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Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system

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Abstract

Raw materials are essential to securing a transition to green energy technologies and for achieving the goals outlined in the European Green Deal. To meet the future energy demand through renewable energy sources, the power sector will face a massive deployment of wind and solar photovoltaic (PV) technologies. As a result, the consumption of raw materials needed to manufacture wind turbines and PV panels is expected to increase drastically in the coming decades. However, the EU industry is largely dependent on imports for many raw materials and in some cases is exposed to vulnerabilities in its supply. These issues raise concerns about the availability of some of the raw materials needed to meet the future deployment targets for the renewable energy technologies.

This study aims to estimate the future demand for raw materials for wind turbines and solar PV in various decarbonisation scenarios.

For the EU, the material demand trends were based on the EU legally binding 2030 targets and deployment scenarios aiming to achieve a climate-neutral economy by 2050. At global level, the generation capacity scenarios were selected based on various global commitments to limit greenhouse gas (GHG) emissions and improve energy efficiency.

In addition to power generation capacity, the material demand calculations took three more factors into account: the lifetime of the power plants, the market share of the sub-technologies and material intensity. By evaluating and combining these factors, three demand scenarios were built, characterised by low, medium and high material demands.

For wind turbines, the annual material demand will increase from 2-fold up to 15-fold depending on the material and the scenario. Significant demand increases are expected for both structural materials – concrete, steel, plastic, glass, aluminium, chromium, copper, iron, manganese, molybdenum, nickel and zinc – and technology-specific materials such as rare-earth elements and minor metals.

In the EU the biggest increase in material demand will be for onshore wind, with significantly lower variations for offshore wind, while on the global scale the situation is the opposite. The most significant example is that of rare earths (e.g. dysprosium, neodymium, praseodymium and terbium) used in permanent-magnet-based wind turbines. In the most severe scenario, the annual EU demand for these rare earths increases 6 times in 2030 and up to 15 times in 2050 compared to 2018 values. As a consequence, by 2050, the deployment of wind turbines according to EU decarbonisation goals alone will require most of the neodymium, praseodymium, dysprosium and terbium currently available to the EU market. In the high demand scenario, the global demand for rare earths in wind turbines could increase 8-9 times in 2030 and 11-14 times in 2050 compared to 2018 values, a slightly lower increase compared to the EU.

For solar PV technologies there are large differences in material demand between different scenarios, especially for those specific materials used in the manufacturing of PV cells. In the most optimistic case, improvements in material intensities could lead to a net decrease in material demand. In the medium demand scenario, the balance between capacity deployment and the material intensities will result in a moderate increase in demand ranging from 3 to 8 times for most materials. In the high demand scenario an increase in demand is expected for all materials, for example a 4-fold increase for silver and up to a 12-fold increase for silicon in 2050. For cadmium, gallium, indium, selenium and tellurium the change in the demand will be more significant, increasing up to 40 times in 2050. The highest demand in 2050 is expected for germanium, which might increase up to 86 times compared to 2018 values.

In the most severe conditions, the EU will require around 8 times (in 2030) and up to 30 times (in 2050) more structural materials, such as those used in frame and staffing materials, than in 2018. However, in the high demand conditions, the EU annual demand for PV cell materials varies more broadly, such as between 4 times for silver and 86 times for germanium in 2050. For silicon, the EU demand is expected to double in 2030 and increase 4 times in 2050 under the medium demand scenario, and increase 7 times in 2030 and 13 times in 2050 under a high demand scenario.

Considering both technologies, such high increases in material demand will put additional stresses on the future availability of some raw materials. The EU's transition to green energy technologies, according to the current decarbonisation scenarios, could be endangered by weaknesses in future supply security for several materials, such as germanium, tellurium gallium, indium, selenium, silicon and glass for the solar PV and rare-earth elements for the wind turbine technologies.

On EU and global scales there are plans to move towards renewable sources and green energy.

The energy will be generated mainly by wind and solar PV.

To build wind turbines and solar cells we need raw materials.

4 factors assessed in high, medium and low demand scenarios

Generation capacity

How much renewable energy will be produced?

Lifetimes

How often do we need to replace the systems?

Market Share

Which sub-technologies will be dominant?

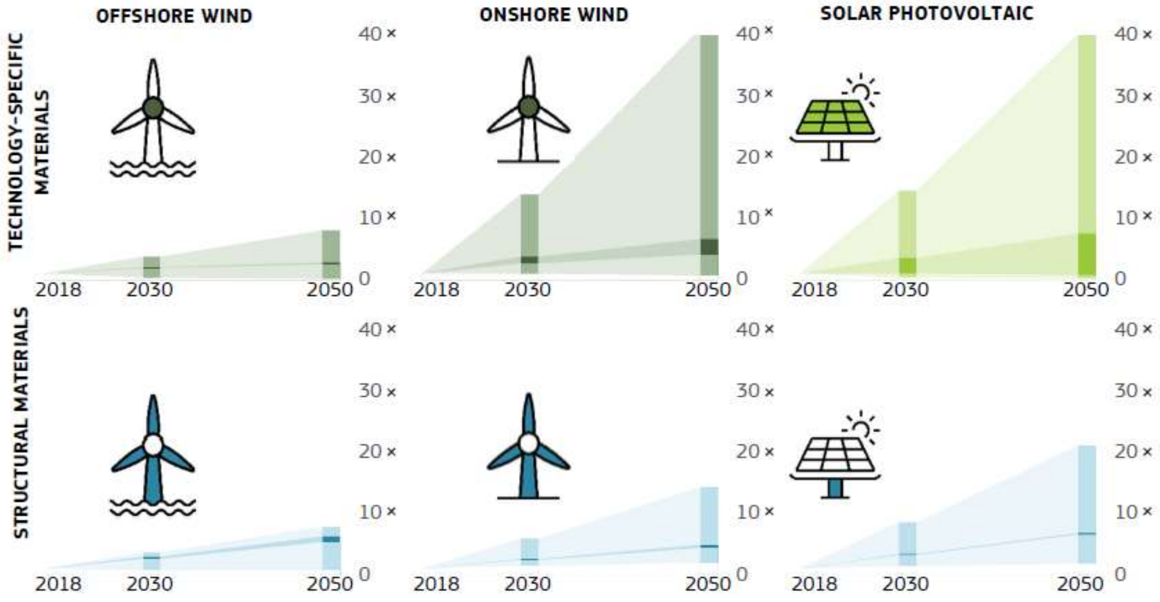
Material intensity

How much will material usage improve?

How much will material demand change?

Raw materials demand forecast for structural and technology-specific materials for offshore wind, onshore wind and solar photovoltaic (relative to 2018)

Materials have been grouped according to the technology (offshore wind, onshore wind, solar) and whether they are structural or technology-specific. The darker area of each vertical bar represents the demand range in a medium demand scenario. The lighter area represents the demand variability considering low demand and high demand scenarios.



Source: JRC analysis.

1. Introduction

This report analyses the future demand for raw materials for wind and solar photovoltaic (PV) technologies based on three potential scenarios, providing a technical framework for policy decisions in the area of critical raw materials and ensuring the availability of resources for the green energy transition. The transition towards a green energy system based on renewable electricity generation will come with an increasing demand for raw materials. For some technologies, the supply of raw materials is already insecure and there are concerns about their availability as it might be insufficient to meet future demand. Reliable estimates are therefore extremely important in supporting policymakers and industries and their decisions on ensuring a secure and sustainable supply of these materials to the EU and reducing its dependence on unreliable countries.

In this first chapter, an introduction is given underlining the importance of the two technologies in the current and foreseen energy scenarios, both in the EU and worldwide. The importance of demand and criticality assessments for key raw materials is also highlighted. Towards the end of the chapter, a general overview of the methodology adopted in establishing and analysing the future scenarios is also provided. In Chapters 2 and 3, there are more detailed insights into wind and solar PV technologies, respectively, including quantitative results from the demand analysis. Finally, Chapter 4 summarises the main conclusions regarding future demands, with a specific focus on the EU.

The main research questions addressed in this report are as follows.

- How much will material demand change by 2050 according to global and EU climate-mitigation scenarios?
- What are the effects of technological developments and material efficiency on future demand patterns?
- To what extent is the deployment of wind and solar PV technologies expected to create additional stress on the global supplies of the relevant materials?

1.1. The role of wind and solar PV technologies in meeting future energy demands

Global demand for energy and electricity is increasing, as proven by the 2.3% growth in primary energy demand and 3.9% growth in global electricity demand registered in 2018 (IEA, 2019). At EU level the demand appears more stable (IEA, 2019).

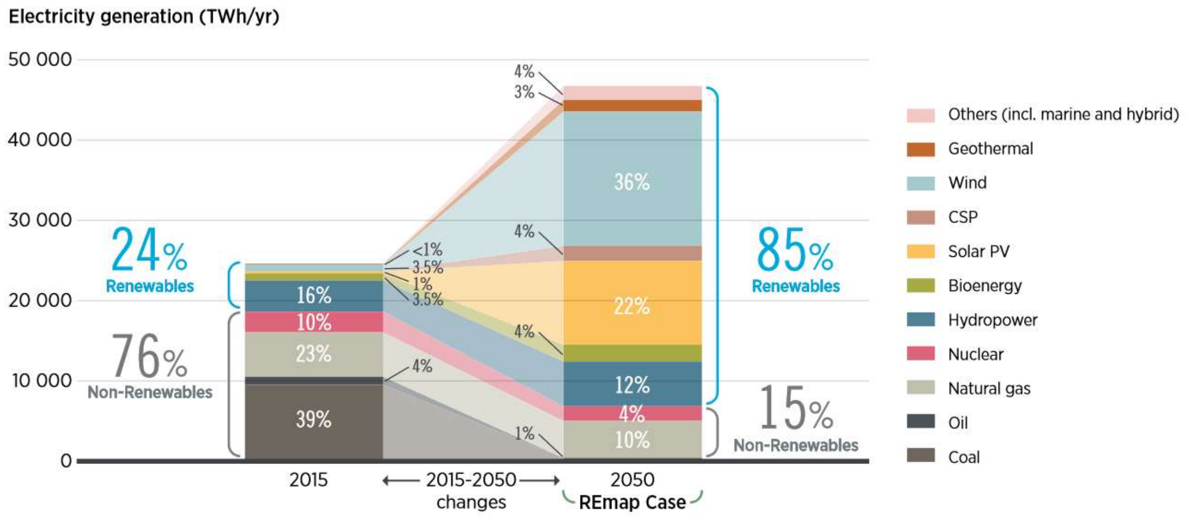
At global level, renewable energy sources represent around 26% of the global power output (REN21, 2019). The International Energy Agency's (IEA) World Energy Outlook foresees an increase in the share of renewables to more than 40% by 2040 (IEA, 2019). In the EU, the share of renewable sources in power generation has already exceeded 30%, and will likely increase even further in the coming decades. The abovementioned study indicates that renewables might account for two thirds of the EU's electricity generation by 2040. This expansion is considered necessary in order to meet the ambitious climate-related goals laid out in the European Green Deal (European Commission, 2019).

According to the International Renewable Energy Agency (IRENA), to meet energy and climate change targets within the context of a successful energy transition, renewable energy would need to provide two thirds of the global energy supply by 2050. In the power sector, the share of renewable energy would increase to 85% by 2050, mostly through growth in wind and solar PV energy generation (Figure 1) (IRENA, 2018).

Even though the predominant renewable source is currently hydropower, a rapid increase in capacity and generation for wind and solar PV technologies has taken place in the past decade, both in the EU and worldwide (Figure 2). As those technologies are expected to dominate the scene in the years to come, they have been chosen for the current analysis as the most relevant in enabling the energy transition.

For both wind and solar PV, the EU already accounts for almost one third of capacity and generation worldwide. Wind contributions are split between onshore and offshore. Currently, offshore contributions account for only 5% of the wind electricity generation worldwide and 15% in the EU; this is explained by the fact that the costs of onshore and offshore facilities differ significantly, even though they use fundamentally similar technologies. The costs of offshore wind projects commissioned in 2016 were on average 150% higher than those of onshore wind projects, and more than 50% higher than those of utility-scale solar PV projects (IEA, 2018). However, at EU level there are plans to significantly increase offshore wind production in the near future (European Commission, 2019), thanks in part to expected decreases in the overall costs of the technology (JRC, 2018).

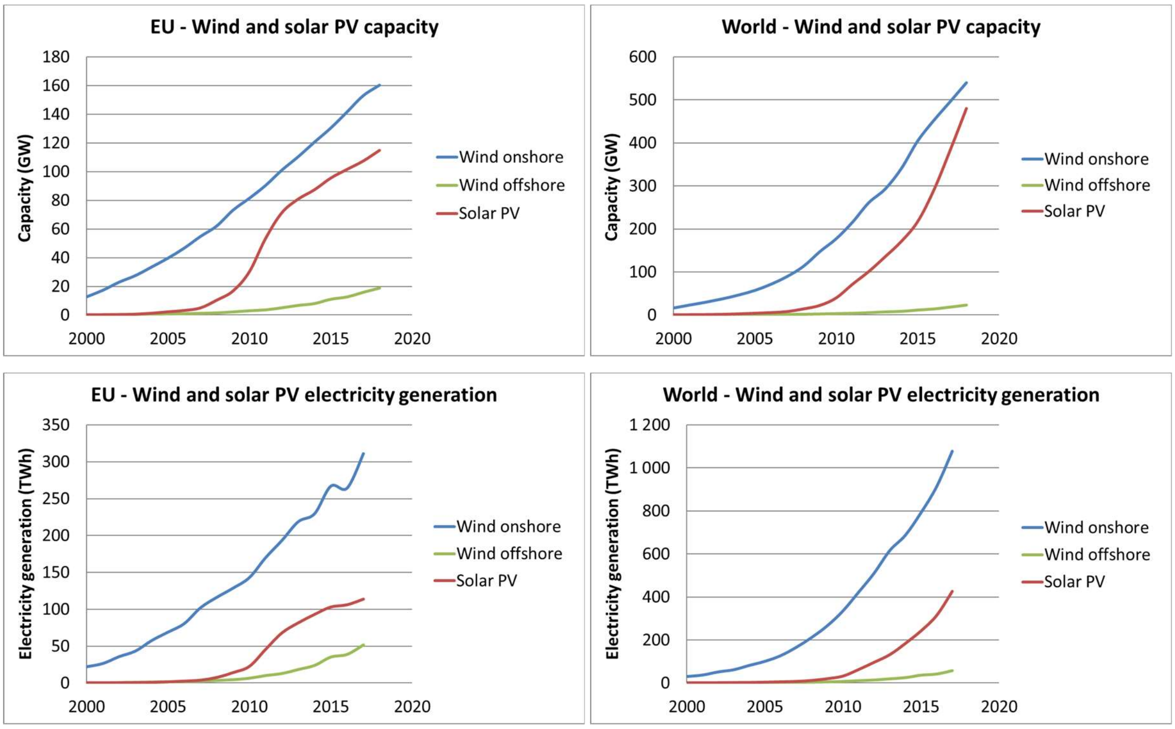
Figure 1. Breakdown of electricity generation by source



Source: IRENA (2018).

Abbreviation: CSP = Concentrated Solar Power.

Figure 2. Wind and solar PV capacity and electricity generation in the EU and worldwide



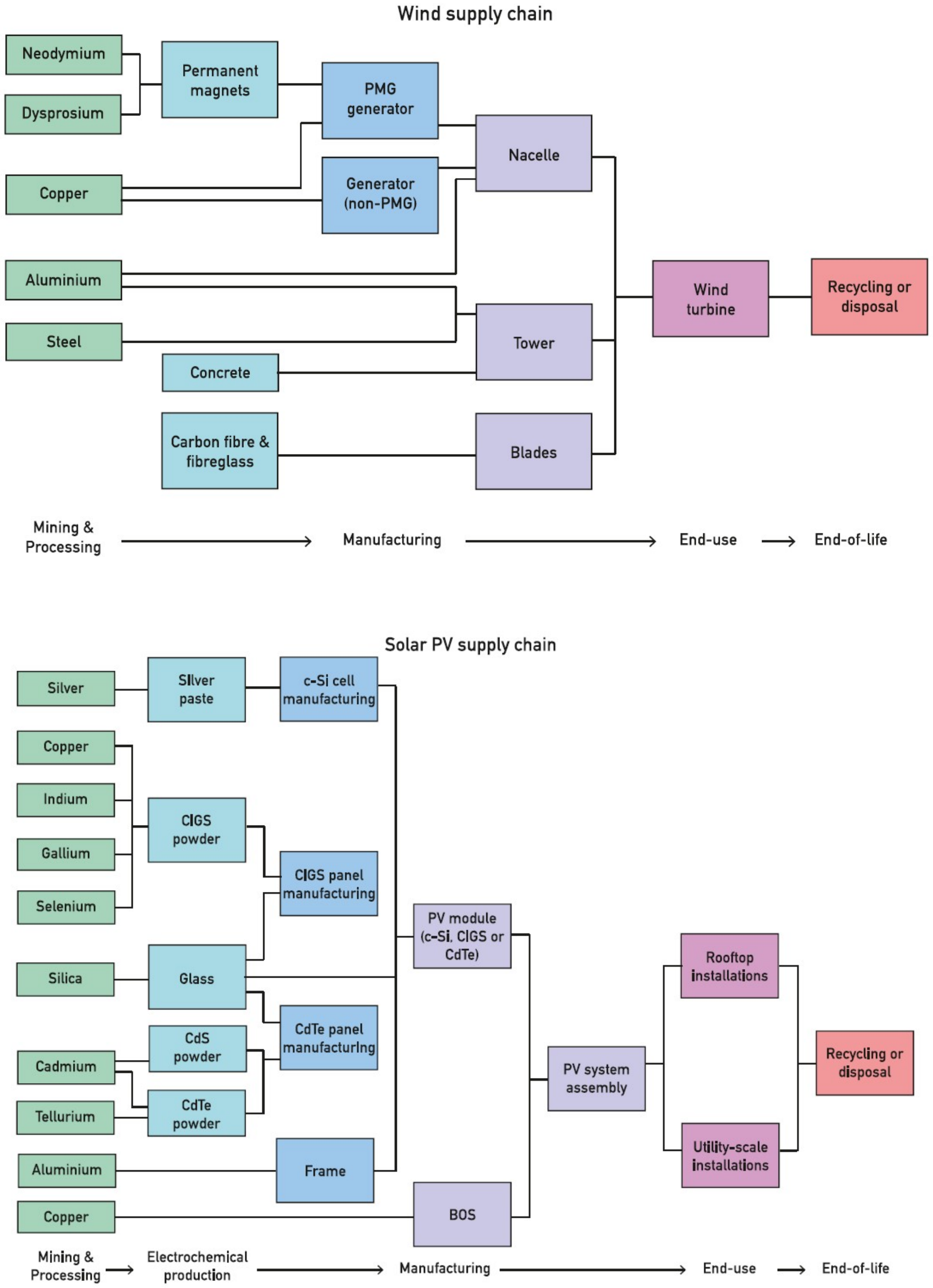
Source: JRC representation based on IRENA database (IRENA, 'Statistics Time Series').

1.2. Materials and supply chain for wind and solar PV

The deployment of increasing levels of renewable power capacity entails the production and installation of new wind turbines and PV systems, which will in turn require large quantities of components and raw materials, mostly metals.

Figure 3 summarises the most important elements of the wind and solar PV power supply chains, identifying the necessary raw and processed materials and components along the chain, up to the final products. Recycling is included as part of the supply chain; however, it is not assessed in this study.

Figure 3. Simplified value chains for wind and solar PV materials



Source: Giurco, Dominish, Florin, Watari and McLellan (2019).

Abbreviations: PMG = permanent magnet generator; BOS = balance of system.

The relevant raw materials for wind and solar PV installations include various base, precious and minor metals along with composite materials such as steel, concrete, fibreglass / carbon fibre and polymers. Many of these are of strategic importance to the EU economy and their supply is already facing increased risk (European Commission, 2017).

This is the case for the rare-earth elements and boron embedded in the permanent magnet of direct-drive wind turbines, as well as for the gallium, germanium, indium and silicon needed for PV systems.

Securing a reliable supply of rare earths at a reasonable price is crucial in enabling the energy transition, particularly for offshore wind energy. In fact, the deployment of neodymium-iron-boron (NdFeB) permanent magnets in direct-drive systems has been central to the debate surrounding potential shortages of rare-earth elements and the expansion of wind power (Centre for Sustainable Energy, 2017).

A major issue is that currently the EU has no mining of rare earths, and the main global producers and suppliers of critical and some non-critical raw materials are highly concentrated in a few countries and in some cases with a poor level of governance. This could pose both risks to security of supply and environmental and social problems.

More specifically, China controls the global market as a leading producer and user of a majority of critical minerals, including rare earths. The EU's dependency on China is certainly a risk factor, and one which needs to be seriously taken into account when planning the future of renewables in Europe and working towards the long-term climate-neutral goals.

To tackle this, and acknowledging the importance of improving the security of material supply and decreasing dependence on Chinese imports, wind manufacturers have attempted to modify sourcing approaches and reduce or eliminate the use of such materials through technological innovations.

The import of rare earths from China is probably the most critical issue in this area, due in part to the recent trade war between the United States and China. However, there are many other materials used for manufacturing wind turbines, supplied from different countries, thereby allowing for supply diversification strategies. An overview of global suppliers of such materials is shown in Figure 4.

Figure 4. Producers of raw materials used in wind turbines

Source: Centre for Research on Multinational Corporations (SOMO) (2018).

1.3. Methodology

To assess the future demands for the materials needed for the deployment of wind and solar PV systems between now and 2050, different policy-relevant electricity generation scenarios for the EU and the world were considered. These scenarios take into account four main factors, detailed below.

1. **Power generation capacities.** Power capacity levels according to political commitments made at EU and global levels. The higher the expected capacity, the more power plants will have to be deployed and the more materials will be needed. Detailed information on the capacity scenarios is given in Section 1.3.1.
2. **Plant lifetime.** Repowering activities influencing annual capacity additions are considered as a function of equipment lifetime. Capacity projections influencing material demand therefore include the obsolete electricity generation capacity that will need to be replaced over time.
3. **Sub-technology market shares.** As different technology designs will have distinct material requirements, predictions about the future mix of technologies are as fundamental as estimates of expected penetration levels of renewable technologies. Projections are developed assuming the maintenance and expansion of current state-of-the-art sub-technologies, and estimates of their market share are extrapolated on the basis of recent deployment trends and the literature. Scenarios were constructed by varying the mix of the sub-technologies expected to be prominent in the future.
4. **Material intensity.** Intensities of material usage will likely change over time as a consequence of technological optimisation. For example, even if the absolute consumption of raw materials increases with the size of the equipment, this effect could be offset by higher energy production thanks to more resource-efficient designs. Material intensities are assessed in terms of t per GW (the amount in t of material *x* embedded per GW of installed capacity of technology *y*).

Combining those factors it was possible to obtain three scenarios:

- **Low Demand Scenario – LDS.**
- **Medium Demand Scenario – MDS.**
- **High Demand Scenario – HDS.**

Those three scenarios are a 'baseline' scenario (Medium Demand Scenario – MDS), and two extreme scenarios where materials demand is either as low as reasonably possible (Low Demand Scenario – LDS) or as high as we can expect (High Demand Scenario – HDS). The baseline scenario was built considering average improvements in lifetimes, market-shares and material intensities, and assuming moderately ambitious goals for decarbonisation, as described in the following section. A visual overview of the methodology adopted and of the key objectives is provided in Figure 5.

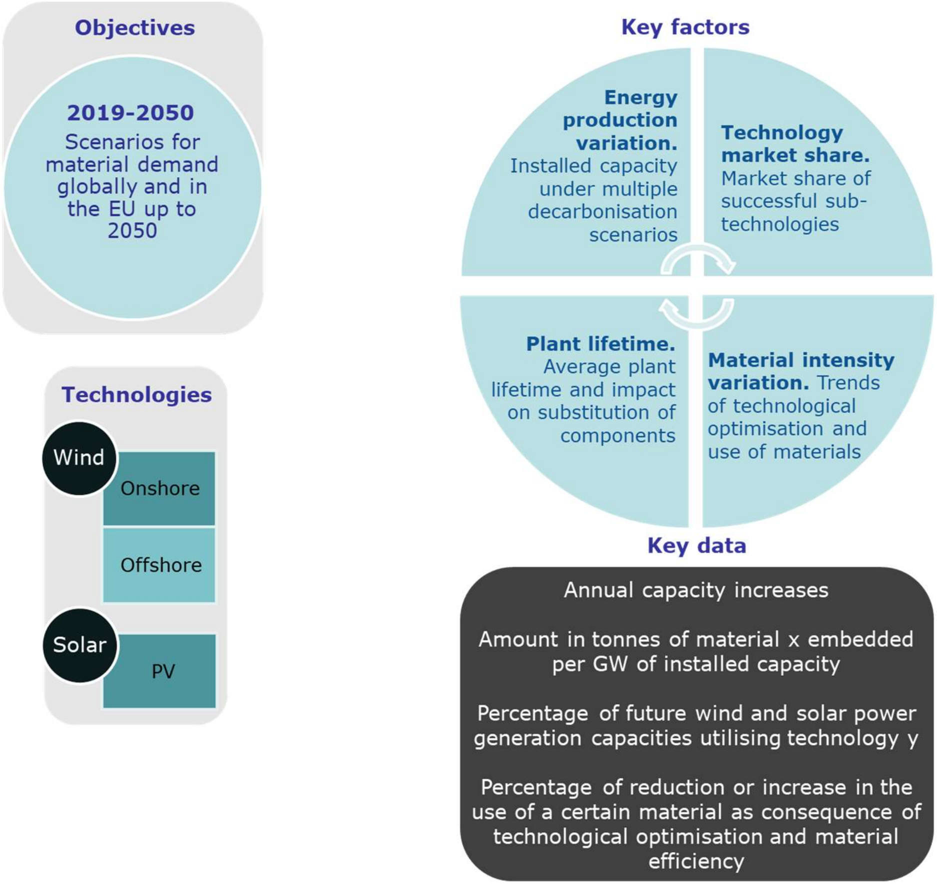
1.3.1. Capacity scenarios for wind and solar PV power generation

Future scenarios of power generation capacity for wind and solar PV have been chosen from a wide selection of policy-relevant strategies.

For the EU, two of the scenarios are from the EU long-term strategy (LTS) 'A Clean Planet for All' (European Commission, 2018) and the third is a JRC-EU-TIMES scenario developed for the Low Carbon Energy Observatory project (Carlsson et al., 2020). In detail, the three scenarios considered in this analysis are as follows.

- **LDS – LTS Baseline Scenario.** Considers the EU legally binding 2030 targets and aims to achieve a 64% reduction in GHG emissions by 2050.
- **MDS – LTS 1.5 °C Technical Scenario.** Considers the EU legally binding 2030 targets (hence it is identical to the LTS Baseline Scenario until that time) and aims to achieve a 100% reduction in GHG emissions by 2050.
- **HDS – JRC-EU-TIMES ZeroCarbon Scenario.** Considers almost complete decarbonisation by 2050 and greater decarbonisation by 2030 than the LTS, in line with the 55% objective laid out in the European Green Deal.

Figure 5. Methodological scheme



Source: JRC representation.

At global level, two of the scenarios are taken from the Energy Technology Perspectives (ETP) 2017 report published by the IEA (IEA, 2017). The third is an optimistic scenario taken from an exercise developed by the Institute for Sustainable Futures of the University of Technology Sydney (Teske, 2019). In detail, the three scenarios for the global context are as follows.

- **LDS – IEA ETP Reference Technology Scenario.** In line with the commitments to limit GHG emissions and improve energy efficiency pledged by countries under the Paris Agreement (In this scenario, the temperature increases by 2.7 °C in the long run).
- **MDS – IEA ETP Beyond 2 Degrees Scenario.** Consistent with a 50% chance of limiting average future temperature increases to 1.75 °C. Energy sector emissions reach net zero around 2060.
- **HDS – Institute for Sustainable Futures 1.5 °C 2019 Scenario.** Mitigation scenario leading to long-term temperature increase of 1.5 °C with 100% renewable primary energy in 2050.

