



Granta EduPack White Paper

Materials and Sustainable Development

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1. Introduction.

This White Paper presents a method and a new resource for introducing ideas of Sustainable Development into the teaching of materials science and engineering. Section 2 provides initial background. Section 3 lays out the method. Section 4 describes the structure and content of a database to support the teaching of sustainable development. Section 5 shows what is in the database via examples of its use. Section 6 illustrates the method with Case Studies exploring two contemporary developments—wind farms and electric cars—that, while simplified, illustrate the method and database in operation. Section 7—the Conclusions—reminds us that the method and resources provide a jumping-off point for analyzing the contribution of a technology to sustainable development, but that they cannot do everything; any in-depth analysis will need further research. The White Paper ends with suggested Exercises for project and team-work.

“Sustainability” is not a simple parameter that can be quantified and optimized in an engineering design. It has many facets—material and energy resources, environment, society, regulation, equality, and human rights, among others. Thus issues of sustainable development are intrinsically complex; their assessment requires acceptance of this complexity and working with it. Individual facets can be explored in a systematic way but the integration of the facets to give a final assessment requires reflection, judgment, and debate.

The aim here is to introduce ways of exploring sustainable development to students of Materials Science and Engineering at the Bachelors and Masters levels in a way that avoids simplistic interpretations and approaches complexity in a systematic way. There is no completely “right” answer to questions of sustainable development—instead, there is a thoughtful, well-researched response that recognizes concerns of stakeholders, the conflicting priorities and the economic, legal, and social aspects of a technology as well as its environmental legacy. There is a risk that computer-based tools are seen as engines that deliver a single metric—an Index of Sustainability, for instance. That is not the intent here. Rather it is to improve the quality of discussion¹ by providing guided access to relevant data.

Before continuing it is helpful to introduce a distinction. “Sustainability” is an absolute term—something sustainable survives, something that is unsustainable does not. “Sustainable development” is a relative term: sustainable development is development that moves us from the present state towards a more nearly sustainable state; thus the base-line is today’s technology; the “development” refers to changes in that technology. This White Paper is about the analysis of technology that claims to contribute to sustainable development.

2. Sustainable technology.

Here is a much-quoted definition of sustainable development.

“Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. (The Brundtland Report of the World Council on Economic Development (WCED, 1987)).

It sounds right. But how is it to be achieved? And where do Materials fit in? The definition gives no concrete guidance.

So let's try another view of sustainability, one expressed in the language of accountancy: the Triple Bottom Line or 3BL (Figure 1). The idea is that a corporation's ultimate success and health should be measured not just by the traditional financial bottom line, but also by its social/ethical and environmental performance. Instead of just reporting the standard bottom line of the income and outgoings ("Prosperity") the balance sheet should also include the bottom lines of two further accounts: one tracking impact on the environmental ("Planet") and one tracking the social ("People") balance. In this view, sustainable business practice requires that the bottom lines of all three columns show positive balances, represented by the "Sustainable" sweet-spot on Figure 1. Many businesses now claim to implement 3BL reporting; indeed the Dow Jones Sustainability Index (Dow Jones, 2012) of leading industries is based on it. But is it really possible for all three bottom lines to be positive at the same time? And again: where do Materials fit in? The 3BL concept does not give clear guidance.

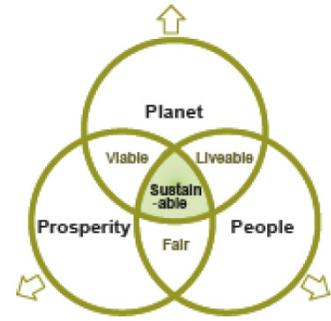


Figure 1.
Triple Bottom Line,
or "PPP" thinking.

The three capitals. We make better progress if we separate circles of Figure 1 and unpack their content, so to speak. Here a view of sustainability seen through the lens of economics can help (Dasgupta, 2010). Global or national "wealth" can be seen as the sum of three components: the net manufactured capital, the net human capital and the net natural capital. They are defined like this.

- *Manufactured capital* — Industrial capacity, institutions, roads, built environment and financial wealth.
- *Human capital* — Health, education, skills, technical expertise, accumulated knowledge, happiness.
- *Natural capital* — Clean atmosphere, fresh water, fertile land, productive oceans, accessible minerals and fossil energy.

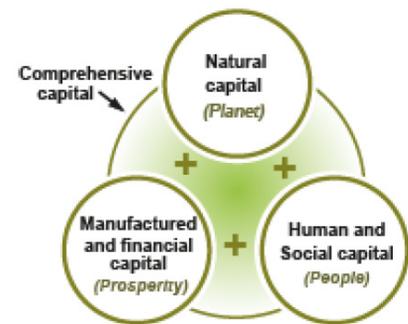


Figure 2.
The three capitals
and their sum.

