Is the future development of wind energy compromised by the availability of raw materials?

E Gonzalez[1,2], **A Ortego**[3], **E Topham**[4,5], **A Valero**[3]
[1]ORSEIDE, C/ Dublín, 62, 31620 Pamplona, Spain
[2]Universidad de Zaragoza, C/ Mariano Esquillor Gómez, s/n, 50018 Zaragoza, Spain
[3]CIRCE, C/ Mariano Esquillor Gómez, 15, 50018 Zaragoza, Spain
[4]Doctoral Training Centre in Wind and Marine Energy Systems, University of Strathclyde, Glasgow, UK
[5]DNV GL, Edificio Trovador, Plaza de Antonio Beltrán Martínez, 50002 Zaragoza, Spain

E-mail: `elena@orseide.com`

Abstract. The installation of new electrical power plants from renewable sources is key in the transition towards a low-carbon economy. An important amount of diverse raw materials is required for this development. Due to its current prominence among renewable energy sources, we assess the expected development of wind energy towards the availability of the required raw materials up to 2050. Wind power is found to be in a favourable position, over solar thermal and photovoltaic power. Among the two main wind turbine technologies, the installation of direct drive turbines with permanent magnets faces a more challenging future. Recycling is an important strategy to simultaneously reduce risks and costs.

1. Introduction

The increasing installed capacity of renewable electricity generation is currently considered as one of the most important steps to address climate change. As stated by the European Commission, all sectors must contribute to achieve a minimum reduction of greenhouse gas (GHG) emissions to 80% of 1990's levels [1]. In this context, the electricity sector presents the biggest potential to achieve these European targets and could almost totally eliminate CO_2 emissions by 2050 [2]. According to the International Energy Agency [3], installed capacity from wind energy, solar thermal or photovoltaic power could reach figures of 2400 GW, 980 GW and 4500 GW respectively. Yet this energy transition must be carefully accomplished as a considerable amount of raw materials are required to build these new installations, increasing the pressure on materials availability.

Renewable technologies demand important amounts of elements to build wind turbines, solar cells or solar concentrator surfaces. Besides, current recycling rates of some of these materials are almost negligible due to higher costs of recycling processes [4]. Although recycling presents evident benefits [5], current recycling rates are still very low [6]. As a consequence, the dependency on critical resources could be pronounced as a potential barrier to a wider implementation of emerging renewable energy technologies [7].

The criticality of materials has been extensively studied from different perspectives, such as vulnerability, economic importance, supply or ecological risks [8, 9]. As concerns mid-term renewable energy development, wind is currently playing the most important role as it currently is the more mature and competitive renewable source. As a result, several recent studies have analysed the effect of raw materials (such as rare earth elements) availability towards the expected development of wind power [10–14].

In this paper, we analysed the potential future demand scenarios for 19 metals resulting from the expected new wind power installations up to 2050. Additionally, both solar sources, solar thermal and photovoltaic, are addressed for comparison purposes. The objective is to identify the constraints for future wind development related to raw materials availability.

2. Methodology

In this work, the demand of 19 different materials is assessed up to 2050, given the expected installations of wind power (WP), solar thermal power (STP) and solar photovoltaic (PV) per year. Then, the cumulative demand of each material until 2050 can be obtained. Finally, the comparison of this total demand against the resources and reserves of each material allows any risk to be identified, related to the three studied technology and the different materials considered.

The constraints related to future development of wind power, as well as STP and PV, were identified considering their related demand of the 19 following materials: Silver (Ag), Aluminium (Al), Cadmium (Cd), Chromium (Cr), Copper (Cu), Dysprosium (Dy), Gallium (Ga), Germanium (Ge), Indium (In), Magnesium (Mg), Manganese (Mn), Molybdenum (Mo), Nickel (Ni), Neodymium (Nd), Tin (Sn), Tellurium (Te), Titanium (Ti), Vanadium (V) and Zinc (Zn).

