) emissions has been widely discussed since the late 20th century, gaining momentum with the adoption of the Paris Climate Agreement in 2015 [1].

Companies across various industries have been actively implementing different pathways to carbon neutrality, driven by political regulators [2] and shareholder demands [3]. To date, reporting on GHG Protocol emissions has already become standard practice for most large international corporations [4]. Management incentive programs now include metrics for reducing carbon footprints, and companies themselves set various goals in this area [5]. This is particularly evident for Scope 1 (direct emissions) and Scope 2 (emissions from energy consumption), where consistent standards for disclosure allow for fair comparisons between companies [6].

Oil and gas (O&G) companies stand out as a unique case, as their products represent a challenge for the global low-carbon transition. Exploring pathways to carbon neutrality for such companies is therefore both an important and complex research problem [7].

O&G companies' pathways to carbon neutrality can be classified in various ways, with a particular focus on decarbonization activities aimed at reducing carbon dioxide emissions generated during hydrocarbon production and utilization [8]. Prior studies [9–11] explored key pathways to carbon neutrality available to O&G companies, shedding light on the diverse solutions that are pushing the industry towards low-carbon practices.

O&G companies' efforts to achieve carbon neutrality are increasingly tied to the growing importance of rare-earth elements (REEs). These 17 elements play a critical role in renewable energy systems [12–14]. In the United States, the projected demand for rare-earth oxides ($REE_2O_3$) is expected to increase by 254% to 815% by 2033 compared to 2018 levels, depending on the scenario [15].

China has established itself as the global leader in the production and supply of REEs [16]. This dominance raises concerns about its monopoly and strategic influence [17], given that REEs are essential not only for renewable energy

**E-mail:* k.danilin@ksc.ru

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technologies but also for high-tech industries such as electronics and defense. The concentration of REE production in China has prompted other countries to seek alternative sources and develop strategies for more diversified and secure supply chains [18]. China's monopoly in the REE market poses risks to global stability, including supply chain vulnerabilities, geopolitical risks, and potential disruptions in critical industries worldwide [19–21]. Countries with major REE reserves, such as Russia, have the potential to develop their own REE mining and processing industries to mitigate these risks.

However, from another perspective, the environmental impact, risks, and consequences of mining and processing REEs have sparked active debate in the literature. Some studies highlight uncertainties and gaps in assessing the environmental consequences of REEs in green energy projects [22]. Researchers have analyzed and quantified the environmental damage caused by the extraction, processing, and utilization of REEs for the purposes of renewable energy production. For example, [23] mapped the full lifecycle of $REE_2O_3$ production, illustrating variations in GHG emissions at different production stages in China. Other studies focus on specific extraction methods, such as ion exchange from clays [24], or assess the environmental impacts of heavy REEs [25].

Another comprehensive study [26] evaluating carbon footprints throughout the REE mining-to-materials production chain reveals a substantial contribution of all stages not only to global GHG emissions but also to more localized pollution processes such as acidification and eutrophication. There are also studies assessing the environmental impact of the REE industry from a cost-benefit perspective, where the cost of environmental damage compensation is evaluated. One of them shows that in a worst-case scenario, environmental damage costs could outweigh benefits by $16 billion for China in 2025 [27]. The most comprehensive study on this topic covers a global scope. It provides an assessment of the widest range of contaminants by systems dynamic modeling with deep immersion into hydrometallurgical processes [28]. In this study, a rough estimate indicates that a 1% global increase in renewable energy use results in a 0.9% increase in GHG emissions during the operational period and a 0.18% increase in REE consumption.

This literature review underscores the scientific community's concerns about the negative environmental impacts of REE mining and processing, China's market dominance, and REE prices on the global market. While some studies connect REEs to achieving carbon neutrality – particularly in renewable energy – there is a research gap in linking all possible pathways available to O&G companies to achieve carbon neutrality and their requirements for REEs, as well as in the analysis of data availability for assessing specific pathways' needs for REEs.

The goal of this study is to identify the full spectrum of pathways to carbon neutrality for O&G companies and assess both their REE demand and the availability of data for detailed quantitative evaluation. Specifically, the study calculates REE demand for wind energy projects, as this pathway allows for quantification. The results demonstrate that achieving carbon neutrality involves complex trade-offs, particularly in terms of REE requirements. We should note that this study understands the negative environmental impact of REEs as the carbon footprint from REE mining and processing.

To achieve this goal, the following research questions are posed:

RQ1: What pathways to carbon neutrality for O&G companies require REEs, and what is their overall REE demand? (Qualitative assessment)

RQ2.1: What data is available for a quantitative assessment of REE demand for these pathways?

RQ2.2: What is the REE demand for pathways that can be quantified? (Using wind energy projects as a case study)

RQ3: What is the approximate carbon footprint of REE mining and processing required for O&G companies' wind energy projects?

