



## Case study: Wind farms



*A wind farm*

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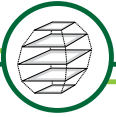
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*Wind farms are the fastest growing sector of the renewable electric power market. The scale of their construction creates a growing demand for materials, some of them “critical” in the sense that their supply chain is at risk. Does this threaten wind power as a future sustainable development?*



# Wind farms – the handout

## Introduction and background<sup>1</sup>.

The Paris Agreement on Climate Change was adopted by consensus of representatives of 195 countries on 12 December 2015 committing nations to present national plans to reduce emissions to limit global temperature rise to less than 2° C. Electrical power generation accounts for about 30% of greenhouse gas emissions in 2016. Nearly a quarter of this power is from renewable sources – biomass, hydropower, geothermal and wind and solar. It is difficult to expand the first three – there are limits on sites and area for biomass production. The fastest growing sectors of renewable electrical power are those capturing wind or solar energy.

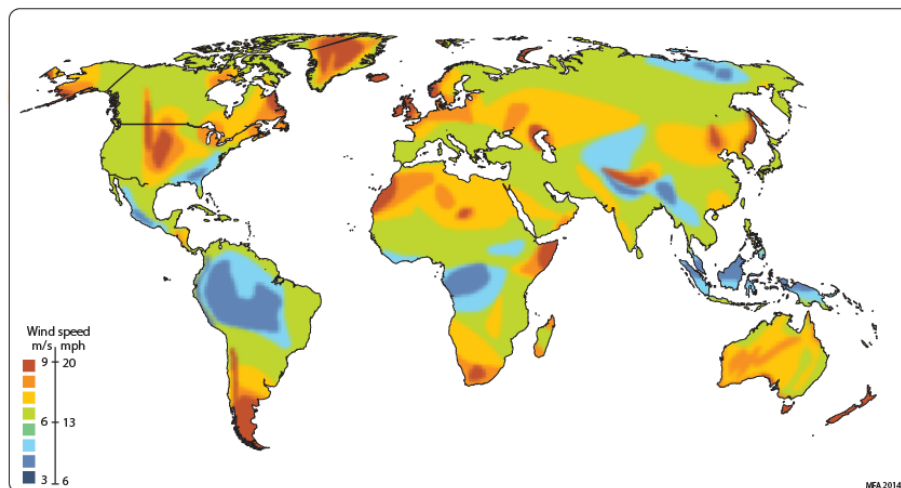
The United Kingdom is legally committed to meeting 20% of its energy demand from renewable sources by 2020. The motives are to increase energy security and meet carbon reduction obligations (80% reduction in greenhouse gas emissions by 2050)<sup>2</sup>. Current renewable energy generation (hydro, wind, solar, biofuel) is 12% of total demand, of which 6% is wind and 0.35% is solar. Growth of wind is 35% per year. If this growth is maintained for the next 7 years, the UK comes close to the 15% target.

Many nations have similar aims and strategies, encouraging the building of wind farms that feed electricity into the national grid. At the start of 2012 there were about 200,000 wind turbines worldwide, averaging 2 MW in power. The number, globally, is increasing at 25% per year, meaning that roughly 50,000 new turbines are installed each year. Is this a sustainable development?

Who are the stakeholders and what are their concerns? What materials, design, environmental, regulatory or social issues involved? To answer these questions we need facts. Armed with those, an opinion can be formed about the impact of wind farms on Human, Natural and Manufactured Capital. Given this information, a judgment can be made of the contribution of wind farms to a more sustainable future.

## Background information

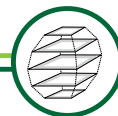
- Wind turbines only produce energy when the wind blows (Figure 1). The ratio of the actual average power output of the turbine divided by the nominal (rated) generating capacity is called the capacity factor. It is typically 20% for on-shore and 28% for off-shore turbines. Thus a 2 MW on-shore turbine will produce, on average, 0.4 MW.