The identification of risks for material scarcity was performed here in different steps, presented in detail subsequently. The core of the methodology relies on the combination of a bottom-up and a top-down approaches. While the bottom-up approach covers the availability in terms of reserves and resources per material, the top-down approach assesses the quantity of each material demanded by each technology.

2.1. Top-down approach

A top-down approach was followed to obtain a cumulative demand of the mentioned materials by the selected renewable energy technologies, in a projected scenario over the period from 2016 to 2050. To do so, the expected yearly installed capacity from wind power [15,16], solar PV [17–19] and STP [20, 21] was assessed until 2050. The projection of the yearly new installed capacity for the three renewable technologies is illustrated in Figure 1. As can be seen, the repowering of old installations will increase the yearly installed power from 2033 with a special growing from 2039 caused by solar PV mainly.

Then, based on the literature [22], the material requirements per manufactured and installed megawatt (MW) of the three renewable technologies were used to translate the expected power installations into expected cumulative material demand, assuming current state-of-the-art developments and competition with the rest of sectors, in the 2016 - 2050 time period. The manufacturing requirements per material for every renewable technology are presented in Table 1, where the different requirements between wind turbines with geared or direct drive technology with permanent magnets are specified. Indeed, the need of permanent magnets presents in many direct drive wind turbine models increases significantly the requirements of Cu, Dy and Nd.

It is important to mention that not all the direct drive turbine models are built using permanent magnets. One of the largest manufacturer of direct drive wind turbines, Enercon, incorporates an annular generator with separate excitation, that leads to wind turbines being produced completely without permanent magnets. For the sake of simplicity, this has not been considered in the present analysis and only direct drive turbines with permanent magnets have been taken into account. As a result, the mentioned direct drive technology considered hereafter is the one that includes permanent magnets.

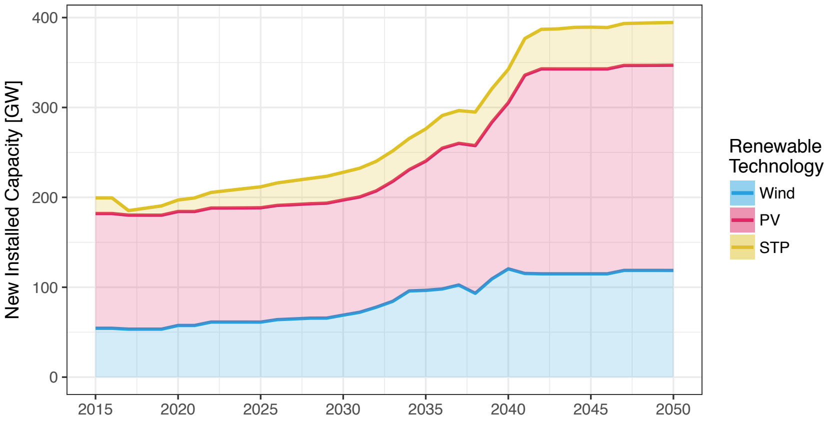


Figure 1: Projection of yearly installed capacity from wind power, solar PV and STP.

Table 1: List of materials used in renewable power installations (in kg/MW).

Material	Wind		PV	STP
	Geared Drive	Direct Drive		
Ag	-	-	113.1	14.2
Al	840.0	560.0	12511.4	9644.0
Cd	-	-	8.5	-
Cr	-	-	2.1	2800.0
Cu	1200.0	5500.0	3551.9	2480.0
Dy	4.9	14.6	-	-
Ga	-	-	0.4	-
Ge	-	-	0.7	-
In	-	-	5.8	-
Mg	-	-	45.5	2840.0
Mn	-	-	-	3480.0
Mo	-	-	9.7	142.4
Nd	60.9	182.8	-	-
Ni	111.0	111.0	0.9	1284.0
Sn	-	-	442.4	-
Te	-	-	7.3	-
Ti	-	-	-	15.0
V	-	-	-	2.0
Zn	-	-	4.3	950.0

