Artículos

The role of Rare Earth Elements in the deployment of wind energy in Colombia

El papel de los elementos de tierras raras en el despliegue de la energía eólica en Colombia

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Abstract: The deployment of renewable energy technologies will play a crucial role in the global transition to a low-carbon economy and ultimately in the fight against global warming. However, this transition could face important problems because most of those technologies rely on the steady supply of critical minerals. Colombia, thanks to its hydrological resources, has relied on the hydropower for electricity generation. However, the government has implemented measures to back-up the energy system in draught periods and, consequently, fossil fuels-based plants have increased the market share and with these, CO2 emissions. This study assesses the mineral demand in Colombia in the period 2020-2050 for the rare earth elements embedded in the deployment of wind power technologies in four different climate policy scenarios in order to establish whether they could face geological bottlenecks that could ultimately hamper the transition to a low-carbon economy. The Gigawatts (GW) of future capacity additions in the energy system are converted into tons of metal using published metal intensities of use and assumptions of Colombia's technological pathway. Then, the cumulated mineral demand is compared against current mining production rates and geological reserves to establish geological bottlenecks. The results show that the reserves will not pose any threat to its transition. However, when compared to current mining rates, the mineral demand in 2050 could pose a problem for the supply of minerals. Finally, this study gives some policy recommendations that could be used to mitigate these issues, such as substitution, improved circular economy and sound technological choices.

Keywords: Renewable energy technologies, mineral demand, climate change mitigation, Dysprosium, Neodymium.

Resumen: El despliegue de tecnologías de energía renovable desempeñará un papel crucial en la transición mundial hacia una economía con bajas emisiones de carbono y, en última instancia, en la lucha contra el calentamiento del planeta. Sin embargo, esta transición podría enfrentar problemas importantes porque la mayoría de esas tecnologías dependen del suministro constante de minerales críticos. Colombia, gracias a sus recursos hidrológicos, ha dependido de la energía hidroeléctrica para la generación de electricidad. Sin embargo, el gobierno ha implementado medidas para respaldar el sistema energético en períodos de sequía y, en consecuencia, las plantas de energía basadas en combustibles fósiles han aumentado la cuota de mercado y con ellas las emisiones de CO2. Este estudio evalúa la demanda de minerales de los elementos de tierras raras en Colombia en el período 2020-2050 incorporados en las tecnologías de energía eólica en cuatro escenarios de política climática con el fin de establecer si estas podrían enfrentar cuellos de botella geológicos que, en última instancia, podrían obstaculizar la transición a una economía baja en carbono. Los gigavatios (GW) de las futuras adiciones de capacidad en el sistema energético son convertidos en toneladas de metal utilizando intensidades de uso de metales publicadas y suposiciones de la trayectoria tecnológica de Colombia. Luego, la demanda acumulada de minerales es comparada con las tasas actuales de producción minera y las reservas geológicas para establecer los cuellos de botella geológicos. Los resultados muestran que las reservas no supondrán ninguna amenaza para la transición. Sin embargo, si se compara con las tasas de extracción actuales, la demanda de minerales en 2050 podría ser un problema para la oferta de minerales. Por último, en este estudio se formulan algunas recomendaciones de política que podrían utilizarse para mitigar estas cuestiones, como la sustitución, la mejora de la economía circular y las opciones tecnológicas racionales.

Palabras clave: Tecnologías de energía renovable, demanda de minerales, mitigación del cambio climático, Disprosio, Neodimio.

1. Introduction

The worldwide transition from high to low-carbon economies will require the extraction and processing of a significant volume of rare earth elements (REEs) and other minerals which are used in Renewable Energy Technologies (RETs). The future physical availability of some of those minerals has become a source of concern, because the reliability of their supply could disrupt this transition, the economic development and ultimately, the fight against climate change. Especially sensitive are the transportation and energy sectors, in which the metal intensity shows a dramatic increase in the years to come (Koning et al., 2018).

For the purpose of this paper, critical minerals are those minerals considered important for any type of technology and which at the same time could face supply disruptions, for instance, because the mineral deposits are concentrated in just a few countries (McCullough and Nassar, 2017). The REEs, —which are classified as critical minerals— play an important role in the development of RETs. They are used in a relatively large amount of applications in key technologies being developed to provide a sustainable mobility and energy supply (Alonso et al., 2012). Wind and solar photovoltaic technologies, which make up a segment of RETs, use a wide variety of REEs. Thus, if they were to be deployed on a large scale, as will be expected to decarbonize the economy in the future, this could pose a threat to such a transition.

The demand for fossil fuels to power up the energy production in Colombia has been increasing steadily thanks to a growing economic sector. Thus far, most of electricity production has been supplied by large hydroelectric power stations, but because of climate change and seasonal climatic oscillations such as El Niño

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that make hydropower less reliable, fossil fuel-powered energy has been gaining share in electricity mix to back up the system in high demand conditions.

Colombia's low-carbon strategy is still in its initial stages. The 1715 law of 2014 aimed to implement plans, policies and projects to promote the mitigation of greenhouse gases (GHG) emissions without compromising social and economic growth (Calderón et al., 2016), as well as to incorporate RETs into the national electricity grid. However, thus far, Colombia has failed to set a course of direction for the implementation of such technologies and policies.

Since the 1980s, many authors (namely, Hayes and McCullough, 2018 and references therein) studied criticality issues and its effects on the global deployment of RETs. In recent years there has been a boom in the research dealing with how the future global deployment of sustainable technologies could be affected by the physical availability of critical minerals, such as the REEs (Koning et al., 2018; Manberger and Stenqvist, 2018; Deetman et al., 2018). However, to date there has been a lack of studies on how the deployment of RETs in developing countries could impact the global market, and more specifically on how the implementation of different climate-policy scenarios in developing countries could affect the global demand for metals.

Therefore, this study aims to fill the research gap described above by analyzing how the adoption of RETs would affect the global demand for REEs in the near to medium future. This study is limited to two REEs (namely dysprosium and neodymium) that are embedded in the wind power generation plans in Colombia during the 2020-2050 period.

The analysis is conducted by using the outcome of Calderón et al. (2016), where they assess the effect of carbon taxes and abatement targets on CO2 emissions in four different climate-policy scenarios using four models form the CLIMACAP-LAMP project (van der Zwaan et al., 2016), giving as a result multiple pathways of how the future energy technologies would deploy during the 2020-2050 period.

Specifically, the variable wind energy capacity additions (in GW) of their research will be used as the main input for the purposes of this research. They are converted here into quantity of metals (kg) embedded in the wind power generation systems by employing intensities of use obtained in the published literature. The derived demand for metals in Colombia is then compared against current mining rates and reserves, ultimately

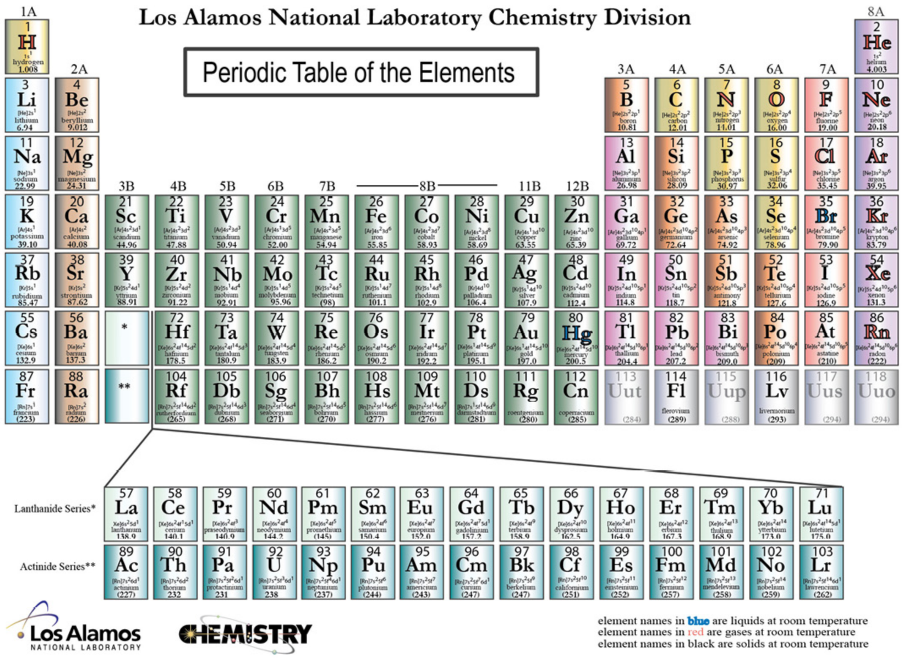

FIGURE 1.
Periodic table of elements
The REEs are those elements highlighted by the rectangle. Source: Los Alamos National Laboratory, Chemistry Division, https://periodic.lanl.gov/images/periodictable.pdf

allowing to establish whether the available resources are sufficient to meet future demand or whether there could be potential shortages of mineral resources that would affect the deployment of RETs. Finally, this study sheds light on whether the REEs would experience geological bottlenecks that could make them more expensive and concludes with a proposal for some policy options to deal with such issues.