The use of the EU LTS scenarios is fundamental to developing an analysis that is relevant for EU policy. However, as the LTS scenarios do not have global scope, a different set of sources has been considered for the global analysis. It is therefore impossible to compare the EU and the global results directly.

1.3.2. Uncertainties in estimating the future material demand

A precise quantification of the long-term material needs constitutes a complex analysis as there are many factors that could influence the demand growth. In this study, the analysis is based on several assumptions and therefore the resulting values should be taken as indicative. Of the challenges faced when analysing the available information, the most prominent were the following.

- **Evolution of the energy system.** Although all energy generation scenarios adopted are relevant in terms of global and European climate targets, covering a range of plausible future outcomes for the energy system, they come from different sources, which might raise issues of consistency.
- **Intra-technology choices.** Projections of choices of wind and solar PV sub-technologies are not generally available in the literature. In most cases, available data are sparse and the level of granularity required for a consistent assessment of raw material usage is not adequate. Thus, technology market share scenarios were developed based on a variety of assumptions. As different designs will have higher or lower material requirements, consistent projections of the future technology mix are as fundamental as estimates of expected penetration levels of renewable technologies.
- **Material intensity for different technologies.** Estimations of material requirements per unit of capacity vary widely across different technologies. Precise estimations of future metal intensity are therefore difficult. This increases the overall uncertainty about the future material demand in all energy generation and technology scenarios.
- **Material efficiency and innovation.** Although the degree of uncertainty surrounding assumptions of future performance is inherently high, capturing the benefits of innovations that may be able to reduce the amount of materials used in a particular technology per unit of service delivered is indispensable. However, while this aspect gives depth to the analysis, it can also give rise to overly conservative estimates of raw material demand.

2. Wind power

This chapter defines the various scenarios for onshore and offshore wind electricity production, along with the main trends and criticalities identified in material demand between today (2018) and 2050.

First, an overview of wind technologies and the materials needed is presented, then the effects of the four individual factors (capacity, lifetime, market share, material intensity) is defined and analysed. At the end of the chapter, the three scenarios arising from the combination of low, medium and high values associated to the four factors are analysed, highlighting the criticalities for each specific material.

2.1. Wind power technologies and material usage

2.1.1. Wind power technologies

There are two main technical designs of wind turbine suitable for use in onshore and offshore applications: direct drive and gearbox. The two types have significantly different constructions, differing in generator design, drivetrain system and grid connection solutions (Pavel et al., 2017). As a result, both the mass and the material content differ greatly between the two (Andersen et al., 2016).

Gearbox configurations are offered with a choice of medium-speed (> 80 rpm) and high-speed (> 900 rpm) drives, further split into designs that contain a permanent magnet (medium-speed hybrid drives that employ both gearboxes and permanent magnets, and lower-speed drives with low magnet content) and ones with electromagnet generators (high-speed induction generators with multistage gearboxes). As it is heavy and requires maintenance, the gearbox design is less competitive in larger plants and offshore solutions.

Direct-drive turbines, on the other hand, can be based on permanent magnet generators (e.g. Siemens and General Electric models), or can incorporate an electrically excited generator (e.g. Enercon direct-drive turbine models). In the latter case, they are produced without permanent magnets.

A key advantage of direct-drive permanent magnets is that by eliminating the gearbox they enable a reduction in size, and thus a reduction in the turbine's overall weight, increasing its attractiveness in offshore applications (Rabe, Kostka and Smith Stegen, 2017; Giurco, Dominish, Florin, Watari and McLellan, 2019; World Bank, 2017). In addition, '*by replacing the mechanical failure-prone gearbox with … permanent magnets, [direct-drive turbines] utilize a simpler, more reliable design that allows them to operate at lower speeds, be more efficient, and require less maintenance*' (Nassar, Wilburn and Goonan, 2016).

Hybrid drives, on the other hand, by combining gearboxes with permanent magnets, are generally more reliable than their multistage gearbox counterparts (Nassar, Wilburn and Goonan, 2016). They also have lower manufacturing costs than direct-drive generators but entail higher maintenance expenses. In addition, by using smaller permanent magnets than direct-drive configurations, hybrid drives are less reliant on rare earths (Nassar, Wilburn and Goonan, 2016).

In the future, direct-drive turbines could additionally be based on high-temperature superconductors (HTS). Gains associated with this technology include improvements in performance owing to a decrease in weight and savings in terms of neodymium and dysprosium consumption. However, moving towards this option, in particular at offshore locations where it can be most beneficial, continues to depend on cost reductions and further technological progress (Månberger and Stenqvist (2018) and references therein).

Table 1 shows the main wind turbine technologies. Marked in grey are the three technologies which were deployed in the past decades but which have progressively been superseded and are no longer, or only very marginally, adopted nowadays. Therefore, the remaining six are the technologies considered in future scenarios (however, HTS is displayed in italics to reflect its current status in research and development (R & D)). To provide a better overview of the relationships between the technologies, a technological tree is shown in Figure 6.

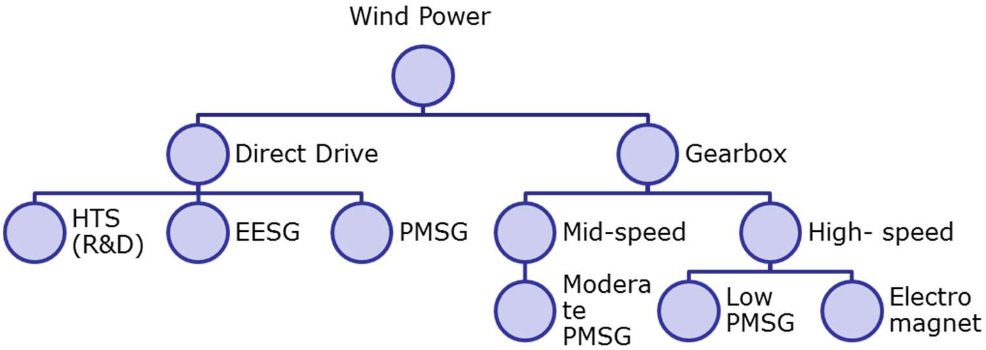
Table 1. Overview of wind turbine technologies

Type of generator	Type of turbine	Application
Direct drive	*High-Temperature Superconductors (HTS)*	*Offshore*
Direct drive	Electrically Excited Synchronous Generator (EESG)	Onshore
Gearbox	Electrically Excited Synchronous Generator (EESG)	Onshore
Direct drive	Permanent Magnet Synchronous Generator (PMSG)	Onshore and offshore
Gearbox	Permanent Magnet Synchronous Generator (PMSG)	Onshore and offshore
Gearbox	Double-Fed Induction Generator (DFIG)	Onshore and offshore
Gearbox	Squirrel Cage Induction Generator (SCIG) – Without full converter	Onshore
Gearbox	Squirrel Cage Induction Generator (SCIG) – With full converter	Offshore
Gearbox	Wound Rotor Induction Generator (WRIG)	Onshore

NB: Technologies which are no longer relevant but that were widely adopted in previous decades are highlighted in grey. HTS technology, in italics, is not yet marketed.

Source: Adapted from Pavel et al. (2017) and Månberger and Stenqvist (2018).

Figure 6. Wind sub-technologies subdivided according to their drivetrain configuration



Source: Adapted from Månberger and Stenqvist (2018).

From now on, when discussing types of turbine in conjunction with their types of generator, the acronyms introduced in Table 1 will be used (e.g. DD-HTS or GB-DFIG, where DD stands for ‘direct drive’ and GB stands for ‘gearbox’). Since both SCIG turbines feature a gearbox generator, the acronym GB-SCIG is potentially ambiguous; however, only the version with full converter is still adopted in the market, so GB-SCIG will be used to indicate that version. The previous version, without full converter, will be distinguished by the suffix ‘NC’ (meaning ‘no converter’), so GB-SCIG_NC.

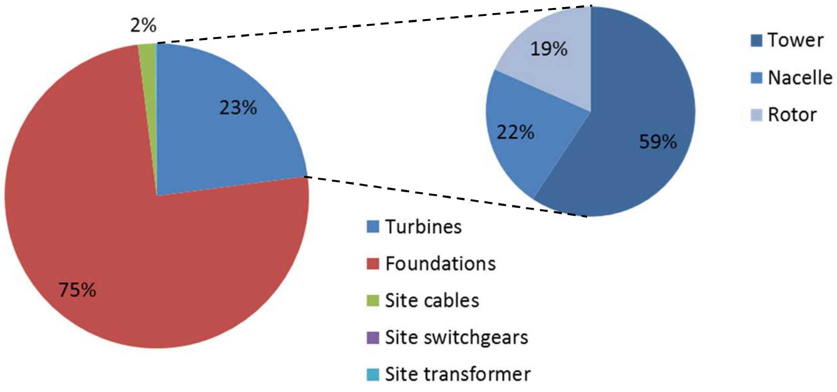
2.1.2. Materials used in wind turbines

When it comes to materials, a wind turbine is constructed of around 25 000 components, which are grouped into several main systems such as the tower, nacelle and rotor (Vestas, 2017).

The rotor comprises blades, a hub and a blade pitch system. It is connected to the nacelle, which in turn is attached to the tower. The nacelle contains many of the electrical and mechanical components, including the main shaft, gearbox, generator and control systems. The rotation of the turbine blades is used to drive an electrical generator through a gearbox, which uses special alloys to accommodate a wide range of wind speeds (Materials Research Society, 2010). The tower is made of large tubular steel sections attached to an anchor component and erected on a foundation (e.g. Ancona and McVeigh, 2001; Haapala and Prempreeda, 2014; Vestas, 2017). A wind power plant also includes conventional ground-mounted components such as the plant transformer, switchgears and site cables (establishing connections between turbines, to the transformer and to the grid) (Vestas, 2017).

The tower accounts for a significant proportion of the entire wind turbine, both in size and mass, but the greatest portion of mass is in the foundation (75%). In the turbine alone (disregarding the foundation) (1), the nacelle and rotor each represent approximately 20% of the turbine's weight (Figure 7).

Figure 7. Mass distribution of a typical onshore wind plant and turbine components



Source: JRC representation based on various Vestas life cycle assessment (LCA) studies.

Various materials make up the individual parts across the system components, as shown in Figure 8 and described below.

Steel and stainless steel are used in the manufacture of several components, including the tower, nacelle, rotor and foundation. Besides iron, a vast array of minor and base metals such as nickel, molybdenum, manganese and chromium are used in steel production.

According to the World Steel Association, about 85% of wind turbines around the world are manufactured primarily from steel. However, concrete towers, concrete bases with steel upper sections and lattice towers are also used (IRENA, 2012). In the turbine itself, steel represents on average 80% of the total mass (World Steel Association, 'Environmental Case Study – Wind energy'). Besides the tower, manufactured primarily of plate steel, the gearbox, generator and turbine transformer also mainly consist of structural steel and stainless steels.

Concrete and steel are essential materials for wind turbine foundations and are used across different types of turbines, depending on the location of the wind power plant, specific requirements from turbine manufacturers and clients or founding conditions across sites. Onshore foundations are made up of large concrete and steel platforms, whether they are gravity- or rock-anchored systems. Most offshore solutions, on the other hand, have relied on monopile structures, made up of a thick steel cylinder that is anchored directly to the seabed. On average, concrete makes up 93-95% of onshore foundations, the remainder being unalloyed to low-alloy steel.

Aluminium is used in the production of resistant but lightweight components, such as the turbine tower and nacelle. Besides the turbine itself, aluminium is also used in the production of cables at the plant site. Copper is predominantly used in the coil windings in the stator and rotor portions of the generator, in the high-voltage power cable conductors, transformer coils and earthing (Copper Alliance). Lead is used for cable sheathing in offshore electricity transmission.

Rare-earth elements and boron are essential for turbine designs that employ permanent magnets. Most direct-drive turbines, but also to different extents certain technical designs with gearboxes, are equipped with permanent magnet generators, which typically contain neodymium and smaller quantities of dysprosium. On average, a permanent magnet contains 28.5% neodymium, 4.4% dysprosium, 1% boron and 66% iron (2) and weighs up to 4 t (Rabe, Kostka and Smith Stegen, 2017). There is also some minor use of rare-earth elements in magnets within the turbine tower for attaching internal fixtures (Vestas, 2018a).

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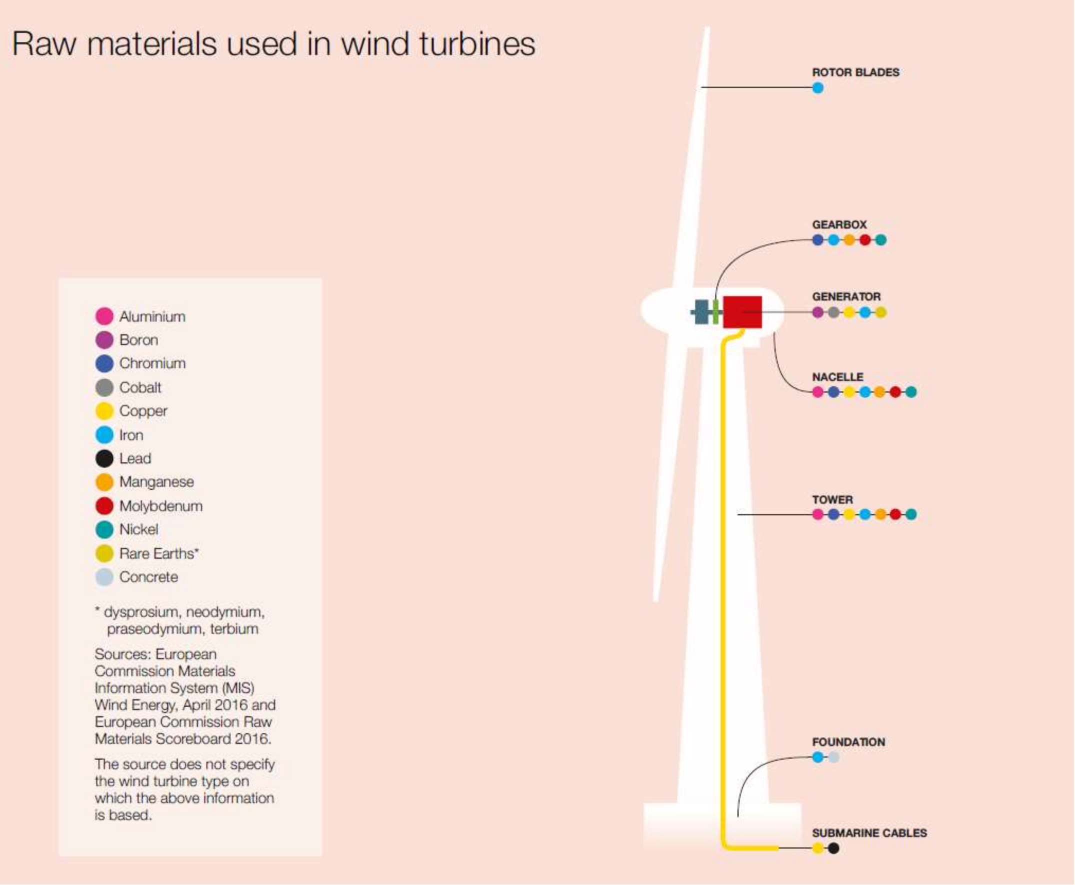
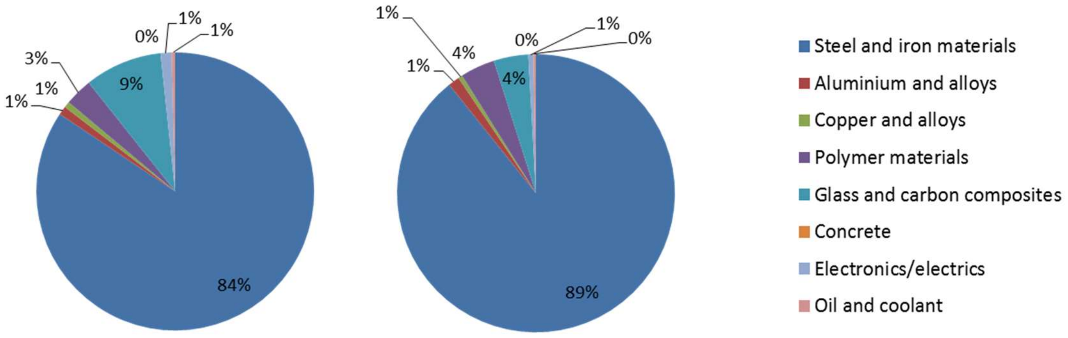
(1) The wind turbine refers to the turbine itself and excludes the foundation and other site parts. The wind power plant includes the wind turbines, foundations, cabling (connecting the individual wind turbines to the transformer station) and transformer station, up to the existing grid.

(2) Average quantities based on several sources detailed in Elshkaki and Graedel (2013).

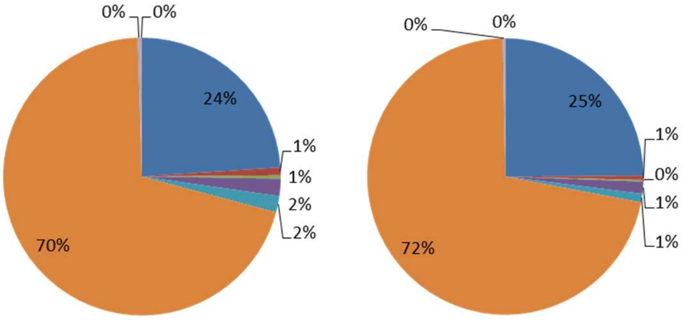
Figure 8. Raw materials used in wind turbines (top) and breakdown of their use in typical onshore wind turbines and power plants (bottom)





V116-2MW (turbine only)
Mass = 236 t

V136-3.45MW (turbine only)
Mass = 601 t



50 MW power plant of
25 V116-2MW turbines
Mass = 25 980 t

100 MW power plant of
29 V136-3.45MW turbines
Mass = 75 236 t

Source: Top: SOMO (2018); bottom: Vestas (2017, 2018a).

Polymers (³) and composite materials of epoxy resin combined with either glass fibres or carbon fibres represent approximately 8-12% of the turbine weight and 2-6% of the plant mass. Composite materials are primarily used in the construction of the blades, as well as the nacelle and hub covers. For example, the hub and spinner parts of the rotor system consist of a cover constructed of glass-fibre-reinforced polyester; the main materials used in the blades are carbon fibre and woven glass fibres infused with epoxy resin; and the nacelle cover is made from fibreglass, which consists of woven glass fibres, polyethylene and styrene (Vestas, 2018a). Polymers are mainly used in the turbine (20%), excluding the blades, and are additionally used together with aluminium, copper and steel in the production of cables for the plant (80%).

Finally, electric and electronic components incorporated in the turbine make up around 1% of its mass (Vestas, 2017). It is estimated that around 9 500 electronic parts form the wind turbine controller units. These consist of electronic signal and power components such as resistors, capacitors and integrated circuits. Aluminium, tin, zinc, tantalum and precious metals, in various amounts, are among their main constituents.

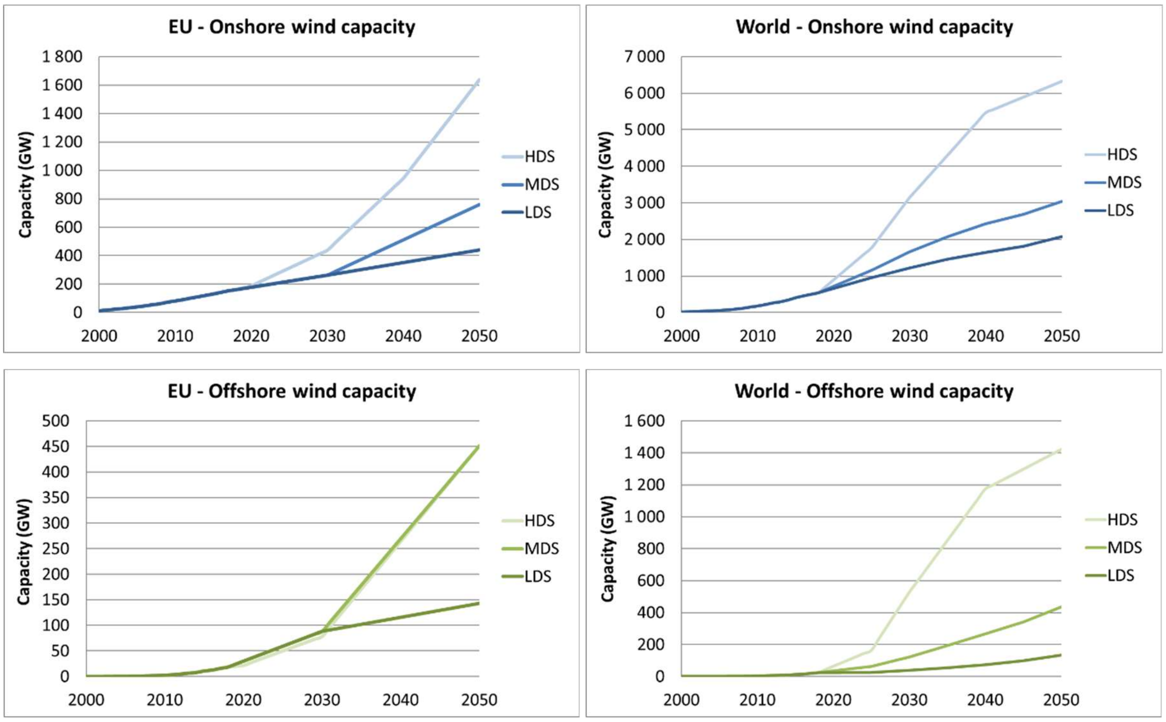
2.2. Wind power generation capacity

The power generation capacity is expected to increase for onshore and offshore wind to meet the ambitious goals set up at both EU and global levels (Figure 9).

For onshore wind systems the capacity should at least double between 2018 and 2050 (in the LDS) and could potentially grow 8 times (in the HDS) both in the EU and worldwide. The more ambitious the commitments, the earlier the deployment of new facilities to handle the capacity needs to increase.

For offshore wind systems, the commitments for increased capacity are even more ambitious, especially for the EU, which is a leader in the sector, accounting for about 80% of global installed capacity. Fulfilling the commitments set by the EU Member States would mean reaching 65-85 GW by 2030, from the current 18.5 GW (IEA, 2019). A further doubling, at least, is expected in the EU by 2050 (LDS), while reaching more ambitious climate targets would entail an increase of more than 20 times the current levels, up to about 450 GW (here the MDS and HDS happen to be almost perfectly overlapping). Ambitious global scenarios anticipate a capacity deployment well above 1 000 GW by the middle of the century.

Figure 9. EU and global capacity scenarios for onshore and offshore wind



Source: JRC representation based on the IRENA database (IRENA, 'Statistics Time Series') for 2000-2018; and European Commission (2018), Carlsson et al. (2020), IEA (2017) and Teske (2019) for 2019-2050.

(³) Polymer materials include thermoplastics, thermoplastic elastomers, elastomers / elastomeric compounds, duromers and polymeric compounds (e.g. Vestas, 2018a).

2.3. Wind turbine lifetime and annual installations

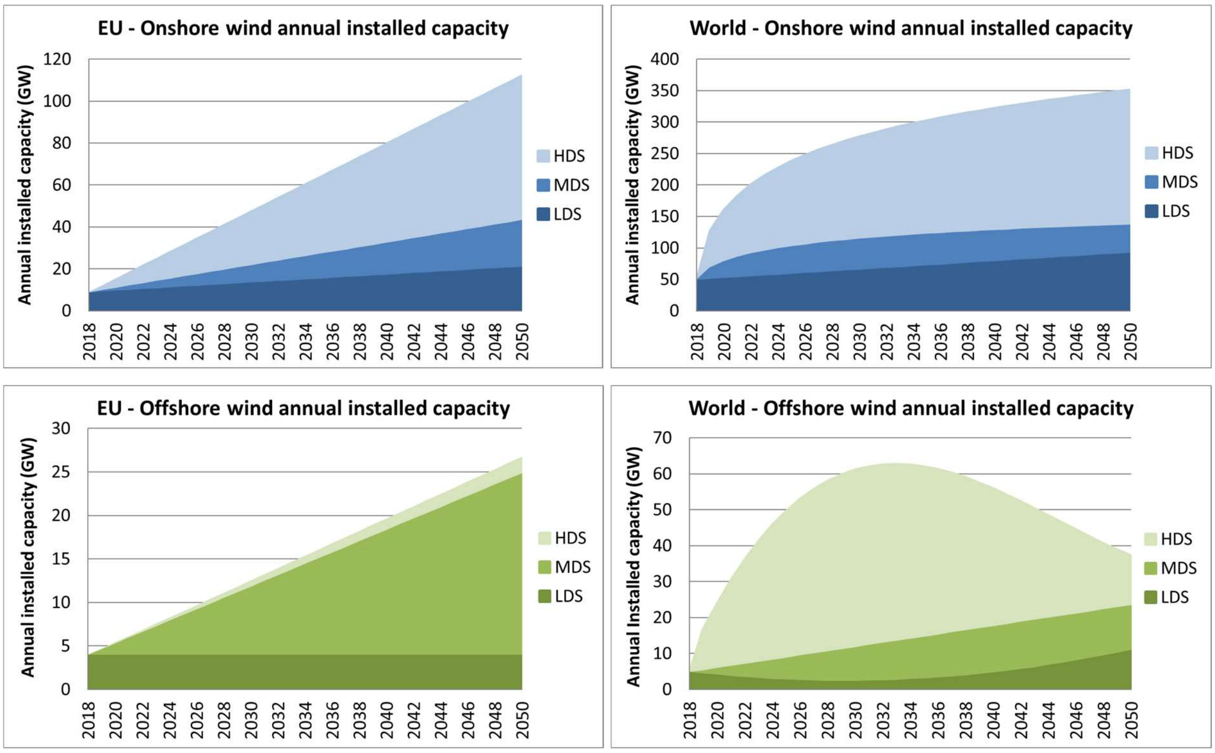
The wind power industry is still relatively young and few turbines have ever been disposed of, therefore it is not easy to formulate assumptions about the relevant lifetimes with a good degree of confidence (Vestas, 2015, 2017).

According to Vestas, the overall lifetime of a turbine can be as low as 20 years. On the other hand, some turbine models have exceeded their design lifetime of 20 years and remained operational for 30 years and more. Some components such as the site cabling and foundations may achieve a longer lifetime of around 50 years (World Steel Association, 2012; Vestas, 2014a, 2015). Experience of the lifetime of offshore turbines is even more limited, as the vast majority of offshore wind capacity is only up to a decade old (IEA, 2018).

In the present study, it has been assumed that an onshore wind turbine is designed to last 25 years and an offshore wind turbine up to 30 years. These values are represented in the MDS, while the two extreme scenarios assume a variability of 5 years. Hence, in the LDS, which assumes a lower replacement rate, the lifetime is assumed to be 30 years for onshore wind turbines and 35 years for offshore wind turbines. In the HDS, which assumes a higher replacement rate, the lifetime is assumed to be 20 years for onshore wind turbines and 25 years for offshore wind turbines. These life expectancies translate into replacement rates, and then again into amounts of additional installed capacity needed to keep up with the demand.

Figure 10 illustrates the annual installed capacity in the EU and in the world to comply with targets for future generation of electricity from renewable sources stipulated in the scenarios adopted, as derived from the capacity scenarios shown in Figure 9 and the assumptions about lifetimes discussed above. Data have been interpolated in order to obtain more uniform patterns. It should be noted that the global forecast predicts a decrease in the capacity deployment of offshore wind turbines at global level in the HDS, after a peak around 2030. This is because, according to global commitments, the expansion rate of global capacity is predicted to slow down after 2040 (Figure 10). This will entail a decrease in the material demand from 2030 to 2050 in this scenario.

Figure 10. Annual installed capacity of onshore and offshore wind by 2050



Source: JRC analysis.