As a result, the quantity of a raw material a demanded for all the analysed technologies, t, for a given year y can be obtained (see Equation 1). N_i is the yearly number of manufactured units per technology i, $M_{a,i}$ is the quantity of material a demanded by one functional unit (1 MW) per technology and r_a is the recycled share of material a.

$$d_{a,y} = \sum_{i=1}^{m} N_i M_{a,i}(1 - r_a) \tag{1}$$

In a projected 2050 scenario, renovation and repowering activities must be considered due to lower lifetime of the studied technologies (20-25 years). As a result, the yearly number of manufactured units per technology can be defined as the sum of the new units added to the global market N_{ns} and the number of units manufactured to repower old installations N_{rn} (see Equation 2).

$$N = N_{ns} + N_{rn} \tag{2}$$

Additionally, renewable technologies will certainly compete with other sectors in terms of materials' demand. In this work, this material demand for other sectors $d_{a,os}$ has been kept constant until 2050, due to the little information available in the literature. $d_{a,os}$ is estimated based on figures from 2015 as the difference between the total material production $(P_a)_{2015}$ and the material demand from renewable technologies for the same year P_a (see Equation 3).

$$d_{a,os} = (P_a)_{2015} - (d_{a,2015}) \tag{3}$$

Finally, the total demand for a given material a in year y, $(d_{a,T})_y$, and the total cumulative demand $D_{a,T}$ up to 2050 are assessed (see Equation 4 and 5).

$$\left(d_{a,T}\right)_y = \left(d_{a,y}\right)_y + (d_{a,os})_{2015} \tag{4}$$

$$D_{a,T} = \sum_{y=2016}^{2050} \left(d_{a,T}\right)_y \tag{5}$$

2.2. Bottom-up approach

As mentioned, the bottom-up approach covers the availability in terms of reserves and resources per material. While the resources are substrates present in the subsoil, regardless their accessibility or the financial and energy viability of their exploitation, the reserves are deposits that have been proven to be exploitable meeting both technological and financial feasibility. Due to this significant difference, it is important to identify the raw material availability in terms of both reserves and resources. In this case, the assessment on a global basis of the reserves and resources trends from 2016 to 2050 for each material was performed assuming a Hubbert-like production trend. More detailed description of this analysis can be found in [22]. The projected cumulative reserves and resources of the studied materials in 2050 are shown in Figure 2.

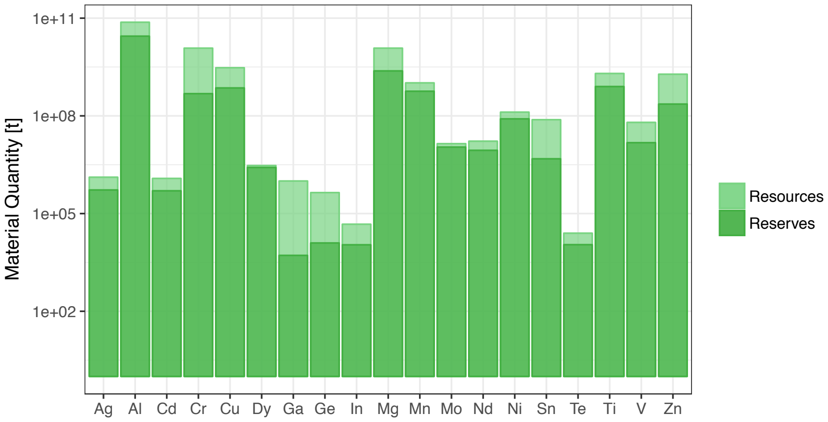


Figure 2: Cumulative reserves and resources of the studied materials in a projected 2050 scenario.