This study focuses on the largest global and Russian O&G companies in terms of their carbon neutrality plans and measures. Particular attention is given to Russian O&G companies, as research on their carbon neutrality strategies is scarce but increasingly relevant in the context of Russia's partial economic isolation from the global market.

## 2. Materials and methods

To identify all possible pathways for O&G companies to achieve carbon neutrality, we conducted a content analysis of scientific articles sourced from the Science Direct database and Google Scholar. The following search queries were used: «decarbonization options», «decarbonization ways», «decarbonization strategies», «pathways to carbon neutrality», «decarbonization options for oil and gas», and «oil and gas decarbonization». The search was limited to articles published within the past eight years and restricted to relevant subject areas. Methods of analysis and synthesis were employed to examine and interpret the data.

A hierarchical listing technique was used to compile a comprehensive list of pathways to carbon neutrality figure 1. Content analysis, alongside methods of analysis and synthesis, was also applied to describe the essence of each pathway and to evaluate the demand for REEs, categorized as «significant,» «insignificant,» or «highly significant». The results were organized using the analytical table method (table 4). Pathways that did not explicitly require REEs were excluded from the subsequent analysis.

To assess the extent to which O&G companies are utilizing pathways to carbon neutrality that require REEs, content analysis of corporate statements and reports – including sustainability reports – was conducted (Section 3.2). The findings are presented using a checklist method (section 3.2, tables 5 and 6).

The analysis included global and Russian O&G companies ranked by market capitalization [29]. The rationale for focusing on market capitalization is that leading companies are theoretically more likely to have the financial resources required to invest in achieving carbon neutrality (tables 1 and 2).

To analyze the features of pathways to carbon neutrality that require REEs and evaluate their calculability, we used content analysis, methods of analysis and synthesis, and the analytical table method.

For information on wind power projects (WPPs) planned or implemented by global and Russian O&G companies, various sources were examined, including company websites, annual reports, sustainability reports, official statements,

news articles, and press releases.

Basic mathematical methods were used to calculate the specific REE demand for O&G companies' WPP projects. Using the average REE demand per unit of capacity (1 MW of installed gross capacity), the total demand was calculated to enable comparisons of REE requirements across different WPPs.

Three main types of wind power generators (WPG) are typically used in WPPs: gearbox double-fed induction generators (GB-DFIG), gearbox permanent-magnet synchronous generators (GB-PMSG), and direct-drive permanent-magnet synchronous generators (DD-PMSG) [30]. Another option, the direct-drive electrically excited synchronous generator (DD-EESG), is not widely used in the industry and was excluded from this analysis. The demand for REEs varies by WPG type, and the global distribution of these types differs for onshore and offshore WPPs. The REE demand for different WPG types is presented in table 3.

Based on the data from table 3, average coefficients can be calculated (Equation 1) for onshore and offshore WPPs, which will allow for assessing the demand for REE in specific projects.

$$K_r = D_{GBDFIG} \times P_{GBDFIG} \times D_{GBPMSG} \times P_{GBPMSG} \times \times D_{DDPMSG} \times P_{DDPMSG} \quad (1)$$

where $D_{GBDFIG}$ – REE demand per MW for GB-DFIG (t/MW); $P_{GBDFIG}$ – average GB-DFIG share in WPPs; $D_{GBPMSG}$ – REE demand per MW for GB-PMSG (t/MW); $P_{GBPMSG}$ – average GB-PMSG share in WPPs; $D_{DDPMSG}$ – REE demand per MW for DD-PMSG (t/MW); $P_{DDPMSG}$ – average DD-PMSG share in WPPs. Kr for onshore WPPs is 0.0645 t/MW and for offshore is 0.1905 t/MW, which will be used for further calculations (Equation 2).

$$D_{ree} = K_r \times GC_{wt} \quad (2)$$

where $D_{ree}$ – the demand for REE in the current WPP (t); $K_r$ – the average specific REE demand for permanent magnets in WPPs (t/MW); $GC_{wt}$ – gross capacity of the current WPP (Mwt)

To calculate the carbon footprint of REE mining and processing for WPP projects in the selected O&G companies (Section 3.3), we performed content analysis of scientific articles sourced from ScienceDirect and Google Scholar. The search queries included: «REE environmental impact», «REE in green energy», «REE carbon footprint», «Rare earths carbon footprint», and «Rare earths in wind power». Articles published since 2021 containing relevant data on WPPs, REE content, and the carbon footprint of REE extraction and processing were selected. Methods of analysis, synthesis, and basic mathematical calculations were used to estimate the carbon footprint associated with REE mining and processing for the O&G companies' WPP projects.