2.4. Wind technology market share

Long-term projections about the future mix of wind technologies and estimated growth are significantly uncertain. Indicative overviews may be available in the literature, but in most cases the level of granularity required for a consistent assessment of raw material usage is not adequate. Available data are sparse and figures from such assessments are indicative, providing merely illustration and orientation, especially up to the end of the forecasting period (2050). However, although the references from the literature identify several different ways forward and anticipate different developments over the same period, their estimates also converge on several points – which can be substantiated as follows.

Despite the fact that permanent magnets are expensive and metal intensive, they are well suited to the offshore environment (World Bank, 2017). In addition, most alternatives to permanent magnets are less efficient and do not perform as well (Rabe, Kostka and Smith Stegen, 2017), justifying their continued use in all scenarios considered.

Despite the broadly accepted technical advantages of permanent magnets in wind turbine design, past spikes in global prices of rare earths, prompted by Chinese export restrictions, have required governments and the wind industry to work towards the adoption of alternative designs as a way to circumvent supply risks. Thus, some scenarios aim to avoid permanent magnets at least in the onshore environment (World Bank, 2017). Among various alternatives to current designs that use permanent magnets, the adoption of 'hybrid-drive' generators, which employ a single-stage gearbox with a smaller permanent magnet, is favoured (Netherlands Organisation for Applied Scientific Research (TNO), 2018). According to the Centre for Sustainable Energy, a hybrid drive can reduce neodymium use from 186 kg/MW installed capacity to just 62 kg/MW, compared with turbines that employ direct-drive permanent magnet systems (Centre for Sustainable Energy, 2017). Dysprosium would be subject to the same proportional drop.

The increasing size and capacity of offshore wind turbines seem to preclude the use of most conventional generators that do not need permanent magnets. This is the case for DD-EESG or GB-DFIG turbines, which, although successful in the onshore, are unsuitable for offshore installations in future scenarios, because of their considerable weight (Rabe, Kostka and Smith Stegen, 2017; Centre for Sustainable Energy, 2017). It is therefore unlikely that a significant shift in usage will occur in the future.

Continued concerns regarding the availability of rare-earth elements may stimulate the development of HTS generators, thus eliminating the need for rare-earth elements in offshore applications (Månberger and Stenqvist, 2018).

Deployment trajectories project a shift towards hybrid-drive generators employing a single-stage gearbox with a smaller permanent magnet (TNO, 2018), an uptick of HTS generators of up to 18% and the highest (44%) deployment of direct-drive generators with permanent magnets in 2030 (JRC, 2012) or the lowest (20 %) deployment of generators with permanent magnets in 2030 (United States Geological Survey, 2012). According to the World Bank, only 20% of next-generation wind turbines will be based on rare-earth permanent magnets and by 2050 offshore wind capacity will mostly (75%) rely on direct-drive technology (World Bank, 2017). The remaining 80% will use either conventional electromagnets or ferrite permanent magnets without rare earths.

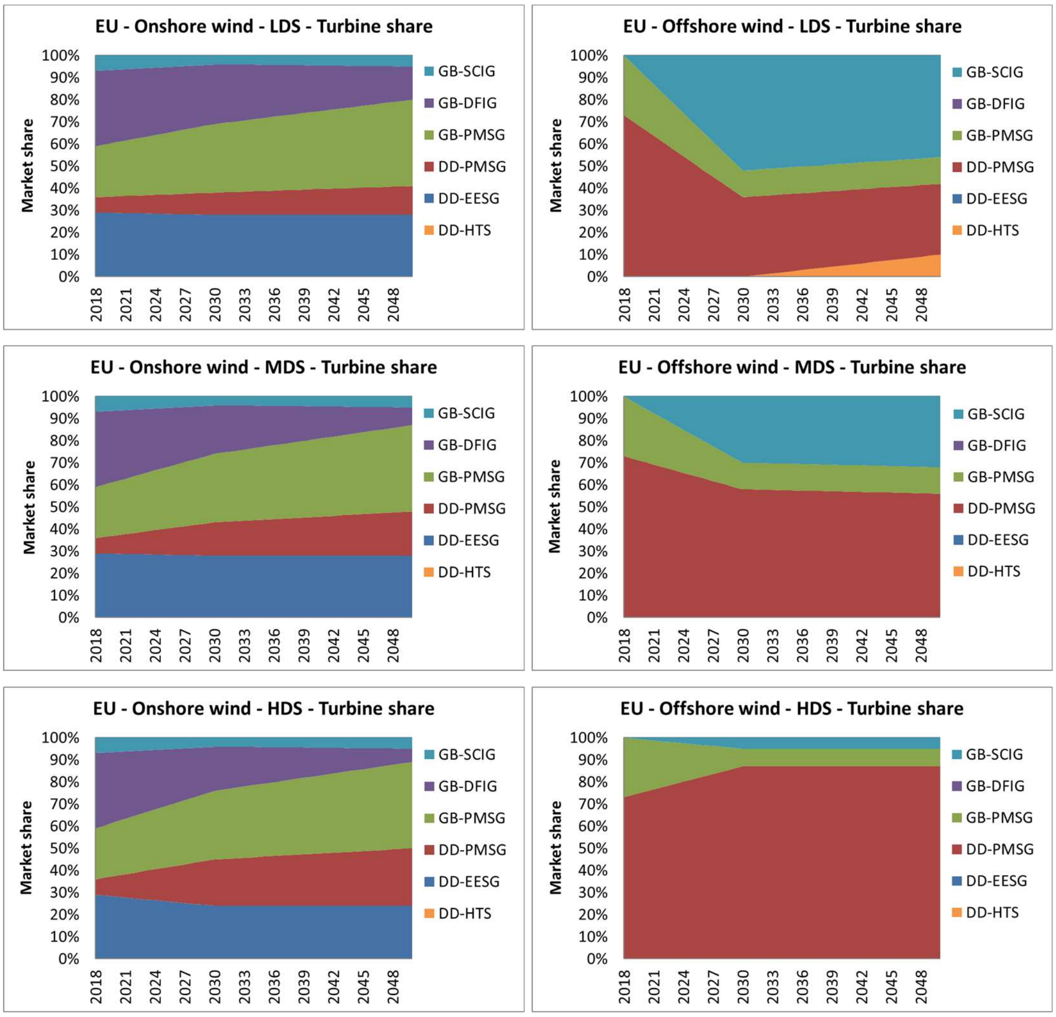
It is important to note that although developing low, medium, and high demand scenarios for renewable capacity and material intensity is conceptually straightforward, it is much more complex for market shares. As the market shares of the different sub-technologies must necessarily add up to 100%, a low demand scenario for one technology will automatically imply a high demand scenario for another. In this exercise, given the importance of rare earths and the market trends described in the previous section, a focus is put on permanent magnet technologies (DD-PMSG and GB-PMSG). Hence, LDS, MDS and HDS have been developed accordingly. The methodology used to develop each scenario is as follows.

- **LDS.** Extrapolation based on historical time series (focusing on the period post 2000) with an uptake of offshore HTS generators (see Annex 1 for more information on historical market shares).
- **MDS.** Extrapolation based on historical time series (same period as above) modified to accommodate a higher penetration of generators with permanent magnets (notably direct drive) in the offshore sector and, to a lesser extent, in the onshore sector.
- **HDS.** For the offshore, mixes of sub-technologies in future energy scenarios are assumed to substantially mimic today's average values at global level. For the onshore, technology replacement

rates are based on historical time series (same as above) modified to accommodate a higher deployment of turbines with permanent magnets (again, notably direct drive).

Figure 11 and Figure 12 provide details on the forecast share distribution of all technologies in the three scenarios at EU level and global level, respectively, while Figure 13 focuses on the aggregate market shares of the two technologies involving permanent magnets.

Figure 11. Share of onshore (left) and offshore (right) wind turbine sub-technologies in the EU market

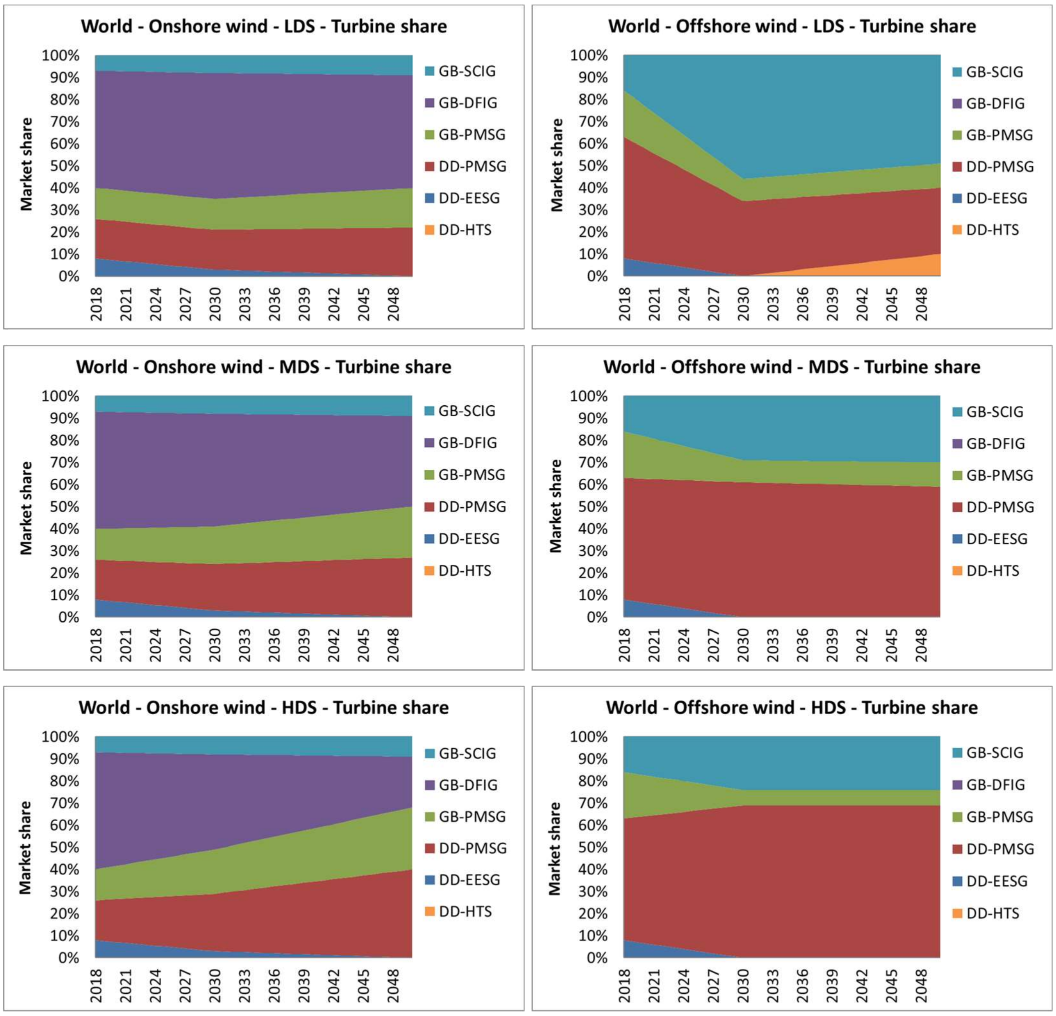


Source: JRC analysis.

In the EU, the share of permanent magnets in the onshore sector starts at 30%. This value grows to 52%, 59% and 65% in 2050 in the LDS, MDS and HDS respectively. Today, the offshore sector is totally dominated by permanent magnets, and the HDS assumes that this dominance will hold steady over time, as the market share only diminishes to 95% in 2050 in this scenario. However, the final share in 2050 is 68% in the MDS and 44% in the LDS. Indeed, in all cases most of the decrease is expected to take place in the next decade, while the following decades are characterised by more stable behaviour.

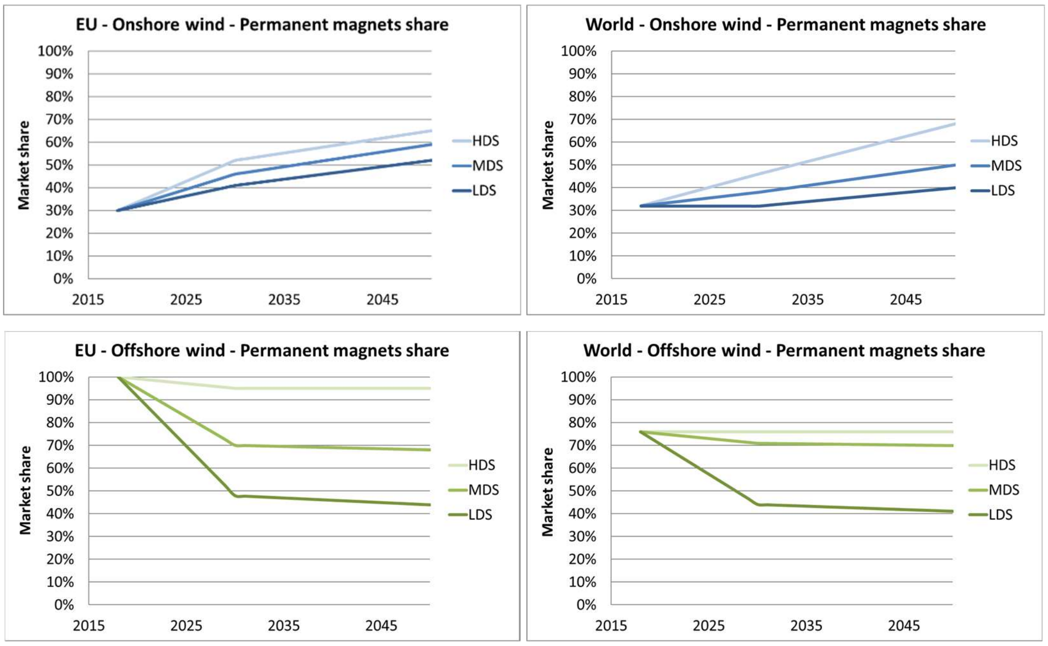
A similar pattern is expected at global level, where permanent magnet technologies currently account for a share of 32% of the market in the onshore sector. Shares in 2050 are anticipated to be 40%, 50% and 68% in the LDS, MDS and HDS, respectively. The current offshore market is mostly cornered by permanent magnets, although they do not hold a monopoly (only 76%). This level is maintained over the decades in the HDS, while in 2050 the market share diminishes to 70% and 41% in the MDS and LDS, respectively.

Figure 12. Share of onshore (left) and offshore (right) wind turbine sub-technologies in the global market



Source: JRC analysis.

Figure 13. Market share of permanent magnets in wind technologies



Source: JRC analysis.

2.5. Material intensity in wind turbines

Material intensity indicates the specific mass of each raw or composite material per unit of installed capacity. The technology behind wind turbines has evolved significantly in the past few decades, leading to notable changes in material intensity. A detailed overview of this evolution and its impact on material demand is presented in Annex 2.

Over the past 30 years, average wind turbine capacity has grown significantly. Since the amount of energy that can be produced from wind depends to a large extent on the size of the turbine (IRENA, 'Wind Energy'; Willett, 2012), capacity growths have essentially been achieved through expenditure on larger rotors, higher towers and longer blades.

In general, adopting Vestas equipment data as a reference and considering the composition of 2-4 MW onshore wind turbines (Vestas, 2014b, 2018b), a strong correlation was found between the rotor diameter or tower height and the turbine mass.

Although the absolute consumption of raw materials increases with the size of the turbine, the effect is offset by greater energy production thanks to more resource-efficient turbine designs. Thus, the relative material input per unit of capacity has decreased in certain cases, while the average usage of other materials has remained constant or increased only slightly.

In addition, increasing the size of the wind energy system results in an increase in consumption of raw materials, a trend that is more visible for steel, aluminium and polymer materials. For example, the total steel consumption increased from 200 to 620 t by increasing the rotor size from 90 to 150 m, which corresponds to an increase of around 200%. Consumption of aluminium and polymer materials also increased by around 150% and 250%, respectively.

It is estimated that on average, consumption of steel and polymer has increased by around 13% following turbine capacity increases from 2 to 4 MW. In the cases of glass/carbon composites and electronics, increasing the turbine's rated power has diminished consumption by around 30%. Small decreases of about 6% in average usages of aluminium and copper were also achieved by the same method (see Table A.1 in Annex 2).

In the future, material efficiency will most likely improve, with a consequent reduction in material demand per turbine (Kim et al., 2015). On the other hand, a portion of the demand is likely to be redirected towards alternative and lighter materials in an effort to reduce costs while maintaining strength and satisfying structural fatigue requirements.

Trends towards the use of more lightweight materials are ongoing and will further change material usage patterns in the future. Lightweight materials already play an important role in the wind energy sector and their use is expected to grow in the coming decades. According to McKinsey, traditional steel will be substituted largely by high-strength steel (HSS), and aluminium and carbon fibre will also be more used in the wind energy, automotive and aviation industries (McKinsey, 2012).

In order to work out the current material intensity values, a number of estimations were made, explained below. The list of data sources and providers used to compile the inventory can be found in a separate list after References.

- Estimates of requirements for rare-earth elements were based on published information on the rare-earth content of wind generators and/or the weight of the permanent magnet. In the latter, the following breakdown was applied: neodymium accounts for about 29%, dysprosium for 4%, boron for 1% and iron for 66% of the weight of a rare-earth permanent magnet.
- When not explicitly available, estimates of chromium, nickel, manganese and molybdenum requirements (alloying elements in steel) were developed based on published information on the amount of steel in wind turbines and the chemical composition of certain high-performance steels, whose split between high-alloy and unalloyed / low-alloy steels is known from Vestas. Amounts of niobium and vanadium known to be present in high-strength low-alloy (HSLA) steels have not been taken into account.
- Polymer materials were treated as a group and include thermoplastics, thermoplastic elastomers, elastomers / elastomeric compounds, duromers and polymeric compounds.

- Glass/carbon composites jointly cover glass fibre and carbon fibre. Even though it was not possible to obtain disaggregated data, it can be assumed that the amount of glass fibre does not exceed 88% and the remaining 12% would be the maximum amount of carbon fibre deployed in next-generation wind turbines (based on the forecast by McKinsey (2012)).
- In addition to wind turbines and foundations, a wind power plant includes cabling (connecting the individual wind turbines to the transformer station) and the transformer station, up to the existing grid. Materials used in the manufacture of site components have been disregarded in this study.

Table 2 shows the material requirements for the main types of wind turbine. A complete set of values has been developed for the DD-EESG, DD-PMSG, GB-PMSG and GB-DFIG turbine types. The DD-EESG values were adopted for DD-HTS as well (DD-EESG being the most similar technology), although the DD-HTS will require about 0.3 t/GW of another rare-earth element such as yttrium (Månberger and Stenqvist, 2018) (4). For this reason, values for dysprosium and neodymium have been set equal to the lower end of the other technologies (the same has been done for praseodymium). Similarly, the GB-DFIG values were adopted for the GB-SCIG turbines because they are both high-speed, gearbox generators.

Table 2. Material usage estimates in t/GW for different wind turbine types

Material	Range	DD-EESG	DD-PMSG	GB-PMSG	GB-DFIG
Concrete	243 500-413 000	369 000	243 000	413 000	355 000
Steel	107 000-132 000	132 000	119 500	107 000	113 000
Polymers	4 600	4 600	4 600	4 600	4 600
Glass/carbon composites	7 700-8 400	8 100	8 100	8 400	7 700
Aluminium (Al)	500-1 600	700	500	1 600	1 400
Boron (B)	0-6	0	6	1	0
Chromium (Cr)	470-580	525	525	580	470
Copper (Cu)	950-5 000	5 000	3 000	950	1 400
Dysprosium (Dy)	2-17	6	17	6	2
Iron (cast) (Fe)	18 000-20 800	20 100	20 100	20 800	18 000
Manganese (Mn)	780-800	790	790	800	780
Molybdenum (Mo)	99-119	109	109	119	99
Neodymium (Nd)	12-180	28	180	51	12
Nickel (Ni)	240-440	340	240	440	430
Praseodymium (Pr)	0-35	9	35	4	0
Terbium (Tb)	0-7	1	7	1	0
Zinc (Zn)	5 500	5 500	5 500	5 500	5 500

Below are some additional notes on the materials used in wind turbines.

- **Concrete.** There are different mass requirements for the onshore and offshore wind turbines. The lower estimate is for DD-PMSG turbines predominantly used at offshore sites; the higher estimate is for type GB-PMSG (larger turbines mostly used in the onshore).
- **Steel.** Existing turbine models use between 107 and 132 t of steel per MW of installed capacity.
- **Polymers.** Values are practically identical across different turbine types.
- **Glass/carbon composites.** Usage is approximately 8 t/MW irrespective of the turbine type.
- **Aluminium (Al).** Across turbine types and models the range of possible values for aluminium is large, varying from 500 to 1 600 t/GW. The lower estimates apply to direct-drive turbines where

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(4) Yttrium is only used in the HTS technology; it will not appear in the material demand projections because it is very marginal compared to the other materials.

copper is the preferred material and possibly stem from different requirements for onshore and offshore wind turbines. In addition, they might also represent to a certain extent the selective replacement of copper with aluminium in the cast-coil transformer in the nacelle or in the tower design. While this option presents some challenges, Vestas for example has adopted aluminium cast-coil transformers in its turbines. In cases where the whole nacelle casing is made of aluminium, the use of this material can exceed 3 500 t/GW.

- **Boron (B).** Boron is used in the permanent magnet of the turbine generator. The lower estimate is for high- to medium-speed turbines with a gearbox; the higher estimate is for direct-drive turbines.
- **Chromium (Cr).** A higher chromium content is related to the use of high-alloy steels (see Annex 3).
- **Copper (Cu).** Across turbine types and models the range of possible values for copper is large, ranging from approximately 950 to 5 000 t/GW, with the median value being around 2 100 t/GW. The higher estimate is for direct-drive turbines. It is the consensus that direct-drive generators can use three times more copper than gearbox configurations. According to Månberger and Stenqvist (2018) and references therein, the difference is however lower for the power plant as a whole.
- **Dysprosium (Dy).** Dysprosium is used in the permanent magnets of the turbine generator, but also in magnets for attaching internal fixtures within the turbine tower. It is therefore used in turbines without permanent magnets, although in small amounts. The lower estimate is for high- to medium-speed turbines with a gearbox; the higher estimate is for direct-drive turbines. In general, hybrid-drive generators use permanent magnets that are approximately one-third the mass of their direct-drive counterparts. Direct-drive generators contain on average 17 t/GW of dysprosium. Dysprosium amounts to 6 t/GW in hybrid-drive generators.
- **Cast iron (Fe).** Cast iron is used in the nacelle foundation, main shafts, gearbox, generator and blade hub. Different cast grades are available. Cast iron usage is very similar for different turbine types. Iron is also used in the permanent magnets: the lower estimate is for high- to medium-speed turbines with a gearbox (around 30 t/GW); the higher estimate is for direct-drive turbines (around 300 t/GW). However, the material intensity for this is about two orders of magnitude lower than the cast iron requirements, so it has been neglected.
- **Manganese (Mn).** Manganese content is identical for different steel grades and potentially identical for different turbine types. As with chromium, the figures relate to different assumptions about steel compositions.
- **Molybdenum (Mo).** The higher content is related to the usage of high-alloy steels. The amount of HSS, a type of lightweight low-alloy steel with a low molybdenum content, might potentially be higher in the offshore. In this case, DD-PMSG turbines would potentially have a lower molybdenum content.
- **Neodymium (Nd).** Neodymium is used in the permanent magnets of the turbine generator, but also in magnets for attaching internal fixtures within the turbine tower. The amount of neodymium in direct-drive turbines is substantially higher. It is estimated at 180 t/GW, up to 15 times as much as a conventional high-speed drivetrain. Neodymium usage is on average 51 t/GW in hybrid-drive generators.
- **Nickel (Ni).** Higher content is related to the use of high-alloy steels (heavier turbines deployed in the onshore). The same considerations as for chromium and manganese apply concerning the assumptions about steel composition.
- **Praseodymium (Pr).** Praseodymium is used in the permanent magnet of the turbine generator together with neodymium. The lower estimate is for high- to medium-speed turbines with a gearbox; the higher estimate is for direct-drive turbines. On average, direct-drive generators contain 35 t/GW of Pr and hybrid-drive generators contain 4 t/GW.
- **Terbium (Tb).** Terbium is used in the permanent magnet of the turbine generator where it replaces dysprosium. The lower estimate is for high- to medium-speed turbines with a gearbox; the higher estimate is for direct-drive turbines. On average, direct-drive generators contain 7 t/GW of terbium and hybrid-drive generators contain 1 t/GW.

- **Zinc (Zn).** Zinc is used as a protective coating against the corrosion of wind turbines, which are subject to climatic and mechanical stresses. Protecting the turbine's components with a coat of zinc could lengthen its lifetime.

Concerning the future evolution of material intensity, two distinct patterns have been established for structural materials on the one hand and technology-specific materials on the other.

The structural materials include concrete, steel, plastic, glass/carbon composites, aluminium, chromium, copper, iron, manganese, molybdenum, nickel and zinc. These materials are characterised by a moderate reduction in material intensity. In particular, the values in 2050 are equal to 80%, 90% and 100% of the current values in the LDS, MDS and HDS, respectively.

The technology-specific materials include boron, dysprosium, neodymium, praseodymium and terbium. For these materials, the following hypothetical situations for material intensity have been considered: an annual 5% reduction in the LDS, an annual 2% reduction in the MDS and a constant level of material intensity in the HDS. The resulting value in 2050 is about one fifth of the current value in the LDS and half of the current value in the MDS, respectively.

Annex 3 lists more details on the potential for optimisation and material substitution relevant for identifying future trends in material intensity.

2.6. Future material demand in wind turbines

Considering all the different contributions from the previous sections, it is possible to develop demand scenarios for all the relevant materials. For clarity, only data for 2030 and 2050 are reported; however, data for all the intervening years are available. Results at EU level are presented first (Section 2.6.1) and then those at global level (Section 2.6.2). When major differences in trends are present, data are shown for each individual material. When the trends are similar, data are shown per category.

2.6.1. Future material demand in wind turbines in the EU

Figure 14 and Figure 15 report the annual demand for structural materials and technology-specific materials, respectively, for wind power in the EU. The data in each figure are presented both as aggregated wind demand and as individual onshore and offshore contributions.

Data for 2030 and 2050 are shown in terms of a scale factor of the current (2018) demand, with the exact value of the current demand reported in the tables in Figures 14 and 15. For example, the EU annual demand for zinc in 2030 and in the HDS can be extrapolated by multiplying 65 865 t/year (current demand as seen in the table) by 5 (approximate scale factor as seen in the figure), resulting in a forecast of approximately 329 325 t/year.

In the LDS, the growth of the demand for structural materials is moderate and is in the order of 30% in 2030 and 65% in 2050 (aggregated wind material demand). Interestingly, when it comes to technology-specific materials (boron, dysprosium, neodymium, praseodymium and terbium) the demand decreases over time. In fact, in this optimistic scenario, the forecast improvements in material efficiency, coupled with the foreseen market trend, will more than compensate the need for increased capacity.

