centre for sustainable energy

Common concerns about wind power (2nd edn)

Chapter 2
Materials consumption and life cycle impacts of wind turbines

This is one of a series of chapters of evidence-based analysis drawing on peer-reviewed academic research and publicly funded studies.

For other chapters, see
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Centre for Sustainable Energy, June 2017

centre for sustainable energy

OFFICE 3 St Peter's Court
Bedminster Parade
Bristol BS3 4AQ

PHONE 0117 934 1400

EMAIL info@cse.org.uk
WEB cse.org.uk
TWITTER cse_bristol

CHARITY 298740
COMPANY 2219673
FOUNDED 1979

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The first edition of Common Concerns about Wind Power was published in 2011 to provide factual information about wind energy, in part to counter the many myths and misconceptions surrounding this technology.

Since 2011, much has changed in the legal and economic sphere, and a second edition became necessary. Research has been carried out for this edition since 2014. Therefore, this edition is formatted as a series of individual chapters available for download at www.cse.org.uk/concerns-wind-power-2017

All chapters written and researched by Iain Cox.

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Chapter 2

Materials consumption and life cycle impacts of wind power

Summary

In addition to the concept of energy investment and energy return on that investment (see chapter 1), one other property of wind power that is fundamental to its role in providing sustainable energy is the material flow involved in their manufacture and operation. From an environmental perspective, all energy infrastructure comes at a cost. Although electricity generated from wind does not require fossil fuel combustion, wind turbines and their associated connections still require significant quantities of steel, copper, aluminium, and other more rare metals, in addition to concrete for wind turbine foundations and fibreglass and resins for the blades. Processing and manufacturing these materials requires energy, which contributes to greenhouse gas emissions, not to mention the requirement to physically extract the necessary mineral resources used in the manufacture of these component materials. Finally, although it is possible to recycle many of the materials used to construct turbines, this does not occur to the extent estimated in many life cycle impact assessments, and some materials (notably concrete and specialised plastics) cannot be effectively recycled at all with present technology. These are challenges that will become increasing pressing for the wind industry due to the rapid expansion of built infrastructure in recent years and projected future growth, which will result in very large numbers of turbines nearing the end of their useful life in the next few decades.

Wind turbines are a good example of modern society's sophisticated material requirements in the context of sustainable development, since they are integral to the provision of low-carbon electricity, but must operate under increasingly stringent resource availability so that broader environmental goals can be realised. Although its material requirements are significant, wind power is still one of best-performing energy technologies from an environmental perspective, with lifetime greenhouse gas emissions just 5–10% of those from fossil fuels.

What is this based on?

The continuing global expansion of wind as a source of electricity reflects its increasing competitiveness in terms of cost and the maturation of the onshore wind industry in particular. In 2012, the level of newly installed wind power capacity surpassed that of any other renewable energy technology, and some countries like Denmark generated 30% of their annual electricity needs from wind alone, with other regions seeing record generation peaks.[1] In the UK, along with a steady year-on-year increase of onshore wind installations, the growth in offshore wind has resulted in half of all renewable electricity generated across the country in 2013 being from wind power, which is 8% of the UK's total electricity supply.[2,3] This strong growth and the vast potential of offshore wind resources means that wind power is likely to form the cornerstone of society's transition away from predominantly fossil fuel-fired electricity generation.[4]

Although the advantage of wind power is that it relies on a renewable source of energy (the kinetic energy in wind flows), this does not mean that a wind turbine is free from non-renewable resource demands and the emissions related to the production and consumption of those resources.[5] Since mitigating rising atmospheric greenhouse concentrations is one of the key aims of moving to renewable energy sources, most studies on the costs associated with wind turbines are focused on the energy consumed and resulting carbon dioxide (CO_2) emissions.[6,7] However, the material resources themselves, which for wind turbines includes cast iron, steel, copper, aluminium, concrete, fibreglass-reinforced plastic and epoxy resin, are subject to supply chain constraints, and one must not forget that these resources are locked up in the wind turbine structure for the duration of its operational lifetime, which will place constraints on material flows to other sectors.[8]