2. Background: Rare Earth Elements, renewable energy technologies and the mineral requirements of the transition to a low carbon economy

2.1. Rare Earth Elements

Rare-earth elements (REEs) range from atomic number 57 (lanthanum) to 71 (lutetium) in the periodic table of elements and are commonly referred to as “lanthanides” (Figure 1, Table 1) (van Gonsen et al., 2017). Yttrium (atomic number 39) and scandium (atomic number 21) are also regarded as REEs as they tend to occur in the same ore deposits as the lanthanides and show similar chemical and physical properties.

The term rare earth is really a misnomer, since they are not as rare as the name implies. Van Gonsen et al. (2017) define its origin: “They were named rare earth because most were identified during the 18th and 19th centuries as ‘earths’, and, in comparison with other ‘earths’, such as lime or magnesia, they were relatively rare”. They are more abundant, on average, than silver, gold, or copper in the Earth’s crust (Table 1).

Not long ago, the REEs were familiar only for a relatively small number of people, such as chemists, engineers, and geologists. However, over the last decades these elements have gained considerable importance mainly due to three reasons: 1) their special properties which have made of them indispensable components of the modern technology; 2) the near-monopolistic market where China controls world production, and 3) the world´s heavy dependence on China´s production and its controlled supply (van Gonsen et al., 2017).

Thanks to their unique magnetic, phosphorescent, and catalytic properties, over the last couple of decades the world has seen a noteworthy increase in the utilization of REEs in technologies deemed important such as clean energy sources and defense sectors.

Consequently, the strategic value of these elements was quickly recognized and the political and economic issues surrounding the global supply gained more visibility. Since then, the number of exploration activities aiming to discover economic deposits of REEs have dramatically increased (van Gonsen et al., 2017).

TABLE 1.
List of REEs with their crustal abundance

REEs	Symbol	Atomic number	Crustal abundance (ppm)
Lanthanum	La	57	39
Cerium	Ce	58	66.5
Praseodymium	Pr	59	9.2
Neodymium	Nd	60	441.5
Promethium	Pm	61	Does not occur in nature
Samarium	Sm	62	7.05
Europium	Eu	63	2.0
Gadolinium	Gd	64	6.2
Terbium	Tb	65	1.2
Dysprosium	Dy	66	5.2
Holmium	Ho	67	1.3
Erbium	Er	68	3.5
Thulium	Tm	69	0.52
Ytterbium	Yb	70	3.2
Lutetium	Lu	71	0.8
Yttrium	Y	39	33
Scandium	Sc	21	22

For the purpose of comparison, the average crustal abundances for silver, gold and copper are 0.075, 0.004, and 60, respectively. Source: van Gosen et al. (2014).

2.1.1. Demand and applications

The rate of economic growth and the development of new technologies are the two major drivers of demand for REEs (Mancheri et al., 2019). Sustainable technologies are one of the biggest sectors which requires REEs, including magnets, phosphors, catalysts, and batteries, and currently accounts for over 60% of the total demand; a tendency that will tend to increase fueled mostly by the heavy investments in clean energy.

The REEs are used in a variety of industrial and technological applications that take advantage of their unique physical and chemical properties. Table 2 shows the amount of REEs demanded by different intermediate products, which is expected to increase between 7-8% annually (Mancheri et al., 2019).

The main consumer of REEs are the permanent magnets made from REE alloys. Particularly important are the neodymium-iron-boron magnets since they are the strongest magnets currently known, especially when space and weight are critical variables. These magnets are used in hard disk drives, cell phones, electric motors for hybrid vehicles and windmills, and actuators in aircraft technologies (van Gonsen et al., 2017).

Another major consumer are the catalytic converters based on cerium used in cars and the catalytic converters based on lanthanum used in the petroleum refining industry, followed by the use in the glass industry because they provide color and special optical properties to glass as well as glass polishing (cerium and lanthanum) (van Gonsen et al., 2017).

TABLE 2.
Global rare earth elements (metric tons of rare-earth-oxide (REO) equivalent) demand by type of intermediate product in 2017

Application	Total (tons)	Market share (%)
Magnets	51000	30
Catalysts	30000	18
Metal alloys	31000	18
Polishing	22000	14
Glass	9500	6
Other	10500	6
Ceramics	8500	5
Phosphors	5000	3
Total	167500	100

Source: Mancheri et al. (2019).

The production of steel alloys and the removal of impurities in the steel-making industry uses cerium, lanthanum, neodymium, and praseodymium, commonly present in the form of a mixed oxide known as mischmetal.

Flat screens, some incandescent, fluorescent, and LED lightning used in phosphors consists of REEs, particularly yttrium, cerium, lanthanum, europium, and terbium. Medical applications such as magnetic resonance imaging (MRI) use gadolimium phosphors (van Gonsen et al., 2017).

2.1.2. Supply

China controls the global REEs industry and has established a dominant position in the entire value chain, from resource extraction to manufacturing of intermediate products such as magnets; products that are critical to high-growth industries such as the renewable energy technologies (RETs) (Mancheri et al., 2019).

Mine production data published by the United States Geological Survey (USGS, 1996-2020) indicate that China produced more than 90% of the total world supply between 2003 and 2012. Afterwards, its contribution to the total world supply has decreased from 86% in 2013 to 63% in 2019 (Figure 2, Table 3). However, it must be noted that the production volume shown for China in Table 3 does not include undocumented ("illegal") production which can be rather significant. According to (Shen et al., 2020), there are estimates indicating that the illegal-sector production comprises, after 2017, between 20% and 50% of China´s total production, even after China announced new policies to curtail illegal production. As a result, total mine production in China, for example for 2019, can account for around 71% of the total world supply.

There are several reasons why China controls the REE market, including government support for the industry, low labor

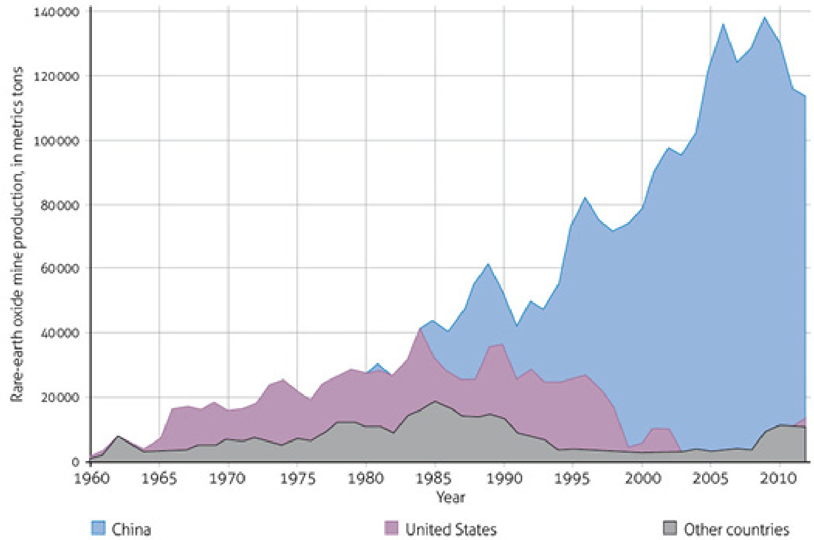

FIGURE 2.
World mine production of rare-earth oxides by country and year since 1962 to 2012
Source: Taken from van Gonsen et al. (2017).

