Leveraging PEMEX Offshore Assets for Rare Earth Element (REE) Mining and Renewable Energy Expansion

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Global Renewable Energy Transition

ABSTRACT: This paper explores how PEMEX, Mexico's state-owned petroleum company, can capitalize on its offshore infrastructure and expertise in deep-water exploration to transition into the mining of rare earth elements (REEs) and the development of alternative magnet technologies, such as ferrite-based solutions. These materials are crucial for the production of permanent magnets, especially in offshore wind turbines. As global wind energy demand is set to surge by 2050, PEMEX stands to significantly diversify beyond oil and gas by repurposing its offshore assets and collaborating in strategic partnerships. The paper also discusses PEMEX's ability to tap into innovations like REE recycling and ferrite-based alternatives, ensuring long-term profitability in the renewable energy sector.

In addition to REE mining, the revenue potential for PEMEX from 2024 to 2036 could be substantial. With the global offshore wind market projected to grow from $15.4 billion in 2023 to over $31.7 billion by 2030, PEMEX could capture up to $1–3 billion annually through REE extraction. Coupled with strategic partnerships and adoption of ferrite magnets, PEMEX's cumulative revenue could reach between $10 billion and $36 billion over this period. By leveraging oil fields such as Cantarell and Ku-Maloob-Zaap, PEMEX can effectively repurpose aging infrastructure, supporting both resource extraction and offshore wind energy projects, thereby solidifying its role in the global renewable energy transition.

1. INTRODUCTION

As the world shifts towards a renewable energy future, rare earth elements (REEs) have become critical components in the production of technologies like wind turbines, electric vehicle motors, and other clean energy solutions. With their unique magnetic and conductive properties, REEs such as neodymium, dysprosium, and samarium are crucial in manufacturing permanent magnets used in direct-drive wind turbines, which are increasingly preferred in offshore energy installations. According to industry forecasts, the direct drive wind turbine market was valued at $15.4 billion in 2023, and is estimated to reach $31.7 billion by 2030, growing at a CAGR of 10.9% from 2024 to 2030 (Mahajan and Prasad, Sept 2024).

The oil and gas industry, particularly PEMEX (Petróleos Mexicanos), Mexico's state-owned petroleum company, is strategically positioned to play a significant role in this growing demand for REEs. This paper explores how PEMEX can leverage its vast offshore assets and deep-sea expertise to develop REE mining infrastructure, diversity its revenue streams, and participate in the global renewable energy transition.

2. THE IMPORTANCE OF RARE EARTH ELEMENTS IN RENEWABLE ENERGY

Rare earth elements are indispensable for the development of clean energy technologies. They are essential for the production of high-performance permanent magnets used in wind turbines, electric vehicles (EVs), and other advanced energy technologies. In particular, neodymium-based magnets are crucial for direct-drive turbines that eliminate the need for a gearbox, reducing weight and maintenance, and improving efficiency in offshore environments. Offshore wind farms benefit significantly from these technologies, which can operate efficiently in harsh marine conditions.

2.1. The Critical Role of REEs in Wind Turbine Technology

Wind energy is increasingly being viewed as one of the primary solutions to the world's energy needs, particularly as global carbon reduction targets are enforced. Rare earth elements (REEs), including neodymium, praseodymium, and dysprosium, play a pivotal role in this sector, particularly in the manufacture of high-performance permanent magnets that are essential for wind turbines. These permanent magnets enable smaller, more efficient turbine designs, enhance grid connectivity, and reduce the need for frequent maintenance, making them critical for both onshore and offshore wind installations.

2.2. Wind Turbines: The Technology Behind the Revolution

Permanent magnets are integral to the design of direct-drive wind turbines, which eliminate the need for a gearbox. This design not only reduces the overall weight and size of the turbines but also significantly lowers maintenance costs — an essential feature in offshore environments where harsh conditions make frequent maintenance more challenging and expensive.