Although these bulk materials are unlikely to run out in the near future, the rapid growth of the wind industry (and renewable energy in general) will place selective pressure on national and global manufacturing supply chains. More broadly, continued global economic growth and development across all industries will mean that the eventual strain on these finite resources may well present a severe impediment to a sustainable and secure future.[9,10] Even if the materials do not physically run out, increased energy expenditure to extract lower-quality mineral ores and the necessity of opening up new deposits will entail greater environmental impacts due to resulting emissions and habitat degradation. It is important to remember that the curtailment of these resources will affect every endeavor of modern society, so this is a constraint within which the wind industry must operate rather than an issue precipitated by the expansion of wind power per se.[11] Nevertheless, there are certain materials for which future wind turbine construction specifically will place greater demands: these are metals known as *rare earth elements,* which are essential for many large, modern turbine designs that employ permanent magnets.[8,12]

What the preceding discussion illustrates is that the need to recycle and reuse raw material stocks will become ever more pressing, but the present situation is that many metals are not recycled on global markets at a sufficient rate to be considered sustainable.[13] This largely reflects modern society's lack of incentive to sacrifice short-term economic gains for material efficiency, even though there are several long-term benefits in terms of increased resource security for nations, lower emissions of pollutants and greenhouse gases, less environmental degradation, and lower levels of finite resource depletion.[9] As far as wind power is concerned, establishing industry standards for recycling materials from turbines upon decommissioning is sorely needed.[14] Although the superior perfomance of wind turbines in comparison to fossil fuels with regards to greenhouse gas emissions and overall energy use is not in serious dispute,[5–7] the exploitation of finite mineral resources and use of non-recyclable materials needs to be properly assessed to ensure a true picture of wind power's sustainability is drawn.[15] This will be critical in optimising wind energy's contribution to climate change mitigation over the next century.[16]

What is the evidence?

Wind turbine structure and material needs

The turbine and substructure is the predominant source of material and energy consumption when considering wind power.* The energy expenditure and overall emissions that result from building a wind turbine and its foundation typically make up at least three-quarters of its lifetime environmental impact, with resources for the turbine itself dominating for onshore wind, whereas the resource burden is shared more equally between turbine and foundation for offshore installations.[5,7,16] The particular design requirements for turbines have changed over the last decade as larger turbines become the norm. Even in 2009, less than 10% of wind turbines were over 2.5 megawatts (MW) in size, yet this had increased to more than 35% by 2012, with many projections for an even greater proportion of significantly larger turbines (around 5 MW) thanks to the rapidly expanding offshore sector.[1,17] Increasing size leads to greater stress on gear mechanisms and increased maintenance requirements,[18] and this has pressured the industry to invest in designs of lower weight and with fewer moving parts.[4,8] One important outcome of this is an increase in turbines that employ a permanent magnet, which allows for a direct-drive system with no gearbox mechanism.[19] There are many types of permanent magnet available, but one in particular offers a superior combination of magnetic field strength combined with lower weight and size – it is a neodymium-iron-boron alloy (often called NdFeB or NIB), and it is central to much of the discussion surrounding potential shortages of rare earth elements and the expansion of wind power (discussed under Critical Raw Materials below).[17]

* The concept of energy expenditure and energy flow over the lifetime of a wind turbine is discussed in Chapter 1. This chapter deals with material flows and thus the material 'by-products' from wind energy are included here, namely greenhouse gas emissions. The reader should keep in mind that energy and material flows, and the overall emissions that result, are intertwined, but they have been separated for the sake of this discussion.