TABLE 3.
Production and reserves of REEs (metric tons of rare-earth-oxide (REO) equivalent) for world producers

Country	Mine production (tons)			Reserves (tons)
	2017	2018	2019	
China	105 000[1]	120 000[1]	132 000[1]	44 000 000
Brazil	1700	1000	1000	22 000 000
Vietnam	200	400	900	22 000 000
Russia	2600	2600	2700	12 000 000
India	1800	1800	3000	6 900 000
Australia	19 000	21 000	21 000	3 300 000[2]
Greenland	-	-	-	1 500 000
United States	-	18 000	26 000	1 400 000
Tanzania	-	-	-	890 000
Canada	-	-	-	830 000
South Africa	-	-	-	790 000
Burma (Myanmar)	NA	19 000	22 000	NA*
Burundi	-	630	600	NA
Thailand	1300	1000	1800	NA
Other countries	180[3]	60	-	310 000
World total	132 000	190 000	210 000	120 000 000

1 Production quota; does not include undocumented production; 2 For Australia, Joint Ore Reserves Committee-compliant reserves were 1.9 million tons; 3 Includes Malaysia; * Not available. Source: USGS (1996-2020).

and production costs, and a lax environmental regulatory framework (Zhou et al., 2016). These factors have allowed China to enjoy a monopolistic market, while countries like the US, which had to close mines such as Mountain Pass, began to import REEs to satisfy their demand (USGS, 1996-2020).

In 1999, China introduced an export quota on REEs "to control total production and illegal activities at the border of the country ..." and "...put specific restrictions on the structure of export quotas to support the development of the downstream sector" (Shen et al., 2020). These quotas reduced the output of Chinese exports by nearly 60% compared to 2008 levels (Haque et al., 2014). Consequently, large price increases were common due to the mismatch between a growing demand and a declining supply. In 2014, China agreed to end those restrictions after multiple complaints from the World Trade Organization (WTO) and countries like USA, Japan, and the European Union.

After China started to impose quotas, licenses and taxes in 2010, citing as the main reasons the need to limit resources for domestic consumption and environmental concerns, the world reacted in different ways, including: increasing its stockpile; increasing exploration; developing new deposits; and increasing the efforts to reuse, recycle, and find new substitutes among the REEs.

Most of the world's REEs production comes primarily natural resources, although recycling as a source of raw materials is increasingly seen as a viable option. However, the recycling process is still in its initial stages and has to overcome several problems before being considered a realistic option, such as industrial scale recycling plants, and the small amount of these elements incorporated in the technological products which makes the recovery an expensive undertaking.

2.2. Wind power technologies

There are two ways to obtain energy from the wind, either by directly converting mechanical power or by transforming kinetic energy. The latter can be achieved through a wind turbine which converts wind energy into mechanical power, which can then be utilized for different purposes.

The wind turbines can be classified as either direct drive (no gear) or those who use gearbox electromagnets according to the drivetrain condition in a wind generator system (Figure 3)(Tong et al., 2010). In the first group the turbine blades are connected directly to the generator, which allows them to rotate at the same speed, but at low revolutions per minute (10-30 rpm) (Pavel et al., 2017). The electric energy is induced by a magnetic field which can be provided either by permanent magnet synchronous generators (PMSGs) or electromagnets which need excitation and consumes reactive power (Lacal-Arantegui, 2015). These types of turbines are popular among offshore windfarms because of their increased reliability and low maintenance costs (Habib and Wenzel, 2014).

Different metals can be employed to produce the permanent magnet. PMSG turbines with NdFeB (which stands for neodymium, iron, and boron) are the most common, however,

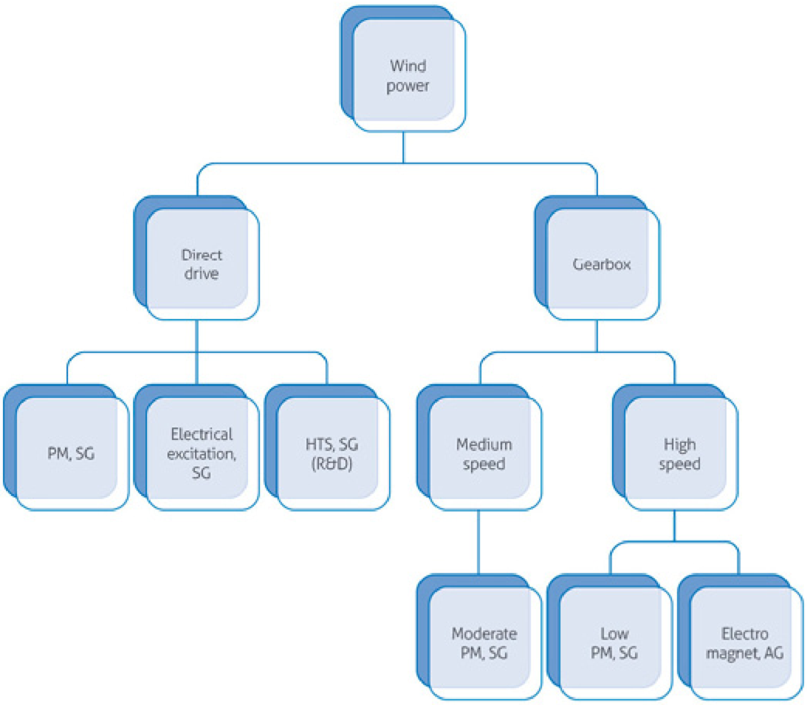

FIGURE 3.
Wind power technologies
PM = permanent magnet, HTS = high-temperature super conductor, SG = synchronous generator, AG = asynchronous generator. Source: Taken from Manberger and Stenqvist (2018).

they contain low but vital amounts of praseodymium (Pr), dysprosium (Dy) and terbium (Tb), which some authors consider as critical minerals (Tokimatsu et al., 2018; Grandell et al., 2016; Brumme, 2011). The conventional electromagnets generators, which in 2015 made up to 77% of the global installed capacity, are produced using magnetic steel and copper windings (Pavel et al., 2017). These metals are not currently classified as critical minerals; however, these turbines are generally heavier and less efficient than turbines using permanent magnets (Manberger and Stenqvist, 2018). The latest generation among direct drive generators is the HTS (high-temperature superconductors), which allows for low weight turbines and do not require critical minerals except for yttrium. Nevertheless, they are currently in research stage (Manberger and Stenqvist, 2018).

Among the geared turbines, there are two groups: the mid-speed drive (≥ 80 rpm) and high-speed drive (≥ 900 rpm). Here, a gearbox allows for the generator to rotate faster than the blades to gain a higher power output (Pavel et al., 2017).

In the mid-speed geared turbines, the generator contains lower quantities of permanent magnets than the low speed configuration. In high-speed generators, a transmission system converts the low speed of the wind turbines into high speed in the generator (≥ 900 rpm). Currently, the onshore market is dominated by the traditional doubly-fed induction generator (DFIG), with capacities up to 6 MW, which is considered a high-speed technology (Pavel et al., 2017). Altogether, the geared drive system is heavier and requires more maintenance than the direct drive, which makes it less competitive for larger plants in offshore locations (Manberger and Stenqvist, 2018).

2.3. Mineral demand in a low carbon economy

There is a vast literature on the future availability of critical minerals such as the REEs in the deployment of RETs that would be required to meet certain climate mitigation targets. Thus, this section presents an overview of the major studies concerning renewable energy technologies.

Based on the future requirements for a low-carbon economy and energy technologies together with long-term socioeconomic scenarios, Koning et al. (2018) examine how the gradual introduction of climate policies by 2050 would prompt the onset of supply bottlenecks of a range of metals, including Fe, Al, Cu, Ni, Cr, In, Nd, Dy, Li, Zn, and Pb. Their results show that, compared with actual levels, the production of almost all metals analyzed would have to increase significantly to keep up with a low-carbon energy system transition. However, given their assumption that the supply of these metals used in other sectors of the society will increase gradually, the supply of metals for such a transition would not be a problem. Yet, the combination of special conditions, characteristics of the mining industry such as the lack of certainty on the return of investment, long lead times in expanding mining production, and social and environmental impacts that delay the expansion of mining capacity could create supply-demand imbalances. One aspect which is not considered in their paper is the importance of recycling and substitution in RETs.

