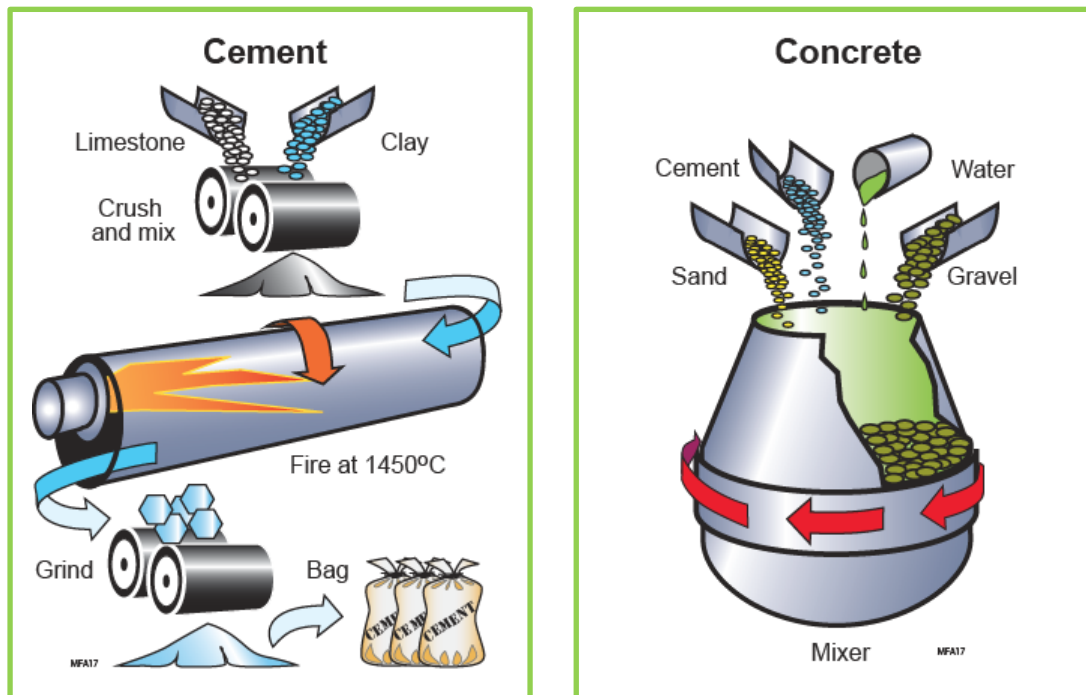


Case study: Low-carbon concrete

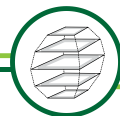
Tatiana Vakhitova, Rui Hao, and Mike Ashby
August 2016



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Cement-production releases almost 5% of the world's annual emissions of greenhouse gasses. This case study explores suggested ways of reducing it and their implications.



Low-carbon concrete - Handout

The proposal.

Concrete is the second most consumed product on earth after water¹. Concrete is cement-bonded aggregate. The bonding agent is usually Portland Cement (PC), made by calcining lime (CaCO_3) at high temperatures. CO_2 emissions arise from fossil fuel combustion and from the calcining reaction ($\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$). At present making 1 tonne of PC releases around 1 tonne of $\text{CO}_{2\text{eq}}$ into the atmosphere². Global carbon emissions from cement making are projected to reach ~5 billion tonnes per year by 2050, assuming no change in current technology (Figure 1). The world's five biggest cement producers are Lafarge, Holcim, Cemx, Heidelberg Cement, and Ialamenti.

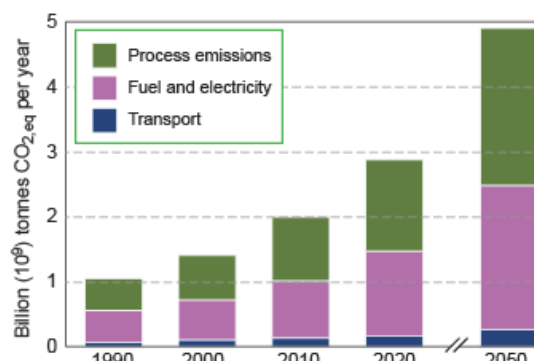


Figure 1. Global emissions from cement making, indicating the source (WBCSD, 2007)

About 1.5% of all greenhouse gas emissions in a developed country come from cement production; globally it is 5%. The EU is committed to reducing these emissions by 2050 to 20% of the levels in 1990. Can the cement industry meet this target? This will involve changes in technology. What are the foreseeable materials, environmental, economic and social consequences?