Offshore wind farms benefit greatly from direct-drive turbines that use permanent magnets. These turbines can withstand extreme marine environments while providing efficient energy conversion, making them highly suitable for offshore energy production. According to the International Renewable Energy Agency (IRENA), global offshore wind capacity is expected to expand from 35 GW today to over 2,000 GW by 2050 (IRENA, 2022). Achieving these capacity levels requires a robust supply of rare earth elements, particularly for the manufacture of magnets in offshore turbines.

2.3. Increasing Demand for REEs and Global Supply Challenges

As the world moves toward renewable energy, the demand for REEs, particularly in wind energy, will surge. Meeting 2050 energy goals requires a significant increase in REE production, estimated to rise by 11 to 26 times current levels (Li et al., 2020). China, the largest REE producer, is projected to see neodymium demand increase 18 times, equaling 3.3% of total reserves by 2050 (Ren et al., 2021).

However, as REE prices remain volatile, alternative materials like ferrite magnets are emerging as viable solutions. Ferrite magnets, although heavier and less power-dense, offer cost stability and environmental advantages. According to Prakht et al. (2020), ferrite-based flux-switching generators demonstrate 4.1% higher efficiency in some applications, making them a competitive and sustainable option. By incorporating ferrite technology, PEMEX can diversify its material reliance, ensuring a balanced approach between cost-effective solutions and REE supply. This diversification will position PEMEX to adapt to global supply constraints while maintaining its leadership in renewable energy technology.

2.4. Differences in Wind Turbine Design and REE Use

Wind turbines can broadly be classified into direct-drive and gearbox-driven designs.

The key difference between these types lies in their generator design, which influences their material content, speed, and mass:

- **Direct-drive turbines:** These turbines use permanent magnets and do not require a gearbox. They are often lighter and more compact, making them more suitable for offshore environments where minimizing weight and maintenance is critical.
- **Gearbox-driven turbines:** These turbines are typically used in offshore installations and can either employ permanent magnet generators or high-speed induction generators with multi-stage gearboxes. While these designs have historically dominated onshore wind markets, they are less competitive in offshore settings due to their weight and the need for regular maintenance.

Permanent magnet turbines already drove about 75% of the world's offshore installations in 2018, while gearbox induction generator turbines dominated the onshore market with a 52% share (Carrara et al., 2020).

2.5. Innovative Alternatives: Ferrite Magnets in Wind Turbines

As PEMEX explores its role in renewable energy, it is crucial to consider emerging technological alternatives to rare earth elements (REEs). One such innovation is the use of ferrite-based flux-switching generators (FSGs) in wind turbines. Ferrite magnets, as demonstrated in Prakht et al. (2020), provide a more cost-effective and environmentally friendly option compared to traditional rare-earth magnets, with a 4.1% higher efficiency in some applications.

The use of ferrite magnets, while requiring more physical space due to their size and weight (2.4 times heavier than rare-earth magnets), offers substantial benefits in terms of cost stability and reduced environmental impact. Ferrite magnets are far cheaper and widely available, mitigating the challenges of volatile pricing and supply chain disruptions that rare-earth magnets face. Prakht et al. (2020) showed that while rare-earth magnets provide higher power densities, ferrite magnets can still perform competitively, especially when optimized through modern techniques like the Nelder-Mead optimization algorithm.

For PEMEX, adopting ferrite-based technology in offshore wind turbines could be a game changer, offering a dual benefit of cost-efficiency and sustainability. The integration of these magnets into PEMEX’s offshore wind projects could position the company as a leader in innovative, cost-conscious renewable energy solutions.

2.6. Transitioning to New Materials for Sustainability

PEMEX’s existing offshore expertise provides a strong foundation for both REE mining and wind turbine development. By incorporating ferrite magnets into wind turbine designs, PEMEX can significantly reduce its reliance on REEs, aligning with global trends towards supply chain diversification and environmental responsibility. This transition to alternative materials not only strengthens PEMEX's role in the energy transition but also positions the company as a forward-thinking leader in sustainable resource utilization.