Both Table 2.1 and 2.2 outline the major material requirements for typical modern wind turbines. Note the way in which the data are presented between the two tables, with lifetime resource consumption of raw materials per unit of electricity generated over the turbine's lifetime (Table 2.1), and the construction materials required to build a new turbine per MW of capacity (Table 2.2). This highlights two important features of any life cycle assessment for energy technologies. First, similar to the principle of energy returned compared with energy invested (see chapter 1, 'Wind turbines and energy payback times'), the operating lifetime of a wind turbine will determine how much electricity it produced in total before it is decommissioned, but the material needed to build the turbine in the first place will be the same regardless of how long it operates for. Second, the increasing size of modern turbines means that less material is required for each unit of generating capacity, not only because improvements in materials technology and design can optimise materials efficiency as the industry evolves, but also because larger turbines can extract more energy from the wind (this is discussed in chapter 4). Indeed, the move away from smaller turbines by the industry to a standard commercial size of several megawatts (at least) has seen the environmental profile of wind turbines markedly improve when measured per kilowatt-hour of electricity produced.[6,7,16] There is some evidence, however, that the rate of improvement slows significantly once the megawatt 'threshold' has been passed, although the general positive trend continues.[5]

Critical raw materials

Since the 1990s, wind turbines have become larger and the penetration of wind into national power systems has grown, which has necessitated several changes in the design principles behind generator technology. This has been largely driven by the need to better integrate with

Table 2.1 Estimated consumption of raw materials used in wind farms as a function of lifetime supply of electricity (values taken from refs. 20–22)

Turbine size used (type)	1.65 MW	3MW	3 MW (offshore)	3 MW (PM)
Resource	Estimated lifetime consumption (g/kWh)			
Water	38	51	49	27
Stone	3.6	3.5	<0.1	nd.
Quartz sand	0.12	0.59	0.34	0.24
Limestone	0.33	0.1	0.13	0.13
Clay	0.02	0.05	0.03	0.18
Rock salt (NaCl)	0.14	0.08	0.05	0.14
Iron	0.99	0.04	0.42	nd.[a]
Zinc	nd.	0.01	0.04	nd.[a]
Aluminium	0.01	<0.01	0.01	nd.[a]
Manganese	nd.	0.01	0.01	nd.[a]
Copper	nd.	<0.01	0.01	<0.01
Lead	nd.	nd.	<0.01	nd.[a]
Chromium	nd.	<0.01	nd.	<0.01
Rare-earth ore	n/a	n/a	n/a	0.1
Hard coal	1.11	0.64	0.74	0.52
Lignite	0.23	0.34	0.32	0.69
Crude oil	0.71	0.54	0.63	0.64
Natural gas	0.53	0.42	0.38	0.73

g/kWh, grammes per kilowatt-hour; MW, megawatt; nd., no data; PM, permanent magnet

All values based on turbine lifetime of 20 years, although it is feasible larger wind turbines will have longer operational lifespans than this.[21,22] Turbines onshore unless otherwise stated. Note fossil fuel consumption is based on energy resources used to extract and process metals and other mineral resources before they can be used in construction.

[a] Data given as unprocessed ore rather than elemental metal so direct comparison not possible.

Table 2.2 Summary of major materials required for construction of wind turbines based on installed capacity in megawatts (MW)

	Materials required per MW installed capacity (tonnes/MW)						
Turbine	Stainless steel	Cast iron	Copper	Concrete	Fibreglass	Nd in magnet	Misc.[a]
1.5 MW onshore, gearbox, wound rotor[b]	115	23.9	2.5	590	9.8	0	8.1
3.0 MW 'next-gen.' turbine on- and offshore, mixed generator technology[b]	103	20	3	402	6.8	0.04	9.3
3.0 MW onshore, PM generator[c]	96	21.7	1.8	298	~7-8	0.04	~10

DFIG, double fed induction generator; Nd, neodymium (27% by weight of NdFeB permanent magnet; Nd is a rare earth element); PM, permanent magnet

[a] Includes aluminium, thermoplastics and other polymers, epoxy resins, lubricants and other materials.

[b] Estimates from ref.8 based on generic 'current generation' (1.5 MW) and 'next generation' (3 MW) turbines rather than a specific turbine model. Note the next-gen. turbines are assumed to make more use of composite materials and approximately 20% of installed turbines will contain a PM generator, with the remainder being DFIG (a type of wound rotor generator).