Four options exist for reducing emissions from cement production³. In order of increasing difficulty:

- Replacing some of the PC with low carbon industrial by-products, notably pulverised fly ash (PFA) or ground granulated blast furnace slag (GGBS)⁴.
- The use of renewable energy sources and low-energy production methods.
- Development of new cement formulations with lower energy consumption and carbon footprint such as reactive MgO cement, a potential substitute for PC⁵.
- Carbon capture and storage (CCS).

Background information. The cement industry has reduced CO_2 emissions per tonne of cement by 25% between 1998 and 2013 by increasing the use of non-fossil fuels. The Mineral Production Association Cement⁶ (MPA Cement) publishes an annual report on cement production. It suggests two scenarios for further carbon reduction.

- Scenario 1 envisages 81% emission reduction by 2050 compared to 1990 by using carbon capture and storage (CCS).
- Scenario 2 recognizes the large technical and financial barriers for CCS; if these are not overcome, the achievable plan for reduction by

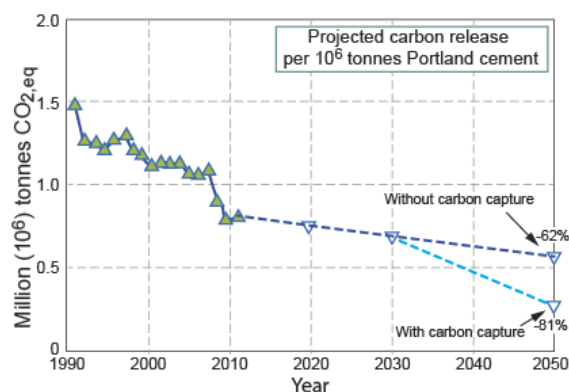


Figure 2. Trends in carbon reduction in cement manufacture

¹ <http://www.wbcsd.org/pages/edocument/edocumentdetails.aspx?id=13559>

² Taylor, H.F.W (1997) "Cement Chemistry" 2nd edition, Technology & Engineering. ISBN 0727725920.

³ http://www.sustainableconcrete.org.uk/PDF/SCF_Performance%20Report_eighth.pdf

⁴ Schneider, M., Romer, M., Tschudin, M. & Bolio, H. (2011). "Sustainable cement production- present and future". Cement and concrete research, vol. 41, 642–650.

⁵ Harrison, J. (2003) "The case for and ramifications of blending reactive magnesia with Portland cement", Proc. 28th Conf. on Our World in Concrete and Structures, Singapore.

⁶ http://cement.mineralproducts.org/documents/MPA_Cement_SD_Report_2013.pdf



2050 is closer to 62% compared to 1990.

Figure 2 show historical data⁷ for the period 1990 – 2010 and the trends predicted by these two scenarios. How are these further reductions to be achieved?

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 the CES EduPack Sustainability 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 **Regulations data-table** includes records for regulations relating to the construction industry



The **Architecture database (not contained in the Sustainability database)** has data for materials for construction

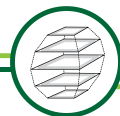


The **Nations of the world data-table** contains records for the environmental, economic and societal statistics of the nations from which elements are sourced.



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

⁷ http://cement.mineralproducts.org/documents/MPA_Cement_GHG_Reduction_Strategy_Technical_Document.pdf



Low carbon concrete – 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 and functional unit

- **Objective:** to reduce green-house gas emissions from concrete manufacture
- **Size scale:** a reduction of 80% relative to 1990 levels
- **Time scale:** by 2050
- **Functional unit:** 1 tonnes of C25 concrete (C25 is a standard concrete mix with 1 part cement to 6 parts mixed aggregate).



Step 2. Stakeholders and their concerns.

Stakeholders include government, cement makers, the construction industry and all those affected by manufacture and use of cement and concrete.