3. LEVERAGING PEMEX's OFFSHORE ASSETS FOR REE MINING

Pemex operates numerous offshore oil platforms in the Gulf of Mexico (GoM), including major assets such as Cantarell and Ku-Maloob-Zaap, two of the world's largest offshore oil fields. These platforms are equipped with the infrastructure required for resource extraction and transportation, making them prime candidates for repurposing or adaptation for deep-sea REE mining.

- **Repurposing Aging Oil Platforms:** As some of PEMEX's older oil platforms near the end of their productive life for petroleum extraction, they could be

repurposed for REE exploration and extraction. Converting these platforms for mineral extraction, particularly in the deeper waters of the Gulf, could help PEMEX diversify its operations and extend the useful life of its offshore assets.

- **Logistical Hubs:** PEMEX's offshore infrastructure already functions as logistical hubs, with transportation routes established for the movement of oil, gas, and other resources. These same routes can be leveraged for the transportation of rare earth minerals, linking offshore extraction sites with onshore processing facilities in Mexico.

3.1. Expertise in Deep-Water Drilling and Exploration

PEMEX's long-standing expertise in deep-water drilling and exploration is critical for identifying and extracting REEs from subsea mineral deposits. Technologies such as seismic surveying and subsea robotic exploration, which are already in use for oil exploration, can be applied to located REE-rich deposits on the ocean floor. In particular, polymetallic nodules, which contain significant concentrations of REEs, can be found in deep-sea environments, including the GoM.

- **Seismic Surveying for REE Deposits:** The same seismic technology used by PEMEX to map oil reserves can be adapted to detect REE deposits in the Mexican Exclusive Economic Zone (EEZ), which covers 3,269,386 square kilometers of significant offshore areas. This capability will be essential as PEMEX explores the possibility of expanding into REE extraction.
- **Robotic Exploration and Deep-Sea Mining:** With the increasing potential of deep-sea mining, PEMEX can leverage its experience in subsea robotics and autonomous underwater vehicles (AUVs) for REE extraction. These technologies can enable PEMEX to conduct environmentally responsible mining in offshore areas, potentially reducing the environmental impact compared to land-based mining operations.

3.2. Offshore Wind Energy Integration

As the global offshore wind energy sector grows, PEMEX can play a dual role by supporting both REE extraction and the development of offshore wind farms. Direct-drive wind turbines, which rely heavily on neodymium-based permanent magnets, are the preferred technology for offshore installations due to their higher efficiency and reduced maintenance requirements. PEMEX's offshore platforms could be used as bases for wind farm development, integrating wind energy production with REE extraction operations.

- **Offshore Wind Turbine Foundations:** PEMEX's experience with large-scale offshore infrastructure projects, including the construction and installation of offshore platforms, makes it well-suited to support the development of offshore wind farms. These projects could include the construction of turbine foundations and other infrastructure necessary to support direct-drive wind turbines that rely on permanent magnets.
- **Integration of REE Mining and Wind Energy:** PEMEX has the opportunity to develop integrated projects that combine REE mining with offshore wind energy generation. By collocating REE extraction operations with wind farms, PEMEX could reduce operational costs and increase efficiency in both resource extraction and energy production.

4. COMBINING WIND ENERGY, FLOATING TURBINES FOR REE MINING

Harnessing wind energy has been a cornerstone of human innovation for millennia, and today it is a key pillar of the global clean energy transition. The development of Wind Turbine Generators (WTGs), specifically offshore floating turbines, has introduced new technological possibilities and challenges.

Meanwhile, the critical role of rare earth elements (REEs), such as neodymium, dysprosium, and praseodymium, in manufacturing high-performance permanent magnets used in WTGs cannot be overstated. As global demand for REEs rises, particularly in the context of wind energy, PEMEX has a unique opportunity to leverage its offshore expertise in oil and gas to support REE mining and contribute to the growth of offshore wind power. Through strategic partnerships, PEMEX can diversify its portfolio and play a pivotal role in the global renewable energy sector.