**Figure 1.** A global map of average wind speed.

<sup>1</sup> Image of wind farm courtesy of [www.windjobsuk.com/wind-farm-jobs.cms.asp](http://www.windjobsuk.com/wind-farm-jobs.cms.asp)

<sup>2</sup> [www.gov.uk/government/policies/increasing-the-use-of-low-carbon-technologies](http://www.gov.uk/government/policies/increasing-the-use-of-low-carbon-technologies)  
[https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/48128/2167-uk-renewable-energy-roadmap.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48128/2167-uk-renewable-energy-roadmap.pdf)



- Most of the materials of a wind turbine are conventional: carbon steel, stainless steels, concrete, copper, aluminum and polymer matrix composites. One is exceptional. The generators of wind turbines use neodymium-boron rare-earth permanent magnets (Figure 2 and Table 1). Neodymium (also used in hybrid and electric vehicles) is classified in the US and Europe as a “critical” material. It is co-produced with other rare-earth metals, of which it forms 15% on average.
- A 2 MW wind turbine contains 25 kg of neodymium. Thus annual construction of 50,000 new turbines per year creates a demand for 1,250 tonnes of neodymium per year.



**Figure 2.** The rotor of a permanent-magnet turbine.

Nd-B magnets	Weight %
*Neodymium (Nd)	30
Iron (Fe)	66
Boron (B)	1
Aluminum (Al)	0.3
*Niobium (Cb) (Nb)	0.7
*Dysprosium (Dy)	2

Starred (\*) elements are on the critical list

**Table 1**

**The steps** follow the procedure described in Section 2 of this Teaching Resource Package

- What is the prime objective? What is its scale and timing? What is the functional unit?
- Who are the stakeholders and what are their concerns?
- What facts will be needed to enable a rational discussion of the proposal?
- What, in your judgment, is the impact of these facts on Natural, Manufactured and Social Capitals?
- Is the proposal a sustainable development? Could the objective be better met in other ways?

### Where can CES EduPack Sustainable Development Edition help with Fact-finding?



The **Materials data-table** has records for cements and concretes including Portland cement, standard concrete and fly ash concrete.



The **Low carbon power data-table** lists characteristics of electric power generating systems



The **Regulations data-table** includes records for regulations relating to the construction industry



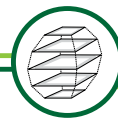
The **Eco-audit tool** allows a fast comparison of the properties, carbon footprint, embodied energy and criticality status of the materials wind turbines



The **Nations of the world data-table** contains records for the environmental, economic and societal statistics of the nations from which elements are sourced.



The **Graph facility** of the **CES EduPack software** allows data to be plotted as property charts, annotated and saved to WORD documents.



## Wind farms – example of assessment

*The numbering of the sections corresponds to that of the 5 steps of the analysis. The CES EduPack Sustainability database helps with fact-finding in ways described in the Handout for this Case Study.*

### Step 1: The objective, size and time scale

**Objective:** to reduce global carbon emissions and increase energy self-sufficiency

**Size scale:** target growth rate of 25% per year means building 50,000 new 2MW (or equivalent, totaling 100 GW) units per year.

**Time scale:** By 2020

**Functional unit:** Per 2 MW turbine



Is the objective realistic? To answer that we need to know a number of things. What demands for materials will this building program create? Can they be met? By how much is the carbon footprint of electrical power from wind lower than that from fossil fuels? And will 100 GW of this lower carbon power make any significant reduction to global carbon emissions?

But first we must consider the stakeholders.

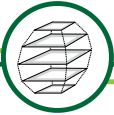
### Step 2: Stakeholders and their concerns

A proper stakeholder assessment needs direct contact with those concerned. A start can be made by exploring the press and internet. Here are eight recent cuttings