Table 1. Stakeholders

Stakeholders	Concerns
Government and health agencies	Protection of public health, both short term (cement dust) and long term (global warming and climate change)
Makers of cement	Public image, restrictive legislation and carbon taxation (see the Cement Sustainability Initiative, CSI ⁸).
The construction industry	Future cost and availability of concrete. Speed of setting (fast setting reduces construction time). Safety (introduction of fast setting high alumina cement in the 1960s led to a number of failures caused by loss of strength). Recycling of concrete.
Cement industry R&D	Alternative chemistries for cement; carbon capture and storage

Step 3: Fact finding

Materials - cement. The base materials for Portland cement are limestone (CaCO_3), clays (hydrated aluminum silicates) and marls (mixed clay-limestone minerals). These are mixed in specific proportions, fired at around 1450°C to give a clinker that is ground to cement powder (see cover image, left). In Europe cements are classified the ways listed in Table 2.



⁸ http://csioprogress2012.org/CSI_ProgressReport_FullReport.pdf

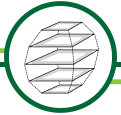


Table 2. Designations for cements.

Code	Name	Composition
CEM I	Portland cement	Portland cement with up to 5% of minor additional components.
CEM II	Portland composite cements	Portland cement with up to 35% of other components.
CEM III	Blast furnace cement	Portland cement with > 35% blast furnace slag
CEM IV	Pozzolana cement	Portland cement with > 35% pozzolana (a natural hydraulic mineral resulting from volcanic activity)
CEM V	Composite cement	Portland cement with differing mixes of blast furnace slag, pozzolana or fly ash (fine ash from coal-fired power stations).

<http://www.cemex.co.uk/Userfiles/datasheets/mortar-cementitious.pdf>

http://gbr.sika.com/content/dam/Corporate/01_General/publications/sika_concrete_handbook.pdf

<http://www.smorris.co.uk/userfiles/downloads/48/concrete-properties-defined.pdf>

Materials – concrete. Concrete is a mixture of sharp sand (fine aggregate), gravel (coarse aggregate) and cement (cover image, right). Its strength depends on the cement / aggregate ratio. The mix designation C25 means that the concrete will attain a cube-compression strength of 25 MPa after 28 days; the mix for C25 is 1 part Portland cement, 2 part sand and 4 parts gravel. The table elaborates further.

Table 3. Concrete designations

Grade	Designation	Use
General	GEN0 (C6/C8)	Lean Mix-Cavity Fill
	GEN1 (C8/C10)	Domestic foundations, blinding and kerbing.
	GEN2 (C12/C15)	Small walls
	GEN3 (C16/C20)	Garages, Shed bases, and Farm foundations
Reinforced	RC 20/25 (C20/25)	A standard mix. Typically used for reinforced foundations.
	RC 25/30 (C25/30)	Driveways, Reinforced Foundations
	RC 28/35 (C28/35)	Raft foundations and industrial floors
	RC 32/40 (C32/40)	Industrial foundations

<https://www.mickgeorge.co.uk/residential/miniload/ready-mix-concrete/rc20or25-c20or25/>

Materials – fly ash. Coal-fired power stations burn pulverized coal at about 1400 C. Fly ash, a bye-product, is the fine alumino-silicate particulate carried out of the furnace with the flue gases. It is removed by filtration and stored with little additional demand for energy or emissions of carbon. Using it to replace up to half the Portland cement in concrete reduces its embodied energy and carbon footprint by up to 30%.

Concrete made with fly ash cement takes longer to set than concrete made with PC alone but the long time

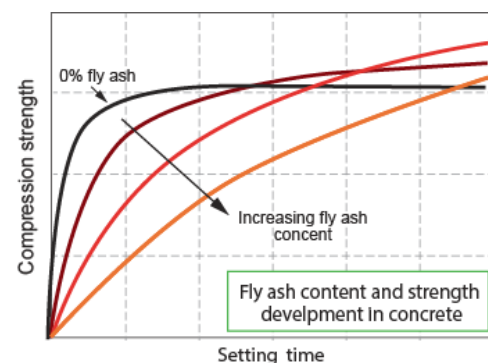
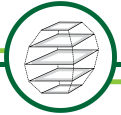


Figure 3. Effect of fly ash on compressive strength development of concrete



performance is as good or better than PC based concrete (Figure 3)⁹. Other mechanical properties (tensile strength, flexural strength and elastic modulus) are not dramatically affected by moderate additions (up to 35%) of fly-ash. (Other mechanical properties can be found in the CES Edupack.)

Energy and the environment. Figure 4 shows the effect of fly-ash additions; the effects of similar additions of blast furnace slag are almost identical. The embodied energy of C20/25 concrete, which is thought of as “normal” concrete, is reduced by 15% and 30%, by 25% and 50% replacement respectively (Data from Hammond and Jones¹⁰).