Manberger and Stenqvist (2018) assess what makes a resource critical and how can it be mitigated, by analyzing different technological development trajectories affecting the demand for metals over time using technological substitutes and the role of recycling to meet supply needs. In their study, twelve metals were used, namely Co, Cu, Dy, Ga, In, Li, Nd, Ni, Pt, Se, Ag, and Te, which are critical for renewable energy production, storage or end-use technology up to 2060. They conclude that the growth rate of solar power, wind power, and electric motors is not likely to be constrained by the reserves of these metals, since they would continue growing to keep up demand. Therefore, given that metal use intensities have improved historically, and will continue to do so, the growth in mining intensity and cumulative demand will be much lower. This would allow the recycling of metals to achieve a bigger share of the demand by 2060.

Tokimatsu et al. (2018) develop a bottom-up cost-minimizing model to calculate the aggregate metal requirements in energy technologies including hydrogen under several climate policy scenarios reflecting uncertainty in future metal intensities, recycling rate and the lifetime of energy technologies. Potentially "critical" metals were identified by comparing metal requirements to current production rates and resource estimates. Their model suggests that vanadium which is commonly used in nuclear, photovoltaic, carbon capture and storage, electric vehicles (plug-in hybrid) and fuel cell vehicles, is "critical" in all three energy policy scenarios, whereas selenium, indium, and tellurium are "critical" in photovoltaic systems, dysprosium in wind power, and nickel, platinum zirconium, yttrium, lithium, and lanthanum in fuel cell vehicles.

Deetman et al. (2018) take a broader approach in their research. They focus on developing climate policy scenarios for five metals like copper, tantalum, neodymium, cobalt, and lithium, used in three kind of applications: appliances, cars, and electricity technologies in 2050. The results show, unsurprisingly, that the demand for materials introduced by these products will increase significantly, regardless of anticipated climate policy ambitions. Similarly, the dominant factors for the demand are not climate policies but rather socioeconomic developments and technological change. Cars would be the major driver for the growth of metal demand, especially lithium and cobalt, which would be a consequence of the transformation of the traditional internal combustion engine car fleet into a hybrid/electric one.

Grandell et al. (2016) perform an analysis of the future availability of some critical minerals used in the clean energy technologies. These authors modeled the demand for 14 critical minerals (Ag, Nd, Pr, Dy, Tb, Yt, La, Ce, Eu, Co, Pt, Ru, In, Te) present in green energy technologies from 2010 up until 2050, including solar energy, wind energy, electric mobility, fuel cells, batteries, electrolysis and efficient lighting. The demand resulting from the expansion of the RET was compared against the known present state of global reserves and resources, and according to their results, the most serious problem could be the future availability of silver in the solar energy sector. Silver demand in 2050 will exceed known global resources by more than 300% and present reserves by almost 450%. Other possible material restriction might be given for indium, tellurium or ruthenium.

In a country-specific approach, Viebahn et al. (2015) assess whether the transformation of the German energy system by 2050, which will consist of a large deployment of renewable energy and GHGs emissions reduced between 80-90% matched against 1990 levels, would be affected by a lack of critical minerals. The main conclusion in their study shows that the deployment of most of the renewable energy would not be limited by the geological availability of minerals. However, possible criticality issues could arise for specific sub-technologies of wind power, photovoltaic, and battery storage. In the wind power technology, the main constraint is the development of technologies that involve the use of REEs. In the case of photovoltaic, the demand for selenium and indium in CIGS cells (Cu-In-Ga-diselenide) does not appear to be secured in the long term. Nonetheless, these restrictions could be overcome by establishing recycling systems.

Brumme's (2011) thesis reviews thoroughly the REEs used to produce wind turbines. She analyzed the REEs market and the requirements for the deployment of the wind power generation based on the projections of the International Energy Agency (IEA) Blue Map scenario for 2050. According to Brumme's results, the REE demand for wind turbines would rise between 66 to 500% -low and high scenarios, respectively- in 2050 compared to 2010 levels. Brumme ends by stating that the current level of supply is highly unlikely to be sufficient in the long run, and this could hamper a climate change mitigation measure, such as wind power generation.

3. Colombian energy sector

Thanks to its geographic location, historically the bulk of electricity generation has depended on hydropower. However, in recent decades there has been an increase in the production of electricity in thermal plants which could support the main system in cases of severe weather events, such as prolonged droughts. As a result, the production share of non-conventional renewable energy sources, (e.g. wind and solar power), has remained at negligible levels, far below other South American countries that have expanded renewable electricity generation, such as Chile and Brazil (Radomes and Arango, 2015).

The aim of this chapter is to provide an overview of the Colombian electric system, which will be covered in two parts. First, the generation system will be discussed and how it has changed over time, which will be followed by an overview of the historical energy demand and its implication for future demand.

3.1. Electricity generation

Colombia is located in the north-western corner of South America, bordered by Brazil and Venezuela to the east, Ecuador and Peru to the south, by the Pacific Ocean to the west and the Atlantic Ocean to the north. The country has three mountain ranges which are sub-ranges of the Andes, and it has plenty of non-renewable resources like coal, nickel, and gold as well as abundant hydrologic resources represented in five great basins from the rivers: Magdalena, Cauca, Putumayo, Guaviare, and Amazon, among many others.

This plentiful of water resources are reflected in electricity generation mix. In 2017, total installed capacity was 17.3 GW, of which hydropower made up for 64.5%, while the thermal power (which includes gas turbines, oil and coal plants) accounted for 30.4%, small hydropower plants 5% and finally, wind power with 0.1%.

Historically, hydropower has been the traditional source of energy production, but since the early 1990s the thermal production has been increasing its share of electricity generation. Microclimatic phenomena such as "El Niño-Southern Oscillation" had severely affected the output of large hydro plants because of prolonged droughts (especially severe was the 1992 drought, see Figure 4). To overcome this vulnerability the government started to approach other sources of electricity as well as to give incentives to the private industry for the investment in thermal plants that could back up the system once climatic phenomena would affect hydropower production (Arango and Larsen, 2010).

The CO2 emissions to the atmosphere in the energy production sector in Colombia have been relatively low due mainly to its hydropower dominance. However, given the increasing uncertainty of the effects of climate change on hydrologic resources and the increasing reluctance of communities to the installation of new hydroelectric projects given their environmental impact, the share of the thermal energy production will likely continue to grow and so will the share of CO2 emissions into the atmosphere.

Regarding the non-conventional renewable energy production like wind and solar photovoltaic, in Colombia there is only one wind power plant with an installed capacity of 19.5 MW which accounts for the 0.11% of the 17.3 GW of the total capacity. Nevertheless, the potential for the installation of

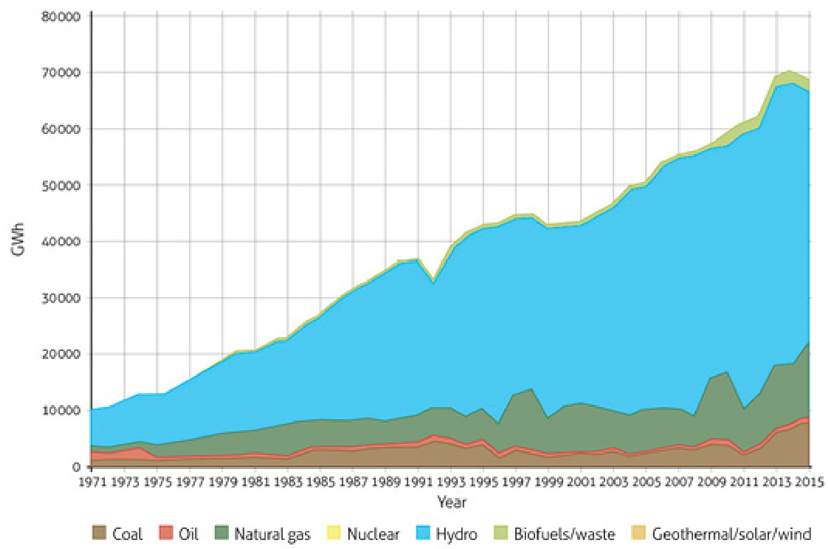

FIGURE 4.
Colombian generation electricity power from 1971 to 2015
Source: Churio-Silvera et al. (2018).

new renewable energy capacity is good; the northern part of the country has been classified as having class 7 winds (over 10 m/s) and a total wind power potential of 25 GW, which is more than enough to meet the entire country demand (Gómez and Ribo, 2018). The solar photovoltaic installed capacity in 2010 was around 9 MW. However, by being located near the Equator, Colombia receives constant solar radiation (average 4.5 KWh/m2/day), which gives it relevant potential for this kind of energy source (Gómez and Ribo, 2018).