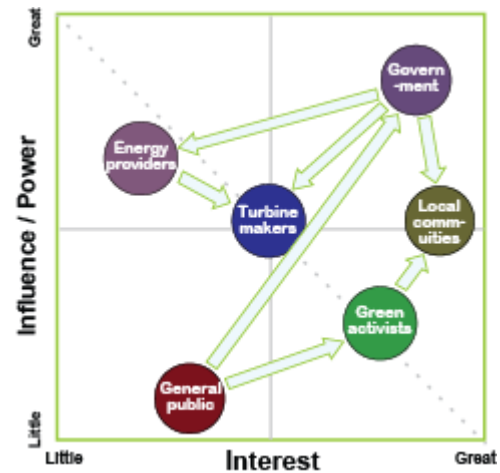
- *“Onshore wind: call for evidence.”* (Title of UK Department of Energy and Climate Change consultative document, 6 June 2013).
- *“Government announces support for offshore wind energy industry”* (The Information Daily.com 1 August 2013).
- *“GE stimulates wind energy growth in the UK”* (Focus.com 5 November 2013)
- *“Marchers protest against wind farm plans”* (The Galloway Gazette, 28 November 2013)
- *“Planned onshore wind farms face uncertain future in Government shakeup that gives local communities a greater say over planning decisions”* (BusinessGreen.com, 6 June 2013)
- *“Centrica criticises policy as seabirds block Dooking Shoal wind farm. Ministers block wind farm.”* (The Telegraph, 6 July 2012)
- *“Strike a blow against wind-farm bullies”* (A columnist protests against the siting of wind farms in landscape he loves. (The Times, 25 February 2013)
- *“Government and industry slam ‘spurious’ anti-wind farm headlines.”* (The Times, 16 April 2012.)



These headlines and the text that follows identify a number of stakeholders and their concerns (Figure 3). Among them are:



- **National and Local Government.** National Administrations have made commitments to reduce carbon emissions over a defined time period. They see wind farms as able to contribute. To encourage their construction they subsidize renewable energy production and impose taxes on carbon emission.
- **Energy providers.** Carbon taxes or carbon trading schemes and carbon penalties create financial incentives for energy providers to reduce the use of fossil fuels.
- **Wind turbine makers.** Turbine makers want assurance that government policy on renewable energy is consistent and transparent, that incentives will not suddenly be withdrawn and that the supply chain for essential materials is secure.
- **Local communities and the wider public.** The acoustic and visual intrusion of wind turbines and their power-distribution system is seen as unacceptable by some, as is the danger they pose for birds.



**Figure 3.** Stakeholders in planning a wind farm.

#### Summary of the significant concerns

- *The security of supply of the critical materials on which wind turbines depend.*
- *Wind farms don't reduce carbon emissions*
- *Wind farms are uneconomic without subsidies; they drive up electricity prices.*
- *Wind farms are visually unacceptable.*
- *Wind farms are a danger to wild life*

### Step 3: Fact finding

What information is needed to analyse the claims made for wind farms and the concerns expressed about them? What additional facts do we need for a rational discussion of the Prime Objective – that of building 50,000 2MW turbines per year? These questions are explored in the sections below. Figure 4 gives an overview.



**Materials and supply chain<sup>3</sup>.** Permanent magnets for electric turbines require high remanent induction with high coercive field. Figure 4 shows these two properties for magnetic materials<sup>4</sup>. Neodymium-based magnets (ringed in red at the upper right) have by far the largest values of this pair of properties. If a substitute were to

<sup>3</sup> Ardente, F., Beccali, M., Cellura, M., & Lo Brano, V. (2008). Energy performances and life cycle assessment of an Italian wind farm. *Renewable and Sustainable Energy Reviews*, 12(1), 200-217. doi:10.1016/j.rser.2006.05.013

Crawford, R.H. (2009) *Life cycle energy and greenhouse emissions analysis of wind turbines and the effect of size on energy yield*, University of Melbourne, Australia, *Renewable and Sustainable Energy Reviews* Vol. 13, Issue 9, pp. 2653-2660.

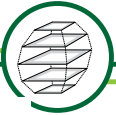
Danish wind industry association, (2003) *What does a Wind Turbine Cost?*, <http://guidedtour.windpower.org> (Accessed 08/10)

Martinez, E., Sanz, F., Pellegrini, S., Jimenez, E., Blanco, J. (2007) *Life cycle assessment of a multi-megawatt wind turbine*, University of La Rioja, Spain. [www.assemblywales.org](http://www.assemblywales.org) (Accessed 08/10)

Vestas (2008) V82-1,65 MW, Vestas Wind turbine brochure

Vindmølleindustrien. (1997, July). The Energy Balance of Modern Wind Turbines. *Wind Power Note*, 16. [http://www.apere.org/manager/docnum/doc/doc1249\\_971216\\_wind.fiche37.pdf](http://www.apere.org/manager/docnum/doc/doc1249_971216_wind.fiche37.pdf) (accessed 08/11)

<sup>4</sup> Ashby, M.F., Shercliff, H.R. and Cebon, D. (2014) "Materials: Engineering, Science, Processing and Design" Butterworth Heinemann, ISBN 978-0-08-097773-7



be sought, the next best choice would be the AlNiCo group of magnets, but all have a smaller remanent induction and a much smaller coercive field. Nd-B magnets are the current materials of choice for compact high performance magnets.