All² can (with some difficulty) be quantified in a common measure, \$, say. The sum of all three, the *net comprehensive capital*, is a measure of national or global wealth (Figure 2).

Assigning precise values to the growth or decline of each capital has obvious difficulties. But it is possible to assign a *sign* and *order of magnitude* to the change in each capital, reporting whether it is positive or negative, large or small. "Strong" sustainability, in this picture, is development that delivers positive growth in all three capitals. "Weak sustainability" is development that delivers positive comprehensive capital, ensuring that the sum of the capitals passed on to future generations is positive, even if one of them is diminished.

² Prof. Karel Munder (private correspondence) points out that both human and manufactured capitals have certain decay-time: people die, a new generation have to be educated; machines wear out and require maintenance or replacement. So keeping human and manufactured capital constant requires a flow of resources. Does the natural capital provide sufficient interest (via the ability to capture the sun's energy in plants and animals, and via the capacity of oceans and soil to absorb emissions) to provide resources to maintain the other capitals?

The main force, today, that drives change in the three capitals is the pressure for economic growth. An economy that grows is seen as healthy; one that does not is stagnant, and one that is in recession is sick. Positive economic growth is seen as so essential to the welfare of a nation that its influence on natural and human capitals is sometimes treated as secondary. Economic growth may contribute to human capital by enabling greater education and health care, for instance, or it may diminish it by encouraging unfair labor practices and social inequity. And unfettered economic growth must, in the long run, diminish natural capital by consuming irreplaceable resources³.

Competing articulations of sustainable development. Perceptions such as these have stimulated activities to diminish the undesired impacts of economic growth—particularly to diminish resource consumption and emission-release. These activities, of which there are many examples, are presented by their proponents as contributions to sustainable development. Each has a particular motivation—to reclaim scarce elements from mobile phones, for example, or to reduce the carbon emissions from cars. Following Mulder et al (2011) we will refer to them as “articulations” of sustainable technology. The difficulty with almost all of them is that they conflict: an articulation that addresses one facet of the problem may aggravate another.

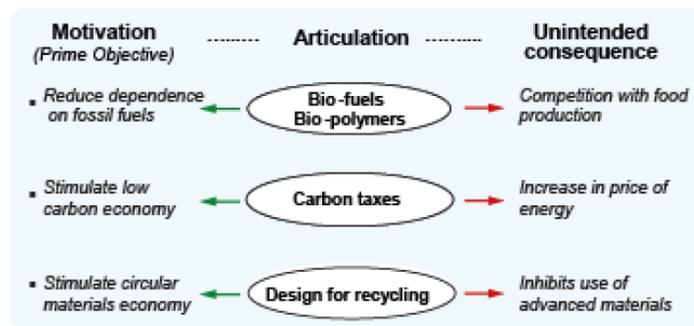


Figure 3. Competing articulations of sustainable technology conflict. The Motivation provides the Prime Objective.

Figure 3 gives examples. Advocates of *bio-fuels* and *bio-polymers* do so because they diminish dependence on fossil hydrocarbons, but the land and water required to grow them is no longer available for the cultivation of food. *Carbon taxes* are designed to stimulate a low-carbon economy, but they increase the price of energy, and hence of materials and products. *Design for recycling* is intended to meet the demand for materials with less drain on natural resources, but it constrains the use of light-weight composites because most cannot be recycled. The motivation for *ethical sourcing of raw materials* (sourcing them from nations with acceptable records of human rights) is that of social responsibility but a side-effect is to increase the prices paid for resources and may deprive subsistence workers of work. The many different articulations of sustainable technology aim to support one or another of the three capitals of Figure 2,

³ We are grateful to Prof. Peter Goodhew (private correspondence) who points out that there are things that we would not wish to grow. The most obvious are probably: global population, use of non-renewable energy, use of non-renewable materials (that’s most of them), the CO₂ or CH₄ content of the atmosphere, and – for a stable society – the wealth-gap between rich and poor and the level of unemployment. A reduction in any of the first four becomes a positive contribution to Natural Capital; a reduction in the final two becomes a positive contribution to Human Capital.

but they generally address a single facet of a multi-faceted challenge and very few support all three nor, often, do they support each other.

Thus sustainable technology is not one thing, it is many. The more narrowly it is articulated, the more neatly it fits into the discipline-organized structure of University departments and (often) corporate interests. But this narrow view is a dangerous one that can inhibit consensus for real progress. Examination of the some 65 articulations (documented in Appendix 1) suggests the following picture. Each articulation has a motivating target that we will refer to as its “Prime Objective” (left hand column of Figure 3). Each involves a set of Stakeholders. In assessing the sustainability of a project the first step is to identify these: if the Prime Objective is not achievable or major Stakeholders are left dissatisfied, the project is unlikely to be sustainable. Further examination suggests that the central issues might be grouped under the six broad sectors shown in Figure 4. Each heads a check-list for what might be called “sustainability analysis” of a design, scheme, project, or product:

- Materials and Manufacture: supply-chain risk, life-cycle recycle potential.
- Design: product function, performance, safety.
- Environment: energy efficiency, bio-efficiency, preserving clean air, water, and land.
- Regulation: awareness of, and compliance with, National and International Agreements, Legislation, Directives, Restrictions, and Agreements.
- Society: health, education, shelter, employment, equity, happiness.
- Economics: the cost of the project, the benefits that it might provide.