In October 2019, the Colombian government held the first of several renewable energy contract auctions, paving the way for the "Energy Transition" (Ministerio de Energía de Colombia, 2020). This plan aims to increase installed capacity from 50 MW to over 2500 MW in wind and solar energy with 14 projects (9 of them wind in La Guajira, and 5 solar in the departments of Cesar, Cordoba, Valle del Cauca and Tolima), which would represent 12% of the total energy mix by 2022.

3.2. Energy Demand

Colombia is the fourth largest economy in Latin America and the Caribbean, behind Brazil, Mexico, and Argentina. Since the early 1990s its gross domestic product (GDP) has been increasing considerably and consequently the energy requirements to sustain this growth. The energy demand during the period between 1990 and 2013 has nearly doubled, increasing from 28.85 to 55.73 TWh per year (Edsand, 2017). The most used energy sources are diesel and gasoline, both associated with the transportation sector, followed by natural gas used mainly in the industry sector. The housing sector uses most of the electricity generated, meanwhile the tertiary and industrial sectors use almost the same amount of electricity (Nieves et al., 2019).

According to the Mining and Energy Planning Unit of Colombia (UPME) in 2030, the demand for energy will increase to 105 000 GWh (UPME, 2016). However, Nieves et al. (2019) foresee that in 2030 the demand for electricity will fluctuate between 74 000 and 125 000 GWh; whereas in 2050, the electric energy demand could reach up to a maximum of 383 000 GWh.

4. Method and data

This chapter's aim is to outline the method employed to obtain the results as well as to discuss the data sources, which will be applied to estimate the derived demand of REEs embedded in RETs in Colombia during the period 2020-2050 (Figure 5).

The first part will briefly explain what scenario analysis is and the parameters used in this type of analysis. Next, it discusses the research of Calderón et al. (2016) and van der Zwaan et al. (2016). In their research they propose a pathway for the deployment of RETs through scenario analysis, the result of which –in this specific case, electricity capacity additions

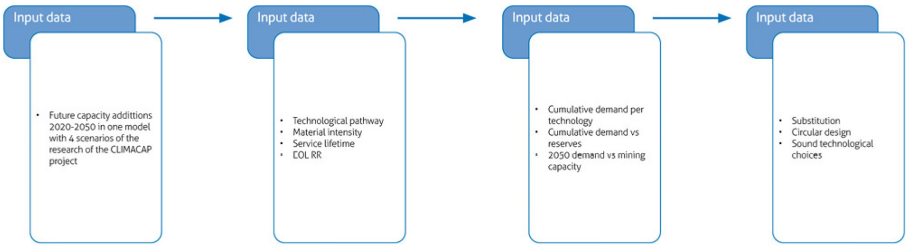

FIGURE 5.
Diagram explaining the method used in this study

(GW) by type of energy source during the 2015-2050 period– will serve as the main input for the development of this study. Finally, it will establish the metal intensity of use of the REE incorporated in RETs, also taking into account possible future material improvements of these technologies. The cumulative demand is then calculated by multiplying the additional capacity (in GW) with the intensity of use of the REE embedded in the wind energy technologies.

4.1. Scenario Analysis

Scenario analysis is a method developed to explore future alternatives; it is an important tool for dealing with the complexity and uncertainty of the future. As Martinot et al. (2007) state:

They could be seen as 'if... then' queries: if policies accelerate the growth of renewables, what is the difference between situations with and without policies? If CO2 emissions should be stabilized, what combinations of renewables and other technologies will achieve stabilization?

They can assist policy makers in decision-making strategies when it comes to long-term planning and are used especially in highly complex climate policy issues. However, emphasis should be given to the notion that scenarios are not predictions, but rather imaginative explanations of how possible futures might unfold (Kishita et al., 2017), and they do so by establishing a given set of assumptions and constraints.

There are three major categories of considerations when building a scenario analysis (TCFD, 2017). These will affect how the scenarios might unfold:

Parameters used: Discount rate, GDP and other macroeconomic and demographic variables.

Assumptions made: Assumptions related to policy changes, technology development/deployment, energy mix, price of key commodities or inputs, and timing of potential impacts, among others.

Analytical choices: choice of scenarios, time horizons, supporting data and models.

4.2. Colombian scenario description

This study is based on the outcomes of several previous studies (e.g. Calderón et al., 2016; van der Zwaan et al., 2016). which were designed to explore the implications of alternative CO2 emission scenarios for Colombia and Latin America's economy and energy system Their research was done under the CLIMACAP-LAMP project, -which stands for Integrated Climate Modelling and Capacity Building in Latin America- and assess the implementation of carbon taxes and abatement targets in reducing the emission of greenhouse gases (GHG) in key countries of the region (Science for Global Insight, 2015).

In this project, Colombia is assessed as a separate country rather than part of an aggregate region, such as Latin America. This allows to evaluate the implications of climate policy scenarios specifically, and thus the outcomes of their investigation form the basis of this study.

Four models were used to build the scenarios: two partial equilibrium models – The Global Change Assessment Model (GCAM), and the TIMES Integrated Assessment Model of the Energy Research Center of the Netherlands (TIAM-ECN)- and two Computable General Equilibrium models (CGE) – the Phoenix Model and Modelo de Equilibrio General para Colombia (MEG4C) (Calderón et al., 2016).

Of these four, this study uses the results of the TIAM-ECN model, which is a model for assessing long term energy systems and climate policy analysis (Table 4). It is based on energy cost minimization with a foresight until 2100 (Kober et al., 2014). The development of the global energy economy over time is simulated from the resource extraction to the final energy use. This model allows to establish future energy supply pathways including the set of possible fossil, nuclear and renewable energy technologies in Colombia (Calderón et al., 2016).

Once the model is established, the next step is the choice of the suitable scenarios. Calderón et al. (2016) chose four scenarios to assess how CO2 emissions would deviate from baseline levels through the implementation of carbon taxes and abatement targets over the period 2020-2050 (Table 5).

By comparing different climate-policy scenarios with a business as usual scenario, the policy-makers are able to assess how the variables analyzed - in this case, CO2 emissions - may deviate from the baseline level in the period of time established (Calderón et al., 2016). Specifically, the different pathways of how the energy mix will develop once adopted different climate mitigation policies is of particular importance for the outcome of this study.

The results obtained in their study were subsequently downloaded from the CLIMACAP website (International Institute for Applied Systems Analysis (IIASA) 2015), then filtered by country, model, scenarios; lastly, the capacity (in GW)

TABLE 4.
Main features of and structural characteristics of the TIAM model

Model/Feature	TIAM-ECN
Economic coverage	Partial equilibrium
Calibrated years	2005, 2010
Endogenous variables	Energy supply, trade, emissions, prices (marginal costs)
Exogenous variables	End-use-demand (population, GDP), technology parameters, (investment costs, etc.)
Emission data sources	EDGAR, IEA
Population data sources	UN
GDP data sources	WB
Energy data sources	IEA
Covered sectors	Energy, Land use
Region	Global, Argentina, Brazil, Chile, Colombia, Mexico, Venezuela.
Covered gases	CO_2, CH_4, N_2O

EDGAR Emission Database for Global Atmospheric Research; IEA International Energy Agency; UN United Nations; WB World Bank; PV Photovoltaic; CSP Concentrated Solar Power. Source: Modified from Calderón et al. (2016) and van der Zwaan et al. (2016).

TABLE 5.
Baseline and climate-policy scenarios explanation

Scenario	Scenario description
Core baseline	Business-as-usual scenario including climate and energy policies enacted prior to 2010.
High co_2 price	A carbon tax of 50 $/t$CO_2$e is levied in 2020 growing each year at 4% to reach 165 $/t$CO_2$e* in 2050.
50% abatement (GHG)	Greenhouse emissions, excluding Land Use Change CO_2, are reduced by 12.5% from 2010 levels by 2020, linearly increasing to 50% of 2010 levels by 2050.
50% abatement (FF&I)	Fossil fuels and industrial CO_2 emissions are reduced by 12.5% from 2010 levels by 2050, linearly increasing to 50% of 2010 levels by 2050.

*US dollars/ton of CO2 emitted. Source: Calderón et al. (2016).

variable was selected as the main input for the purposes of this study. The 2010-2050 period of their study is also in accordance with the scope of this study.