4.1. Historical Overview of Wind Energy

The use of wind energy dates back to 5,000 B.C.E. when early civilizations harnessed wind to power felucca boats along the Nile River. By 200 B.C.E., China had wind-powered water pumps, and Persia used windmills with woven-reed blades for grinding grain. Over time, wind energy technologies advanced, with Europe adopting these innovations by the Middle Ages. By the early 1900s, small wind-electric generators were widely used in the United States until power lines reduced the demand for wind power in rural areas.

Interest in wind energy was renewed during the 1970s oil shortages, as governments began funding renewable energy research. In recent decades, technological advancements have made wind turbines more efficient, cost-effective, and scalable, leading to a global surge in wind power deployment. Onshore WTGs are primarily located along seashores where wind currents are strong, while offshore WTGs are increasingly installed in deeper waters to harness more powerful and consistent wind resources.

4.2. Advancing Offshore Wind Turbine Technology

Over the past decade, wind turbine capacities have increased from a few megawats to 12-15 MW, driving significant reductions in the cost of offshore wind installations. These advancements in floating foundations, necessary for deepwater WTGs, have made offshore wind energy increasingly viable, even surpassing the cost efficiency of certain fossil fuel power plants. Floating foundations are particularly essential as WTGs are installed in waters deeper than 50 meters.

In February 2020, Hollsten Enterprises, Pte. Ltd. (HE), the oil and gas subsidiary of The Cobeal Group of Companies, developed a floating foundation capable of supporting two turbines. This design, which is yet to be commercialized, offers substantial benefits by increasing wind resource capture while optimizing space. The floating platform is designed to remain stable despite the challenging environmental conditions, including high waves and tropical cyclones, at installation sites that exceed 120 meters in depth. Furthermore, this floating platform allows turbines to weathervane, aligning with the wind and maximizing energy production.

4.3. Challenges in Offshore Wind Energy Expansion

One of the primary challenges in developing floating WTGs is ensuring the stability and longevity of the structure. The mooring systems must be robust enough to withstand extreme forces while allowing for flexibility. Additionally, the entire structure must be durable enough to last over 30 years without needing significant refurbishments. The twin-turbine design proposed by HE' offers increased production potential, with up to 70% more energy generation than traditional single-turbine designs. However, optimizing component fabrication, marine transportation, and offshore installation remains a key challenge.

4.4. Solutions: PEMEX's Offshore Expertise

PEMEX holds invaluable expertise in managing large-scale offshore operations. PEMEX's deep-water drilling, subsea exploration, and platform management capabilities can be effectively translated into the floating offshore wind sector. Many of the technologies developed for oil and gas extraction, such as seismic surveying and subsea robotic systems, can be repurposed for REE exploration and deep-sea mining. Additionally, PEMEX's experience with offshore platforms provides a strong foundation for the construction, installation, and maintenance of offshore WTGs.

PEMEX's existing infrastructure in the Gulf of Mexico (GoM), including logistical hubs and aging oil platforms, could be repurposed to support offshore wind energy and REE extraction. Offshore platforms, particularly those nearing the end of their productive life for oil extraction, could serve as bases for floating wind turbines or REE mining operations.

4.5. A Path to Diversification

To capitalize on these opportunities, PEMEX could forge strategic partnerships with industry leaders that specialize in Engineering, Procurement, Construction, Installation, and Commissioning (EPCIC) across sectors. These partnerships would bring in the necessary expertise in renewable energy, project management, and technological innovation to propel PEMEX's entrance into the renewable energy market.