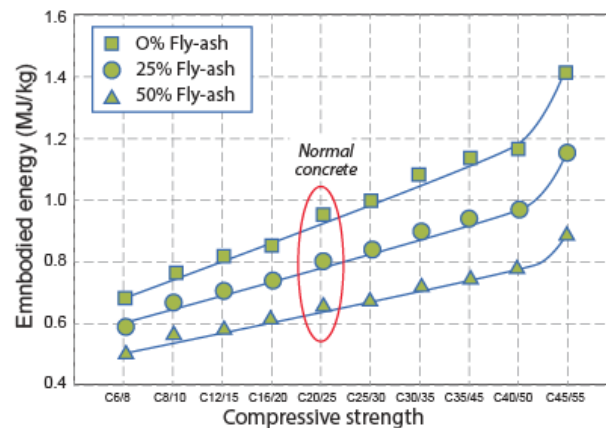


Figure 4. The effect of fly-ash additions on embodied energy of concrete.
Data from Hammond and Jones

The carbon footprint, too, is reduced. (Figure 5); once again the effects of similar additions of blast furnace slag are almost identical. The carbon footprint of C20/25 “normal” concrete is reduced by 20% and 40%, by 25% and 50% replacement respectively.

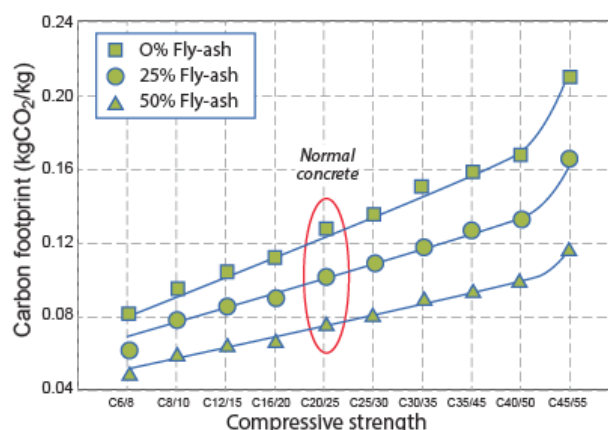
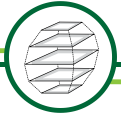


Figure 5. The effect of fly-ash additions on the carbon footprint of concrete

⁹ http://www.cement.org/docs/default-source/fc_concrete_technology/is548-optimizing-the-use-of-fly-ash-concrete.pdf
<http://www.ctre.iastate.edu/pubs/sustainable/mehtasustainable.pdf>
<http://www.concrete.org.uk/fingertips-nuggets.asp?cmd=display&id=525>

¹⁰ <http://www.circularecology.com/embodied-energy-and-carbon-footprint-database.html#V-EJ6fArKU> and
<http://perigordvacance.typepad.com/files/inventoryofcarbonandenergy.pdf>



Economics. The cost of fly-ash cement is typically 75% of that of Portland cement as delivered, assuming a means of batching is already in place¹¹.

Legislation and Regulations. In Europe cements are controlled by the standard EN 197-1. Fly ash suitable for use in concrete is produced to the European standard EN 450¹².

Society. Development since 1990 demonstrate ways in which improved environmental profile can be combined with lower costs. These developments go some way to meeting the concerns of stakeholders; but further technology advances are needed to even approach the 2050 target set as the objective.

Step 4: Forming a judgement

Now comes the difficult bit: assessing the impact of the facts assembled in Step 3 on Natural, Manufactured and Social Capitals, and then forming a judgment of which course of action best balances all three. This judgement will inevitably be affected by values, ethics, culture and attitude to risk (Figure 7).



Natural Capital. Fly-ash and blast furnace slag are both waste materials that were, at one time, dumped. Using them instead as substitutes for resource-intensive Portland cement is an example of a circular materials economy in operation. Doing so reduces dependence on natural minerals and energy, and reduces damaging emissions. There are, however, risks associated with reliance on the bye-product of another industry – should that industry decline, supply may be disrupted. Figure 6 shows the view of the UK Department of Environment and Climate Change on future electricity sources. Coal-fired power stations, the source of fly ash are essentially phased out by 2030. The supply-chain for blast furnace slag, too, looks questionable as steel making relies increasingly on recycling of scrap rather than pig-iron production (the UK's last blast furnace is expected to close in 2017). Importing fly-ash or blast furnace slag from China or India negates at least part of the environmental and economic advantage of locally sourced materials.