Figure 6 shows what will be the installed capacity by type of energy source for the different scenarios in Colombia for the 2020-2050 time interval according to the results of the CLIMACAP project. In the core baseline scenario, wind and solar energy capacity does not show a significant increase in the total capacity. Therefore, in this scenario, Colombia will continue to rely mainly on hydropower and fossil fuel-based technologies for electricity generation; whereas, in the most ambitious scenarios (50% abatement GHG and FF&I and the High CO2 price), the renewable energy penetration rate could reach up to 60% of the total energy mix in 2050. In all of these scenarios, the wind power is the dominant renewable energy source.

4.3. Global metal intensities of use and market shares of the wind energy technologies

Once established the input data, the next step is to assign the metal intensity of use of the REEs embedded in the wind energy technologies. This will be based on the current published literature, taking into account possible future technical improvements, as well as recycling rates.

Regarding recycling, table 6 displays current and future recycling rates of selected REEs used in this study according to literature. Presently, recycling of rare earth elements is nearly absent, but will steadily increase mainly by concerns about future scarcity and rising prices of metals (Grandell et al., 2016).

Table 7 summarizes the metal intensity of use (IU) of the REEs present on the wind technologies used in this study, as well as a future projection of this parameter for the years 2025 and 2050. For this study, the average lifetime of the wind technologies is set to 25 years.

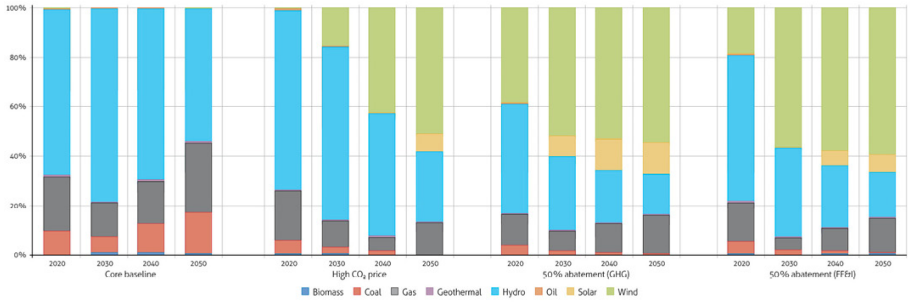

FIGURE 6.
Development of electricity capacity from 2020 to 2050 in four climate policy scenarios, according to the outcomes of CLIMACAP project research (International Institute for Applied Systems Analysis (IIASA), 2015).

In addition, there are other factors when considering future deployment of the wind technology which are related to how the different sub-technologies will evolve over time. Table 8 shows the forecast of how wind energy will be shared between onshore and offshore technologies on a global basis/scale (DNV GL, 2017). Table 9 shows the market share evolution of the different subtypes of wind turbines from 2020 to 2050 for both onshore and offshore locations. The latter values were taken from the study of Viebahn et al. (2015), since there are no studies for Colombia regarding that matter.

TABLE 6.
Current and future end of life recycling rates (EOL RR) for selected REEs

	Nd	Dy
Current EOL RR	<1%	<1%
2050 EOL RR	45%	45%

Future values were taken from Grandell et al. (2016) and Viebahn et al. (2015).

TABLE 7.
Current and future metal intensities of use of wind technologies according to different authors

Sub-type	Element	This study*	2025**	2050**
Direct Drive (DD-PM)	Dysprosium	18	11.7	11.7
	Neodymium	199	162.5	130
Middle speed (MS)	Dysprosium	3.7	2.9	2.9
	Neodymium	49.6	40	32
High speed (HS)	Dysprosium	1.8	1.4	1.4
	Neodymium	24.8	20	16

All values are in t/GW; * Average values from Tokimatsu et al. (2018), Manberger and Stenqvist (2018), van Gosen et al. (2014), Viebahn et al. (2015), Habib and Wenzel, (2014), and Brumme (2011); ** Forecast of future IU according to Viebahn et al. (2015).

TABLE 8.
Projection of the world share of wind energy according to its location

Location	2020	2030	2040	2050
Onshore	78.6%	66.7%	68.2%	76.9%
Offshore	21.4%	33.3%	31.8%	23.1%

Source: DNV GL (2017).

TABLE 9.
Distribution of the wind energy according to type of location and windmill technology

Location	subtype	2020	2030	2040	2050
Onshore	AG*	10.0%	6.6%	2.7%	1.5%
	SG*	30.0%	15.6%	8.3%	3.8%
	HS	50.0%	51.1%	43.3%	42.2%
	MS	0.0%	4.7%	4.6%	12.5%
	DD-PM	10.0%	22.0%	41.1%	40.0%
Offshore	AG*	61.0%	31.5%	11.5%	2.0%
	SG*	0.0%	0.0%	0.0%	0.0%
	HS	0.7%	0.5%	0.3%	0.0%
	MS	38.3%	49.5%	59.2%	60.0%
	DD-PM	0.0%	18.5%	29.0%	38.0%

* These types of wind turbines do not use REEs. Modified from Viebahn et al. (2015).

5. Derived metal demand and material availability

This chapter aims to assess the demand for metals in a quantitative manner. The first step to calculate the metal requirement in the specified period is to divide the ten-year capacity additions into specific renewable energy technologies, as described in the previous chapter, by sub-type, location and market share. Then, for each scenario, the added capacity of a certain type of technology (e.g. DD-PM onshore wind turbines) is multiplied by its specific metal consumption in a given period.

Finally, the cumulated demand for the different elements is considered in relation not only to their current annual global extraction rate but also to estimates of world reserves. The reserves are defined by the (USGS, 1996-2020) as "that part of reserve base which could be economically extracted or produced at the time of the determination", thus allowing to make a fair comparison with the amount of metals that can be mined at current market prices. Reserves are a dynamic measure, they can change due to alterations such as political and social factors, change in demand and price, as well as technological development (Davidsson and Höök, 2017).

5.1. Cumulative demand for REEs in the wind energy technologies

Figure 7 shows the cumulated demand for neodymium and dysprosium in the deployment of onshore wind technology in Colombia for the 2020-2050 period. The 50% abatement GHG scenario is the highest regarding REE demand, with a cumulated total demand of 6,150 tons of Nd and 498 tons of Dy. It is closely followed by the 50% FF&I scenario with 5,581 tons and 456 tons for Nd and Dy, respectively. This indicates that to halve emissions by 2050, the energy system will depend heavily on renewable energy technologies for electricity generation, and consequently, this will increase the amount of metals needed for such deployment.

In contrast, in the business-as-usual scenario (core baseline) the amount of metal needed is almost negligible because, as explained above, the energy mix in this scenario will rely mostly of hydropower, gas and coal for electricity generation. Interestingly, in the High CO2 price scenario, which is a scenario where a growing tax on CO2 emissions is levied, only moderate values of Nd and Dy 2050 demand are shown, with 2,135 tons and 181 tons respectively.

In offshore wind technology deployment, trends are similar but with lower general metal requirements (Figure 8). In the 50% abatement GHG scenario, cumulated metal demand for Nd and Dy in 2050 is 2,609 tons and 192 tons, respectively, followed closely by the 50% abatement FF&I scenario with 2,403 tons and 177 tons of Nd and Dy.

The cumulated demand for Nd and Dy in the business-as-usual scenario is, as in the case of the onshore technology, negligible, with Nd and Dy values of metal demand in 2050 of just 1.33 tons and 0.10 tons, respectively.