[c] This is based on life cycle impact assessment for a specific model (see ref. 22). Note estimates for fibreglass and miscellaneous categories are approximations made to fit with categories from ref.8 (see rows above). It is estimated that using a neodymium magnet in this model can save around 10 tonnes of steel per turbine (see ref.15).

the grid, so that wind turbines can operate at variable speeds and cope with dips in grid voltage, and also to improve the cost-effectiveness of larger turbines through lowering the weight and size of the generator, power converter and gearbox mechanisms, and minimising the level of maintenance required.† [4,19] There are several different ways in which these aims can be realised, but one of the most effective devices that assists with this overall goal is the use of a permanent magnet.‡ Neodymium-iron-boron (NIB) permanent magnets combine higher magnetic field strength with low weight, thus making them ideal for high-torque applications where space and weight must be minimised. This means NIB magnets are of especial importance to renewable technologies, such as electric motor vehicles and wind turbines.[17]

On the periodic table, neodymium is grouped as a lanthanide; along with scandium and yttrium, the lanthanides are classed as rare earth elements. Of a total of 17 rare earth elements, 10 of these are of ongoing commercial interest, although it is conceivable that more will find uses given the increasingly specific and exacting demands of modern materials technology.[11,12] Rare earth elements are so-called because of their geological dispersal rather than their lack of abundance – this simply means concentrated ore deposits do not exist and therefore these elements have been mined as a by-product of larger deposits of useful commodities, typically iron ore.[23] Indeed, until commercial uses were found for these elements they were typically treated as contaminants or waste products.[24]

Permanent magnets used in wind turbines typically contain neodymium and smaller quantities of another rare earth element, dysprosium (this latter element is added to NIB magnets to improve their performance at higher temperatures). The supply of both of these materials is considered critical over the next decade, due to the concentration of viable deposits in one region (China mines 95% of the world's supply) at a time when demand for clean energy technologies is growing rapidly.[12,17] In fact, wind turbines are a relatively small contributor to this supply bottleneck. For instance, the demand for neodymium and dysprosium consumption due to electric vehicle manufacture is higher than for wind turbines.[12] By far the biggest driver of consumption, however, is the extraordinary volume of rare-earth magnets used in the electronics sector: around 75% of global stocks of neodymium used today are in personal computers and audio equipment, and these also contain the largest dysprosium stocks.[25] The type of use will have important implications for the future sustainability of some of these critical materials. Since rare earth elements are used in comparatively large quantities per device in wind turbines and electric vehicles, they are more amenable to recycling; recovering these precious metals from electronics, however, requires specific knowledge of how each device is manufactured to enable precision dismantling, none of which routinely occurs today.[12,24,25] The vast majority of in-use rare earth element stocks are therefore destined to be lost from the material flow 'loop' thanks to the high growth and turnover of the consumer electronics market.

Despite the advantages of permanent magnets in wind turbine design, recent spikes in global prices due to Chinese export restrictions at a time of growing demand have prompted governments and the wind industry to reassess wind turbine design and deployment in an attempt to reduce their reliance on rare materials.[23] There are several alternatives to current designs that use permanent magnets, a proven one being the use of 'hybrid drive' generators, which employs a single-stage gearbox with a smaller permanent magnet. This type of design evolution can result in less maintenance needed thanks to the lower number of gears involved when compared to a conventional turbine gearbox. At the same time, a hybrid drive can reduce neodymium use compared with turbines that use direct-drive permanent magnet systems from 186 kg per MW installed capacity to just 62 kg/MW, and the small amount of dysprosium used will also see the same proportional drop.[17,19] More conventional generators can also be used that do not need permanent magnets, thanks to updated designs that eliminate parts subject to wear and tear (e.g. 'brushless' induction generators, although not all designs have been commercially proven for MW-rated turbines).[19] Finally, one must remember that existing generator and gearbox designs are still effective and in constant use.