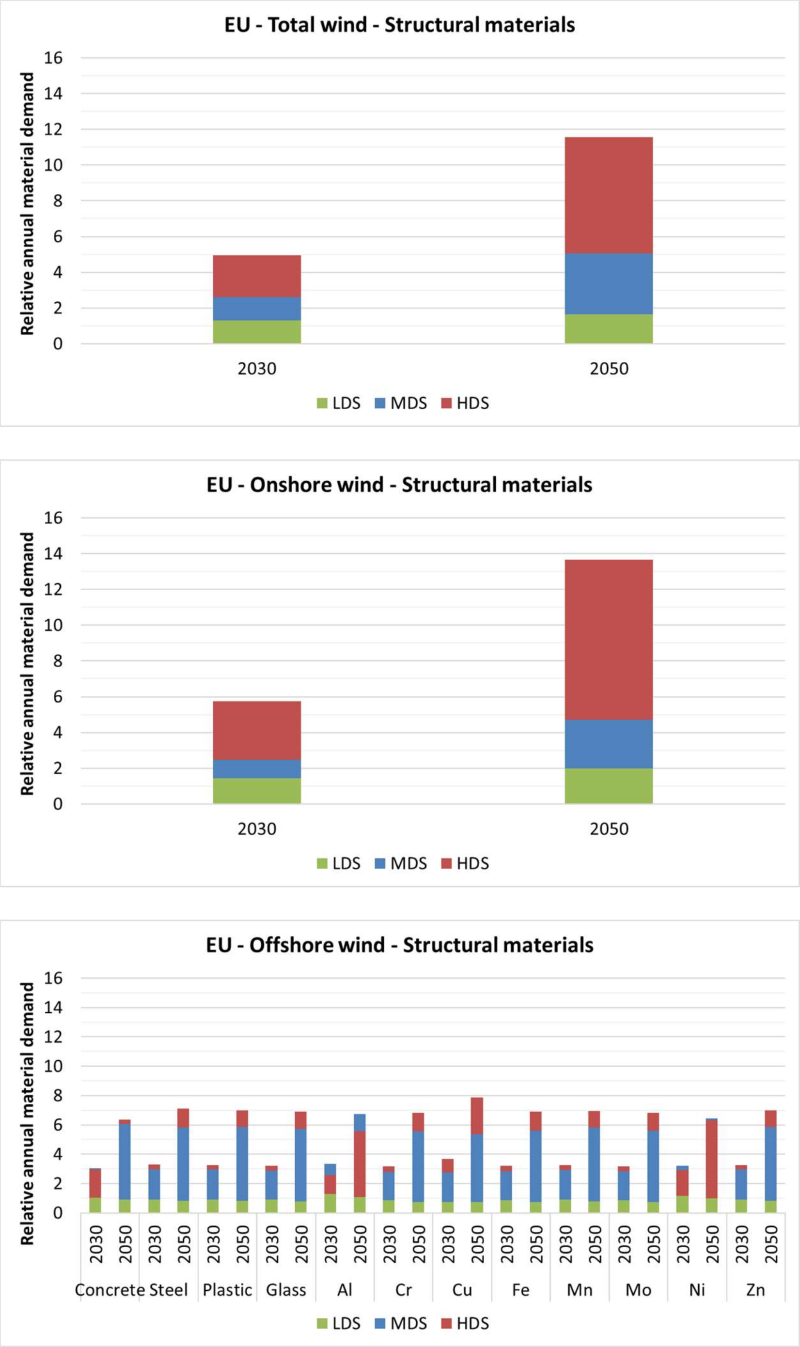
In the MDS and HDS, on the other hand, we see an increase in demand for these specific materials. In the MDS, material demand more than doubles in 2030 and increases from 3.5 to 5 times in 2050. In the more severe HDS, material demand increases between 4 and 5 times in 2030, and by over 10 times in 2050.

The situation is similar when looking at the individual contributions from onshore and offshore wind. However, for technology-specific materials especially, the biggest increase in demand is always forecast for onshore wind, with significantly lower increases for offshore wind. This is because the future offshore capacity expansion is proportionally less marked than that of the onshore, notably in the HDS.

Another major difference in the case of offshore wind is that the demand for structural materials is similar in the HDS and MDS, and in some cases (concrete, aluminium, nickel) the MDS demand exceeds the HDS. This is because the forecast material intensities for structural materials and the forecast energy capacity for offshore are very similar in the two scenarios. The tipping factor is thus the market share, which in the MDS is higher for technologies that are more demanding in terms of structural materials (see Figure 11 and Table 2).

Figure 14. Annual EU demand for structural materials in 2018 in t/year (table, left) and relative demand in 2030 and 2050 as a ratio of current demand (charts, right) for total (top), onshore (middle) and offshore (bottom) wind

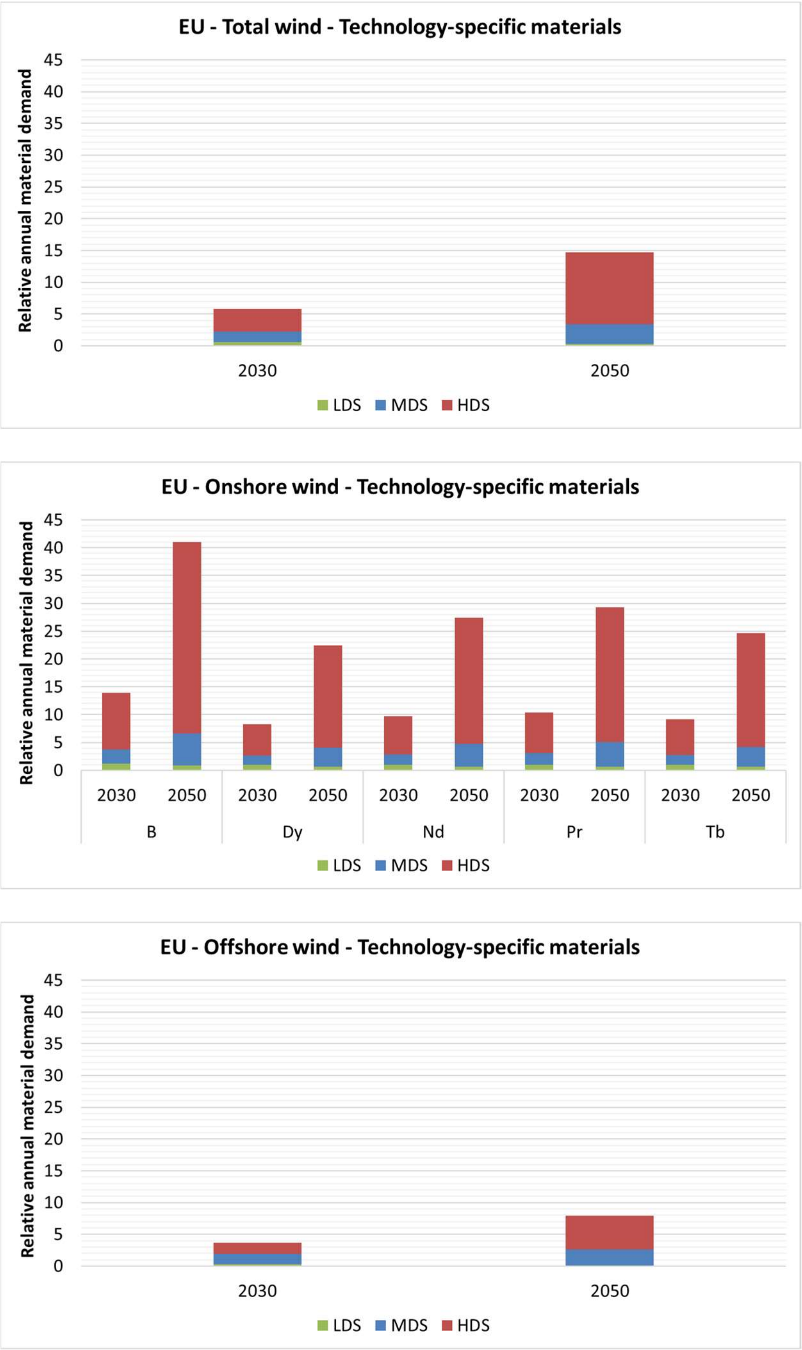
Concrete	Total	4 078 129
	Onshore	2 979 731
	Offshore	1 098 398
Steel	Total	1 402 588
	Onshore	961 081
	Offshore	441 507
Plastic	Total	55 087
	Onshore	37 598
	Offshore	17 489
Glass	Total	96 533
	Onshore	65 429
	Offshore	31 104
Al	Total	12 675
	Onshore	9 645
	Offshore	3 030
Cr	Total	6 263
	Onshore	4 210
	Offshore	2 053
Cu	Total	29 347
	Onshore	20 046
	Offshore	9 302
Fe	Total	235 705
	Onshore	158 566
	Offshore	77 139
Mn	Total	9 456
	Onshore	6 442
	Offshore	3 014
Mo	Total	1 301
	Onshore	876
	Offshore	425
Ni	Total	4 329
	Onshore	3 211
	Offshore	1 118
Zn	Total	65 865
	Onshore	44 954
	Offshore	20 911



Source: JRC analysis.

Figure 15. Annual EU demand for technology-specific materials in 2018 in t/year (table, left) and relative demand in 2030 and 2050 as a ratio of current demand (charts, right) for total (top), onshore (middle) and offshore (bottom) wind

B	Total	23
	Onshore	5
	Offshore	18
Dy	Total	95
	Onshore	42
	Offshore	53
Nd	Total	857
	Onshore	305
	Offshore	552
Pr	Total	150
	Onshore	49
	Offshore	101
Tb	Total	32
	Onshore	12
	Offshore	20



Source: JRC analysis.

To put these results into perspective and to evaluate the potential for supply risks, the predicted demands were charted as a proportion of the current global supply (Figure 16 and Figure 17). Here the aggregated wind material demands are split, not according to the use of the materials (general v specific), but rather based on the ratio of demand to current supply. Data for the global supply were sourced from European Commission (2017, 2020) and Jean, Brown, Jaffe, Buonassisi and Bulovic (2015).

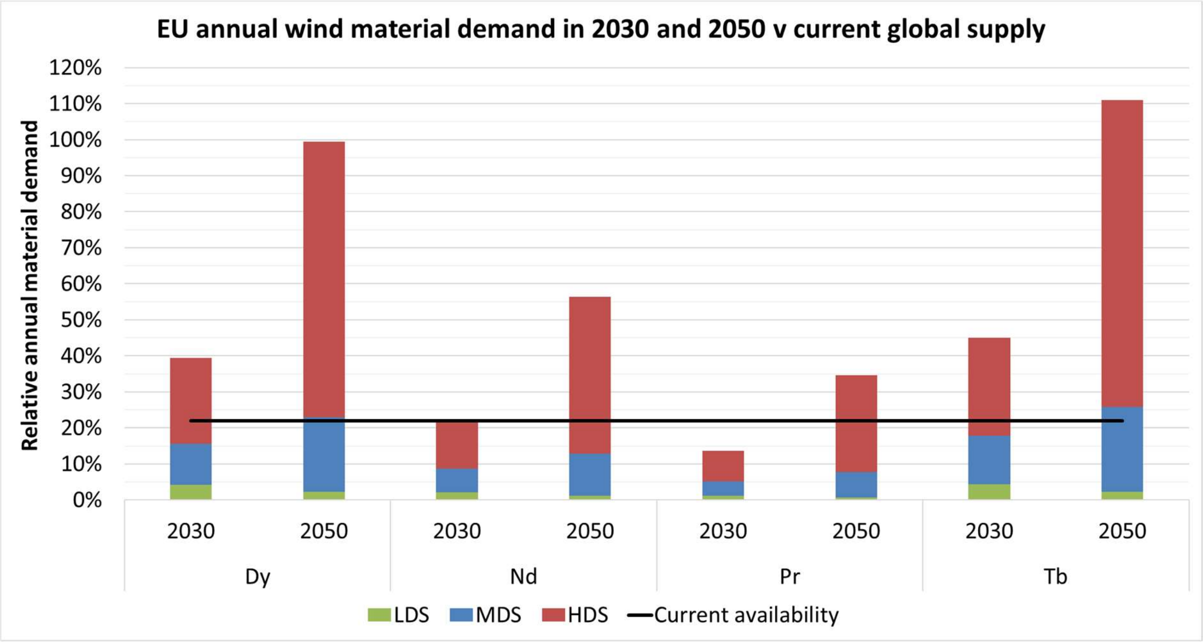
The potential for supply risk is assessed by comparing the relative demand with an indicative availability threshold. A reference value of 22% was taken as the baseline, assuming that the EU's access to the supply market for raw materials or components is proportional to its share of the global gross domestic product.

Even though this assumption is likely not correct, it provides a general idea of whether a material could be subject to potential supply risks or not.

An increase in demand disproportionate to the current supply was identified for dysprosium, neodymium, praseodymium and terbium, with dysprosium and terbium overcoming the availability threshold in the MDS. Within this group, praseodymium raises the fewest supply concerns.

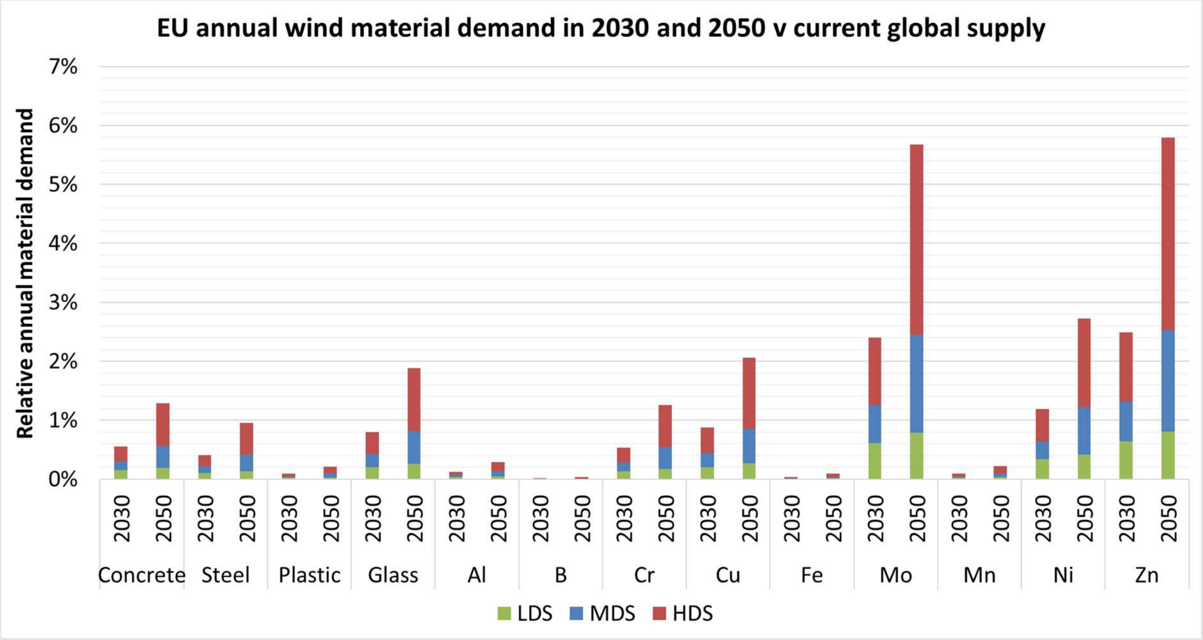
In these results, the threshold is indicative of the current supply for all technologies, not just wind power. The deployment of wind turbines according to EU plans alone will require most of the neodymium, praseodymium, dysprosium and terbium currently available at global level.

Figure 16. EU wind demand-to-global supply ratio for 2030 and 2050 – levels of demand close to current availability



Source: JRC analysis.

Figure 17. EU wind demand-to-global supply ratio in 2030 and 2050 – levels of demand below current availability



Source: JRC analysis.

2.6.2. Future material demand in wind turbines at global level

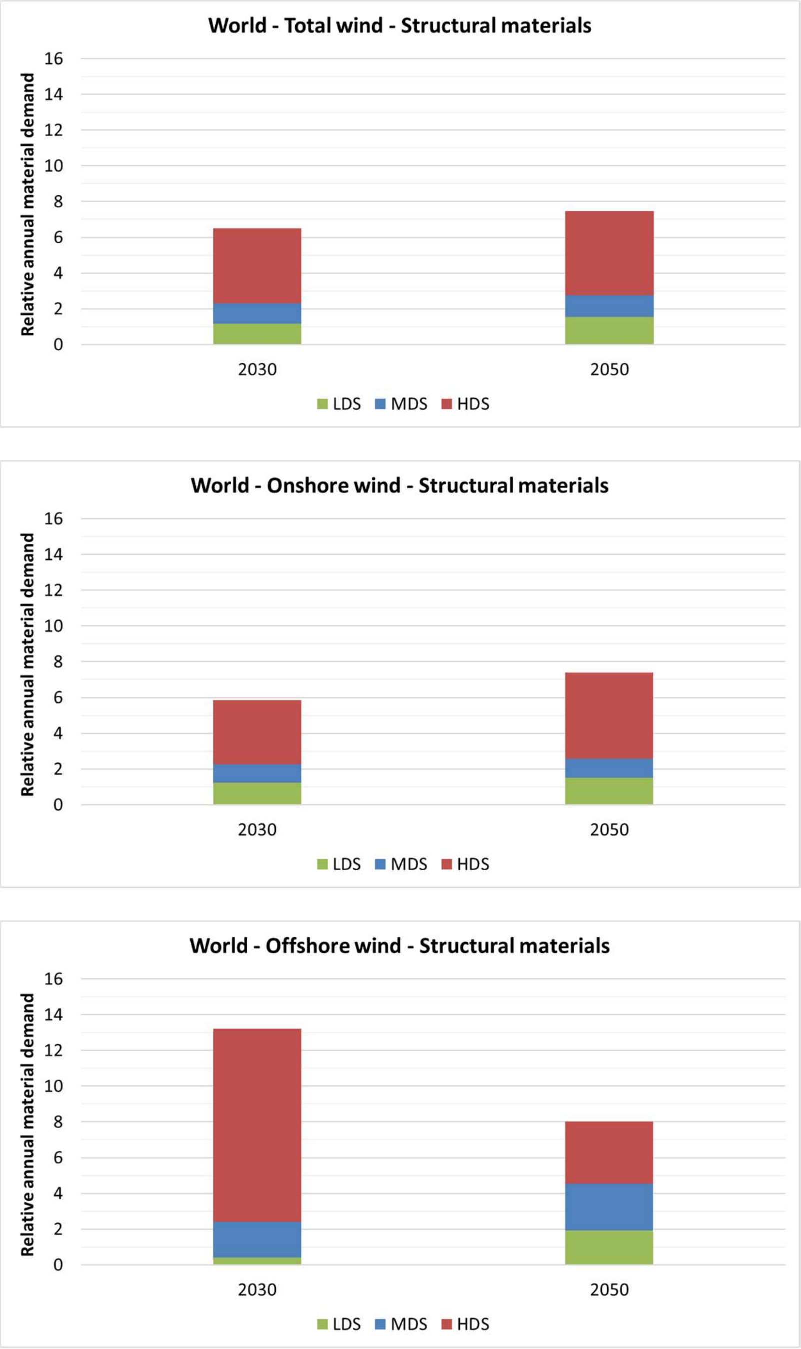
Figure 18 and Figure 19 report the global annual demand for structural materials and technology-specific materials, respectively, for wind power. In addition, within each figure data are presented both as aggregated wind demands and as individual onshore and offshore contributions. As in the EU-related figures, data for 2030 and 2050 are shown as a scale factor of the current (2018) demand, with the exact value of the current demand reported in the tables in Figures 18 and 19.

Worldwide material demand for aggregated wind turbine technologies is rather stable from 2030 to 2050, as the foreseen increases in the annual installed capacity can be considered moderate in all scenarios. Future material demand is about 2.5 times higher than current demand in the MDS, while it is around 6-7 times higher in the HDS. The only exceptional increases are for technology-specific materials in the HDS, where an increase of 8 to 10 times in 2030 and of up to 15 times in 2050 can be seen.

Looking at the individual contributions, the biggest relative increase in material demands is for offshore wind, which is the opposite of the situation forecast for the EU. This is because at global level offshore wind is currently under-represented and will experience a large boost in the next few years. At EU level offshore wind has already been characterised by some development and thus a lesser degree of future deployment is expected.

Figure 18. Annual global demand for structural materials in 2018 in t/year (table, left) and relative demand in 2030 and 2050 as a ratio of current demand (charts, right) for total (top), onshore (middle) and offshore (bottom) wind

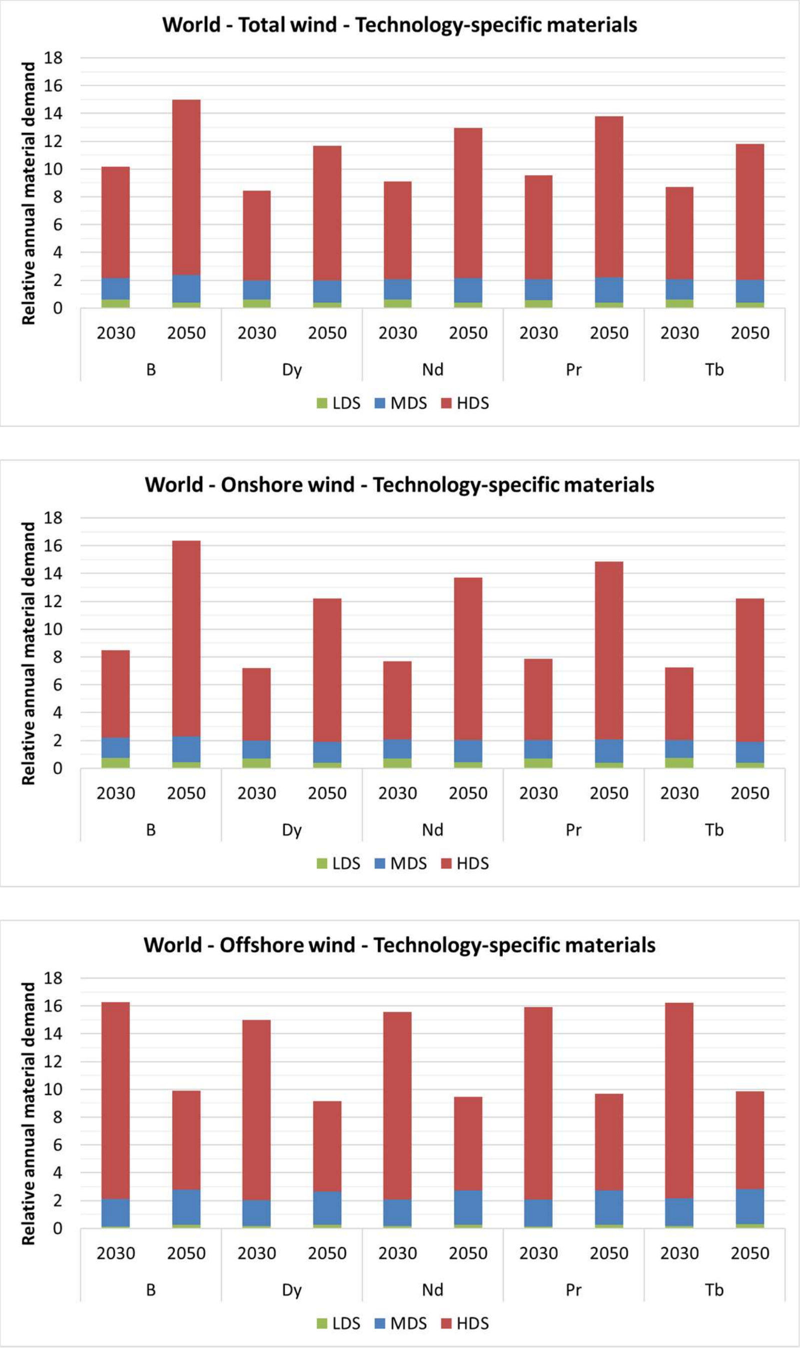
Concrete	Total	17 551 910
	Onshore	16 171 760
	Offshore	1 380 150
Steel	Total	5 923 708
	Onshore	5 397 950
	Offshore	525 758
Plastic	Total	236 900
	Onshore	216 200
	Offshore	20 700
Glass	Total	407 840
	Onshore	371 394
	Offshore	36 446
Al	Total	60 880
	Onshore	56 870
	Offshore	4 010
Cr	Total	25 861
	Onshore	23 486
	Offshore	2 375
Cu	Total	101 042
	Onshore	89 911
	Offshore	11 131
Fe	Total	979 686
	Onshore	890 086
	Offshore	89 600
Mn	Total	40 471
	Onshore	36 914
	Offshore	3 557
Mo	Total	5 400
	Onshore	4 907
	Offshore	493
Ni	Total	19 772
	Onshore	18 330
	Offshore	1 442
Zn	Total	283 250
	Onshore	258 500
	Offshore	24 750



Source: JRC analysis.

Figure 19. Annual global demand for technology-specific material in 2018 in t/year (table, left) and relative demand in 2030 and 2050 as a ratio of current demand (charts, right) for total (top), onshore (middle) and offshore (bottom) wind

B	Total	73
	Onshore	57
	Offshore	16
Dy	Total	314
	Onshore	262
	Offshore	51
Nd	Total	2 814
	Onshore	2 302
	Offshore	512
Pr	Total	450
	Onshore	356
	Offshore	94
Tb	Total	117
	Onshore	98
	Offshore	19

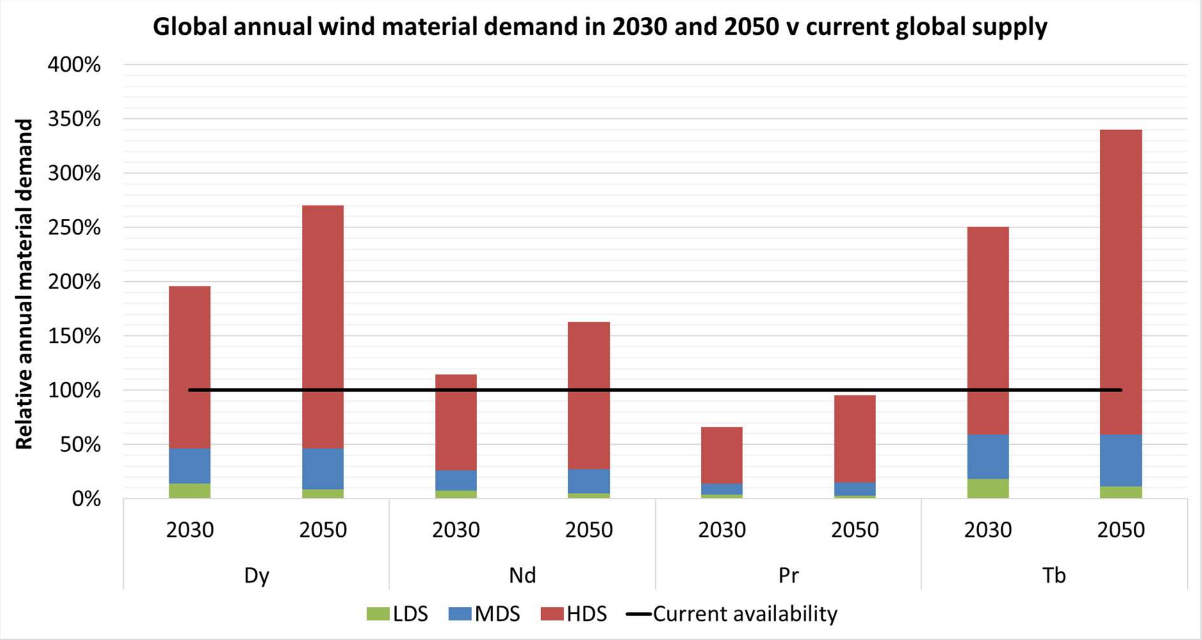


Source: JRC analysis.

As done for the EU analysis, the predicted material demand was charted as a proportion of the current global supply (Figure 20 and Figure 21). The current global supply, equivalent to 100% in the figure, was used as an indicative availability threshold.