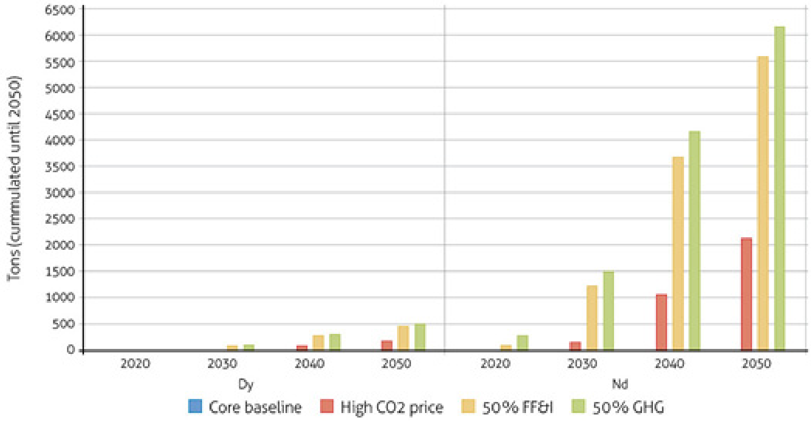

FIGURE 7.
Cumulative metal demand for Nd and Dy in the onshore wind power in Colombia during the 2020-2050 period

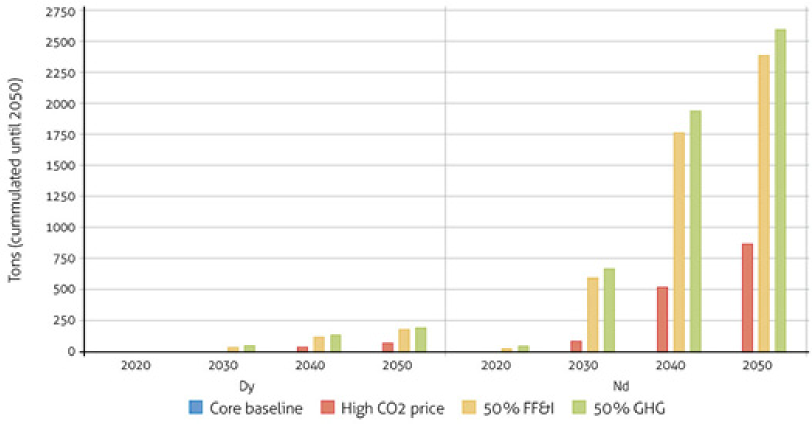

FIGURE 8.
Cumulative metal demand for Nd and Dy in the offshore wind power in Colombia during the 2020-2050 period

5.2. Cumulative demand from a resource perspective

In this section the material requirement of REEs is compared to their annual global extraction rate as well as to the global reserves (Table 10). The comparison with the former provides insight as to what percentage of the current production would have to be employed to meet future rare earth demand from the wind industries. In contrast, the reserves will allow to establish comparison points with the geological availability of metals by considering current market prices.

TABLE 10.
Production rates and reserves (in metric tons of rare-earth oxide (REO) equivalent content) for selected REEs

Element	Production rates (2016) in tons	Reserves (2016) in tons
Dy	1600[1]	480 000[1]
Nd	7000[2]	800 000[1]

1) Grandell et al. (2016); 2) Arrobas et al. (2017).

Figure 9 shows the results of the estimated annual mineral demand in the year 2050 in relation with the actual annual production rates for the selected REEs analyzed. Nd and Dy embedded in wind technologies are the elements with the highest values in both of the abatement scenarios with ratios varying between 15% for Dy and 37% for Nd. Although in the High CO2 price the percentage of Dy and Nd drops to 8% and 20% respectively. In the business-as-usual scenario the values are insignificant.

Figure 10 displays the ratio between cumulated metal demand for Nd and Dy and current reserves for those metals. Dysprosium shows values around 0.14% for both 50% abatement scenarios, whereas for the High CO2 price is 0.05%. The values for the business-as-usual scenario are negligible. For neodymium the highest values are around 0.11% for both the 50% abatement scenarios, 0.04% for the High CO2 price and 0% for the business-as-usual.

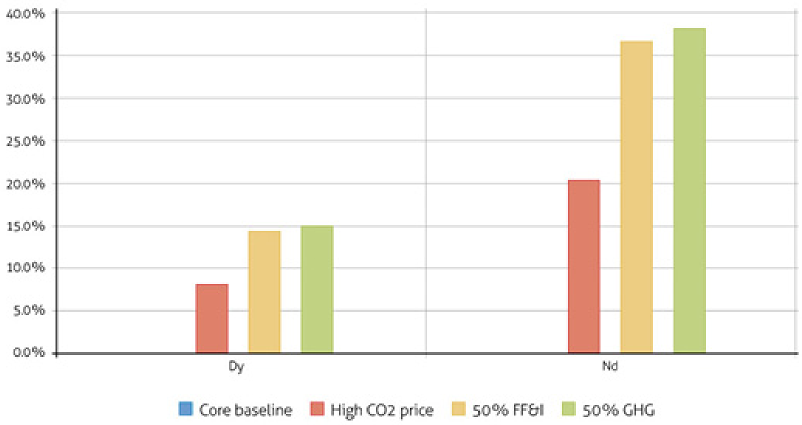

FIGURE 9.
Ratio of the 2050 metal demand and 2016 production levels for selected REEs embedded in renewable energy technologies

6. Discussion

This chapter discusses the main findings of the previous chapter, the assumptions made, the scope and limitations, concluding with some recommendations regarding the future availability of critical minerals for the deployment of RETs, not only in Colombia, but also taking into consideration a global perspective.

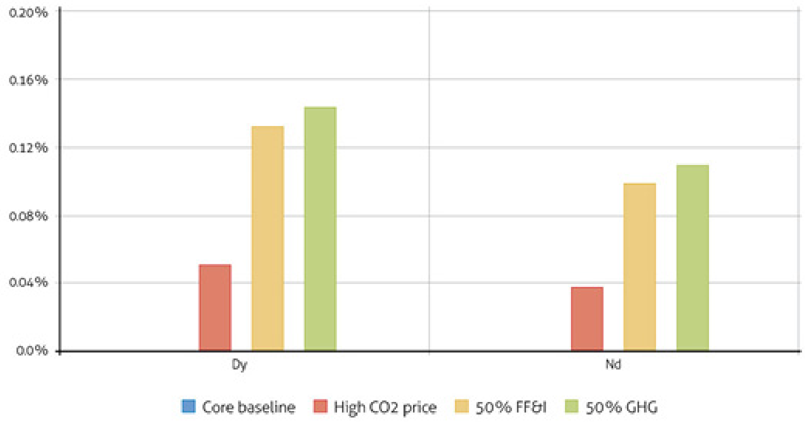

FIGURE 10.
Ratio of cumulated metal demand and 2016 reserves for Dy and Nd embedded in renewable energy technologies

6.1. Future REEs availability

The future availability of critical metals, such as the REEs, can be estimated by combining the technology and resource development over long-term scenarios. This allows to assess the energy system transformation of a country, a region or even the whole world.

Assessments, such as the one presented, are only possible when certain assumptions are made. Assumptions like the technological pathway for the next 30 years or so in Colombia, including the market share of the sub-technologies (e.g. onshore vs. offshore), future improvements in the material intensity of use and end-of-life (EOL) recycling rates, can greatly affect the outcome of the cumulative demand of the selected REEs. Nonetheless, it is starting point for the development of more detailed methodological frameworks dealing with criticality assessments in developing countries such as Colombia.

Future assessments of the Colombian energy transformation could include a broader range of critical minerals, other than the REEs, such as copper, indium, tellurium, and could also take into consideration the deployment of other clean technologies (e.g. solar technologies, battery storage, and electric mobility, among others).

According to the results of this study, Dy and Nd are considered here as “critical” elements for the deployment of the renewable energy technologies in Colombia during the 2020-2050 period, with a total cumulated demand of 690 t and 8,758 t respectively, included in the wind energy technologies.

When the cumulated demand in Colombia for both wind energy technologies, in 2050, for Nd (8759 t) and Dy (648t) is compared to the global reserves (800 000 t and 480 000 t, respectively; see Table 10), it can be seen that the cumulated demand for Nd and Dy constitutes less than about 1.1% and 0.15% of the global reserve values. Therefore, from a reserve point of view, the geological availability of the REEs will not constrain growth rates and total penetration levels of wind power deployment in Colombia during the 2020-2050 period. Furthermore, given the fact that reserves include economic, social, environmental, and geological variables that can change over time, these will likely increase in the future through the discovery and commissioning of mines as demand rises.

Now, when it comes to current production rates, things are somehow different. The estimated Colombian annual mineral demand for Dy and Nd in the year 2050 would constitute 13% and 37% of the world’s current annual production rate, respectively. This will become an issue that needs careful consideration given the fact that by 2050 a massive deployment of the wind power for the global electricity generation is expected.

Possible bottlenecks might arise and could influence the technology mix and maximum growth rates of some sub-technologies, such as the permanent magnet direct drive (PMDD).