2.3. Risk identification

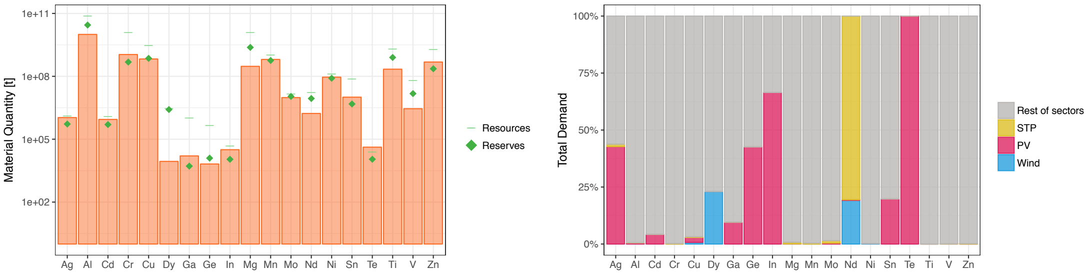
Two risk categories are defined considering material demand towards the available resources or reserves. As one can see in Table 2, category A is more restrictive than B, although resources and reserves are dynamic; they can change with extraction technology, prices or discovery of new deposits.

Table 2: Risk definitions related to material availability.

Type	Definition
A	Cumulative demand between 2016 and 2050 $\geq$ current resources ($D_{a,T} \geq RES_{2016}$)
B	Cumulative demand between 2016 and 2050 $\geq$ current reserves ($D_{a,T} \geq RSV_{2016}$)

3. Results

The baseline scenario obtained from the combination of the bottom-up and a top-down approaches is illustrated in Figure 3. This baseline Scenario 1 considers a share of 75% and 25% between geared drive and direct drive wind turbine technology [23], and a constant recycled share per material (r_a), meaning that no increase of the annual recycling rate was deemed. Figure 3B details the material demand share between the renewable technologies studied in the present work.



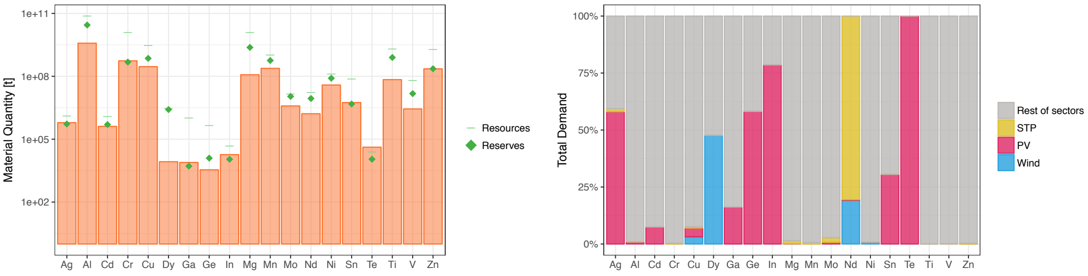
(A) (B)

Figure 3: Cumulative demand (orange bars), reserves and resources of the studied materials in a projected 2050 scenario (A) and material demand share by renewable technology (B) (Scenario 1).

As can be seen, the development of PV will be the most constrained by material availability, followed by STP. On the contrary, wind energy does not seem to be at high risk in the projected 2050 scenario. The unique unfavourable case corresponds to Nickel (Ni) availability. Also, while the availability of rare earth elements (REEs), Dysprosium (Dy) and Neodymium (Nd), does not seem to affect future wind development, a problem may arise related to their supply, almost exclusively from China. The identified risks, together with the most affected technology are summarised in Table 3.

3.1. Impact of annual recycling rate

The baseline Scenario 1 was built with an annual constant recycling rate. Nevertheless, it appears obvious that having increasing recycling rates would allow to overcome bottlenecks in terms of material availability. Recent research has shown the need of recycling rates of up to 5% for some materials to overcome the most severe risks [22]. To illustrate the impact of recycling, a common annual growth of 2% of every material recycling rate has been considered to build the Scenario 2. Results are presented in Figure 4. Additionally, the cumulative demand towards material availability is compared for both Scenario 1 and 2 in Figure 5.