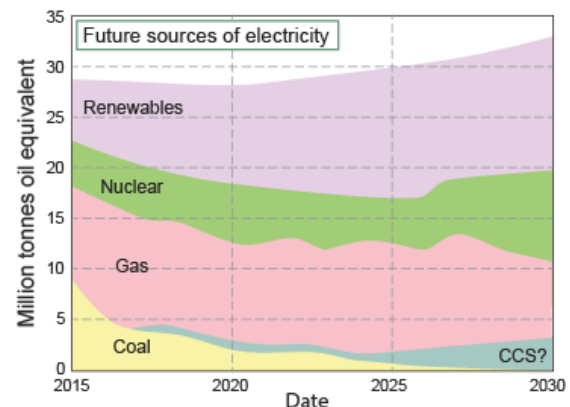


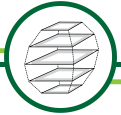
Figure 6. Coal plays a diminishing role in future electricity generation globally

What about existing stock of these materials? Here the picture is rosier. Large quantities of fly ash are stored in accessible dumps around the world – UK stockpile is reported to be over 50 million tonnes. If one third of the PC in the cement used for C25 concrete were replaced by fly ash this stockpile is sufficient to support the UK production of cement until about 2035 at current consumption rates. But there is a long term risk: if coal-fired power is phased out, fly ash supply will diminish.

The other scenario envisaged carbon capture and storage (CCS). CCS not only allows a dramatic reduction in the emission for cement making, it also allows the continued burning of coal. This scenario (unlike the last) relies on a new, unproven technology. And that carries financial risk. We turn to that next.

¹¹ <http://www.monolithic.org/blogs/construction/fly-ash-properties-and-uses>

¹² http://gbr.sika.com/content/dam/Corporate/01_General/publications/sika_concrete_handbook.pdf



Manufactured and Financial Capital. Fly-ash and blast furnace slag reduce cost with no loss of long term strength. The setting time is longer and this, on a construction site, has cost implications. The process of cement-making is also made a little more complex because of replacement addition. Despite these drawbacks this industry has welcomed the new developments.

The carbon reductions made possible by the use of cement replacements are not sufficient to meet the EU targets. Further reductions are possible by introducing carbon capture and storage (CCS), but this adds cost. The current cost of CCS in the electrical power sector is 60/tonne of CO₂ although this is expected to decline in the early 2020s¹³. Portland cement costs €100/tonne; its manufacture releases one tonne of CO_{2,eq} per tonne of cement, so removing this entirely would drive up the price by at least 50%, a significant increase.

Human and Social Capital. Developments in cement and concrete technology since 1990 show that an improved environmental profile can be combined with lower costs. These developments go some way to meeting the concerns of stakeholders but further technology advances are needed to even approach the 2050 target set as the objective. Meanwhile the adverse influence of the immense release of emissions from a single industry is perceived by many to be unwanted.

Against this must be set the benefits that concrete brings to society. There are good reasons that concrete is a material used in greater quantities than any other: it provides compression strength and – when reinforced with steel – tensile and bending strength far more cheaply than any other material. The great dams, bridges and buildings of the world would not be possible without concrete.