**Table 1**

**Global O&G companies ranked by market capitalization (January 2024)**

| O&G Company | MarketCAP, billion $ | Country |
|---|---|---|
| Saudi Aramco | 2,062.00 | S. Arabia |
| Exxon Mobil | 399.47 | USA |
| Chevron | 278.00 | USA |
| Shell | 207.55 | UK |
| PetroChina | 179.60 | China |
| TotalEnergies | 155.88 | France |
| ConocoPhillips | 132.63 | USA |
| Petrobras | 105.96 | Brazil |
| BP | 99.54 | UK |

*Source: compiled by the authors based on [29]*

**Table 2**

**Russian O&G companies ranked by market capitalization, (January 2024)**

| O&G Company | MarketCAP, billion $ |
|---|---|
| PJSC Rosneft Oil Company | 52.21 |
| PJSC Gazprom | 73.26 |
| PJSC Novatek | 46.65 |
| PJSC Lukoil | 39.92 |
| PJSC Surgutneftegas | 14.53 |
| PJSC Tatneft | 14.35 |

*Source: compiled by the authors based on [29]*

**Table 3**

**REE demand for different WPG types per 1 MW of gross capacity**

| WPG type | REE demand per 1 Mwt (D) | Average share of the WPG type in onshore WPPs (P) | Average share of the WPG type in offshore WPPs (P) |
|---|---|---|---|
| GB-DFIG | 15 kg | 70% | 10% |
| GB-PMSG | 60 kg | 10% | 15% |
| DD-PMSG | 240 kg | 20% | 75% |

*Source: compiled by the authors based on [29]*

## 3. Results and discussion

### *3.1 Pathways to carbon neutrality for O&G companies in terms of REE*

To assess the demand for REEs, the study first identified the primary pathways through which O&G companies aim to achieve carbon neutrality. These pathways were classified based on their relationship to production processes figure. This classification framework enabled a clear organization of carbon neutrality strategies into two levels: operational and corporate. It also provided a comprehensive overview of the pathways used.

Previous studies often classified pathways based on production cycle stages (upstream, midstream, and downstream). While helpful, this approach risks duplication, as the same pathways may be attributed to multiple stages [11].

The first group includes pathways aimed at preventing or reducing carbon dioxide emissions during the production, transportation, processing, and storage of hydrocarbons. These pathways allow O&G companies to align with decarbonization goals while maintaining hydrocarbon production.

The second group involves pathways unrelated to hydrocarbon extraction, transportation, and processing. These focus on restructuring project portfolios, such as reducing oil