(A) (B)

Figure 4: Cumulative demand (orange bars), reserves and resources of the studied materials in a projected 2050 scenario (A) and material demand share by renewable technology (B) assuming an annual increase of 2% of the material recycling rate (Scenario 2).

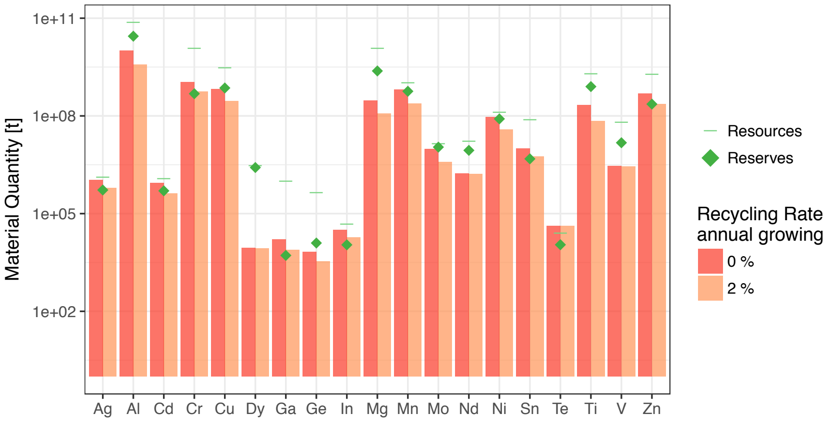


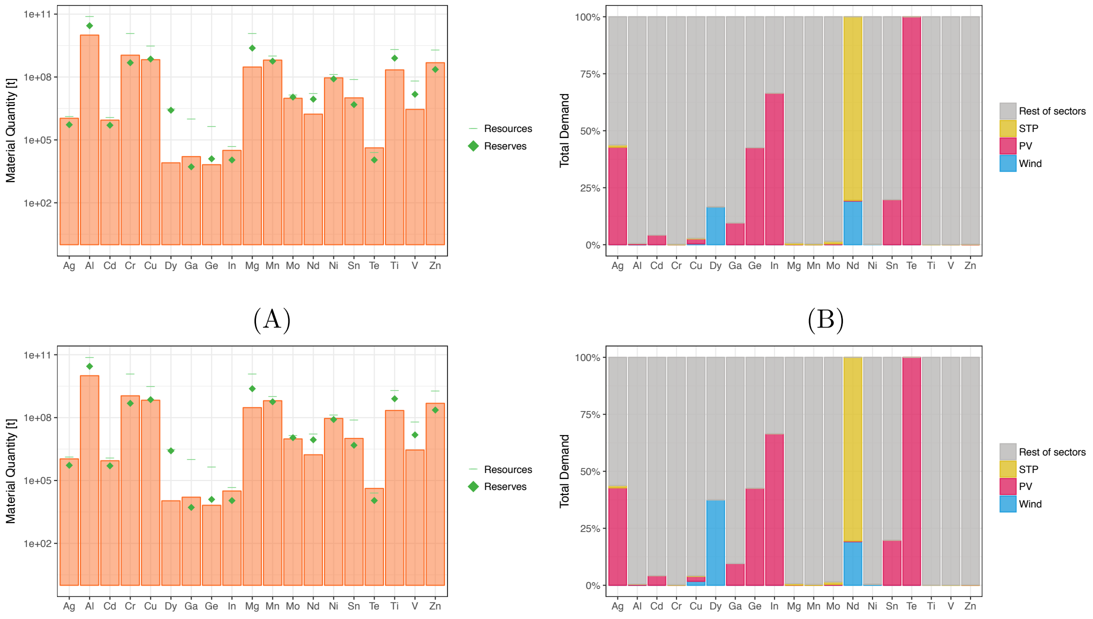
Figure 5: Comparison of the cumulative demand for the scenarios 1 and 2, against the reserves and resources of the studied materials in a projected 2050 scenario.