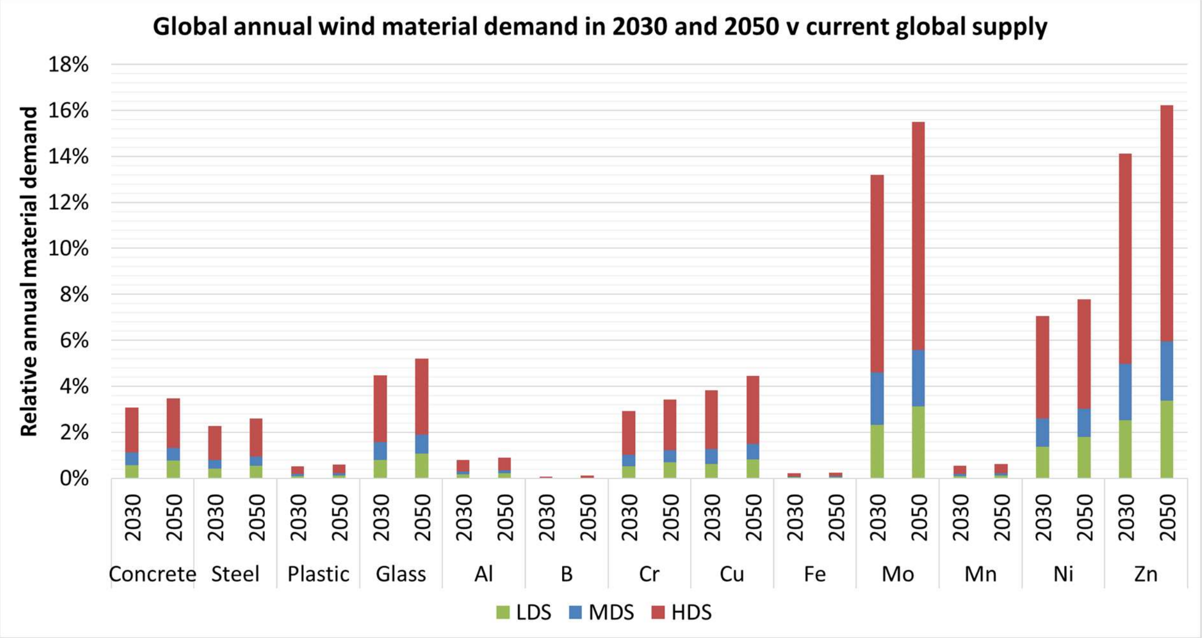
As with the EU, an increase in demand to above or close to the current supply levels was identified for the rare earths used in permanent magnets, such as neodymium, praseodymium, dysprosium and terbium, even though at global level the MDS demand level was satisfactorily far from the availability threshold in both 2030 and 2050. Still, considering that only the needs of wind technologies are compared with the whole global supply, the deployment of the predicted number of wind power plants (in the MDS) alone may require up to half of the current supply.

Figure 20. Global wind demand-to-global supply ratio in 2030 and 2050 – levels of demand close to current availability



Source: JRC analysis.

Figure 21. Global wind demand-to-global supply ratio in 2030 and 2050 – levels of demand below current availability



Source: JRC analysis.

3. Solar PV

This chapter defines the various scenarios for solar PV electricity production, along with the main trends and criticalities identified in material demand between today (2018) and 2050.

First, an overview of solar PV technologies and the materials needed is presented, then the effects of the four individual factors (capacity, lifetime, market share, material intensity) is defined and analysed. At the end of the chapter, the three scenarios arising from the combination of low, medium and high values associated to the four factors are analysed, highlighting the criticalities for each specific material.

3.1. Solar PV technologies and material usage

3.1.1. Solar PV technologies

Solar PV panels are currently based on different sub-technologies, the most common of which are:

- wafer-based crystalline silicon (c-Si), either single-crystalline or multi-crystalline silicon (no distinction between the two will be made in this study) (5);
- cadmium telluride (CdTe);
- copper indium gallium diselenide (CIGS);
- amorphous silicon (a-Si).

The latter three technologies are collectively known as thin-film technologies, due to the limited thickness of the PV cell, which is in the order of few micrometres, compared to the 150-200 μm of silicon-based wafers. This difference is because the materials used in thin-film technologies absorb light 10-100 times more efficiently than c-Si.

Other innovative PV technologies such as multi-junction cells or hybrid devices at nanoscale level are currently under development. These new technologies promise greater efficiency and/or cost reductions in the long term. The most promising technologies are (Jean, Brown, Jaffe, Buonassisi and Bulovic, 2015):

- copper zinc tin sulphide;
- perovskite solar cells, developed from solid-state dye-sensitised cells;
- organic PV;
- dye-sensitised solar cells;
- colloidal quantum dot PV.

However, the market success of these emerging technologies is uncertain and in any case highly unlikely to take place on a large scale in the near future. Therefore this report only considers the four mature technologies listed above, which will monopolise or at least dominate the market over the next three decades.

3.1.2. Materials used in solar PV

It is possible to classify the materials used in solar PV technologies into two main groups: the non-cell general materials that are used in the PV modules and systems (balance of system) and the materials that are necessary for the manufacturing of the solar cell itself.

Figure 22 provides a diagram of a solar panel, illustrating the different constituent layers. As can be seen, the solar cell, actively converting light into electricity, is but one of many components in a complete solar panel.

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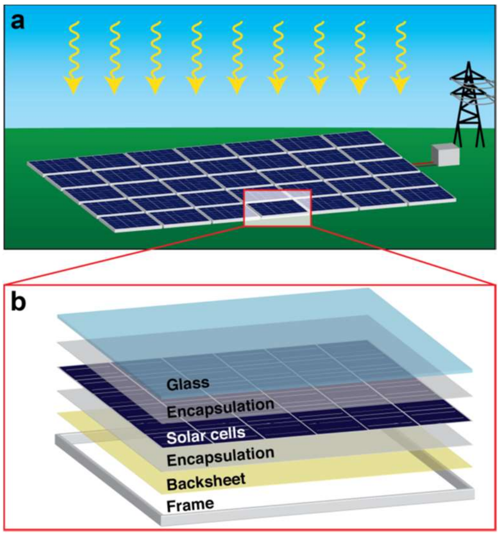
(5) In single-crystalline PV panels, cells are composed of one single grain. Multi-crystalline cells, on the other hand, contain several grains with a random orientation, typically with a width of 1 cm^2 (Jean, Brown, Jaffe, Buonassisi and Bulovic, 2015).

Figure 22. Simplified illustration of a PV panel



Source: Jean, Brown, Jaffe, Buonassisi and Bulovic (2015).

The general materials are listed below, along with their main applications as reported in Jean, Brown, Jaffe, Buonassisi and Bulovic (2015) and Copper Alliance.

- **Concrete.** System support structures.
- **Steel.** System support structures.
- **Plastic.** Environmental protection.
- **Glass.** Substrates, module encapsulation.
- **Al.** Module frames, racking, supports.
- **Cu.** Wiring, cabling, earthing, inverters, transformers, PV cell ribbons.

The specific materials, and the solar cells they are used to manufacture, are as follows.

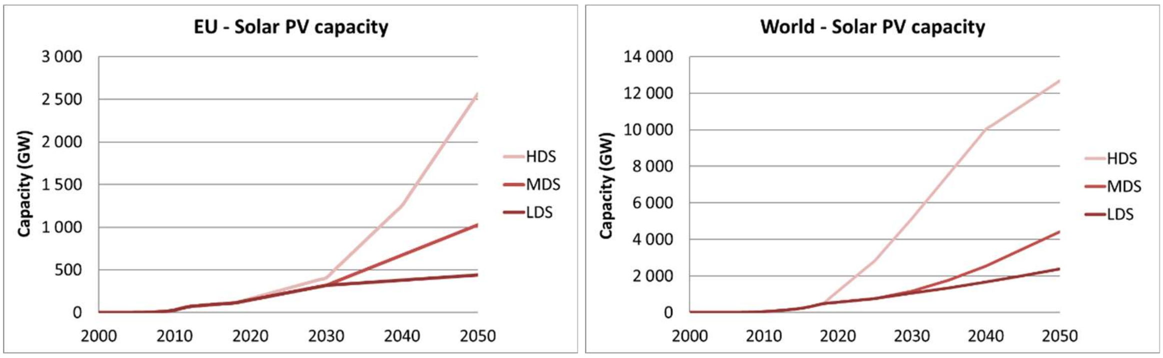
- **Si.** c-Si and a-Si technologies.
- **Ag.** c-Si technologies.
- **Ge.** a-Si technologies.
- **Cd.** CdTe technologies.
- **Te.** CdTe technologies.
- **Cu.** CIGS technologies.
- **In.** CIGS technologies.
- **Ga.** CIGS technologies.
- **Se.** CIGS technologies.

Many materials are technology dependent, meaning that their usage is related to the relative market shares of each technology (see following chapters), therefore the need for the materials can vary significantly.

3.2. Power generation capacity of solar PV

Capacity scenarios based on the political commitment discussed in Section 1.3.1 are shown in Figure 23. As can be seen, there is little difference between the scenarios for the EU up to 2030 as the political commitments laid out for the next 10 years are roughly the same for all of them. Worldwide, the LDS and MDS situations are similar, but the HDS will require a significant increase in the annual installed capacity from day one. This is due to the fact that the global HDS is extremely ambitious and aims to produce all energy using renewable sources by 2050. In order to achieve these ambitions, a huge and immediate expansion of renewable energy is required.

Figure 23. Capacity scenarios for solar PV



Source: JRC representation based on the IRENA database (IRENA, 'Statistics Time Series') for 2000-2018; and European Commission (2018), Carlsson et al. (2020), IEA (2017) and Teske (2019) for 2019-2050.

3.3. Lifetime and annual installations of solar PV panels

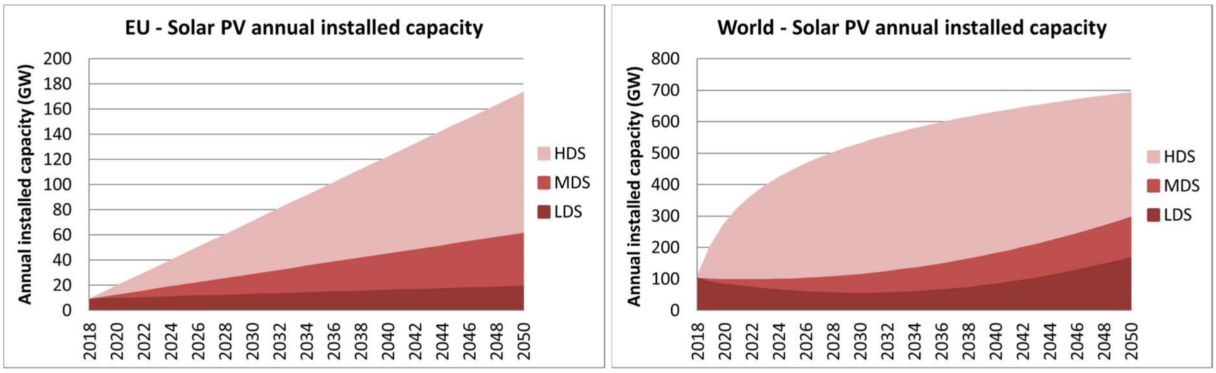
Solar PV technology has been experiencing a surge that only started about 10 years ago, so it is difficult to make solid assumptions about the relevant plant lifetimes: the operational lives of the large majority of PV plants installed worldwide are still ongoing.

In general, a range of 20-30 years of operation, with a central reference value of 25 years, is commonly assumed for solar panels (Fraunhofer Institute for Solar Energy Systems (ISE), 2019), even if lifetimes can also be longer than 30 years (JRC, 2018b). This study follows the first assumption, favouring a more conservative approach.

A lifetime of 25 years is thus the reference value associated with the MDS, with a variability of 5 years to cover a reliable range of potential lifetimes under optimistic and pessimistic conditions. Therefore, the LDS assumes an operational lifetime of 30 years, implying lower replacement rates and thus a reduced need for materials. On the other hand, the HDS assumes an operational lifetime of 20 years, implying higher replacement rates and hence an increased need for materials.

Combining these lifetime data with the capacity scenarios shown in Figure 23, the annual deployment rate shown in Figure 24 can be obtained.

Figure 24. Annual installed capacity of solar PV by 2050



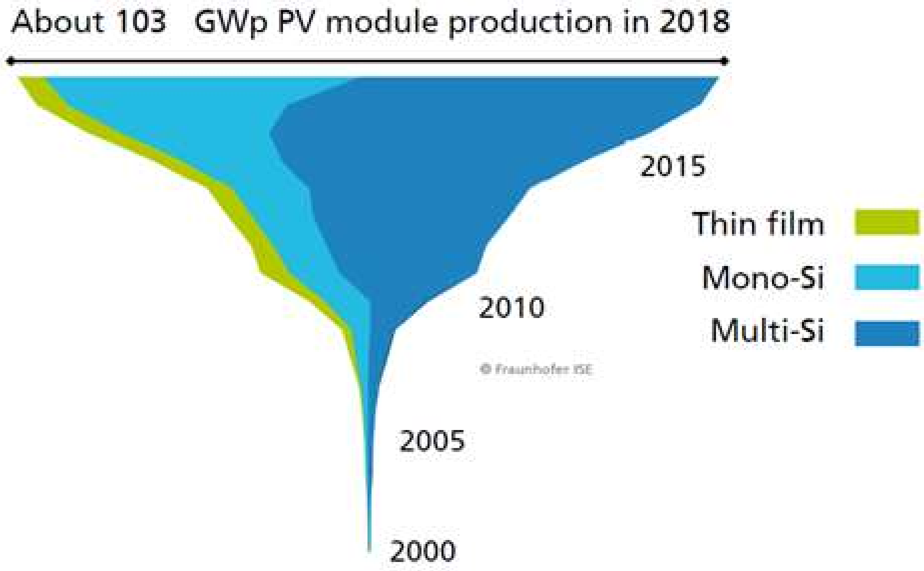
Source: JRC analysis.

At EU level the rate of increase in annual installed capacity of solar PV will be roughly constant throughout the timeline and in all scenarios. Worldwide, the relative annual deployment will be more gradual in the LDS and MDS, while in the HDS it will require a steep increase in the next few years with a slower rate of increase from 2026 onwards. The difference between the EU and global forecasts is mainly due to two factors. On the one hand, it is expected that a significant rise in installed capacity will come from Asia, more than from the western world. On the other hand, the forecasted deployment of European installed capacity is steeper in the scenarios used for global analysis than in the scenarios used for EU analysis. As mentioned in the sections on methodology, there are indeed some discrepancies between the underlying assumptions in the EU and global scenarios. One reason for the difference is that we decided to design our EU models on the basis of specific and up-to-date policy scenarios and targets that were currently relevant at EU level, as this would provide more insightful results.

3.4. Market share of solar PV technologies

The global PV market has been dominated by c-Si panels since its take-off at the beginning of the century (Figure 25). This is because c-Si panels are still more efficient than commercial thin-film modules (whose efficiency is only 12-15% compared to 15-21% for c-Si) (Jean, Brown, Jaffe, Buonassisi and Bulovic, 2015).

Figure 25. Global annual solar PV market share over time



Source: Fraunhofer Institute (ISE, 2019).

Details on thin films are reported in Figure 26. In the early 2000s, a-Si panels dominated the thin-film sector, but their market share has continuously decreased since then due to low efficiency. CdTe panels peaked towards 2009, followed by a constant decrease. CIGS panels started to grow during that period and now they have almost the same share as CdTe.

The current market shares of various PV technologies are summarised as follows.

- **c-Si.** 95.4%.
- **CdTe.** 2.4%.
- **CIGS.** 1.9%.
- **a-Si.** 0.3%.

Thus, thin-film technologies amount to 4.6% of the current market share (6).

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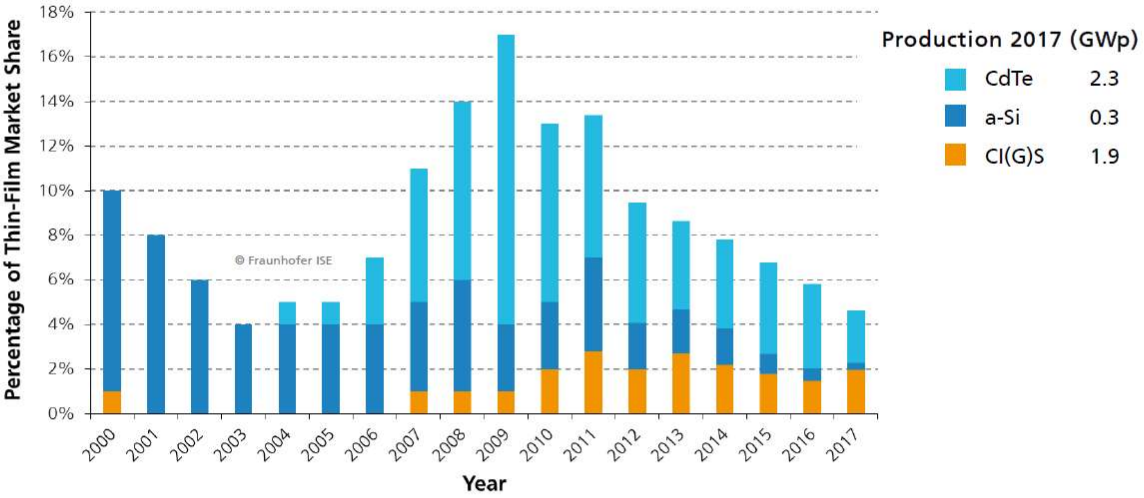
(6) These values refer to 2017 but they have been treated as valid for 2018 as well.

Figure 26. Global annual thin-film market share

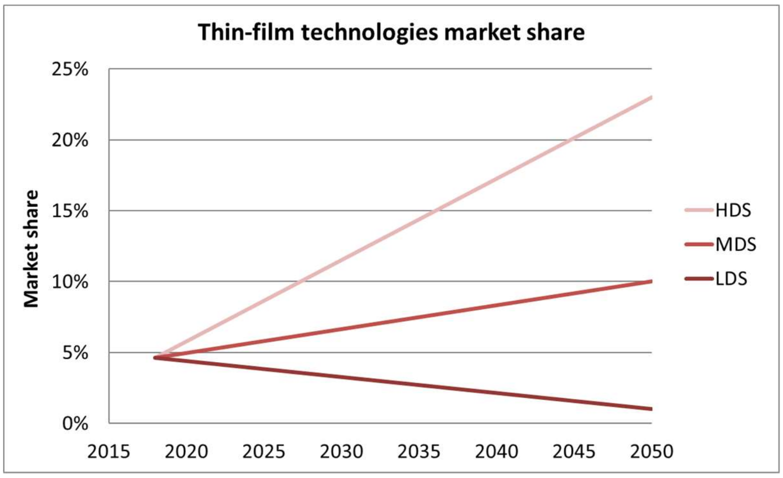


Source: Fraunhofer Institute (ISE, 2019).

Thin-film technologies contain the more critical raw materials according to the EU 2020 assessment, so the definitions of the LDS, MDS and HDS are based on this group of technologies, while c-Si fills the remaining market share. In the MDS, the share of thin-film technologies grows linearly until it reaches 10% in 2050 (CdTe and CIGS each have 4.5% and a-Si has 1%), which roughly corresponds to the average aggregate level of the past 20 years but maintains the current sub-technology composition. Hence, c-Si slightly decreases to 90% in 2050. The LDS hypothesises that c-Si will gain an almost full coverage of the market, following a trend that began in 2009. Specifically, it hypothesises that c-Si will reach 99% in 2050 and CdTe and CIGS will share the remaining 1%, while a-Si will disappear from the market. In the HDS, thin-film technologies are characterised by a massive growth that partly challenges the dominance of c-Si: the share of CdTe and CIGS panels each reach 10%, while a-Si is expected to be limited to 3%, based on the current issues related to its low efficiency. Hence, c-Si decreases to 77%. These values are applied to both the EU and the global scenarios. These assumptions are of course indicative and are based on currently observed trends.

Figure 27 summarises the resulting aggregate market shares of thin-film technologies.

Figure 27. Projections of thin-film market share by 2050



Source: JRC analysis.

3.5. Material intensity in solar PV technologies

Concrete, steel, plastic, glass, aluminium and copper are general materials used in the structural and electric components of the PV power plants and are common to all technologies. The following material intensities have been assumed for 2018 (Jean, Brown, Jaffe, Buonassisi and Bulovic, 2015).

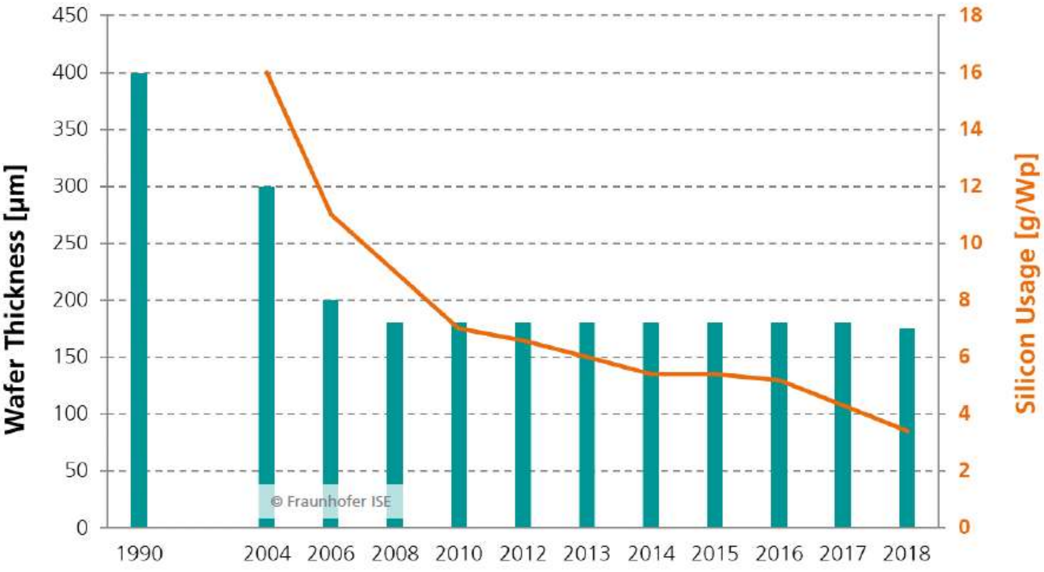
- **Concrete.** 60.7 t/MW.
- **Steel.** 67.9 t/MW.
- **Plastic.** 8.6 t/MW.
- **Glass.** 46.4 t/MW.
- **Al.** 7.5 t/MW.
- **Cu.** 4.6 t/MW.

Only minor innovations are likely to affect these materials, hence the material intensity in 2050 is set at 80%, 90% and 100% of the current values in the LDS, MDS and HDS, respectively, in line with the assumptions for wind power. These assume that the structure of the PV modules will be based on the current design frameworks. This is because to the best of our knowledge no major R & D activities are under way on panel design that could lead to significant changes in the composition of the materials.

More articulated assumptions have been made for the specific materials used in the solar cells, i.e. silicon, silver, cadmium, tellurium, copper, indium, gallium, selenium and germanium.

The material intensity of silicon in c-Si panels has been characterised by a massive reduction in the last decades, especially in correspondence with the solar PV expansion that took place about a decade ago (see Figure 2). Specifically, it has now reached 4 g/W (i.e. t/MW), compared with 16 g/W in 2004 (see Figure 28 (ISE, 2019)). This trend is likely to continue in the future, as silicon consumption is expected to drop to between 2.1 and 3 g/W in 2028 (JRC, 2018b).

Figure 28. Changes in wafer thickness and silicon usage in c-Si



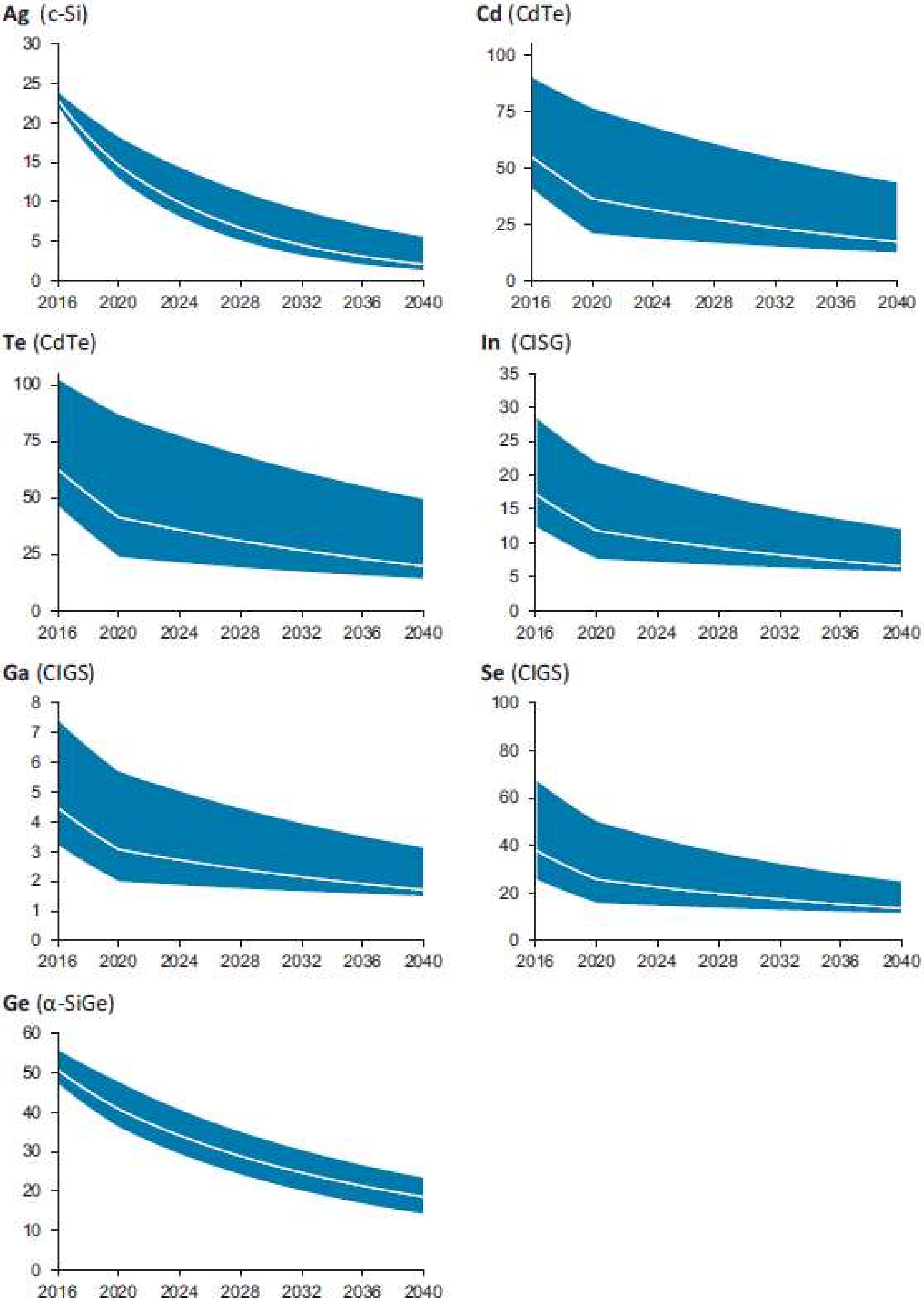
Source: Fraunhofer Institute (ISE, 2019).

The material intensities of the other materials used in solar cells have been taken from Nassar, Wilburn and Goonan (2016), the results of which are compatible with the modelling framework adopted in this study.

In general, it is difficult to determine the composition of solar panels precisely as the technology is still recent and most of the manufacturing processes are trade secrets, especially for CdTe and CIGS. This means that a range of values can be found for current material intensities. The literature provides an overview of current material intensities, which highlights the great variability that characterises some materials (Valero, Valero, Calvo and Ortego, 2018; Nassar, Wilburn and Goonan, 2016).

A significant technological development is forecast for all materials, following advancements in conversion efficiency or in the production process. This results in a marked decrease in the material intensity in the HDS. Figure 29 reports the material intensity scenarios as found in the literature (Nassar, Wilburn and Goonan, 2016). Material intensities for silver and germanium (i.e. the two materials used in silicon-based technologies) originate in a common starting point in 2010, while the other materials show different material intensities as early as the base year.

Figure 29. Future material intensities for solar cell materials (t/GW)



Source: Nassar, Wilburn and Goonan (2016).

Table 3 summarises the values for material intensity as reported in Nassar, Wilburn and Goonan (2016) and other relevant references. For some materials, a range of values is reported. If three values are reported, they correspond to optimistic (low), neutral (medium) and pessimistic (high) intensity assumptions respectively.