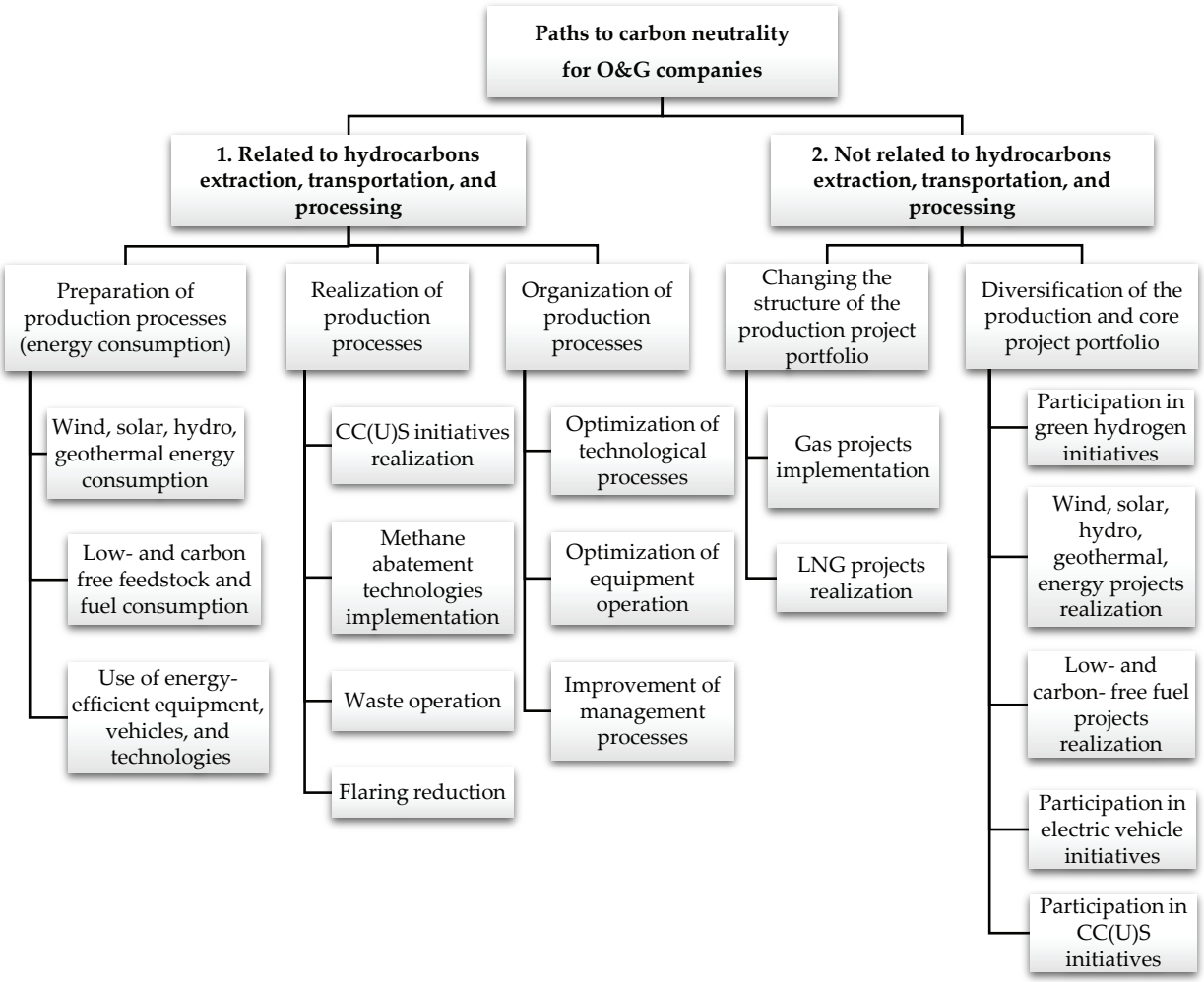


**Fig. Basic pathways to carbon neutrality for O&G companies**
**(***Source: Compiled by the authors based on [10, 11]***)**

production, increasing natural gas or liquefied natural gas (LNG) production, or diversifying into new areas like renewable energy and low-carbon fuels.

Diversification of the core project portfolio includes participation in renewable energy projects, low-carbon or carbon-free fuel initiatives, green and blue hydrogen projects (often combined with carbon capture, utilization, and storage (CC(U)S), and electric vehicle initiatives.

In the next stage of the research, the demand for REEs along pathways to achieve carbon neutrality was evaluated and categorized as significant, insignificant, or highly significant.

The distinction between «significant» and «insignificant» lies in the role of REEs in the pathway. REE demand is classified as significant if it is essential to the carbon neutrality pathway. In contrast, REE demand is classified as insignificant if REEs are used only as components in conventional construction materials or auxiliary technologies, such as alloys, electronic devices, or transport systems. Highly significant demand denotes pathways where current technologies rely on REEs as critical materials for their practical implementation.

Since some pathways to carbon neutrality overlap in terms of their technological essence, particularly those involving production processes and project portfolio diversification, they were combined in the table. For instance, the use of renewable energy sources and diversification into these sources are closely related. Among renewable energy sources, wind and solar energy were highlighted as the most widely adopted pathways [31]. Additionally, since green hydrogen production depends on wind and solar energy, the REE requirements for this area are identical. The results are summarized in table 4.

Table 4 O&G companies' pathways to carbon neutrality and the demand for REEs

The results presented in table 4 indicate that the majority of pathways to carbon neutrality require some level of REE utilization. However, the specific demand varies significantly depending on the nature of the project. The highest demand for REEs, with limited or no viable alternatives, is observed in projects involving a transition to renewable energy sources (particularly wind power plants) and the adoption of electric vehicles for operational purposes. For these technologies, REEs are indispensable.

### *3.2 Demand for REEs: Global and Russian O&G companies' pathways to carbon neutrality*

The pathways to carbon neutrality adopted by global and Russian O&G companies are summarized in tables 5 and 6. These tables include pathways where the demand for REEs is classified as significant or highly significant, as outlined in table 4.

Table 4

O&G companies' pathways to carbon neutrality and the demand for REEs

| Pathways to carbon neutrality | Description | The demand for REEs | REE | Alternatives without much REE required | Comments |
|---|---|---|---|---|---|
| Wind energy consumption and diversification by WPP | Utilization of renewable energy, either produced by the O&G company or purchased externally, for primary and auxiliary infrastructure facilities, as well as in the production, processing, and storage of hydrocarbons. Participation in or implementation of renewable energy projects for external sale, with potential partial use for internal needs. | Highly significant | Nd, Dy, Pr | Using electromagnets (multiplies the cost of energy) | Permanent magnets are used as an essential component of most modern WPGs. Permanent magnets require a lot of REEs [32]electrified transport and LED-lights. The new technologies have led to swiftly expanding markets for REE products, in which China has achieved a monopolistic role in all segments of the REE value chains. Political strategies aimed to establish REE supplies outside China are currently being implemented within the EU and in other Western countries in order to ensure an adequate future REE supply. However, new REE value chains outside China have not yet materialised. The aim of this paper is to assess whether the global REE supply from present and potential mines can keep pace with the REE demand for the expanding offshore wind energy sector (fig. 1) |
| Solar energy consumption and diversification by solar energy projects | | Significant | Yb, Sc | Monocrystal silicon cells, organic cells, polycrystal silicon cells | Some types of solar photovoltaic cells depend heavily on REE complexes [33]. However, there are other types of solar panels that are not so dependent on REEs |
| Hydro and geothermal energy consumption and diversification by hydro or geothermal energy projects | | Insignificant | - | - | - |
| Low- and carbon-free feedstock and fuel consumption and diversification by low- and carbon-free fuel projects | Adoption of LNG, liquefied petroleum gas, biofuels, methanol, blue hydrogen, and ammonia in marine logistics operations. Use of biofuels as low-carbon fuel components in transportation and as feedstock in oil refining and petrchemical processes. Utilization of natural gas as vehicle fuel. Participation in or imple-mentation of low- and carbon-free fuel projects for external sale, with possible partial use for internal needs. | Significant | La, Ce, Nd, Pr | Alternative catalysts without the use of REEs (noble metals, etc.) | REEs can be used as catalysts in biofuels [34] and blue hydrogen [35] |
| Use of energy-efficient equipment, vehicles, and technologies and diversification by means of electric vehicle initiatives | Modernization of industrial equipment to reduce energy consumption, including the deployment of energy-efficient systems at infrastructure facilities. Use of marine and land vehicles with improved energy efficiency. Implementation of resource-saving technologies in hydrocarbon production and processing. Replacement of logistics vehicles with electric vehicles. Participation in or implementation of electric vehicle initiatives for external sale, with possible partial use for internal needs. | Significant | Nd, Dy, Pr, Sm | Using electromagnets (multiplies the cost of engine production) | Electric vehicles engines require a lot of REEs because of the use of permanent magnets [36] |