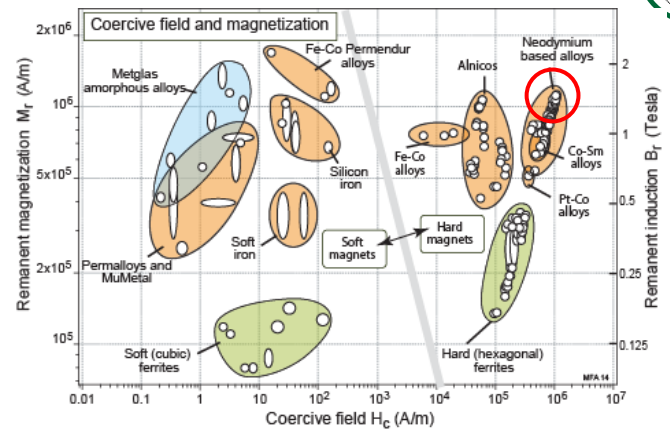
Neodymium is co-produced with other rare-earth metals, of which it forms 15% on average. Table 2 lists the nations that produce rare-earths and the quantities they produce. The present global production is 133,600 tonnes per year, yielding 20,000 tonnes of Nd per year. Over 95% derives from a single nation, China. Nd is listed as a “critical” material because of its uniquely desirable magnetic properties for high field permanent magnets, because its supply-chain is so narrow and because its price is volatile. The current rate of building wind turbines described in the Introduction carries a requirement of 1,250 tonnes of neodymium per year. This is 6% of current global production.

**Energy and energy pay-back time.** Energy is used to make materials and to manufacture them into products. More energy is used transporting the products to where they will be used and assembling them to make a wind farm. Still more energy is used to connect the farm to the national grid. Numerous estimates<sup>5</sup> have been made of the energy required to build and commission a wind turbine – it is of general magnitude of  $2 \times 10^7$  kJ per kW of nominal (rated) generating capacity.

How long will it take before a turbine has generated the energy that it took to make it? At a capacity factor of 0.2 it will take a time  $t$ :

$$t \approx \frac{2 \times 10^7}{0.2} = 10^8 \text{ seconds} = 3 \text{ years}$$

**The Environment.** The Prime Objective of a wind farm is to generate electrical power with less carbon emissions than at present. It meets this objective only if the carbon emissions associated with its construction are more than offset by the low carbon emissions during life. Figure 5 compares the carbon emission per kW.hr of delivered power for alternative systems<sup>6</sup>. They are approximate, but sufficiently precise to establish that wind power has the ability to generate electrical power with significantly lower carbon emissions than gas or coal fired power stations when averaged over life.

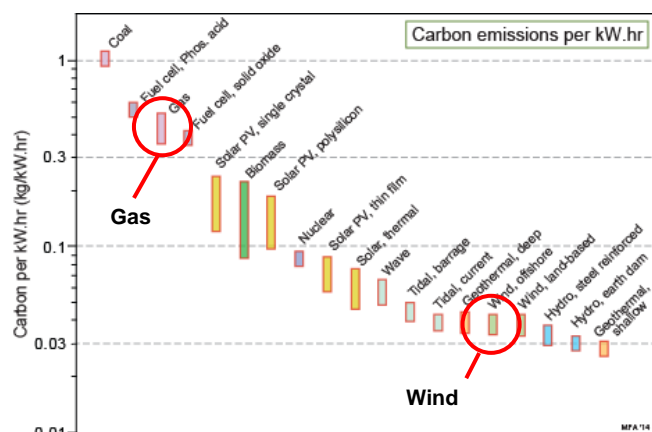


**Figure 4.** The remanent magnetization and coercive force of magnets. Nd-B magnets are ringed.

Rare Earth producing nation	Tonnes/year	2011
China	130,000	
India	3,000	
Brazil	550	
Malaysia	30	
<b>World</b>	<b>133,580</b>	

Minerals.usgs.gov/minerals/pubs/commodity

**Table 2**



**Figure 5.** The carbon footprint of electrical power from coal, gas and low carbon sources

<sup>5</sup> Ashby, M.F. (2013) “Materials and the Environment” Butterworth Heinemann, and the CES EduPack 2014

<sup>6</sup> MacKay, D.J.C (2009) “Sustainable energy – without the hot air” UIT Press, Cambridge, UK and Ashby, M.F. (2013) “Materials and the Environment” Butterworth Heinemann, Oxford.