Table 3. Material intensities for solar PV panels reported in the literature

Material	Year	Material intensity (t/GW)	Reference
Ag	2010	84	Nassar, Wilburn and Goonan (2016)
	2020	13; 15; 18	
	2040	1; 2; 6	
	2019 (*)	20	Giurco, Dominish, Florin, Watari and McLellan (2019)
	2050 (**)	4	
Cd	2010	79; 89; 116	Nassar, Wilburn and Goonan (2016)
	2020	21; 36; 77	
	2040	12; 17; 44	
	2013	116.7-143	Wellmer et al. (2019)
	2025	63.8	
	2050	33.0	
Te	2010	89; 101; 132	Nassar, Wilburn and Goonan (2016)
	2020	23; 41; 87	
	2040	14; 20; 50	
	2013	99.7-135	Wellmer et al. (2019)
	2025	43.1	
	2050	35.3	
	2010	74	Woodhouse et al. (2013)
	2030	17-19	
	2014 (*)	30; 70; 300	Bustamante and Gaustad (2014)
In	2010	23; 29; 43	Nassar, Wilburn and Goonan (2016)
	2020	8; 12; 22	
	2040	6; 7; 12	
	2013	55.5-75	Wellmer et al. (2019)
	2025	45	
	2050	3	
	2050	5; 9; 20	Stamp, Wäger and Hellweg (2014)
Ga	2010	6; 8; 11	Nassar, Wilburn and Goonan (2016)
	2020	2; 3; 6	
	2040	1; 2; 3	
	2013	2-7.2	Wellmer et al. (2019)
	2025	3.2	
	2050	1.2	
Se	2010	48; 67; 107	Nassar, Wilburn and Goonan (2016)
	2020	15; 26; 51	
	2040	11; 14; 25	
	2013	10-39.3	Wellmer et al. (2019)
	2025	17.4	
	2050	6.3	
Ge	2010	73	Nassar, Wilburn and Goonan (2016)
	2020	36; 41; 48	
	2040	14; 19; 24	

NB:
(*) Values are reported as 'current': the year of publication has therefore been indicated.
(**) The precise year is not reported but the analysis covers the period up to 2050.

For copper used in CIGS panels and silicon used in a-Si panels, values are often not reported in the literature. However, the relevant material demands are negligible. This is firstly because the material intensities are three orders of magnitude lower than those of the copper used in the general electric system and the silicon used in c-Si, respectively, and secondly because in no scenarios do CIGS and a-Si reach high market shares, whereas c-Si dominates the market in all scenarios and the copper used in the general electrical system is used in all technologies. However, these two contributions have been taken into account for the sake of completeness.

Concerning copper in CIGS, we based our choice on a previous JRC study (JRC, 2016), which reports 24 t/GW in 2015 and 15 t/GW in 2030. This is in line with other information in Wellmer et al. (2019), which indicates 21 t/GW in 2013.

With respect to the material intensity of silicon in a-Si, Jean, Brown, Jaffe, Buonassisi and Bulovic (2015) indicates a value of 60 t/GW, assuming record efficiencies obtained in laboratory conditions and 100% utilisation of materials and manufacturing yield. In order to calculate a more realistic commercial value, we considered the intensity of silicon used in c-Si: the report indicates 2 t/MW, when the commercial value in 2015 (issue date of the reference) was 5 t/MW. The same proportionality (40%) has been applied, which has led us to assume an intensity of 150 t/GW of silicon in a-Si. This approximation seems reasonable as the report estimates the current material utilisation for a-Si in the range 15-70%. No values are reported in Wellmer et al. (2019) for this material.

The values finally adopted in this work, both for the current status (2018) and the future prospects (2030 and 2050) are summarised in Table 4.

Table 4. Material intensity estimates for solar PV panels

Technology	Material	Scenario	Unit	2018	2030	2050
All	Concrete	LDS	t/MW	60.7	56.2	48.6
All	Concrete	MDS	t/MW	60.7	58.4	54.6
All	Concrete	HDS	t/MW	60.7	60.7	60.7
All	Steel	LDS	t/MW	67.9	62.8	54.3
All	Steel	MDS	t/MW	67.9	65.3	61.1
All	Steel	HDS	t/MW	67.9	67.9	67.9
All	Plastic	LDS	t/MW	8.6	7.9	6.9
All	Plastic	MDS	t/MW	8.6	8.3	7.7
All	Plastic	HDS	t/MW	8.6	8.6	8.6
All	Glass	LDS	t/MW	46.4	42.9	37.1
All	Glass	MDS	t/MW	46.4	44.7	41.8
All	Glass	HDS	t/MW	46.4	46.4	46.4
All	Al	LDS	t/MW	7.5	6.9	6.0
All	Al	MDS	t/MW	7.5	7.2	6.8
All	Al	HDS	t/MW	7.5	7.5	7.5
All	Cu	LDS	t/MW	4.6	4.3	3.7
All	Cu	MDS	t/MW	4.6	4.5	4.2
All	Cu	HDS	t/MW	4.6	4.6	4.6
c-Si	Si	LDS	t/MW	4.0	2.0	1.0
c-Si	Si	MDS	t/MW	4.0	2.75	2.0
c-Si	Si	HDS	t/MW	4.0	3.5	3.0
c-Si	Ag	LDS	t/GW	20.0	4.0	1.0
c-Si	Ag	MDS	t/GW	20.0	6.0	2.0
c-Si	Ag	HDS	t/GW	20.0	11.0	5.0
CdTe	Cd	LDS	t/GW	35.0	20.0	10.0
CdTe	Cd	MDS	t/GW	50.0	27.0	12.0
CdTe	Cd	HDS	t/GW	85.0	60.0	35.0
CdTe	Te	LDS	t/GW	35.0	20.0	11.0
CdTe	Te	MDS	t/GW	52.0	27.0	15.0
CdTe	Te	HDS	t/GW	95.0	70.0	40.0

CIGS	Cu	LDS	t/GW	20.0	12.5	6.0
CIGS	Cu	MDS	t/GW	22.0	15.0	10.5
CIGS	Cu	HDS	t/GW	24.0	17.5	15.0
CIGS	In	LDS	t/GW	10.0	8.0	5.0
CIGS	In	MDS	t/GW	15.0	10.0	6.0
CIGS	In	HDS	t/GW	27.0	17.0	10.0
CIGS	Ga	LDS	t/GW	3.0	2.0	1.0
CIGS	Ga	MDS	t/GW	4.0	2.5	1.5
CIGS	Ga	HDS	t/GW	7.0	4.5	2.5
CIGS	Se	LDS	t/GW	22.0	17.0	9.0
CIGS	Se	MDS	t/GW	35.0	20.0	12.0
CIGS	Se	HDS	t/GW	60.0	40.0	20.0
a-Si	Si	LDS	t/GW	150.0	75.0	40.0
a-Si	Si	MDS	t/GW	150.0	100.0	75.0
a-Si	Si	HDS	t/GW	150.0	130.0	110.0
a-Si	Ge	LDS	t/GW	48.0	22.0	10.0
a-Si	Ge	MDS	t/GW	48.0	27.0	15.0
a-Si	Ge	HDS	t/GW	48.0	32.0	20.0

Source: JRC analysis.

3.6. Future material demand scenarios for solar PV

In an assessment of all the different contributions from the previous sections it is possible to obtain demand scenarios for all the relevant materials. For clarity, only data for 2030 and 2050 are reported; however, data for all the intervening years are available. Results at EU level are presented first (Section 3.6.1) and then those at global level (Section 3.6.2). When major differences in trends are present, data are shown for each individual material. When the trends are similar, data are shown per category.

3.6.1. Future material demand in solar PV at EU level

Figure 30 shows the annual material demand for solar PV in the EU in 2030 and 2050. The different materials are divided into structural materials used for the frame and staffing of the PV systems and technology-specific materials.

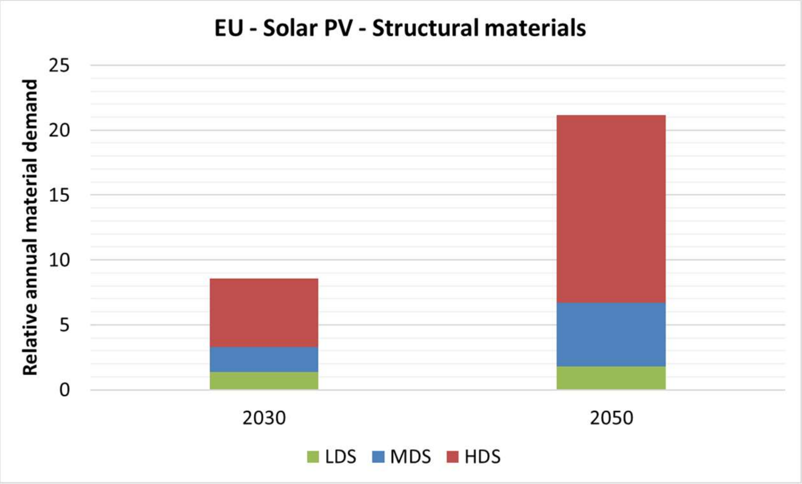
As in the section on wind, data for 2030 and 2050 are shown as a scale factor of the current (2018) demand, with the exact value of the current demand reported in the table in Figure 30.

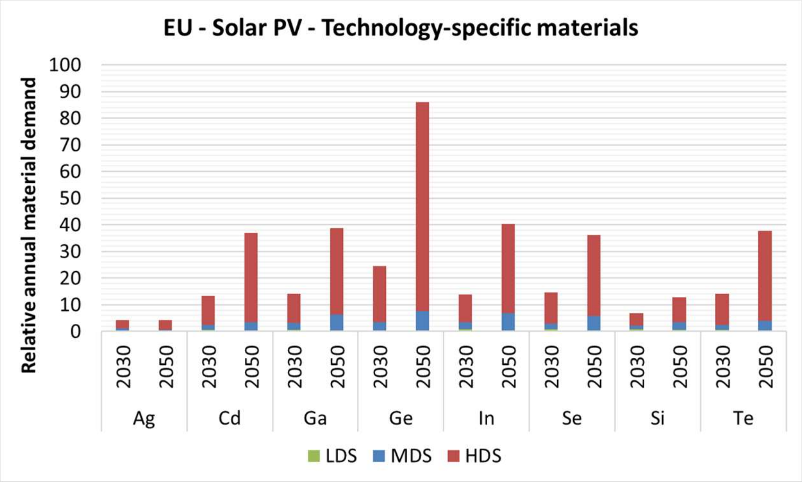
For structural materials, a net increase in material demands is expected in all scenarios, ranging from 2 (LDS) to 21 times (HDS) the current value by 2050.

For technology-specific materials there is a large difference between the different scenarios. In the LDS we see a net decrease in material demand due to technological improvements and a subsequent significant decrease in material intensities (see Section 3.5). In the MDS the balance between increased capacity deployment and a moderate decrease in material intensities results in a moderate increase in demand (3 to 8 times) for most materials. In this scenario, gallium, germanium, indium and selenium are the elements with the highest demand increases. The only material that still shows a slight decrease in demand in the MDS is silver, and this is due to the large increase in material efficiencies. In the HDS we see an increase in demand for all materials: by 2050 for silver we have a 4-fold increase, while for silicon we have up to a 12-fold increase. For cadmium, gallium, indium, selenium and tellurium the change will be more significant, as their demand will increase by 40 times, and germanium will see its demand rise to up to 86 times the current values. This distribution is mostly driven by the predicted relative market shares (see Section 3.4).

Figure 30. Annual EU demand for solar PV materials in 2018 in t/year (table, left) and relative demand in 2030 and 2050 as a ratio of current demand (charts, right)

Concrete		493 959
Steel		552 072
Plastic		69 735
Glass		377 734
Ag		155
Al		61 019
Cd	LDS	6.7
Cd	MDS	9.6
Cd	HDS	16.3
Cu		37 777
Ga	LDS	0.5
Ga	MDS	0.6
Ga	HDS	1.1
Ge		1.2
In	LDS	1.6
In	MDS	2.4
In	HDS	4.3
Se	LDS	3.5
Se	MDS	5.5
Se	HDS	9.5
Si		31 045
Te	LDS	6.7
Te	MDS	10.0
Te	HDS	18.2


EU - Solar PV - Structural materials


EU - Solar PV - Technology-specific materials

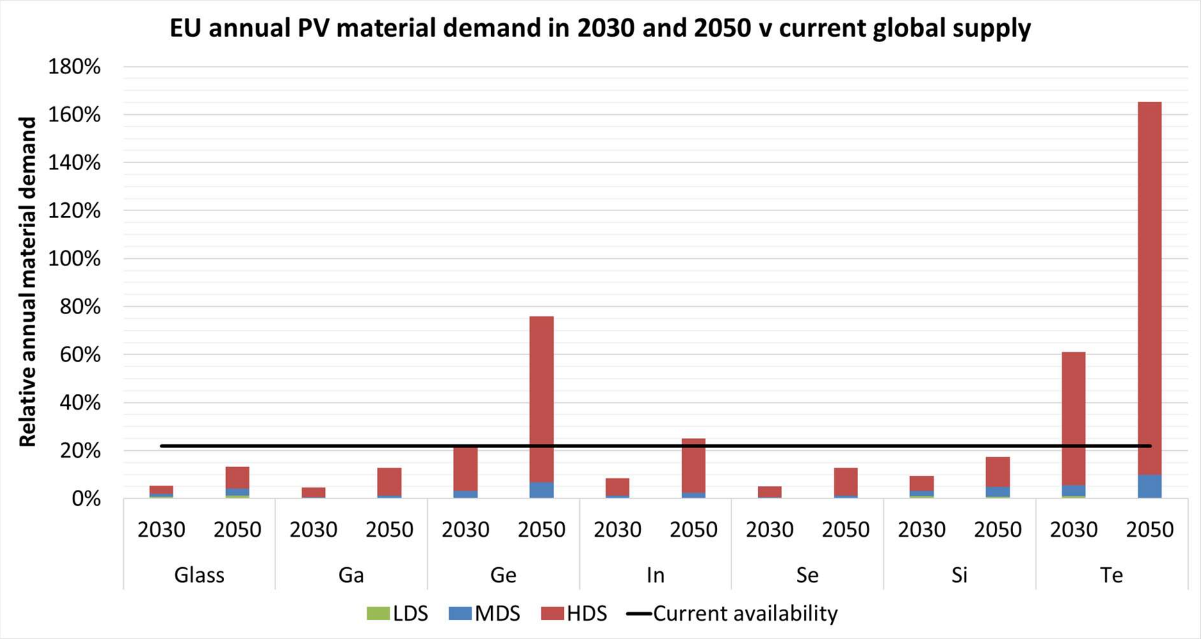
Source: JRC analysis.

For easier comparison, the predicted material demands have also been charted as a function of the current global supply (Figure 31 and Figure 32), with 100% being equal to the current global supply of each material.

The potential for supply risk is assessed by comparing the relative demand with an indicative availability threshold. A reference value of 22% was taken as the baseline, assuming that the EU access to the supply market for raw materials or components is proportional to its share of the global gross domestic product. Even though this assumption is likely not correct, it provides a general idea of whether a material could be subject to potential supply risks or not.

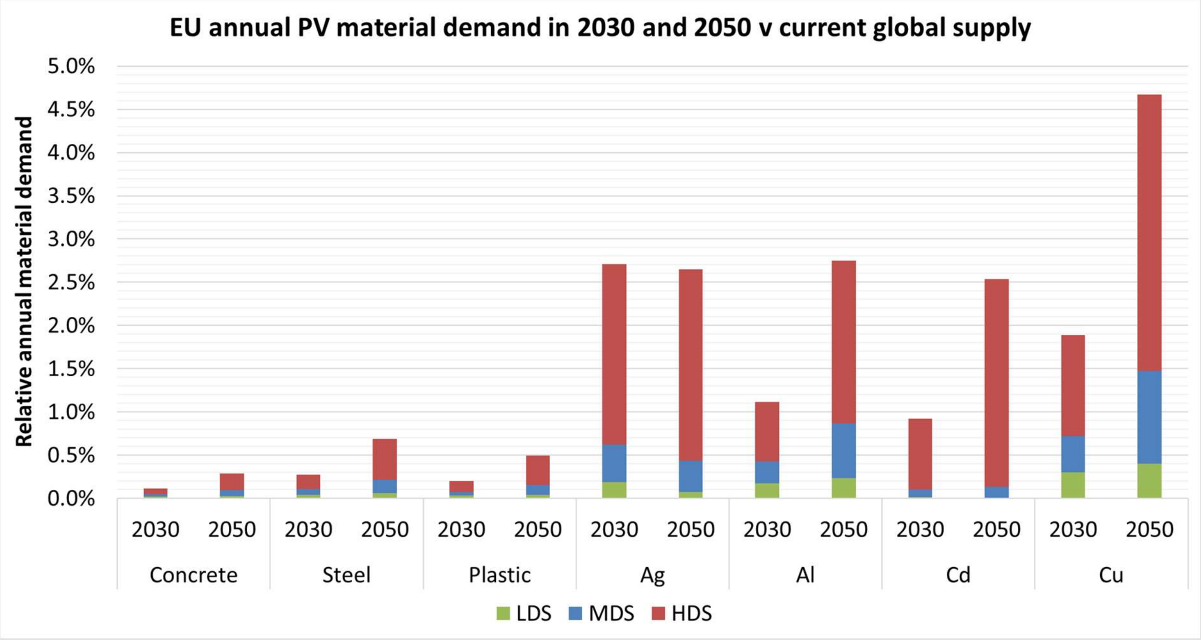
For solar PV deployed at EU level the availability threshold is only significantly exceeded by germanium and tellurium in the HDS. However, it is important to bear in mind that the threshold is indicative of the current supply for all technologies, not just solar PV systems. Thus these two elements together with gallium, indium, selenium, silicon and glass could pose threats to the overall supply chain.

Figure 31. EU PV demand-to-global supply ratio in 2030 and 2050 – levels of demand close to current availability



Source: JRC analysis.

Figure 32. EU PV demand-to-global supply ratio in 2030 and 2050 – levels of demand below current availability



Source: JRC analysis.

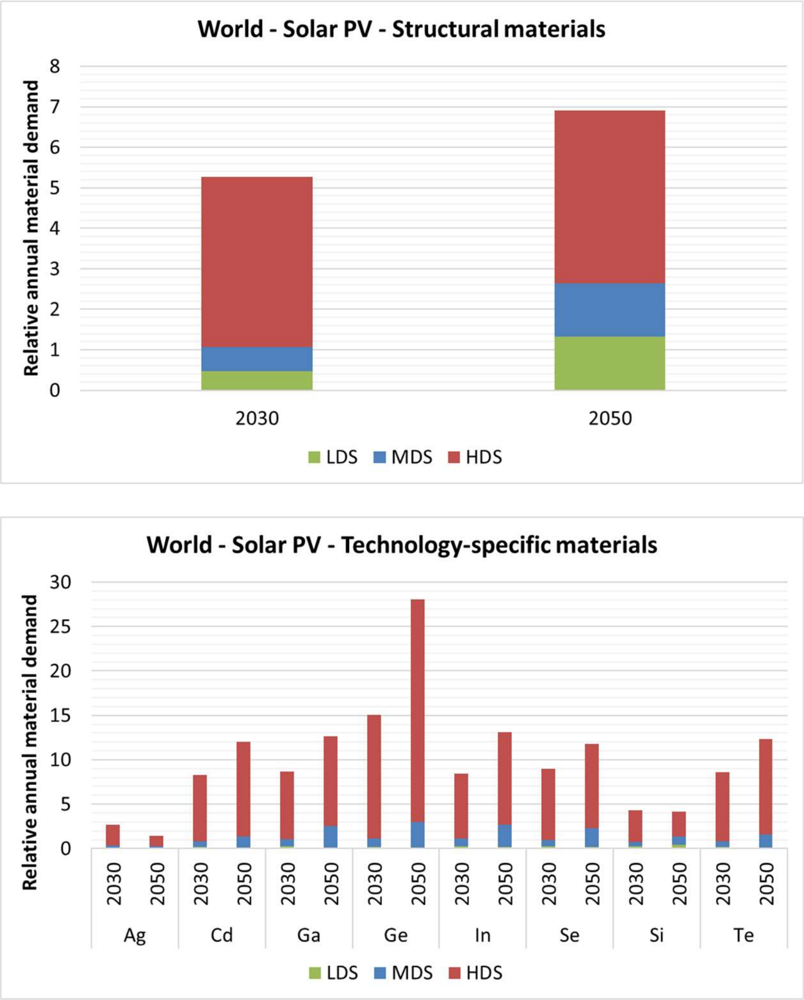
3.6.2. Future material demand in solar PV at global level

Figure 33 shows the annual material demand for solar PV at global level in 2030 and 2050; the different materials are divided into the general materials used for the frame and staffing of the PV systems and those used for specific and unique components, such as the PV cells themselves.

Data for 2030 and 2050 are shown as a scale factor of the current (2018) demand, with the exact value of the current demand reported in the table.

Figure 33. Annual global solar PV material demand in 2018 in t/year (table, left) and relative demand in 2030 and 2050 as a ratio of current demand (charts, right)

Concrete		6 071 429
Steel		6 785 714
Plastic		857 143
Glass		4 642 857
Ag		1 908
Al		750 000
Cd	LDS	83
Cd	MDS	118
Cd	HDS	201
Cu		464 329
Ga	LDS	6
Ga	MDS	8
Ga	HDS	14
Ge		15
In	LDS	19
In	MDS	29
In	HDS	53
Se	LDS	43
Se	MDS	68
Se	HDS	117
Si		381 585
Te	LDS	83
Te	MDS	123
Te	HDS	224

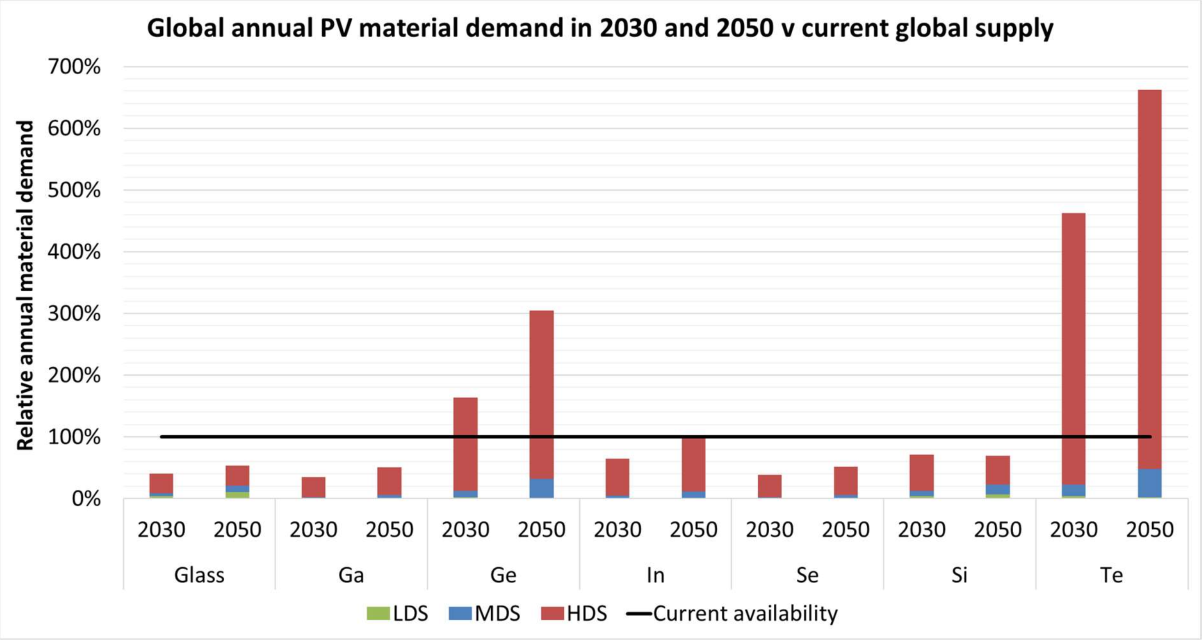


Source: JRC analysis.

To put these results into perspective and to evaluate the potential for supply risks, the predicted demands were charted as a proportion of the current global supply (Figure 34 and Figure 35). We used the current global supply, equivalent to 100% in the figure, as an indicative availability threshold.

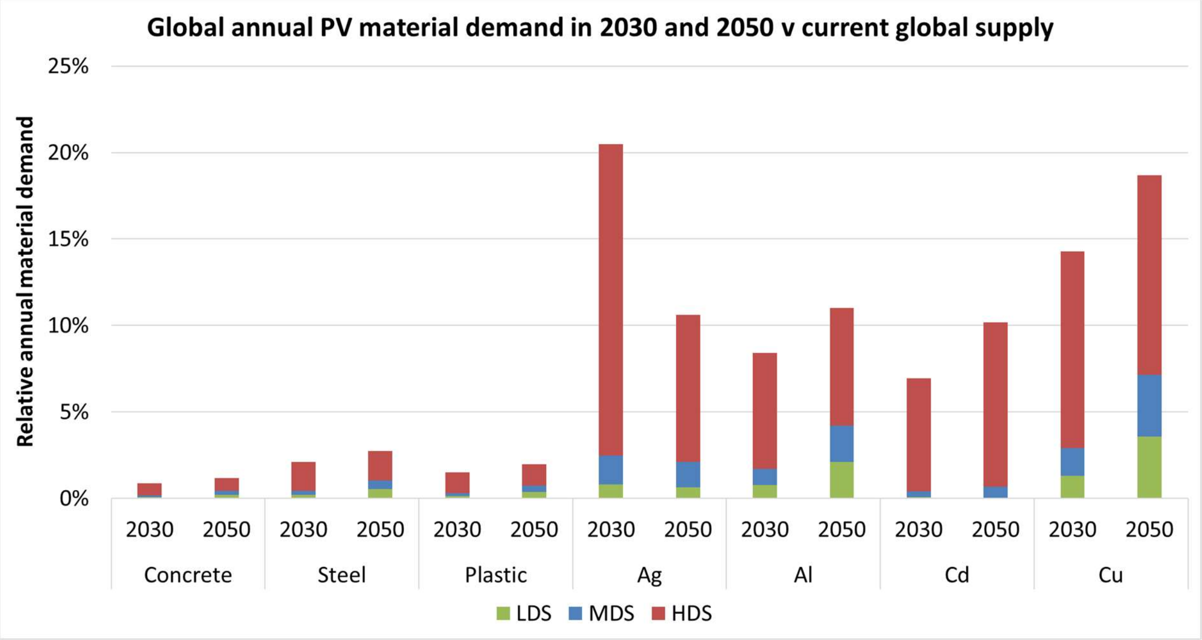
As in the EU case, the availability threshold is only exceeded by germanium and tellurium in the HDS. However, the same warning as before applies as we are comparing solar PV demands with the overall supply. Compared to the EU case, however, the overall risk is less severe, with only indium, selenium and silicon threatening the supply chain, together with the aforementioned germanium and tellurium.

Figure 34. Global PV demand-to-global supply ratio in 2030 and 2050 – levels of demand close to current availability



Source: JRC analysis.

Figure 35. Global PV demand-to-global supply ratio in 2030 and 2050 – levels of demand below current availability



Source: JRC analysis.

4. Conclusions

To meet the ambitious goals established for 2030 and 2050 both at EU and at global level, the power generation capacity of renewables, and specifically of wind and solar PV systems, will have to increase in all possible scenarios. This will require the deployment of new power plants, which will lead to an increased need for components and raw materials.

Compared to 2018 values, the EU demand for materials used in wind turbines will increase at different rates depending on the scenario analysed. By 2050, the demand is expected to vary as follows:

- **LDS.** Demand will double for structural materials and will decrease to one third for technology-specific materials, thanks to technological improvements and a more efficient use of materials.
- **MDS.** Demand will increase around 5 times for structural materials and around 3.5 times for technology-specific materials.
- **HDS.** Demand will increase between 11 and 12 times for structural materials and between 14 and 15 times for technology-specific materials.

At global level, a similar trend is expected for structural materials. For technology-specific materials, however, the demand increases are more severe: up to 15 times for boron and 16 times for neodymium in 2050 compared to 2018.

Looking at individual contributions for onshore and offshore wind, the EU demand for materials will increase more strongly for the onshore wind technologies. This is the opposite of the global trend, where a higher increase in material demands is expected for the offshore wind turbines. This is because globally, offshore wind is currently under-represented and will most likely experience a surge in the coming decades. At EU level offshore wind has already been characterised by some development and thus a lesser degree of future deployment is expected.

The deployment of wind turbines according to EU plans alone will require in 2050 most of the neodymium, praseodymium, dysprosium and terbium currently available. As a consequence, a strong pressure on supplies is expected for the rare earths, particularly for dysprosium and terbium, but also for neodymium and praseodymium.