Table 4 continued

| Pathways to carbon neutrality | Description | The demand for REEs | REE | Alternatives without much REE required | Comments |
|---|---|---|---|---|---|
| CC(U)S initiatives realization or diversification by such initiatives | Capturing carbon dioxide emissions at the company's industrial infrastructure or other facilities for enhanced oil recovery or conversion into valuable products. | Insignificant | - | - | - |
| Methane abatement technologies implementation | Use of methane leak detection and elimination technologies across all stages of the hydrocarbon production cycle. Introduction of equipment designed to minimize methane emissions. | Significant | La, Ce, Nd, Pr | Alternative catalysts without the use of REEs (noble metals, etc.) | REEs can be used as catalysts [37] |
| Waste operation | Reuse of hydrocarbon production and processing waste in the production process. Introduction of technologies aimed at reducing the volume of waste generated. | Significant | La, Ce, Nd, Pr | Alternative catalysts without the use of REEs (noble metals, etc.) | In oil refinery waste management, REEs can be used as catalysts in thermochemical conversion, photocatalysis, and thermal desorption [38] |
| Flaring reduction | Electricity generation for internal needs or supply to the power grid. Processing of associated petroleum gas (APG) at gas plants or small field units to produce propane-butane fractions and condition residual gas. Chemical processing of APG. | Significant | La, Ce, Nd, Pr | Alternative catalysts without the use of REEs (noble metals, etc.) | REEs can be used as catalysts [39] |
| Optimization of technological processes | Automation, digitalization of production processes. Rational organization of production processes | Insignificant | - | - | - |
| Optimization of equipment operation | Minimizing production equipment downtime. Elimination of errors when choosing key production equipment. Ensuring rational spatial arrangement of equipment. | | | | |
| Improvement of management processes | Increasing the responsibility and competence of performers. Introduction of a quality management system and lean production principles. | | | | |
| Gas projects implementation | Substitution of oil production by increasing the share of natural gas production. | Insignificant | - | - | - |
| LNG projects realization | Substitution of oil production by increasing the share of LNG production. | Insignificant | - | - | - |

*Source: Compiled by the authors based on [10, 11, 32–39]*

**Table 5**
**Pathways to carbon neutrality declared by the largest global O&G companies**

| Company/ Pathway to carbon neutrality | Wind energy | Solar energy | Low-carbon feedstock and fuel consumption | Use of energy-efficient equipment, vehicles, technologies | Methane abatement | Waste operation | Flaring reduction |
|---|---|---|---|---|---|---|---|
| Saudi Aramco | + | + | + | + | + | + | + |
| Exxon Mobil | + | + | + | + | + | + | + |
| Chevron | + | + | + | + | + | + | + |
| Shell | + | + | + | + | + | + | + |
| PetroChina | - | + | + | + | + | + | + |
| TotalEnergies | + | + | + | + | + | + | + |
| ConocoPhillips | + | - | + | + | + | + | + |
| Petrobras | + | + | + | + | + | + | + |
| BP | + | + | + | + | + | + | + |
| TAQA | - | + | + | + | + | + | + |

*Source: compiled by the authors based on [40, 41, 50–52, 42–49]*

**Table 6**
**Pathways to carbon neutrality declared by Russian O&G companies**

| Company/ Pathway to carbon neutrality | Wind energy | Solar energy | Low-carbon feedstock and fuel consumption | Use of energy-efficient equipment, vehicles, technologies | Methane abatement | Waste operation | Flaring reduction |
|---|---|---|---|---|---|---|---|
| PJSC Rosneft Oil Company | + | + | + | + | + | + | + |
| PJSC Gazprom | + | + | + | + | + | + | + |
| PJSC Novatek | + | + | + | + | + | + | + |
| PJSC Lukoil | + | + | ' | + | + | + | + |
| PJSC Tatneft | + | + | + | + | + | + | + |