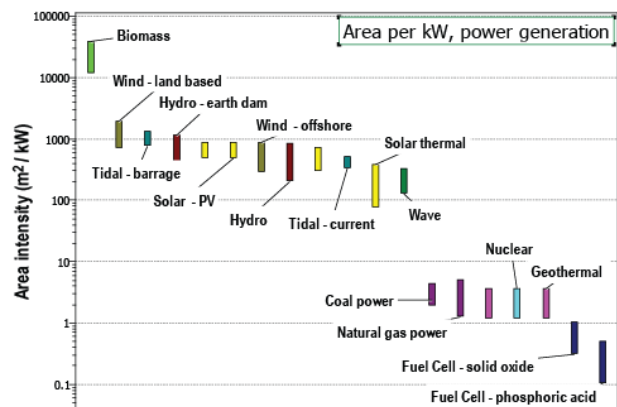


This, however, neglects power distribution: wind farms need windy places, often far from where the power will be used, and they may need energy storage systems to smooth intermittent generation.

**Regulation.** Much recent legislation across the world bears on reducing carbon emissions. They include carbon taxes, carbon trading and carbon off-setting. Making and installing wind farms is made financially attractive by “green” subsidies and feed-in tariffs but these have sometimes changed (usually down-graded) with little warning, making the market unpredictable.

**Society.** The manufacture and maintenance of wind farms creates jobs. If a proportion of the revenue generated by the farm is reinvested in the local community, it can build social capital as well.

Against this must be set the visual and acoustic intrusion caused by the turbines. Wind farms require a land-area per unit of generating power that is almost 1000 times greater than that of a gas-fired power station<sup>7</sup> (Figure 6) and while this land can still be used for agriculture the scale of the intrusion is considerable. To put this in perspective, if 10% of the electric power requirement of New York State (average 33 kW.hr per day, equivalent to 1.4 kW continuous per person, population 19.5 million) were to be met by wind power alone, the necessary wind farms would occupy 15% of the area of the entire State (area 131,255 km<sup>2</sup>).



**Figure 6.** The area-intensity of power systems, using the Low Carbon Power data-table.

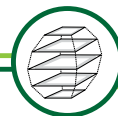
**Economics.** Are wind farms economic? Most of the commercial-scale turbines installed today (2014) are 2 MW (nominal) in size and cost between \$3 million and \$4 million<sup>8</sup> each. With a design life of 20 years, a load factor of 0.2 and allowing a sum equal to the cost of installation for life maintenance, ground rent and management, the cost of wind-farm electricity is \$0.1 per kWhr, somewhat more than that from a contemporary (2014) gas-fired power station. This, however, neglects the intermittency of wind power, which may create the need for energy storage. Grid-scale energy storage is expensive.

#### Summary of significant facts

- Wind power can produce electrical power with significantly lower carbon emissions than gas or coal-fired power stations.
- The construction energy of a wind farm is returned as electrical energy in 3-5 years.
- Compact, efficient turbines require neodymium, classed as critical, with significant supply-chain risk

<sup>7</sup> MacKay, D.J.C (2009) “Sustainable energy – without the hot air” UIT Press, Cambridge, UK and Ashby, M.F. (2013) “Materials and the Environment” Butterworth Heinemann, Oxford.

<sup>8</sup> <http://www.windustry.org/resources/how-much-do-wind-turbines-cost>



- The cost of energy from a wind farm is significantly higher than that from gas or coal-fired stations. The cost rises further if grid-scale energy storage is needed to smooth the intermittent generation..
- Wind farms are intrusive to the communities in which they are sited. If wind farms are to contribute a significant fraction (say 10%) of energy needs this intrusion becomes widespread.