In solar PV, by 2050, the various potential levels of EU need for materials are as follows.

- **LDS.** Demand will double for structural materials, but will decrease slightly for specific materials used in PV cells. This is due to the great improvements in material efficiency and because this scenario considers low market shares for sub-technologies relying on specific materials.
- **MDS.** Demand will increase 7.5 times for germanium, 6-7 times for indium, copper, plastics, aluminium, glass, concrete and steel, around 6 times for gallium and selenium and 3-4 times for tellurium, cadmium and silicon. A small decrease in demand is observed for silver.
- **HDS.** Demand will increase 86 times for germanium, 36-40 times for indium, gallium, tellurium, cadmium and selenium, around 21 times for copper, glass, steel, concrete, aluminium and plastic, 13 times for silicon and 4 times for silver.

Material demands for solar PV vary greatly between the scenarios, as they are largely dependent on the relative market share of each technology. Although no major supply issues are foreseen, the MDS and HDS still imply a significant additional pressure on several materials, in particular germanium, tellurium, indium, selenium and silicon. Similar trends are also expected at global level.

Meeting material demand will be key to achieving the low-carbon energy transition. As such it is important to keep monitoring the changes in the supply, consumption and criticality of the materials used in renewable wind and solar PV technologies. Efforts should be made to ensure stable and secure supplies of technology-specific materials, in order to prevent any possible future shortages.

To better assess EU resilience to such increasing demands for raw materials, additional studies are needed, looking at the evolution of future material supplies and comparing them with the material demand results presented in this report.

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List of abbreviations

a-Si	Amorphus silicon
c-Si	Crystalline silicon
CdTe	Cadmium telluride
CIGS	Copper indium gallium diselenide
DD	Direct drive
DFIG	Double-fed induction generator
EESG	Electrically excited synchronous generator
GB	Gearbox
GHG	Greenhouse gas
HDS	High demand scenario
HTS	High-temperature superconductors
LDS	Low demand scenario
MDS	Medium demand scenario
PMSG	Permanent magnet synchronous generator
PV	Photovoltaic(s)
SCIG	Squirrel cage induction generator
WRIG	Wound rotor induction generator

List of elements and their symbols

Ag	Silver
Al	Aluminium
B	Boron
Cd	Cadmium
Co	Cobalt
Cr	Chromium
Cu	Copper
Dy	Dysprosium
Fe	Iron
Ga	Gallium
Ge	Germanium
In	Indium
Mn	Manganese
Mo	Molybdenum
Nb	Niobium
Nd	Neodymium
Ni	Nickel
Pr	Praseodymium
Se	Selenium
Si	Silicon
Sm	Samarium
Sn	Tin
Sr	Strontium
Ta	Tantalum
Tb	Terbium
Te	Tellurium
Ti	Titanium
V	Vanadium
Y	Yttrium
Zn	Zinc

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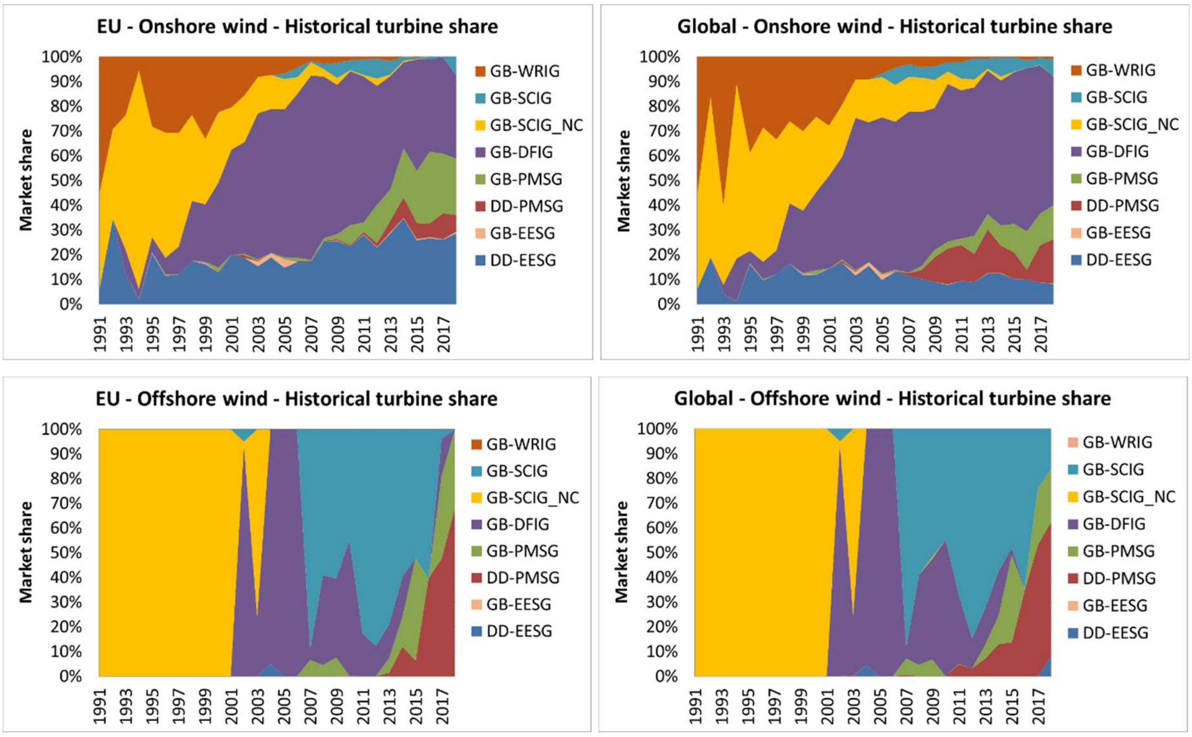
Annexes

Annex 1. Historical market shares for wind sub-technologies

Figure A.1 shows the market shares in terms of annual installation of wind turbines in the EU and at global level, for onshore wind and offshore wind from 1991 to 2018. For details on the different technologies and acronyms, please refer to Section 2.1.1 and Table 1.

Figure A.1. Share of onshore (top) and offshore (bottom) wind turbine sub-technologies in the EU (left) and global (right) markets



Source: JRC representation.

In 2018, permanent magnet turbines accounted for the totality of the European offshore market and 76% of the global market. The DD-PMSG configuration in particular was most widely adopted. In the onshore market, turbines were largely based on the traditional GB-DFIG technology, which accounted for 34% and 52% of the EU and global installed capacities, respectively. Permanent magnets have been gaining market shares, but they are still less widespread, accounting for 30% and 32% of the EU and global markets, respectively (JRC wind database).

The offshore market has been characterised by distinct phases, common to both the EU and global level. From the beginning of the 1990s to the beginning of the 21st century, the market was monopolised by GB-SCIG_NC turbines. These were abruptly replaced by GB-DFIG turbines, which were in turn displaced due to the widespread adoption of GB-SCIG turbines around 2007. These turbines are themselves now being replaced by permanent magnet turbines.

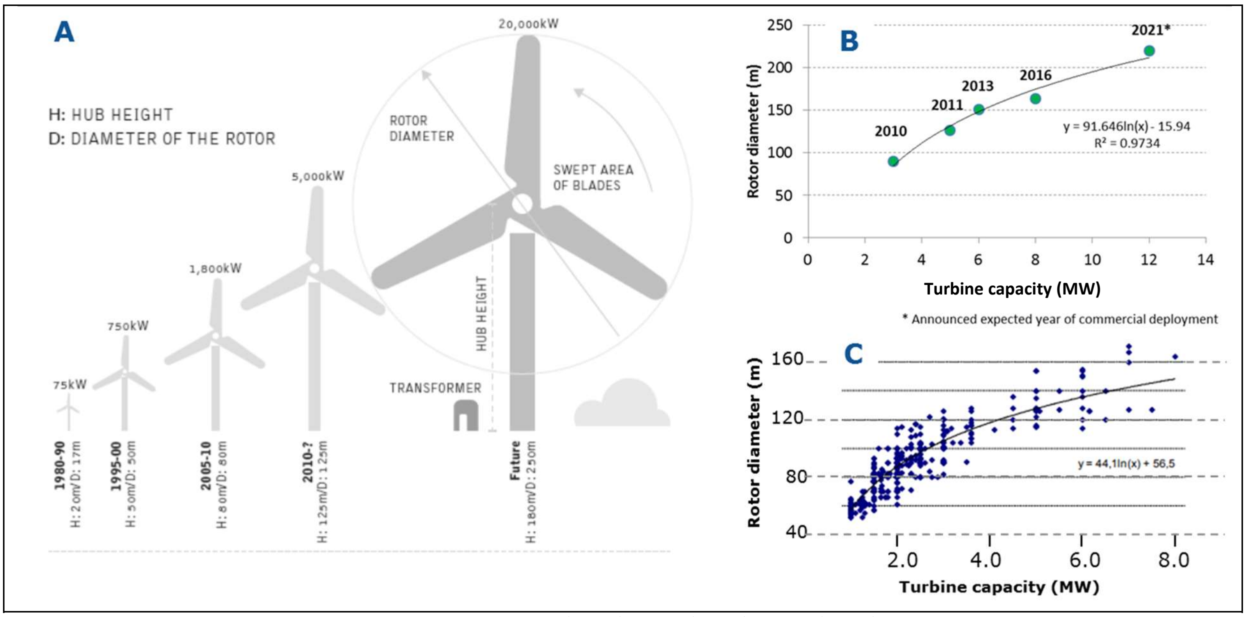
On the other hand, technology adoption developed gradually in the onshore sector leading to a better balanced mix of technologies. GB-SCIG_NC and GB-WRIG turbines were progressively phased out over the years, as GB-DFIG gradually gained market shares (51% on average since the beginning of the century at EU level, 57% at global level), and is now itself being challenged by the rise of permanent magnet turbines.

Annex 2. Technological evolution of wind turbines

The particular design requirements for turbines have changed over the last decade as wind turbines have grown larger and the penetration of wind into national power systems has increased (Centre for Sustainable Energy, 2017). The most obvious changes in design principles behind generator technology have been those that enable operation at variable speeds, driven by the need to better integrate with the grid, to reduce the generator weight and size and to minimise maintenance requirements (the rise of lighter designs with fewer moving parts has been driven by the greater stress placed on the gear mechanisms of large modern turbines).

From 1980 to 1990, a typical turbine had a rated capacity of 0.075 MW and a rotor diameter of 17 m (Greenpeace, 2015) (Figure A.2.A). In 2009, less than 10% of wind turbines had a capacity of over 2.5 MW, yet this had increased to more than 35% by 2012 (Centre for Sustainable Energy, 2017). In 2013 the average capacity of wind turbines installed at offshore locations was 6 MW, up from 3 MW in 2010 (IEA, 2018). In 2016 the largest commercially available turbines had a capacity of 8 MW (rotor diameter 164 m), and significantly larger turbines of 12 MW were projected to be commercially available in 2021 (IEA, 2018).

Figure A.2. A. Evolution of size of typical commercial wind turbines; B. Evolution of size of offshore wind turbines; C. Evolution of rotor diameter compared with turbine capacity



Source: A. Greenpeace (2015); B. IEA (2018); C. JRC (2012).

The move away from smaller turbines towards a standard commercial size of several megawatts, thanks to the rapidly expanding offshore sector, has brought about an increase in turbines that employ an NdFeB permanent magnet, which allows for a direct-drive system with no gearbox mechanism (Centre for Sustainable Energy, 2017).

The optimisation of design and the utilisation of lighter materials have historically offset the resulting increase in cost of towers and foundations related to the increase in size, and consequently in weight, of turbines and blades (IRENA, 2012). Accordingly, the relationship between the turbine capacity and the rotor diameter is logarithmic (Figure A.2.B and C).

To maximise return on investment and the general cost-effectiveness of larger turbines, the industry has relied on material efficiency optimisation, meaning that less material is required for each unit of generating capacity.

As a result, wind power system prices have declined significantly in most countries, driven by lower turbine costs. Wind turbine cost reductions in the last two decades, for both onshore and offshore wind turbines, have been achieved by economies of scale as the technology has improved and designs have become more standardised. According to IRENA (2012), this decline in cost also reflects increased competition between wind turbine manufacturers, along with lower commodity prices for steel, copper and cement. In the case of onshore systems, '*[t]he supply chain has progressively caught up with demand, aided by more stable (but still volatile) commodity prices*' (IRENA, 2012).

Turbine configuration

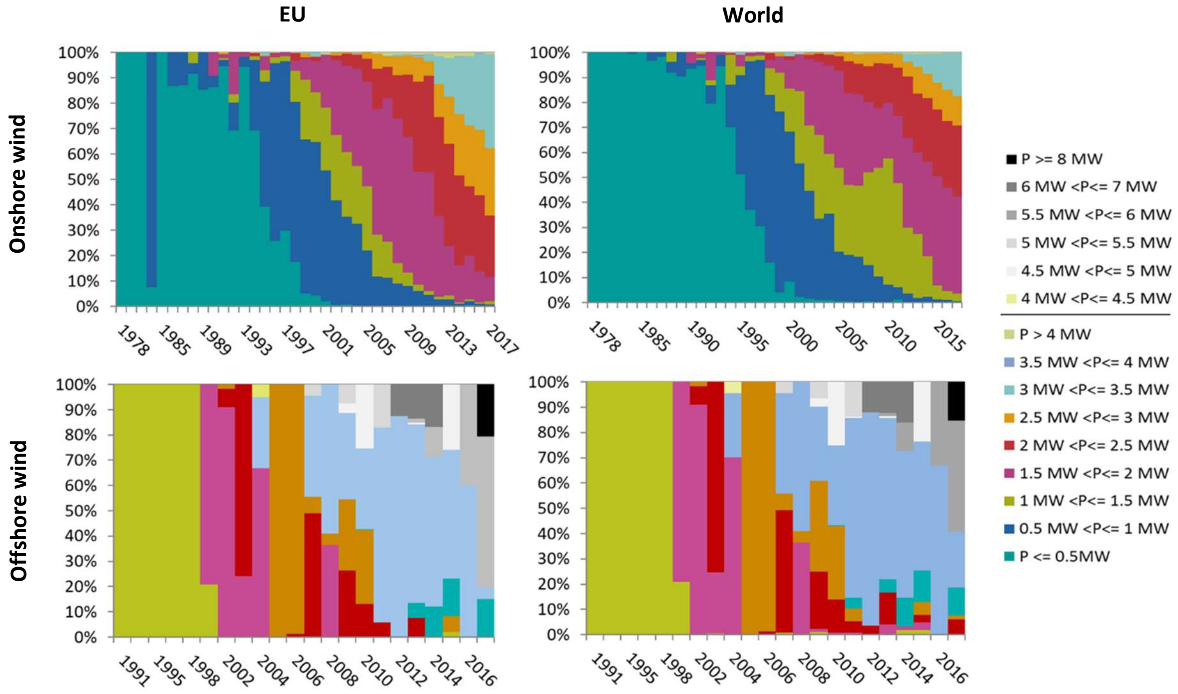
As anticipated in the previous section, the average wind turbine capacity has grown significantly over the past 30 years (Figure A.3). In 1985 typical turbines had a rated capacity of 50 kW (i.e. 0.05 MW) and a rotor diameter of 15 m; in 2016 commercially available wind turbines achieved 8 MW (IRENA, 'Wind Energy') and now a 12 MW turbine design is in development, to be marketed in 2021 (IEA, 2018).

In 2017, 39% of onshore wind turbines installed globally had a capacity of between 1.5 and 2 MW, and 44% of offshore equipment had a capacity nominally in the range of 5.5-6 MW. In the EU, 37% of wind turbines used on land were capable of producing 3-3.5 MW, and the average capacity of offshore systems was identical to the capacity at global level (JRC web-based work programme database). Figure A.3 describes the evolution of the nominal capacity of wind turbines deployed at onshore and offshore sites since 1978 and 1991, respectively, globally and in the EU (JRC web-based work programme database).

As the amount of energy that can be produced from wind depends to a large extent on the size of the turbine (IRENA, 'Wind Energy'; Willett, 2012), capacity growths over time, as described above, have essentially been achieved through the expense of larger rotors, higher towers and longer blades (7).

Towers are designed for different heights to suit different wind speeds and physical loading. Thus, there are different options for tower height when configuring a turbine model for a specific wind plant location. In general, tall wind turbines tend to have shorter towers, while short wind turbines tend to operate on taller towers (Vestas, 2015).

Figure A.3. Evolution of wind turbine size



Source: JRC wind database.

Abbreviation: P = Power.

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(7) NB: The energy output is proportional to the dimensions of the rotor and the cube of the wind speed (IRENA, 'Wind Energy').

While the choice of the appropriate height depends on local site conditions, there appears to be a general trend towards taller towers in the wind turbine market.

In 2014-2015, onshore wind turbines typically had towers 80-120 m tall, and in Germany, for example, they were on average 93 m tall (Greenpeace, 2015). In 2016, the height of commercially available models capable of producing 8 MW was over 200 m (IEA, 2018).

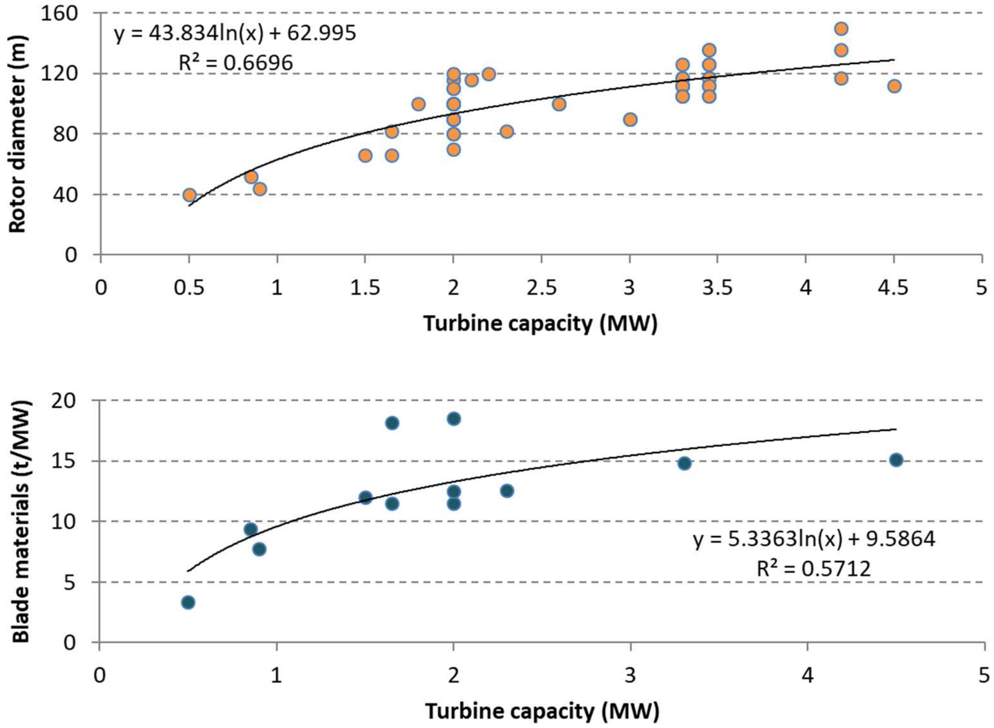
The rotor diameter of this equipment has also increased significantly. As of 2015, onshore wind turbines had rotors ranging from 80 to 125 m in diameter (Greenpeace, 2015) and in 2016 the largest turbines available to the offshore market were equipped with rotors of over 160 m in diameter (IEA, 2018).

The average blade size is also growing longer as this greater size '*effectively increases the tip-speed ratio of a turbine at a given wind speed, increasing the amount of energy that can be produced*' (Willett, 2012).

As the rotor increases in size on larger machines, so does the turbine mass and the amount of materials needed for manufacturing. As shown in Figure A.2, the relationship between turbine capacity and rotor diameter seems to be best described as logarithmic, which suggests that although material consumption will continue to grow, the rate of increase will likely decelerate. A comparable trend is to be found in Figure A.4 below, produced with data obtained from Andersen et al. (2016), Vestas (2014b, 2018b) and several Vestas LCA studies. Here, a positive logarithmic correlation is shown between the rotor diameter or the quantity of blade materials and the turbine's rated capacity.

Other studies found that linear or exponential progressions better represent the interdependence of blade mass and turbine capacity (8) and of rotor mass and rotor diameter, as shown in Figure A.5. It is concluded, based on the latter, that increasing the rotor diameter by 200% has the effect of increasing rotor mass by around 100%.

Figure A.4. Correlation between turbine capacity and rotor diameter



Source: Various, including Andersen et al. (2016), Vestas (2014b, 2018b) and several Vestas LCA studies.

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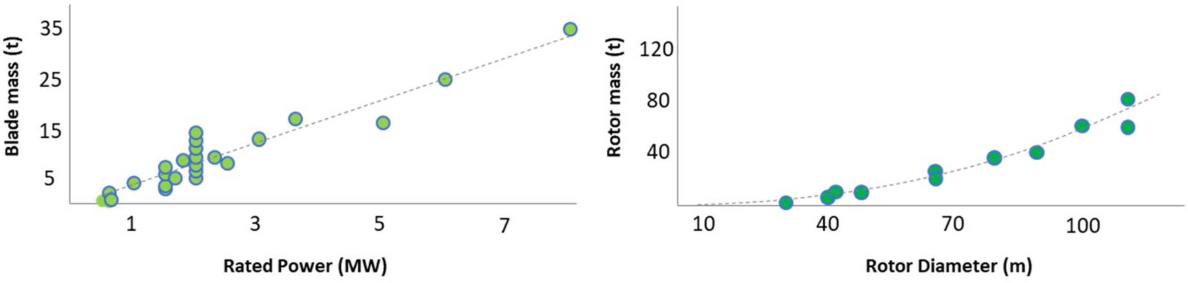
(8) NB: According to Willett (2012), blade mass scales as the cube of the turbine radius. Loading due to gravity constrains systems with larger blades.

Figure A.5. A. Documented examples of correlations between blade mass and turbine capacity; B. Documented examples of correlations between rotor mass and rotor diameter



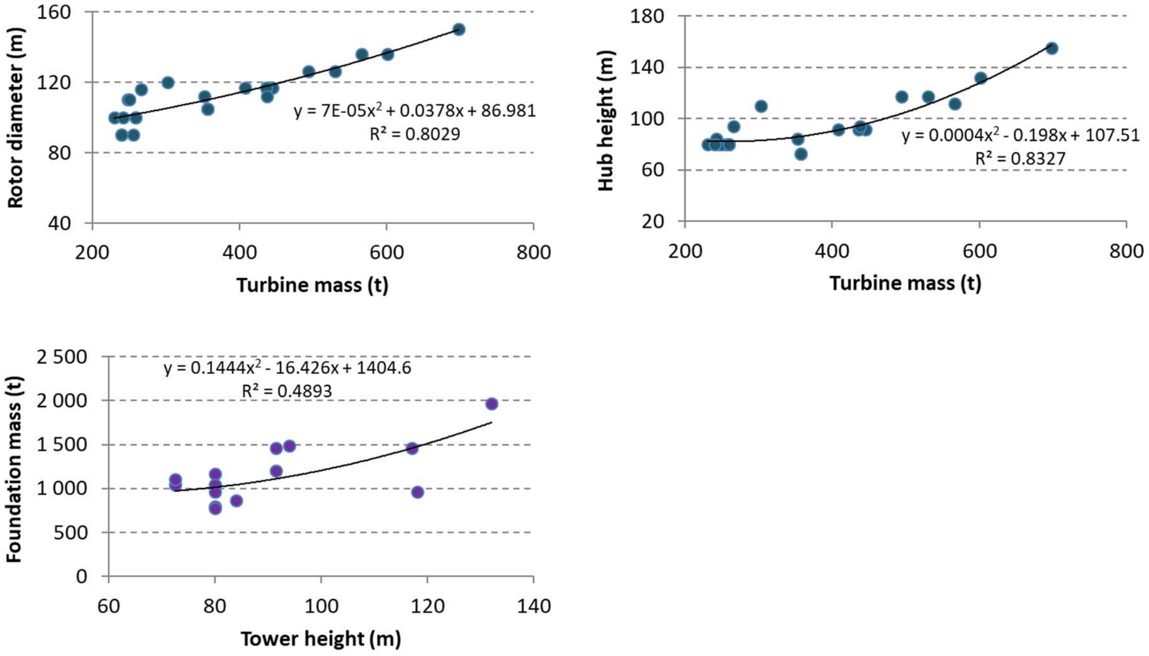
Source: A. Pu and Barlow (2017); B. Andersen et al. (2016).

Based on the considerations discussed, a key aspect enabling larger turbine systems to work is the limiting of the weight of components, by using lighter materials and increasing resource efficiency.

In the present study, an attempt was made to decode and understand these correlations. A dataset based on Vestas equipment data (Vestas, 2014b, 2018b) with the composition of 2-4 MW onshore wind turbines was used as reference. All turbines considered are of type GB-DFIG.

Figure A.6 shows that there are strong positive correlations between the rotor diameter or tower height and the turbine mass. For example, increasing the rotor diameter from 90 m to 150 m or the tower height from 80 m to 155 m has the potential to increase the turbine mass by 191%. Following an increase of 65% in the tower height, the foundation weight will also be increased about 75% on average.

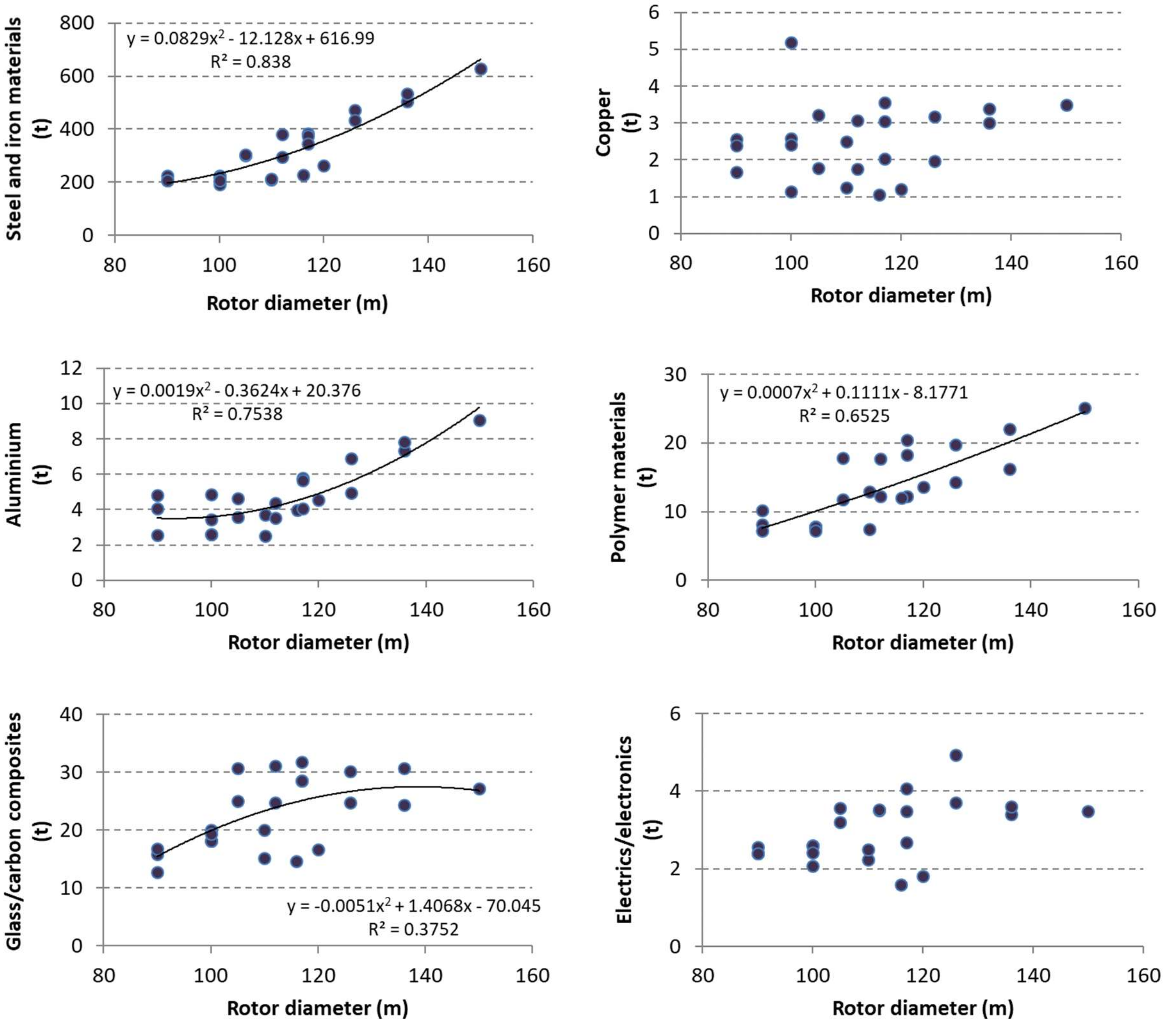
Figure A.6. Different masses of 2-4 MW onshore Vestas turbines and correlations with turbine size (rotor diameter, hub height and tower height)



Source: Vestas (2014b, 2018b) (rotor and hub height); various Vestas LCA studies (foundation).