*Source: compiled by the authors based on [53–58]*

**Table 7**
**Features of the paths to carbon neutrality that require REE and their quantification possibility**

| Pathways to carbon neutrality | Features | Calculability of the demand for REEs |
|---|---|---|
| Wind energy | These types of energy are actively used in O&G fields and production facilities by global O&G companies, with significant potential for further integration. These technologies are well-tested, and both capital and production costs are decreasing. Many companies plan to replace traditional energy sources with renewable ones. | Possible based on the open data |
| Solar energy | | There are difficulties in calculating |
| Low-carbon feedstock and fuel consumption | The use of blue hydrogen and ammonia holds promise but remains in its early stages of development. Hydrogen-ammonia cell technologies are not yet mature, and high capital and production costs limit their immediate application. Similarly, biofuels for operational processes may only become feasible in the future. Few companies are actively involved in electric vehicle initiatives. | The potential for use is not clear. There are difficulties in calculating |
| Use of energy-efficient equipment, vehicles, and technologies | The adoption of electric vehicles in logistics and operations by O&G companies is seen as a potential pathway to reducing carbon emissions. However, experts debate the viability of this approach due to the immaturity of the technologies and their high capital and operational costs. Only a few companies are currently implementing such initiatives. | The potential for use is not clear. Possible based on the open data |
| Methane abatement | O&G companies have significant experience in addressing methane emissions. These technologies are widely utilized and have relatively low capital and operating costs. Given the scale of methane emissions, their reduction is viewed as a major contributor to carbon neutrality efforts. | There are difficulties in calculating |
| Waste operation | Waste management is an area where O&G companies have considerable expertise. Technologies are actively used and generally cost-effective, though some are not yet economically efficient. Companies are exploring innovative waste recycling solutions, making this a promising pathway to carbon neutrality. | There are difficulties in calculating |
| Flaring reduction | O&G companies have long been adopting technologies to reduce emissions from flaring. These solutions are actively implemented and relatively cost-effective, though some methods are not economically optimal. Companies often prioritize the least expensive option. Nevertheless, this pathway is considered to be promising. | There are difficulties in calculating |

*Source: compiled by the authors based on [32–39]*

**Table 8**

**REE demand in global O&G companies' WPP projects**

| Company | Location | Project (Group of projects) | Type of project | Gross capacity, MW | Average demand for REE, t |
|---|---|---|---|---|---|
| Saudi Aramco | S. Arabia | National Renewables Program | offshore | 9500 | 1809.75 |
| Exxon Mobil | USA, Texas and Oklahoma | North Central Wind Energy | onshore | 1794 | 115.713 |
| | Belgium | Wind4Flanders | onshore | 26 | 1.677 |
| Chevron | USA, Wyoming | Casper Wind Farm | onshore | 16.5 | 1.06425 |
| Shell | Netherlands | HollandseKust Noord | offshore | 759 | 144.5895 |
| | Netherlands | Egmondaan Zee | offshore | 108 | 20.574 |
| | USA | Atlantic Shores Offshore Wind | offshore | 1500 | 285.75 |
| | USA | SouthCoast Wind | offshore | 2200 | 419.1 |
| TotalEnergies | Portugal | Pinhal Interior | onshore | 144 | 9.288 |
| | UK, Scotland | Seagreen | offshore | 1100 | 209.55 |
| | USA | Attentive Energy One | offshore | 1400 | 266.7 |
| | USA | Carolina Long Bay | offshore | 1000 | 190.5 |
| | Brazil | Rio do Vento | onshore | 1038 | 66.951 |
| | UK | West of Orkney | offshore | 2000 | 381 |
| | Taiwan | Formosa 3 | offshore | 2000 | 381 |
| | Kazakhstan | Mirny | onshore | 1000 | 64.5 |
| | Taiwan | Yunlin | offshore | 640 | 121.92 |
| ConocoPhillips | China | Shandong Penglai Oilfield Offshore wind farm | offshore | 34 | 6.477 |
| Petrobras | Brazil | Ibama | offshore | 14000 | 2667 |
| BP | US | Empire Wind | offshore | 2100 | 400.05 |
| | US | Beacon Wind | offshore | 2400 | 457.2 |
| | Germany | 2 potential projects | offshore | 4000 | 762 |
| | S. Korea | 4 potential projects | offshore | 6000 | 1143 |
| | UK | Morven field | offshore | 3000 | 571.5 |
| | UK | Morgan and Mona field | offshore | 2900 | 552.45 |
| TOTAL | | | | | 11049.3 |

*Source: compiled and calculated by the authors based on [49, 62–69]*

Major global O&G companies have outlined plans to reduce flaring emissions and methane emissions into the atmosphere. Nearly all of the analyzed companies employ technologies aimed at improving energy efficiency, utilizing low-carbon feedstock and fuel, and optimizing waste operations. Additionally, most companies are actively involved in developing renewable energy projects, both to meet their own energy needs and for commercial purposes.