Since the early days of expansion in the 1990s, when there were higher than expected failure rates for some component parts (surprisingly, and contrary to expectations, these failures were rarely related to gearbox assemblies), there has been a steady reduction in failure rate to the point where the reliability of wind turbines is comparable to that of gas turbine generators.[26] As the industry learns how best to

† Staying online during a low-frequency voltage dip is know as 'fault ride-through capability', and most national grids in Europe now regard this as mandatory for new wind installations. The use of variable-speed generators allows the turbine electrical output to be better synchronised with the grid connection, and fault-ride through can be facilitated by using power converters. The generator, gears and power converters are the main contributors to the overall weight and size of the wind turbine nacelle, so maximising efficiency is key. One obvious way to reduce size and weight is to remove the gears altogether, as is achieved with direct-drive designs; this has an additional advantage in reducing maintenance requirements.

‡ Normal high-power generators rely on an electrical current passed through the field coils to create the necessary magnetic field around the rotor. Strong permanent magnets can maintain a persistent magnetic field without the need for a power supply to the coil; by mounting permanent magnets on the rotor shaft, the generator also becomes synchronous. Both of these features enable fault ride-through and improved grid connectivity, and reduces many of the parts in a conventional generator that are subject to wear.

implement the most effective preventive maintenance, this reliability is likely to improve further; thus, the range of designs available to the industry means that is better placed to cope with critical materials shortages should they arise.[19,26,27]

Life cycle greenhouse gas emissions

Finally, what are the implications of these material requirements? There are many life cycle assessments (LCAs) for wind power that have been published in the last few decades, which seek to quantify the environmental impact of wind energy, especially with regards to the greenhouse gas emissions it produces for every unit of electricity it generates. The LCA can be subject to different results for emissions or energy used, based simply on the methodology applied to deriving the inventory of energy and material inputs – all LCAs for energy technologies are subject to these differences, wind energy among them.[15] A very recent review, which sought to aggregate and analyse many different published LCAs for wind energy, usefully filtered many studies due to criteria such as lack of completeness, not directly presenting impacts in the form of greenhouse gas emissions, being outdated, quoting secondary sources, or only focusing on CO_2 to the exclusion of other greenhouse gases.[16] A summary of the findings is presented in Table 2.3.

The average rate greenhouse gas emissions (in CO_2 equivalents per megawatt-hour) is roughly 34 kg $CO_{2\text{-}eq}$/MWh (see Table 2.3). This is in line with a broader review by the IPCC that looked at LCAs published over a longer period, which found the emissions value to be grouped between 8 to 20 kg $CO_{2\text{-}eq}$/MWh, with some outliers as high as 80 kg $CO_{2\text{-}eq}$/MWh.4 Another recent meta-review of energy technologies also found a similar range for wind power, this time ranging from 3 to 41 $CO_{2\text{-}eq}$/MWh.28 However, Table 2.3 also reveals that the value for offshore is lower overall when compared with onshore (19 vs 39 kg $CO_{2\text{-}eq}$/MWh); this also follows the same pattern found in the IPCC report.[4,16] Despite the greater material requirements for offshore wind due to larger turbine and foundation structures, the increased electricity production means overall emissions are lower per MWh.

One can also see the importance of lifetime estimates in Table 2.3, because when LCA results are grouped by age in five-year increments we see almost a two-thirds drop in the emissions rate between 20 years and 30 years (from 41 to 25 kg $CO_{2\text{-}eq}$/MWh). As we saw when considering energy invested (chapter 1), because the inputs for wind power are predominantly upfront (i.e. only a small fraction of the total material and energy inputs are required once a turbine is built and operating) an extended lifetime means more electricity is produced for only a neglible increase in total emissions.