In addition, Figure A.7 shows that increasing the size of the wind energy system has the effect of increasing the consumption of raw materials, a trend which is most visible for steel, aluminium and polymer materials. Total steel consumption, for example, is increased from 200 t to 620 t by increasing the rotor size from 90 m to 150 m, which corresponds to an increase of around 200%. Aluminium and polymer materials, on the other hand, are increased by around 150% and 250%, respectively.

Figure A.7. Correlations between rotor diameter and consumption of materials in 2-4 MW Vestas turbines



Source: Vestas (2014b, 2018b).

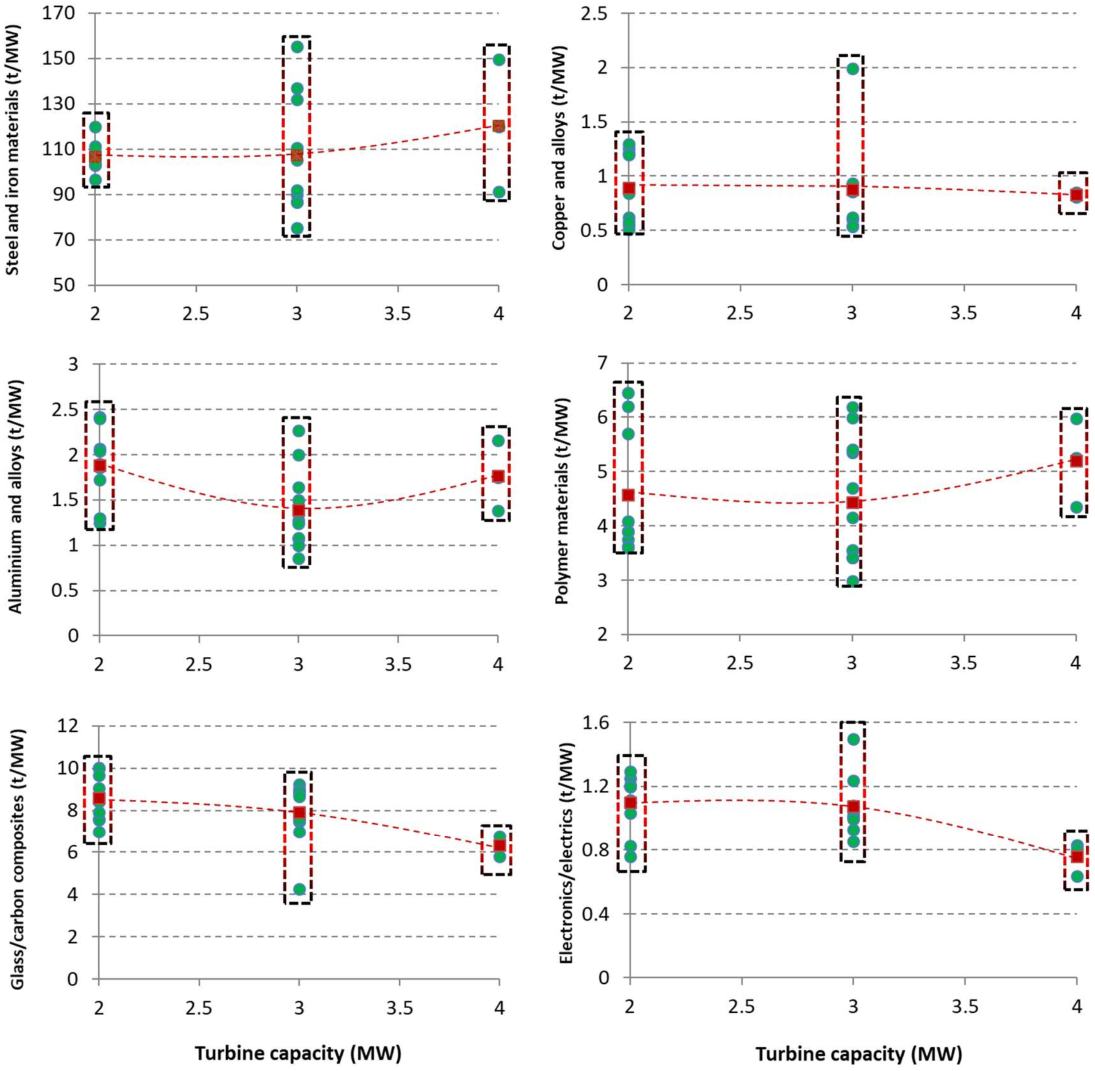
Although the absolute consumption of raw materials increases with the size of the turbine, the effect is offset by a higher energy production thanks to more resource-efficient turbine designs. Thus, the relative material input per MW generated has decreased in certain cases, while for other materials the average usage has remained constant or increased only slightly (Figure A.8).

For example, it is estimated that on average consumption of steel and polymers has increased by around 13% following turbine capacity increases from 2 MW to 4 MW. In the cases of glass/carbon composites and electronics, increasing the turbine's rated power has had the effect of diminishing consumption by around 30%. Small decreases of about 6% in average usages of aluminium and copper were also achieved by the same method (Figure A.8; Table A.1).

In the future, further efficiency improvements will likely take place, with a consequent reduction in material demand (Kim et al., 2015). On the other hand, a portion of the demand is likely to be redirected towards alternative and lighter materials in an effort to reduce costs while maintaining strength and satisfying structural fatigue requirements.

Assuming that the average offshore turbine capacity will increase from 5.5 MW (the capacity of 60% of turbines currently deployed in the EU) to 7 MW in 2030 and later to 8 MW (towards the upper limit of the range defined so far), the material usage patterns shown in Table A.1 are likely to emerge in the future.

Figure A.8. Trends in material usage compared with turbine capacity. Average figures and general trends given in red



Source: Vestas (2014b, 2018b); Vestas LCA reports.

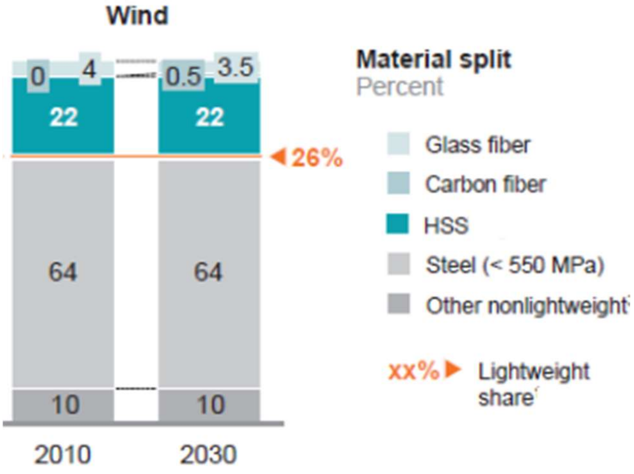
Table A.1. Percentage of increase or decrease in material usage based on the increase in turbine size, in two timeframes

		Increase in material usage				
	Turbine capacity increase (MW)	Steel	Aluminium	Copper	Polymers	Glass/carbon composites
	2	13%	– 6%	– 6%	13%	– 30%
2030	1.5	10%	– 5%	– 5%	10%	– 23%
2050	2.5	16%	– 8%	– 8%	16%	– 38%

Deployment of lightweight materials

Trends towards the use of more lightweight materials have already changed material usage patterns and will continue to do so in the future. Lightweight materials already play an important role in the wind energy sector and their use is expected to grow in the coming decades (Figure A.9). According to McKinsey (2012), in industries such as the wind energy, automotive and aviation, traditional steel will be substituted to a large extent by HSS; aluminium and carbon fibre will also be increasingly used.

Figure A.9. Trends towards the use of lightweight materials between 2010 and 2030



Source: Adapted from McKinsey (2012).

As discussed in Section 2.1.2, steel represents over 80% of the total turbine mass. Part of this amount (around 20%) was already made up of HSS (of above 550 MPa) in 2010 (McKinsey, 2012). The turbine tower is almost entirely made of steel (around 93%) and represents the largest portion of the turbine cost (around 26%).

Turbine towers are a relatively mature component and represent a large part of the turbine cost. Therefore, although further integration of lightweight materials is possible, such a trend is unlikely to materialise (IRENA, 2012). As HSS offers the potential for weight reduction but at a much higher cost (9), no major change from the current situation is expected until 2030 (Figure A.9).

Carbon fibre, on the other hand, will most likely be increasingly used. This is an extremely lightweight material already used in turbine blades, and which offers comparative advantages over glass fibre (the main structural material used today across turbine blades, regardless of manufacturer or model). Its use can reduce the high stress to which turbine blades are subjected due to their size (length and mass), at high wind speeds. Besides weight, carbon-fibre-reinforced laminates can also increase stiffness, resulting in improved stabilisation (Willett, 2012; McKinsey, 2012).

These benefits increase as blade size increases and thus might also '*allow for a further increase in blade length that cannot be achieved with glass fiber, resulting in greater output per wind turbine*' (McKinsey, 2012). Such developments would be especially relevant in offshore applications.

'*The use of carbon fibres in 60 m turbine blades is estimated to reduce total blade mass by 38% and decrease cost by 14%*' in comparison with a situation where blades are composed entirely of fibreglass (Willett, 2012).

McKinsey (2012) forecast that carbon fibre usage would increase from 0% in 2010 to 0.5% in 2030, which will result in a proportional reduction in the use of glass fibre from 4% in 2010 to 3.5% in 2030 (Figure A.9).

Although carbon fibre costs have prohibited high penetration so far (the cost of carbon fibre is 57 times the cost of steel), a significant cost decline of up to 70% is expected over the next two decades (McKinsey, 2012). Based on market expansion and improvements in production and the aerodynamic efficiency of turbine blades, a significant cost decline has also been predicted by IRENA (2012).

A trend towards more lightweight blades is indeed starting to emerge. Figure A.10 shows a reduction in the amount of glass/carbon composites as turbine mass and capacity increase, which was possible by replacing glass with more lightweight carbon fibre. A decrease of 15% on average in the amount of glass/carbon composites per MW of installed capacity was discussed above.

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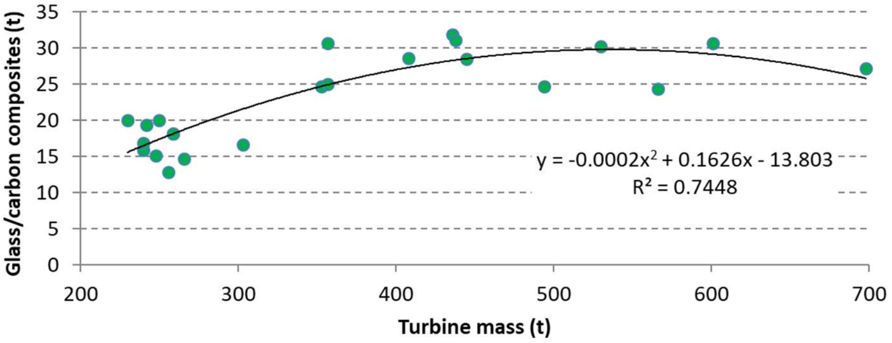
(9) HSS offers a weight advantage of 20% over steel at an additional cost of 15% per part. Aluminium is 40% lighter but 30% more expensive (McKinsey, 2012).

Figure A.10. Different masses of 2-4 MW onshore Vestas turbines and correlation with the weight of glass/carbon composites



Source: Vestas (2018b, 2014b); Vestas LCA reports.

Type of foundation – implications for material consumption patterns

The foundations for onshore and offshore wind power plants differ considerably.

Onshore foundations are of two types: gravity base foundations (the most commonly used) and rock-anchored foundations, consisting of large platforms made of reinforced concrete and steel (steel-reinforced concrete slabs). Their size varies depending on the turbine tower height and the wind class, which affects the mechanical loads on the foundation (Vestas, 2011). The typical foundation for the V90-3.9 MW equipment for example is 15 × 15 m and 2 m deep (Vestas, 2006).

Onshore foundations weigh between 800 and 2 000 t, 95% of which is made of concrete. On average, around 120 t of steel and 392 t of concrete are used per MW (Vestas LCA reports).

The size of onshore foundations will additionally depend on the groundwater level. In terrains with a high groundwater level, more concrete and steel reinforcement is required. It is estimated that the usage of steel and concrete is increased by around 2-5% in comparison with a low groundwater scenario, which is however more representative of the majority of wind power plant sites (Vestas, 2011).

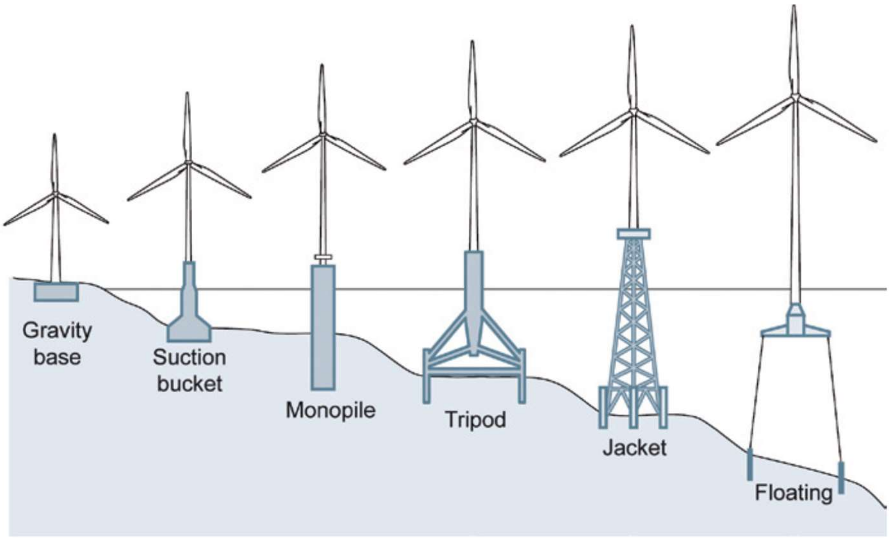
Offshore foundations, on the other hand, differ in terms of the depth at which the wind turbine will be installed (Figure A.11). Offshore wind farms placed in maximum water depths of 30 m can use a gravity base foundation, which involves a large concrete or steel platform or monopile foundations made up of a thick steel pipe cylinder of up to 6 m in diameter with a wall thickness of 150 mm, anchored directly to the seabed.

In 2012 most of the offshore wind turbines installed around the world used a monopile structure (IRENA, 2012).

Tripod and jacket foundations are used at greater depths. A jacket foundation has a lattice framework that features three or four seabed anchoring points. Although it is more expensive than a monopile or gravity base foundation, it is cost-efficient at greater depths (World Steel Association, 2012; Iberdrola).

Additional types of foundation consist of floating designs, employed at higher depths. However, of more than 4 400 existing offshore turbines, so far only 10 units are based on floating structures (Hexicon AB, 2018). The first floating design (the HyWind installed in 2009 by Siemens and StatoilHydro) consisted of a steel floating structure filled with ballast of water and rocks and anchored to the seabed by steel wires (World Steel Association, 2012). Other designs such as the Hexicon (currently being evaluated) consist of a large platform supporting multiple turbines. The Hexicon's platform is 480 m in diameter, supporting 54 MW of turbine capacity (World Steel Association, 2012).

Figure A.11. Types of offshore foundations

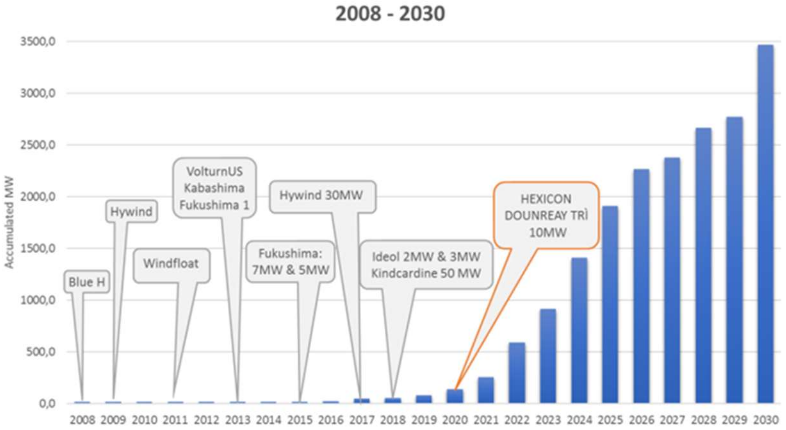


Source: World Steel Association (2012).

The large-scale introduction of offshore wind would be greatly facilitated by floating technologies enabling deployment in deep waters (European Commission, 2008). Potential developments based on floating foundations are being explored and the first projects using floating turbines are now entering into operation (IRENA, 2012; IEA, 2018). '*At present, there are over 20 different concepts for offshore floating wind power. Most of these are so far only in a conceptual stage'* (Hexicon AB, 2018). A significant research and investment push is still needed to integrate or mainstream such technologies (IEA, 2018).

Potentially, floating offshore systems could make up around 3% of the wind power market in 2030, assuming that by then global offshore installed capacity has reached 122 GW (IEA ETP Beyond 2 Degrees Scenario) (Figure A.12). Such forecasts additionally assume that by 2030, floating offshore wind power's levelised cost of energy would be comparable to or below that of conventional offshore systems (Hexicon AB, 2018). Significant opportunities to reduce costs could be realised by reducing the concentration of steel in the platform (Hexicon AB, 2018).

Figure A.12. Market growth projections of floating offshore wind power up to 2030

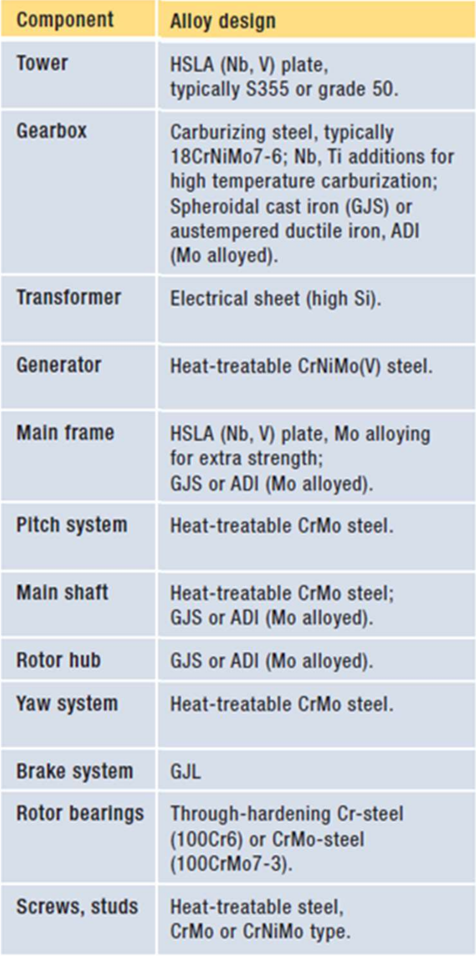


Source: Hexicon AB (2018).

Annex 3. Potential for steel optimisation and material substitution

Potential for steel optimisation

Table A.2. Types of steel used in the various components of a 2 MW onshore wind turbine with hub height of 100 m



Component	Alloy design
Tower	HSLA (Nb, V) plate, typically S355 or grade 50.
Gearbox	Carburizing steel, typically 18CrNiMo7-6; Nb, Ti additions for high temperature carburization; Spheroidal cast iron (GJS) or austempered ductile iron, ADI (Mo alloyed).
Transformer	Electrical sheet (high Si).
Generator	Heat-treatable CrNiMo(V) steel.
Main frame	HSLA (Nb, V) plate, Mo alloying for extra strength; GJS or ADI (Mo alloyed).
Pitch system	Heat-treatable CrMo steel.
Main shaft	Heat-treatable CrMo steel; GJS or ADI (Mo alloyed).
Rotor hub	GJS or ADI (Mo alloyed).
Yaw system	Heat-treatable CrMo steel.
Brake system	GJL
Rotor bearings	Through-hardening Cr-steel (100Cr6) or CrMo-steel (100CrMo7-3).
Screws, studs	Heat-treatable steel, CrMo or CrNiMo type.

Source: IMOA (2011).

Steel is used in the manufacture of multiple wind power components.

Table A.2 presents a summary of the typical steels used in a 2 MW onshore turbine design, based on International Molybdenum Association (IMOA) (2011). These materials can be additionally divided into two categories: high-alloy and unalloyed or low-alloy steels.

The main difference between the two types lies in the carbon content and the quantities of alloying elements. Unalloyed steels have an average carbon content of 0.22 to 0.60%, and besides iron they contain only minor amounts of alloying elements. Alloy steels on the other hand contain additive amounts of manganese (the most common alloying material), nickel, chromium and molybdenum, in quantities above 1% by weight. HSLA steel, a type of low-alloy steel, has enhanced mechanical properties obtained by the addition of small amounts of alloying elements and special processing techniques (ASM International, 2001). These microalloyed steels usually also contain niobium and vanadium to increase yield strength.

Unalloyed or low-alloy steels represent the largest portion of steel consumption, i.e. 86% (Vestas LCA reports). The turbine tower is the main place where these types of steel, an example of which is the S355, are used.

High-alloy steels represent 14% of the steels used. Examples of such steels include the grade 18CrNiMo7-6, which in 2011 was the standard steel for windmill gearboxes (IMOA, 2011).

Besides the turbine structure, steel is also used in the turbine foundation. A standard onshore foundation uses on average about 20% of steel compared with the turbine. Steel used in foundations is mainly unalloyed steel (94%) and the remaining 6% is high-alloy steel.

The range of main alloying elements for high-performance steels used in wind turbines is provided in Table A.3. The average value of the range was used to calculate the demand for materials involved in making steels used in wind power systems.

Optimisation of steel is an important aspect as the weight reduction of wind turbines is essential to allow for an increase in the size of components, and thus in the power performance, especially for offshore turbines. According to IMOA (2011), several weight-saving opportunities exist, notably through steel upgrading (for example steel grades used in support frames can be upgraded to grade 80 or 100 ksi) or by switching to stronger materials such as austempered ductile iron (ADI) in larger castings such as the hub, hollow shaft and gearbox.

Upgrading the steel of a wind tower structure from grade S355 to S500 is also feasible, and would result in a weight saving of 30% (IMOA, 2011). A cost increase of 20-25% per t for the higher-strength steel would be offset by a reduction in material consumption (World Steel Association, 2012).

Table A.3. Range of main alloying elements for high-performance steels used in wind turbines. Chemical composition (mass fraction) (wt%)

Type of steel	Functional unit	Si (%)	Mn (%)	Cr (%)	Mo (%)	Ni (%)	Reference
High-alloy steel	18CrNiMo7-6	< 0.4	0.5-0.9	1.5-1.8	0.25-0.35	1.4-1.7	IMOA (2011)
HSLA steel, structural quality	Type S355	0.55	< 1.60	0.30	0.08	0.30	Steel Grades, 'EN S355J2CJ3'
Unalloyed steel	n/a	< 0.4	0.4-0.9	< 0.4	< 0.1	< 0.4	Dillinger Hütte GTS (2010)

NB: For calculations of material usage developed in this study the following values were used. Unalloyed/low-alloy steels: Cr = 0.4%, Mo = 0.1%, Ni = 0.4% and Mn = 0.7%; high-alloy steels: Cr = 1.65%, Mo = 0.3%, Ni = 1.55% and Mn = 0.7%.

In addition, the chemical composition of carburising steels can also be improved for large and heavily loaded gears, improving the reliability of key components. According to IMOA (2011), optimisation of the alloy 18NiCrMo6-7 used in the turbine gearbox can be achieved by increasing the Mo content from around 0.3% in the standard alloy to 0.5%. In addition, '*microalloying this steel grade with Nb [niobium] and Ti [titanium] reduces the carburizing time by up to 60%, leading to major processing cost savings and to significant reduction of the component's CO_2 footprint*' (IMOA, 2011).

Material-for-material substitution

Most of the attention to substitution is on permanent magnets, and specifically on the relevant rare-earth elements.

Substitution options are available for NdFeB permanent magnets in wind turbines both at component and at material level, but with some limitations. Price spikes and concerns over supply risks have, for example, caused manufacturers to substitute certain rare earths for others; however, this has not changed the overall quantity of rare-earth elements in the permanent magnet. For example, praseodymium can be used in place of neodymium without impairing the magnet performance. Praseodymium can therefore account for up to approximately 7.5% of the magnet's mass, although currently it is around 3-4% or as low as 1% (Nassar, Wilburn and Goonan, 2016). Dysprosium can be reduced or eliminated with a proportionate increase of neodymium, which is significantly less costly.

Departing from the average amount of 3-6% dysprosium embedded in permanent magnets, certain manufacturers have redesigned their direct-drive generators to use less dysprosium. For instance, Siemens Gamesa Renewable Energy has reduced the amount of dysprosium to significantly below 1% in their wind turbines. Goldwind eliminated the use of dysprosium entirely in some generators and reduced its use in other models to less than 1% (Wind Power Monthly, 2018).

Additionally, dysprosium can be replaced with terbium, which is noted to be more effective at improving a magnet's coercivity than dysprosium, such that a magnet requiring 4% dysprosium is replaced with only 3% terbium (Pavel et al. (2017) and Nassar, Wilburn and Goonan (2016) and references therein). However, '*because Tb has historically been more expensive than Dy, its use in permanent magnets has, however, typically been limited*' (Nassar, Wilburn and Goonan, 2016).

In Vestas turbines, rare-earth elements are used in the permanent magnet generators of the older GridStreamer models and in the EnVentus platform. In comparison to '*older permanent-magnet generators, the EnVentus uses less light rare-earth material per MW and has eliminated the use of heavy rare earth materials altogether*' (Vestas, 2019).

According to Rabe, Kostka and Smith Stegen (2017) '*[t]here is further potential to reduce the use of dysprosium in permanent magnets, and experts anticipate that, within a few years, permanent magnets for wind turbines may no longer contain any significant amounts of the element*'.

From a component substitution perspective, ferrite magnets containing iron and strontium can be used instead of permanent magnets – however, in comparison, this reduces the efficiency by 3% (Månberger and Stenqvist (2018) and references therein).

In addition, wind turbines could theoretically be engineered with permanent magnets based on samarium and cobalt ($SmCo_5$). However, the lower energy density of $SmCo_5$ magnets and concerns regarding the price and the availability of both samarium and cobalt would render such an option unrealistic.

Finally, the substitution of copper with aluminium is also a possibility. In particular, the selective incorporation of aluminium into certain turbine components (for example in the cast-coil transformer in the nacelle or in the tower design) can reduce copper usage significantly (BBF Associates and Kundig, 2011).

Some leading European manufacturers have already adopted aluminium cast-coil transformers, reducing overall copper intensity by 27% (from 3 500 t/GW in Gamesa turbines with a copper cast coil to 2 500-3 000 t/GW in Vestas turbines with an aluminium cast coil). However, the replacement of copper with aluminium to lower the turbine cost presents some challenges due to lower strength, relaxation behaviour and corrosion resistance (BBF Associates and Kundig, 2011).

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