Russian O&G companies primarily focus on pathways such as improving energy efficiency, reducing flaring, and minimizing methane leakage. Some Russian companies, including PJSC Lukoil and PJSC Gazprom, have also incorporated solar and wind energy to meet internal energy demands. While PJSC Lukoil's portfolio includes small-scale renewable energy projects for sale, its activities in renewable energy remain limited compared to those of major global O&G companies.

Table 7 provides details on the characteristics of the pathways to carbon neutrality and the potential for calculating REE demand.

As shown in table 7, calculating REE demand for most pathways is challenging due to limited data. These pathways primarily rely on standard materials, with REEs forming only a small fraction of the total composition [59, 60]. Publicly available information, including details on catalysts, is sparse, making precise calculations difficult.

One exception is wind energy, which critically depends on permanent magnets composed of significant REE quantities. Permanent magnets in WPPs require 29-34 % REEs by weight [61]. Given the widespread use of WPPs by O&G companies as a pathway to carbon neutrality, their REE demand is quantifiable.

Table 8 and table 9 present data on WPP projects planned or implemented by global and Russian O&G companies, as well as the average REE demand for permanent magnets (see the «Materials and Methods» section for calculation details).

Based on open-source data on the production capacities of selected companies, approximate calculations indicate that the largest global O&G companies will require 11049.3 tons of REEs, while Russian O&G companies will need 54.051 tons to install or replace equipment for their WPP projects.

**REE demand in Russian O&G companies' WPP projects** — Table 9

| Company | Location | Project (Group of projects) | Type of project | Gross capacity, MW | Average demand for REE, t |
|---|---|---|---|---|---|
| PJSC Rosneft Oil Company | Russia | Wind energy park as part of the Vostok Oil project | onshore | 200 | 12.9 |
| PJSC Gazprom | Russia | Arctic WPP in the Varandey settlement | offshore | No data | - |
| | Serbia | Green energy generation cluster | onshore | 100 | 6.45 |
| PJSC Novatek | Russia | WPP in the Sabetta settlement | | 200 | 12.9 |
| PJSC Lukoil | Russia | Kola Wind Farm | onshore | 202 | 13.029 |
| | Russia | Azov WPP | onshore | 90 | 5.805 |
| | Russia | Rodnikovskaya WPP | onshore | 71 | 4.5795 |
| | Azerbaijan | Offshore WPP | offshore | No data | - |
| PJSC Tatneft | Russia | WPP in Sorochie Gory | onshore | 75 | 4.8375 |
| | Russia | Krasnovidovo WPP | onshore | 50 | 3.225 |
| | Russia | Izmeri WPP | onshore | 50 | 3.225 |
| TOTAL | | | | | 54.051 |

*Source: compiled and calculated by the authors based on [70–79]*

### *3.3 Carbon footprint of REE use in WPP projects*

To estimate the carbon footprint associated with REE mining and processing for WPP projects, the carbon footprint for each REE element in permanent magnets must be calculated. On average, permanent magnets consist of: 75% neodymium (Nd), 14% praseodymium (Pr), 7% dysprosium (Dy), and about 4% terbium (Tb) [80].

At the extraction stage, REEs are not yet separated. The total carbon footprint for all REE extraction in 2020 was 152973 $tCO_2e$ [28], with an extraction volume of 240000 tons [81]. It means that at the extraction stage, 0.63 tons of $CO_2$ equivalent (CFmi) is produced per ton of REE. Table 10 presents the results of calculating the carbon footprint for each considered REE element.

To calculate the average carbon footprint resulting from the mining and processing of 1 t of REE required in permanent magnets, we will use the following equation:

$$CF_{PM} = CF_{mi} + CF_{Nd} \times 0.75 + CF_{Pr} \times 0.14 + \\ + CF_{Dy} \times 0.07 + CF_{Tb} \times 0.04 \quad (3)$$

where $CF_{PM}$ – average carbon footprint resulting from the mining and processing of 1 t of REE ($tCO_2e/t$); $CF_{mi}$ – average carbon footprint resulting from the mining of 1 t of REE ($tCO_2e/t$); $CF_{Nd}$ – average carbon footprint resulting from the processing of 1 t of Nd ($tCO_2e/t$); $CF_{Pr}$ – average carbon footprint resulting from the processing of 1 t of Pr ($tCO_2e/t$); $CF_{Dy}$ – average carbon footprint resulting from the processing of 1 t of Dy ($tCO_2e/t$); $CF_{Tb}$ – average carbon footprint resulting from the processing of 1 t of Tb ($tCO_2e/t$).