Further sources of concern regarding mining production rates are competing demand from other technologies and recycling limitations. For the former, the increasing consumption of permanent magnets which utilizes Nd-Dy in other applications such as electric mobility will put more stress on the already strained production rates.

The supply of REEs come from two sources: either primary production, i.e. mining, or from secondary sources such as recycling. However, the secondary resources obtained through recycling are limited by several factors. Firstly, the limited EOL recycling rates – current levels are usually < 1% but will growth steadily to almost 45% by the end of the study period -; and secondly, the expected service life of RETs, which is 25 years, implies that only a small amount of the materials used in the period of the study will be available for recycling. In addition, even when EOL recycling rates improve, the recovery of the materials is not guaranteed, since many turbines that have reached the EOL have not been properly dismantled and recycled (Davidsson and Höök, 2017).

Furthermore, expanding mining capacity is not an easy task either. There are certain aspects of the REEs mining that makes it a complicated enterprise to achieve, including: 1) long lead times that take for a mineral deposit to become a producing mine, which oscillate between 10-20 years; 2) uncertainty of the return on investment caused by inherent mining factors; 3) environmental and social impacts that could delay the expansion of mines; and 4) the fact that these minerals are produced as by-products, which means that as even their prices increase, the production does not necessarily increase immediately, since this normally implies a larger output of the material which is primarily mined (Davidsson and Höök, 2017).

All of these issues may cause supply-demand imbalances and consequently, price hikes could occur, especially if governments were to implement climate policy scenarios such as the 50% abatement GHG, where the renewable energy technologies play an important role in electricity generation.

6.2. Worldwide perspective

To put these results into perspective, they will be compared against the outcomes of other national and global studies. Viebahn et al. (2015) and Brumme (2011) performed assessments of the mineral demand for RETs in Germany during the 2010-2050 period and found that the supply of Dy and Nd (among other critical minerals) will be a source of concern, inasmuch as present levels of REEs supply will presumably not be able to satisfy a rising demand in the future.

The same trend is also observed on a global scale. Figure 11 shows the cumulative demand of several elements used in different clean energy applications. Here, Dy and Nd demand shows significant increments for each decade to keep up the pace of the world deployment of renewable energy technologies, well above current mining production levels.

As it can be seen, the world could face potential shortages of metals such as Dy and Nd, and that could in turn, hinder the deployment of RETs and consequently, the fight against climate change.

6.3. Policy implications

Supply and demand policies can be used to mitigate the issues that the world could face related to the massive deployment of the renewable energy technologies and the mineral demand that a low-carbon economy could create. In this section, three policy options related with the mitigation of criticality issues are discussed.

6.3.1. Substitution

Material substitution is a way to decrease the amount of minerals utilized in RETs. It is an efficient measure to deal with criticality issues as long as the replacement is a more abundant material. However, this method has also certain drawbacks, such as the drop in performance of the technology when suboptimal materials are used. Moreover, it could also shift the criticality burden from one mineral to another, which could

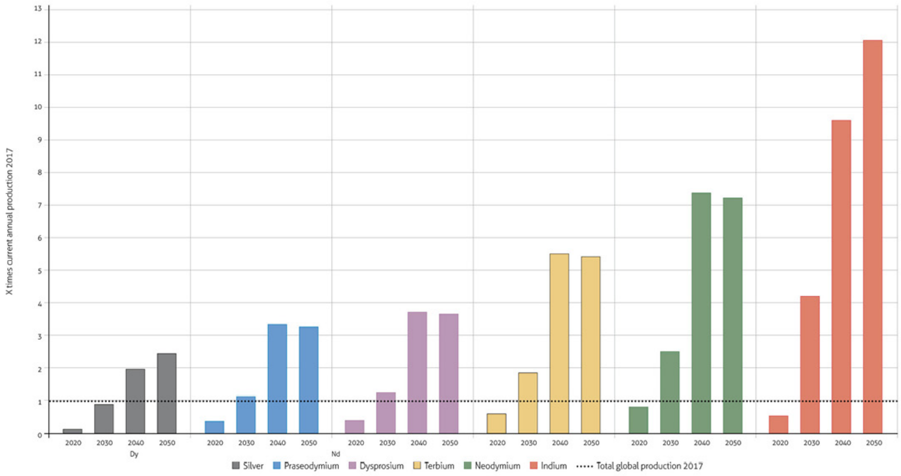

FIGURE 11.
Metal demand for wind and photovoltaic power generation between the 2020-2050 period, compared against metal production (2017 = 1)
Source: Taken from van Exter et al. (2018).

worsen the issue. Many materials could become scarce at the same time if the global demand is high; this is likewise expected in the transition to a low carbon economy (van Exter et al., 2018).

6.3.2. Improve circular design and recycling efforts

In this group of policies there are two main considerations that could help reach a sustainable future in the renewable energy technologies:

1. Design products with longer lifespans
2. Improved modular design which facilitates the separation of components

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For wind power, increasing the lifespan of turbines seems more relevant, given the fact that minimal material additions would be needed for producing electricity. For photovoltaic power, however, improvements in modular design seems more relevant. In addition, current recycling allows for most of the materials to be barely recycled. Therefore, areas for improving include the energy consumption associated with the recovery and increasing the purity of recovered materials (van Exter et al., 2018).

6.3.3. Sound technological choices

Policy-makers can influence the choice of technology a country or region could adopt when bottlenecks such as the mining capacity of critical elements are expected. The level of awareness among policy-makers has heightened, given that the increased use for critical materials such as Nd-Dy embedded in the renewable energy technologies may bring important issues for the development of a low carbon global economy.

6.3.4 World's dependency on China

The dependency on China's exports of REEs is being tackled on different fronts. In the United States, President Trump´s Executive Order 13953, which addresses "the threat to the domestic supply chain from reliance on critical minerals from foreign adversaries and supporting the domestic mining and processing industries", was signed on 09/30/2020 and published on 10/05/2020 (see: Federal Register, Vol. 85, No. 193, Monday, October 5, 2020).

The decision of the Australian Government to strengthen its position in the world market of critical minerals, particularly REEs, with several projects currently at the feasibility stage that include Nd and Pr (see: https://austrade.gov.au/ArticleDocuments/5572/Australian_Critical_Minerals_Prospectus.pdf. And also: https://www.industry.gov.au/sites/default/files/2019-10/outlook-for-select-critical-minerals-in-australia-2019-report.pdf).

Finally, the European Commission created ERECON (European Rare Earths Competency Network) as an initiative to strengthen the European Rare Earths supply chain. This network focuses on opportunities and road-blocks for primary supply of rare earths in Europe, European rare earths resource efficiency and recycling, and European end-user industries and rare earths supply trends and challenges. As stated by ERECON "rather than focusing on admonishing China over its REE policy, European industry and policy-makers must consider what they are prepared to do to support the development of a more diversified and sustainable supply chain" (European Commission, 2015; see also ERECON, 2015).

7. Conclusions

Overall, from a reserve perspective, the deployment of renewable energy technologies in Colombia during the 2020-2050 period and the associated mineral demand will not be affected by the worldwide geological availability of rare earth elements such as dysprosium and neodymium. Instead, certain sub-technologies, such as the permanent magnet direct drive in the wind power generation, could experience some future supply availability problems related to deficient mining capacity.

Demand from other industries such as electric mobility will also increase, and thus already troubled mining production rates will experience even more pressure. Consequently, the energy transition to a low-carbon economy and the fight against climate change could become a vulnerable process.

The supply of these minerals will come mainly from primary resources, as the supply from secondary sources will not be available in large quantities within the time frame of this analysis. In the extraction and refining processes, REEs only occur as byproducts, which means that these minerals are subject to supply restrictions related to the primary mineral with which they are associated. Therefore, even when prices increase, supply will not immediately increase, making it difficult to predict future availability. Recycling could become a significant mitigation measure, but only after 2050.

Policies that promote improved circular design, recycling, substitution, and sound technological choices are vital measures for achieving a more sustainable and resource-efficient future. At the same time, these support strategies will help avoid potential shortcomings in the availability of critical minerals, such as the supply of rare earth elements, on a global scale.

Upcoming assessments of the Colombian energy system could use a broader range of critical minerals and include other clean energy technologies. There is also the need to improve the knowledge of the REEs in Colombia, which ensures the dissemination of accurate information to develop geological and mining projects, and consequently, help mitigate future supply constraints.

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