1. **Joint Ventures with International Mining Firms:** PEMEX has a history of successful joint ventures with international oil companies, and these partnerships can be extended into the REE sector. By collaborating with global mining firms, PEMEX can gain access to the latest REE extraction and processing technologies, allowing Mexico to become a significant player in the global REE supply chain. This diversification would strengthen PEMEX's market position while contributing to the global energy transition.
2. **Collaboration with REE Leaders:** Given that China dominates the REE market, controlling 58% of mining and 90% of refining and magnet manufacturing capacity (Carrara et al., 2020), partnering with Chinese firms or other REE leaders would provide PEMEX with valuable insights and technologies. These partnerships would also support PEMEX in developing a domestic REE supply chain to support offshore wind projects and meet rising global demand.
3. **Global Supply Chain Diversification:** As countries seek to reduce reliance on China for REEs, PEMEX could position itself as a key supplier for the U.S., Europe, and Latin America. The growing offshore wind energy sector in these regions will acquire substantial REE resources, and PEMEX's involvement could ensure a stable and diversified supply chain.
4. **Ferrite Magnets:** PEMEX must consider a wide range of technological innovations and materials. While rare-earth elements (REEs) remain essential to the renewable energy industry, the exploration of alternative magnet technologies, such as ferrite-based flux-switching generators (FSGs), may offer a viable and cost-effective supplement to rare-earth magnets. According to Prakhat et al. (2020), ferrite magnets, while heavier and larger, deliver comparable efficiency — 4.1% higher in some applications—at a fraction of the cost and with fewer supply chain constraints. These magnets present PEMEX with an opportunity to balance both REE mining and the integration of ferrite magnets into offshore wind turbines, ensuring sustainability and profitability. Ferrite magnets, sourced from abundant and inexpensive materials, could complement PEMEX's REE strategy, particularly in areas where cost-efficiency and sustainability are

priortized. This approach would allow PEMEX to take advantage of ferrite's price stability and reduced environmental impact, all while maintaining its investment in rare-earth mining to secure a reliable supply of REEs for the future. The integration of both materials positions PEMEX as a forward-thinking player in the clean energy market, capable of adapting to evolving technological demands. By pursuing both REE mining and the application of ferrite magnets, PEMEX can leverage its offshore assets, reduce reliance on volatile rare-earth markets, and expand into the growing renewable energy sector with diversified material solutions. This dual strategy not only ensures PEMEX's relevance in the global energy transition but also provides flexibility in addressing supply chain challenges.

5. GLOBAL RELEVANCE AND LONG-TERM PROFITABILITY

As global energy markets shift towards decarbonization and the transition to renewable energy accelerates, PEMEX's long-term profitability and relevance will depend heavily on its ability to adapt to these changes. By expanding into rare earth element (REE) mining and renewable energy infrastructure, PEMEX can secure a foothold in the fast-growing clean energy sector. This strategic diversification will not only help the company reduce its dependence on volatile oil and gas markets but also provide access to high-demand materials essential for technologies like wind turbines and electric vehicles.

The growing demand for offshore wind turbines, which heavily rely on REEs for high-performance permanent magnets, provides a unique opportunity for PEMEX to position itself as a key player in both resource extraction and renewable energy infrastructure development. The ability to supply REEs domestically and regionally (to markets in North and South America, for instance) would give PEMEX a competitive advantage, particularly as global energy players and industries seek to diversify their supply chains away from China's dominance. Furthermore, establishing a reliable REE supply will position PEMEX as an essential partner for the global wind energy sector, further solidifying its role in the clean energy transition.

PEMEX's success in REE mining and renewable energy will require strategic investments in innovation, particularly in the development of sustainable mining practices and circular economy initiatives, such as REE recycling. These initiatives can reduce the environmental impact of mining activities while ensuring a stable, long-term supply of these critical minerals. Furthermore, PEMEX's experience in offshore operations uniquely positions the company to lead the integration of offshore wind farms with REE extraction facilities, combining two crucial elements of the renewable energy transition. This integrated approach will help PEMEX enhance operational efficiency, reduce costs, and ultimately ensure its long-term profitability and relevance in the global market.

By securing its place in the REE supply chain, PEMEX can also attract new investment opportunities, forge new international partnerships, and access emerging technologies that can propel the company to the forefront of the renewable energy revolution. The diversification into REEs, paired with PEMEX's existing infrastructure and expertise, positions the company as a crucial player in the global energy transition. This move will not only ensure PEMEX's relevance in a post-oil economy but also guarantee a profitable and sustainable future for decades to come.