After completing the calculations using data from table 10, CFPM=19.114. This result allows us to calculate the carbon footprint resulting from the mining and processing of REE for use in WPPs of global and Russian O&G companies, using the calculations from Section 3.2 (211196.32 $tCO_2e/t$ for global O&G companies and 1033.13 $tCO_2e/t$ for Russian O&G companies)

### *3.4 Discussion*

The key pathways to carbon neutrality were classified according to their relevance to O&G companies' production processes. This approach helped identify pathways requiring REEs for their implementation. For global and Russian O&G companies – the leaders in market capitalization – we compiled a list of carbon neutrality pathways by analyzing corporate reports. These findings build on previous work by several key authors [8, 28, 30].

All pathways to carbon neutrality were classified based on the feasibility of calculating REE demand (table 7). A sig-

**Carbon footprint of processing neodymium, praseodymium, dysprosium, and terbium** — Table 10

| | Global carbon footprint for element processing 2020, $tCO_2e$ | Global estimated production of selected REE elements in 2020 | Carbon footprint per one ton of processed element, $tCO_2e/t$ (CF) |
|---|---|---|---|
| Neodymium | 729,716 | 39,600 | 18.42 |
| Praseodymium | 185,549 | 7,390 | 25.1 |
| Dysprosium | 60,887 | 3,690 | 16.5 |
| Terbium | 24,853 | 2,110 | 11.77 |

*Source: compiled by the authors based on [28, 80–82]*

nificant limitation emerged, as it was only possible to calculate REE demand with sufficient accuracy for WPPs.

This study stands out for its focus on REE requirements specific to O&G companies' decarbonization efforts. However, the findings underscore a major gap: the reporting frameworks currently used by O&G companies provide only general insights. When more specialized data is required, such as REE consumption, it becomes evident that information is scarce or unavailable.

Planned and ongoing WPP projects by global and Russian O&G companies were identified, and general REE demand estimates were calculated. Open-source information was used to compile this list, and while we acknowledge that it may not be exhaustive, it provides a solid foundation for understanding REE demand. A limitation of this method is its reliance on the current distribution of WPG types, which may evolve over time. Numerous studies highlight innovative WPG designs [83–85], suggesting that future WPG configurations could alter REE demand. However, given the lengthy timeline for commercializing new designs, we consider it reasonable to assume that current WPG technologies will dominate in the medium term.

This study specifically focused on REE demand for the key component of modern industrial WPGs: permanent magnets. While this method excludes standard materials used in large-scale WPP construction, it provides an initial estimate of REE demand. A key limitation is that the analysis assumes the use of currently dominant permanent magnet types. Ongoing innovations in magnet technology may eventually require adjustments to the methodology and results.

The study also assessed the carbon footprint associated with the extraction and processing of REEs required for WPP by global (211196.32 $tCO_2e$) and Russian (1033.13 $tCO_2e$) O&G companies. However, these figures represent only a fraction of the total carbon footprint of WPP construction and operation. They do not include transportation, magnet manufacturing, turbine construction, or infrastructure development. Nonetheless, these calculations provide a basis for estimating the full carbon footprint of specific WPP projects, highlighting their significance for future research.

## Conclusions

The research can be summarized by the following conclusions:

1. This study provides a detailed analysis of pathways to carbon neutrality in the O&G sector, with a specific emphasis on the critical role of REEs. Approximately 11049 tons of REEs are required to support global O&G WPP projects alone, accounting for 3.15% of global REE output in 2023. This underscores the strategic importance of REEs in achieving carbon neutrality targets but also highlights a significant vulnerability: global dependence on China for REE supply. China currently dominates the REE market, controlling over 70% of global production and nearly 90% of processing capacity. This monopoly poses substantial geopolitical and economic risks to O&G companies and other industries dependent on REEs. These risks have prompted countries to explore alternative REE sources, enhance the recycling of end-of-life REE products, and invest in the development of substitute materials.
2. The study also highlights disparities in REE reliance between global and Russian O&G companies. While Russian projects demand only 54 tons of REEs – 1.5% of the total required by 10 global companies – this still poses challenges. Despite Russia's annual REE production of 2600 tons [86], the country lacks a full-cycle REE production process and remains dependent on imports, primarily from China. Given Russia's limited renewable energy capacity and reliance on alternative decarbonization pathways, its O&G sector faces less immediate exposure to REE supply risks. However, as global carbon neutrality efforts intensify, Russia will need to address its access to REEs, scale up domestic production, or develop alternative technologies.
3. The findings also reveal shortcomings in current corporate reporting practices. Transparency on REE use and associated environmental impacts is limited, hindering comprehensive life cycle analyses of carbon-neutral technologies. For example, the carbon footprint of REE mining and processing – estimated at 211196 $tCO_2e$ for global companies – represents a significant environmental cost that is often overlooked in corporate disclosures. The lack of consistent data prevents stakeholders from fully evaluating the sustainability of carbon-neutral initiatives.

This study contributes valuable insights into the intersection of REE demand and carbon neutrality within the O&G sector. Future research should refine REE demand calculations as corporate reporting improves, while also exploring alternative materials and technologies that support more sustainable and resilient pathways to carbon neutrality.

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