What is clear from the many LCA studies available is that wind performs significantly better than fossil fuel-powered electricity. Using the figures presented in Table 2.3, wind power has emissions roughly one-tenth of those of natural gas (34 vs 350–443 kg $CO_{2\text{-}eq}$/MWh)

Table 2.3 Summary of findings from review of 22 studies dealing with LCA of wind power systems. Data from Nugent and Sovacool (2014), Energy Policy, 65:229–44

	Greenhouse gas emissions (kg CO_2eq/MWh) contributed by each stage of a turbine's life				
	Overall total (n=39)	Extraction, processing & manufacture	Construction	Operation	Decommissioning (incl. recycling)
Mean	**34.1**	43.0	14.4	14.4	-11.6
Median	**12**	12	8.3	2.4	-3.3
s.d.	**67.2**	77.0	21.2	26.3	18.8

	Greenhouse gas emissions (kg CO_2eq/MWh) based on whether turbine is onshore or offshore	
	Onshore (n=31)	Offshore (n=6)
Mean	38.9	18.9

	Greenhouse gas emissions (kg CO_2eq/MWh) based on operational lifetime of turbine Estimated lifetime of turbine (years)[a]		
	20 (n=26)	**25 (n=3)**	**30 (n=4)**
Mean	40.7	28.5	25.3

kg CO_2eq/MWh, kilogrammes CO_2 equivalents per megawatt-hour; n, sample size; s.d., standard deviation

[a] This shows data when categorised by average operational lifetime of the turbine. Note that offshore wind turbines typically have an estimated operational lifetime of 30 years and are therefore mainly represented by this longer time frame; in contrast, the 20-year lifespan is typical of onshore wind turbines.

and anywhere from one-twentieth to one-thirtieth that of electricity from hard coal (34 vs 660–1050 kg $CO_{2\text{-}eq}$/MWh).[16,28] An in-depth LCA of nuclear power arrived at average emissions of 66 kg $CO_{2\text{-}eq}$/MWh; but the studies that were included, even after a stringent selection process, differed widely in assumptions about the full life cycle processes for uranium fuel, such as estimates of the quality of uranium ore, the energy intensiveness of the enrichment method and the effort required to treat spent fuel and decommission plants.[29] Indeed, although well-established as an energy commodity, uranium fuel can also be considered a critical material, since any expansion of the global nuclear fleet in the next century will require a substantial construction effort and the exploitation of new, as yet undiscovered, uranium deposits.[30]

What are the implications of these emissions figures? Take the UK's present level of carbon emissions from the electricity sector, which is 450 kg $CO_{2\text{-}eq}$/MWh, on average. Projected installed capacity for wind power is expected to generate roughly 51 GWh per annum by 2020. This would save over 22 million tonnes (Mt) of CO_2, or around 15% of the present-day electricity sector's total emissions.[31] Taking into account the less carbon-intensive nature of the UK's generating portfolio by 2020, largely due to less carbon-intensive coal-fired generation,[§] these savings may be lower, but will still be in the region of 20 Mt CO_2.[32]

Other life cycle impacts

In addition to greenhouse gases and their effects on climate change, LCA methodology takes into account other pollutants, attempting to present these in a meaningful way to allow a comparison of overall environmental effects.[15] These effects are typically categorised under several impact indicators: acidifcation, eutrophication, particulates, photochemical oxidants, ecotoxicity and human toxicity. Many of these impacts are caused by fossil fuel combustion releasing particulate matter, sulphur dioxide (SO_2), nitrogen oxides (NO_x) and other chemicals. It is important to account for these impacts, since the extraction and processing of the raw materials needed for wind turbines will rely to a large extent on energy from fossil fuels in the present energy infrastructure.[5] Over their lifetime, wind turbines produce much lower levels of particulates and the pollutants responsible for acidification and eutrophication (primarily SO_2 and NO_x), typically in the order of one-tenth or even one-hundredth of that emitted by electricity from fossil fuels.[28,33,34] It is acknowledged, however, that a more detailed analysis of toxic emissions is needed as many LCA models are incomplete in this regard, a problem which extends to LCAs for all energy technologies, both conventional and renewable.[5] This is especially important if the proportion of wind turbines employing rare-earth magnets increases, because the ecotoxicity of rare-earth mining can be significant when compared to bulk metal commodities on a per weight basis.[35] In addition, there is currently little that can be done to recycle the composite fibreglass and plastic materials used for construction of the blades in a turbine. The environmental impacts of these materials if placed in landfill are significant, and the wind industry is experimenting with recycling these products to be used as filler material or heat-treating them so that fibreglass and synthetic resins can be used in other industrial processes.[5,14] Unfortunately, at present, these avenues have met with limited success.