As can be seen, the cumulative demand is positively affected by increasing the annual recycling rate. Moreover, as presented in Table 3, the occurrence of risks is also significantly reduced.

Although the development of new wind power projects does not seem to be in risk in terms of material availability, recycling appears also as an important topic. Indeed, it is thought that improving the recycling rates during the decommissioning phase of a wind farm would allow to reduce the levelised cost of energy (LCOE) together with a reduction of the environmental impact. The wind industry agrees that recycling metallic components is relatively straightforward; their transportation cost remains a negative factor though [24]. As wind turbines are mainly manufactured using metallic elements, this can be translated into a recyclability rate of about 83%, including mainly big components from the tower, the gearbox, the main shaft, the generator, castings, bearings and parts from the nacelle and the hub. The remaining 17%, non-recyclable, encompasses elements from electronics, oil and coolants, polymers but mainly derives from the blades (nearly of this 13%) [25]. Blades are currently the big challenge from a recycling point of view, a part from being a logistical transportation nightmare. Blades are typically made from a composite of glass fibres and epoxy or other thermoset resin, where the cross-linked polymers are difficult to melt down and be recycled [26]. Alongside the decommissioning phase, blades are currently being shredded and then often end up in landfills, while other alternatives such as incineration and recycling could be explored [27]. The first option is becoming less popular due to the willingness of countries to reduce the land fill mass. For instance, Germany banned the disposals of glass fibre reinforced plastics (GRP) in June 2005, due to their high rate (30%) of organics content such as resin and wood. The second most common route is incineration, where the heat is reused to generate electricity in combined heat plants (CHP), but the inorganic loads lead to the emission of hazardous flue gazes. The blades also need to be dismantled and crushed before transportation placing further strain on the environment in terms of energy used and polluting emissions [27]. As a result, recycling should be definitely encouraged, either way it consists of material recycling or product recycling, i.e repowering.

3.2. Impact of wind turbine technology share

The baseline Scenario 1 considered a share of 75% and 25% of geared and direct drive (with permanent magnets) wind turbine technologies respectively. However, direct drive wind turbine technology seems to be privileged from some wind turbine manufacturers, especially if they cover an important share of the offshore wind market. To assess the effect of this technology share, two additional virtual scenarios (3 and 4) have been investigated; Scenario 3 considers a 100% share of geared drive wind turbines, while Scenario 4 assumes no new geared drive turbines installed, so a 100% of direct drive wind turbines. Results from both scenarios are illustrated in Figure 6.



(A) (B)

(C) (D)

Figure 6: Cumulative material demand given a 100% share of geared drive wind technology (A) - Scenario 3 - and given a 100% share of direct drive wind technology (B) - Scenario 4 -; material demand share by renewable technology for Scenario 3 (B) and Scenario 4 (D).

As can be seen, no significant changes are appreciated in terms of the cumulative demand per material, toward the availability. However, there is a significant increase of the required cumulative quantity of Dy in Scenario 4. As mentioned, this is mainly due to the presence of permanent magnet generators in most direct drive turbines. A more thorough discussion is presented in Section 4.

3.3. Summary of identified risks in each studied scenario

The different risks identified in the four presented scenarios are summarised in Table 3.

Table 3: Type of risk per material in the four different projected scenarios.