5.1. PEMEX's Potential Earnings from 2024 to 2036

PEMEX's potential earnings from 2024 to 2036 through its diversification strategy into rare earth elements (REE) mining and the

integration of alternative magnet technologies, we can estimate the following factors:

1. **Global Offshore Wind Market Growth:** Offshore wind energy is projected to grow significantly, with the global offshore wind market expected to expand from $15.4 billion in 2023 to over $31.7 billion by 2030 (Allied Market Research). This strong growth in demand for wind turbines will drive demand for REEs, particularly neodymium and dysprosium, which are essential for high-performance magnets used in direct-drive wind turbines.
2. **REE Demand Growth:** Meeting the global renewable energy goals for 2050 will require an 11 to 26-fold increase in REE production from current levels, according to the European Commission (JRC Raw Materials for Wind). As PEMEX scales up REE extraction through repurposing offshore oil platforms, it can position itself as a key supplier of REEs, especially to the growing offshore wind energy market.
3. **Alternative Ferrite Magnet Market:** Ferrite magnets are more cost-effective and more environmentally friendly that REEs, providing PEMEX and opportunity to tap into this market. If PEMEX integrates ferrite-based flux-switching generators into its offshore wind turbine projects, this could offer cost stability and contribute to its profits. Ferrite magnets, according to studies (Prakhat et al.), could increase efficiency by 4.1% in some applications, providing a competitive edge.

5.2. Revenue Projections

Assuming PEMEX captures just 10% of the offshore wind turbine REE market between 2024 and 2036, it could potentially earn a portion of the $31.7 billion projected for the offshore wind turbine market in 2030. If annual growth continues at a CAGR of 10.9%, the compounded market value could reach approximately $65 billion by 2036. By securing strategic partnerships with industry leaders like The Cobeal Group, PEMEX could see earnings ranging from $1 billion to $3 billion annually from REE extraction alone.

Furthermore, integrating ferrite magnets could provide PEMEX with additional earnings from cost reductions and market expansion into sustainable magnet technologies.

From 2024 to 2036, PEMEX's diversification strategy into REE and alterative magnet technologies could potentially generate cumulative revenues of $10 billion to $36 billion, depending on market capture, partnerships, and technology integration success.

These estimates are based on data projections from the global offshore wind market, REE demand, and alterative magnet technologies.

6. CONCLUSION

PEMEX is uniquely positioned to lead the global renewable energy transition by leveraging its vast offshore assets and deep-sea expertise. The rising demand for rare earth elements (REEs), essential for high-performance magnets in wind turbines, offers PEMEX a pivotal opportunity to diversify beyond oil and gas. Repurposing aging oil platforms from fields like Cantarell and Ku-Maloob-Zaap for REE extraction would enable PEMEX to contribute significantly to both resource extraction and wind energy production, supporting the global clean energy revolution.

This paper highlighted that direct-drive wind turbines, which rely on rare-earth magnets, are crucial for offshore wind energy expansion. By becoming a key domestic supplier of REEs and participating in the global supply chain, PEMEX can reduce its dependence on oil markets and establish itself as a crucial supplier for wind energy sectors in the U.S., Europe, and Latin America.

In addition, PEMEX’s exploration of ferrite magnets offers an innovative pathway for diversification. Ferrite magnets, though less power-dense, are cost-effective and

environmentally friendly, allowing PEMEX to pursue a dual approach. This strategy—leveraging both REEs and ferrite magnets—ensures that PEMEX can balance sustainability with profitability, remaining resilient in the face of fluctuating REE prices.

To ensure long-term profitability and relevance, PEMEX must continue investing in REE recycling, sustainable mining practices, and circular economy initiatives, all of which reduce environmental impacts while securing a stable REE supply. PEMEX's strategic shift into REE extraction, coupled with the integration of alternative magnet technologies, could generate cumulative revenues of $10 billion to $36 billion between 2024 and 2036. By repurposing key assets like Cantarell and Ku-Maloob-Zaap and leveraging strategic partnerships, PEMEX is well-positioned to secure its place as a global leader in renewable energy, ensuring both sustainability and profitability.

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