Finally, coming back to the material requirements of different energy technologies, the level of resource depletion is another important indicator of sustainability (this is often termed 'abiotic depletion' because it is focused on mineral resources). The level of resource depletion can be mitigated to a sizeable degree (up to 70%) through effective recycling and reuse of core construction materials used in a wind turbine.[14] At present, however, it is known that many LCAs for wind turbines apply recycling rates for metals used in construction that are not indicative of the real world.[13] A common misconception is the level of recycled steel incorporated into construction stock, which is generally considered to be overestimated in LCAs for wind, often stated in excess of 90% when the recycled content is typically less than 50%.[5,13,15] For rare metals the current recycling rate is practically zero.[13] This is due, to some extent, on there being no market for it, but largely because the consumer electronics industry uses the lion's share of such metals, which presents a considerable obstacle to effective recycling on account of the intricacy of components and a lack of mandates to persuade manufacturers of such products to husband these resources effectively.[24] In comparison, the wind industry is well-placed to implement an effective 'closed loop' for many of the rare metals used in turbine generators, since the larger components are more amenable to recycling and the renewables industry does not operate along the lines of fast product turnover and rapid obsolescence seen in the consumer electronics industry.[5,24,25]

Conclusions

Like any energy infrastructure, wind power requires significant quantities of material for construction, notably iron, steel alloys, aluminium, copper and fibreglass. In addition, some modern turbine designs make significant use of rare earth metals, for which there are expected to be critical bottlenecks in supply over the coming decade. One should bear in mind that

§ This is based on an approximation from DECC's projected gas/coal mix (see ref.32, p.39), and taking into account the Emissions Performance Standard that will limit coal-fired plants to 450 gCO_2/kWh. This gives average carbon emissions from combined gas and coal-fired generation of 409 tCO2/GWh in 2020.

the wind industry is not the sole driver of material demand, or even the largest. Global demand for all energy technologies is increasing at a phenomenal rate due to the continued economic expansion of countries such as China and many developing nations. Where specific material requirements exist, like that for rare earth metals, other industries predominate, not least the already large consumer electronics market and the burgeoning electric vehicle sector.

Material consumption will increase over the short-term if the wind industry, and the renewables sector generally, continues to expand following current projections. This will create supply constraints for some critical materials, although the range of existing alternative options for turbine generator design allows some adaptations to be made in the face of resource constraints and rising prices. The extensive literature on life cycle impacts shows that wind energy, in terms of greenhouse gas emissions and other indicators, has one of the best environmental profiles of any generating technology, and is far superior to fossil fuel-powered electricity in particular. However, the present rate of recycling for the vast majority of metals, both rare and non-critical, is very low across all sectors. It is imperative that more action is taken in this regard. With its sustainable credentials and a central role to play in the world's future energy mix, the wind industry must take a strong lead in improving recycling and materials efficiency as the number of turbines worldwide continues to increase.
What are the implications of wind energy's material requirements? Despite these short-term increases in materials consumption, the need to accelerate the transition to renewable energy technologies is the more pressing need, because the lag time between reductions in greenhouse gas emissions and the stabilising of global temperatures means any delay of even a decade will increase the likelihood that extreme climate effects will be unavoidable over the next century.[36,37]

It has been shown that the short-term increase in material and energy use resulting from widespread implementation of renewables will pay dividends by the second half of this century, as overall environmental impacts from energy supply will be considerably reduced.[33] Greenhouse gas emissions alone could be more than 60% lower when compared with a 'business as usual' scenario, and this from just 39% of the world's electricity being generated by a mix of wind, solar and hydropower. Thus, although it is likely to lead to a short-term increase in consumption of certain materials, the expansion of wind and other renewables now will help guarantee the wider benefits of a sustainable energy future by the middle of the 21st century.

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