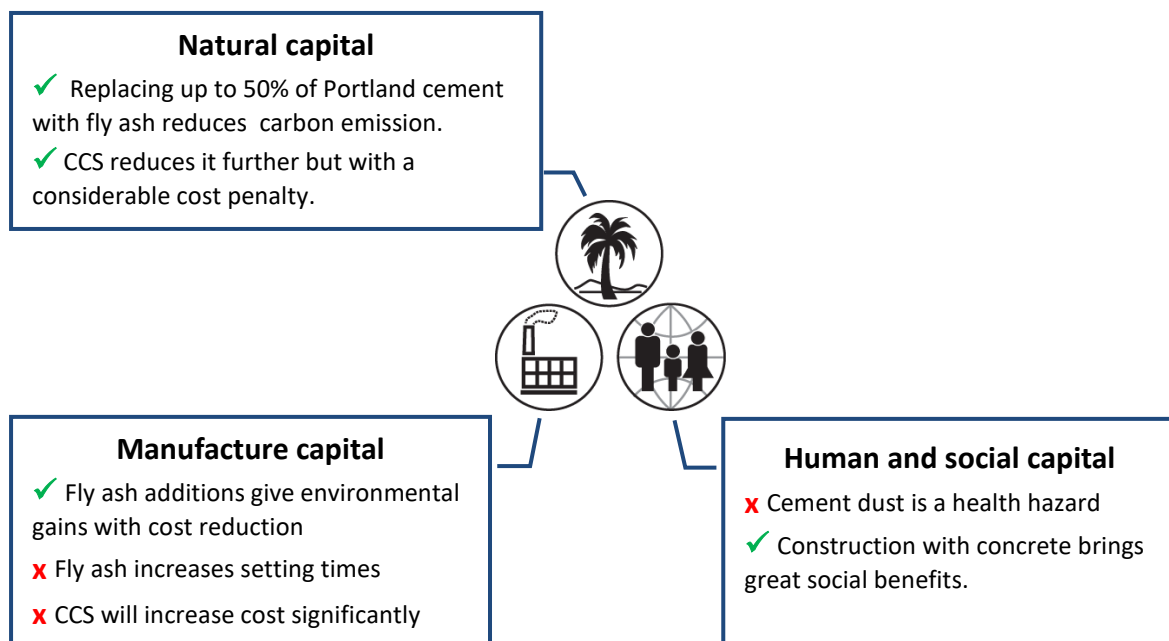
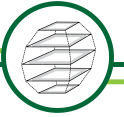


Figure 7. An overview of the impact of the findings on the three capitals.

¹³ <http://www.ccsassociation.org/why-ccs/affordability/>



Step 5: Reflection

Short term (up to 2020). Cement production in UK in 2010 was 7,900,000 metric tons¹⁴. If this stays the same up to 2020 and only cement replacement technologies are applied, reductions of 30-40% of CO₂ and embodied energy are possible. Supply of fly ash over this period is adequate and the cost reduction makes this option attractive to the industry.



Longer term (2050). The anticipated increase in cement production with associated carbon emissions and the expected decline in coal-fired power stations (and thus fly ash) make the short term solution questionable in the longer term; it also fails to meet the EU commitment for carbon reduction by 2050. Carbon capture and storage can overcome this but at a cost that maybe unacceptable to the industry.

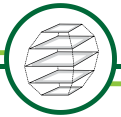
In the past research and development on energy-efficient building focussed on heating and cooling. Progress with these has been so great that academic research is now turning to the embodied energies and carbon footprint of the materials of the building itself: the Zero Carbon Building project, for instance, explores not only the use of industrial wastes (fly ash or slag) but also new formulations for cement-like materials..

Related projects.

Other related projects include MgO cement replacement technology, higher percentage of cementitious substitution, carbon capture and storage development, fuel switching to biomass and oxygen enrichment technology¹⁵.

¹⁴ https://en.wikipedia.org/wiki/List_of_countries_by_cement_production

¹⁵ https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/416674/Cement_Report.pdf



Sustainable Development Teaching Resources

Case studies

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

Resources

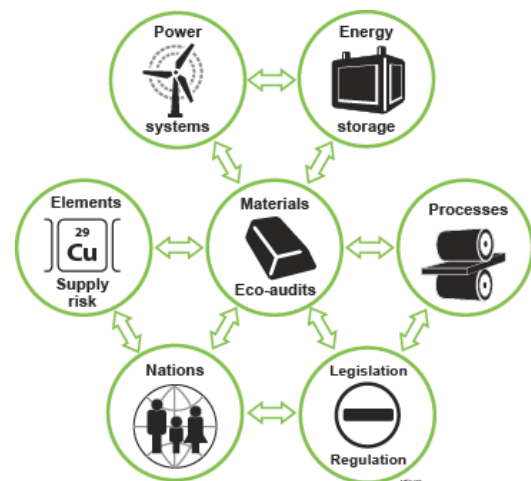
- Granta Teaching Resource Package: Assessing sustainable developments – a Tool Kit (coming up)
- PowerPoint presentations
- Explanatory handouts
- Templates
- Micro-projects

The CES EduPack Sustainable Development Edition

The Sustainability Database of the Sustainable Development Edition in CES EduPack 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 book “Materials and Sustainable Development” (ISBN-13: 978-0081001769) and a Granta Design White Paper of the same name (describe this method and its applications in more detail).

<http://teachingresources.grantadesign.com/Type/Papers/PAPSSDEN13>



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www.grantadesign.com/education