#### **Step 4: Forming a judgement**

This is the moment to debate the relative importance of the information unearthed in the Fact-finding step, assessing its impact on the three capitals. It will, inevitably, require an element of personal judgement and advocacy. Here is one view, summarized in Figure 7.



**Natural Capital.** The Prime Objective in building wind farms was to reduce green-house gas emissions. The studies cited above suggested that they can. The dependence on critical elements, particularly neodymium, for the turbines, might give concern but the placement of wind turbines is fixed and known, and large groups of them are managed by a single operator, making their recovery, reconditioning or recycling at end of life straightforward. Injury to bird life might be dismissed as trivial when domestic cats kill far more, but this is not a productive way to respond to stakeholder concerns – a more considered response and exploration of mitigating measures (ultrasound, perhaps) is a better way forward.

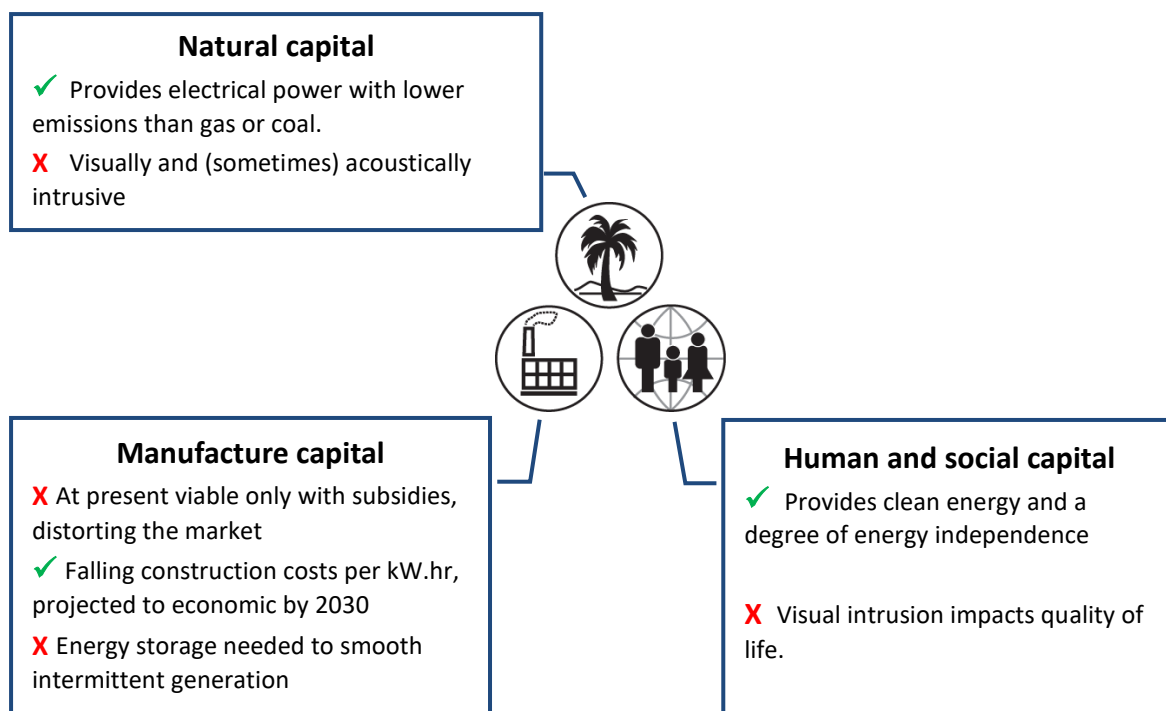
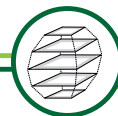
The beauty of the countryside is a component of natural capital. All power-generating plant occupies space and is visually intrusive. The problem with wind farms is the scale of this intrusion if they are to contribute significantly to national needs for power. The long-term impact of acoustic intrusion is not known.

**Manufactured and Financial Capital.** The typical design-life of a wind turbine is 25 years. Building 50,000 turbines per year is a significant investment in energy infrastructure. Is it a good investment? Some argue that it is not because, without a subsidy, the electricity they produce is more expensive than that from gas-fired power stations. Governments have been inconsistent in dealing with subsidies, encouraging investment at one moment and then cutting the subsidy with little warning the next. Much will depend on the price and predictability of hydrocarbon fuels over the next 25 years and the cost of carbon-induced climate change.