	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
	Risk	Most affected technology	Risk	Most affected technology	Risk	Most affected technology	Risk	Most affected technology
Ag	B	RoS	B	PV	B	RoS	B	RoS
Al	-	-	-	-	-	-	-	-
Cd	B	RoS	-	-	B	RoS	B	RoS
Cr	B	RoS	B	RoS	B	RoS	B	RoS
Cu	-	-	-	-	-	-	-	-
Dy	-	-	-	-	-	-	-	-
Ga	B	RoS	B	RoS	B	RoS	B	RoS
Ge	-	-	-	-	-	-	-	-
In	B	PV	B	PV	B	PV	B	PV
Mg	-	-	-	-	-	-	-	-
Mn	B	RoS	-	-	B	RoS	B	RoS
Mo	-	-	-	-	-	-	-	-
Nd	-	-	-	-	-	-	-	-
Ni	B	RoS	-	-	B	RoS	B	RoS
Sn	B	RoS	B	RoS	B	RoS	B	RoS
Te	A	PV	A	PV	A	PV	A	PV
Ti	-	-	-	-	-	-	-	-
V	-	-	-	-	-	-	-	-
Zn	B	RoS	-	-	B	RoS	B	RoS

4. Discussion

While the future development of wind energy should not be constrained by the demanded raw materials, geopolitical problems might tip the balance towards geared drive technologies. Many recent studies have compared the two main wind turbine technologies, i.e. geared and direct drive, in terms of manufacturing costs, reliability and maintainability. Nevertheless, the materials demanded by each configuration have not been addressed. Most direct drive turbines are equipped with permanent magnet generators, relying heavily on REEs (Dy and Nd) [28], provided almost exclusively by China. Additionally, the future demand of permanent magnets will significantly increase from the electrical vehicle industry, creating a direct competition with direct drive turbines manufacturers. Reusing [29] and recycling [30] can be therefore seen as promising strategies. End-of-life recycling could help in the current global supply crisis surrounding REEs so that dependence on China can be decreased.

The risk for future development of wind power projects could be further lowered by promoting alternative strategies at the end-of-life of current installations. Two main options are suggested here. First, lifetime extension should be privileged over repowering, when possible [31]; this would imply evident benefits regarding the materials life-cycle assessment. Secondly, the recycling rates should be increased. In a longer term, recycling could provide a significant secondary supply to reduce the future demand of raw materials [12]. Apart from the environmental benefits, recycling could also contribute to reduce the levelised cost of energy (LCOE). Indeed, this is almost not considered during the decommissioning phase of a wind farm [32]. Higher recycling rates could halve the decommissioning costs, generally underestimated [33], and hence lower the capital expenditures and the LCOE. Also, reusing should be considered as part of the operation and maintenance (O&M) phase. Reusing subcomponents from critical assemblies, such as the gearbox [34], could also reduce the O&M costs.

5. Conclusions

The development of future wind power projects, as other renewable technologies, depends on the availability of certain materials required for the manufacturing and installation of wind turbines.

In this study, the available resources and reserves for 19 different materials have been compared to the expected development of wind energy in a 2050 projected scenario. Two other renewable sources of electricity generation, solar thermal power and photovoltaic power, have also been assessed for comparison purposes. Wind power seems to be the least affected technology given the availability of materials. Among the two main wind turbine technologies, some risks have been identified related to direct drive turbines though. The need of REEs for the production of permanent magnets creates a competition with other industries, as the electrical vehicle, and involves an important risk of shortage due to its geological availability.

Several alternatives, such as lifetime extension and recycling, have been suggested to further lower the risks for future wind development. Nonetheless, these are also valid for the two other explored renewable sources, that are found to be at higher risks.

Finally, if the current materials demands and recycling quotes are maintained, the transition to a low-carbon economy could be threatened by the availability of certain elements. This issue should be deeply analysed to define appropriate strategies that avoid the mentioned constraints.

6. Learning objectives

- A shift towards a low-carbon economy hugely depends on the availability of raw materials.
- The development of wind energy might be compromised by the simultaneous requirement of certain materials from other renewable technologies or other industries.
- While wind energy development seems to be at a lower risk than other renewable sources, direct drive technology using permanent magnets is in a less favourable position.
- Encouraging reusing and recycling of raw materials shows important and diverse benefits.

Acknowledgments

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