**Human and Social Capital.** On the positive side, large-scale deployment of wind farms creates employment. If these jobs and the wealth they generate are distributed in a fair and equitable way, a contribution is made to Human Capital. The reduction in emissions is a contribution to a healthier population. The mix of energy sources increases independence and a distributed rather than a centralized power system is more robust, harder to disrupt and less vulnerable to a single catastrophic event.

On the negative side, the visual and acoustic intrusion, already mentioned, represents to many people a significant loss of quality of life. Schemes to re-invest a proportion of the revenues generated by the wind farm in the local community in ways that help everyone, coupled with research to reduce the acoustic problem, offer a way forward.





**Figure 7.** Synthesis – debating the impact of the facts on the three capitals. Check-lists help with this and the other steps.

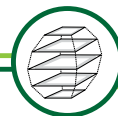
### Step 5: Reflection.

**Short term** The Prime Objective of wind farms – to generate electrical power with a low carbon footprint – appears to be met, making a contribution to Natural Capital. The relatively small scale of wind farms at present means that sites can be found for them without major disruption, and the reduction in emissions is a positive contribution to Human Capital. It is less clear that wind farms are economic, leaving a question mark over impact on Manufactured and Financial Capital.



**Long term.** Energy is one of mankind's most basic needs and electrical energy is the most versatile and valuable form it takes. We are in transition from a carbon-powered economy to one powered in other ways but the detailed shape of the future is not yet clear. A distributed energy-mix in the economy is desirable. If the cost of fossil fuels continues to rise in the future as it has in the past the economic case for the farms becomes stronger, but if grid-scale energy storage becomes necessary to smooth intermittent power from wind the cost again rises. Interestingly, electric vehicles, if they become the norm, might partly solve this problem. On average a private car is used for less than 4% of the day; the rest of the day is available for charging. Introducing intelligent battery charging that draws on power when there is surplus generating capacity turns the grid itself into a virtual storage device.

The evidence suggests that wind farms can make a contribution to national power needs but that it is likely to remain small. The intrusion caused by farms on a scale that could provide, say, half the nation's power appears to present very great problems. For now the dominant source power continues to be fossil fuels. Wind-farms can offer one, perhaps transient, contribution while striving for other ways to establish a supply of clean energy and manage demand more effectively.



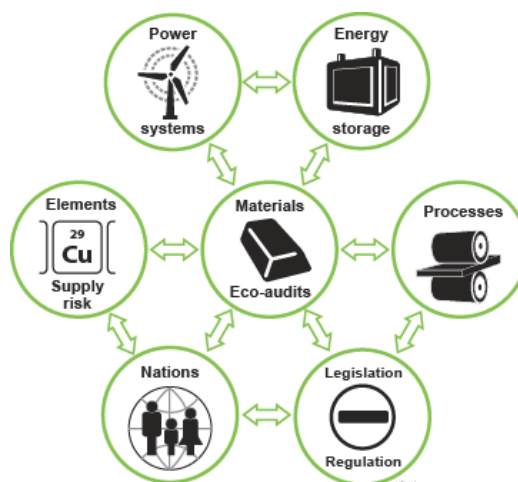
# Sustainable Development Teaching Resources

## Resources

- *Granta Teaching Resource Package: Active-Learning Tool Kit – Sustainable Development*
- *PowerPoint presentations*
- *Explanatory handouts*
- *Templates*
- *Micro-projects*

## Case studies

- *Greener beer cans*
- *Bioplastic or polyprop?*
- *Electric cars*
- *Electric buses*
- *Which hand dryer?*
- *Plastic books*
- *Wind farms*
- *Low carbon concrete*



## The CES EduPack Sustainable Development Edition

The Sustainability Database is a fact-finding tool to introduce students to the complexity of decision-making for sustainability. It helps contextualize the role of materials and it expands competences in critical thinking about complex issues (including resource use, legal barriers, ethical considerations, societal and economic concerns). The individual data-tables are explained in Section 3 of this Teaching Resource Package.

The book “Materials and Sustainable Development” (ISBN-13: 978-0081001769) describes this method and its applications in more detail.

**Authors.** Professor Mike Ashby and Education Division team at Granta Design Ltd.  
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