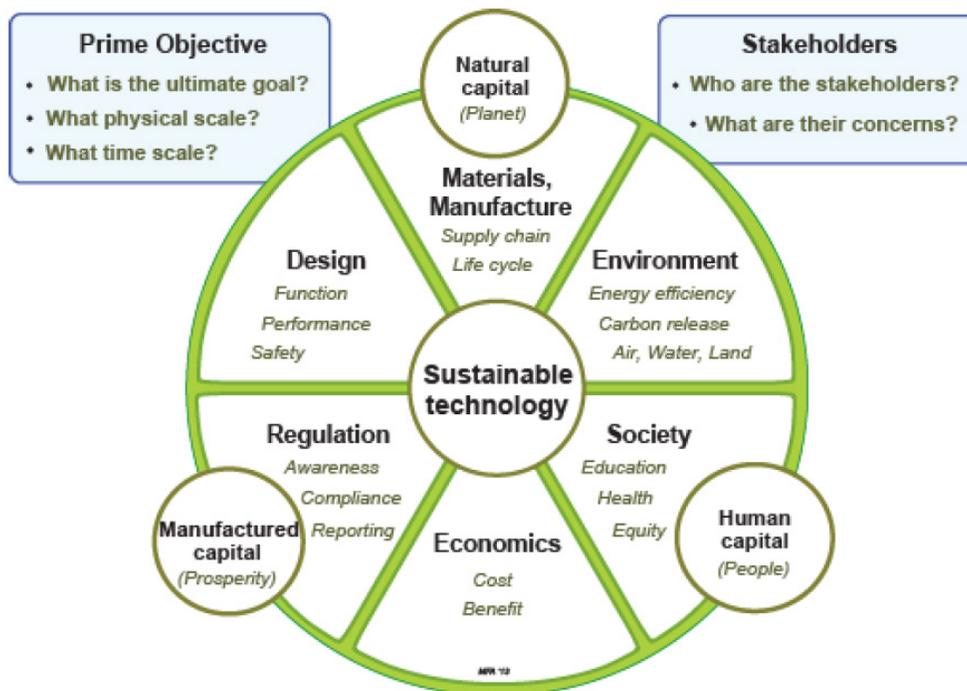


Figure 4. Necessary components of sustainable technology

3. Analyzing articulations of sustainable development—the method

This reasoning suggests a five-step strategy, illustrated in Figure 5, for sustainability assessment of a design or project (articulation) that claims to contribute to sustainable development. The steps are summarized here and detailed in Appendix 2 with check-lists to guide their implementation.

Any articulation of sustainability has an underlying motive—a *Prime Objective*—with both a physical scale and a time scale. If the articulation is going to make a significant difference the physical scale is likely to be large and may demand significant natural resources. Thus the first step is to *clarify the Prime Objective and its scale, physical and temporal*.

Stakeholders are involved. If their concerns are not addressed the articulation will face opposition and may fail to gain acceptance. The second step, then, is to *identify the stakeholders and their concerns*—they set the context in which the assessment is carried out.

The third step is one of *fact-finding*. The questions posed by the six headings in the cart-wheel of Figures 4 and 5 are straight-forward and factual. Each can be researched; relevant information can be assembled from generally-available books, databases, and the Internet, guided by check-lists. Conclusions about each can be drawn from this information in an objective way. The database described in the next Section is designed to help with this step.

The fourth step, *integration*, is one of informed debate, drawing together the six blocks of information from Step 3 to form a balanced judgment about their impacts on the three capitals. Each capital has a base-value. The technology, if implemented, will change these values. If the changes increase human and manufactured capital and reduce the drain on natural capital, and do so on a non-trivial scale, the technology makes a contribution to a more sustainable society. If positive change in one capital comes at the expense of increased drain on another, the relative merits require further examination.

The fifth and last step is that of *reflection on alternatives*. Is the Prime Objective achieved? Does it do so on a scale that makes a significant difference? Do the negative impacts on the three capitals outweigh the benefits? Have the stakeholders concerns been met? Can the analysis suggest a new, less damaging, way of achieving the Prime Objective? There is no completely “right” answer to questions of sustainability—instead there is a thoughtful, well-researched response that recognizes the many conflicting facets and seeks the most productive compromise.

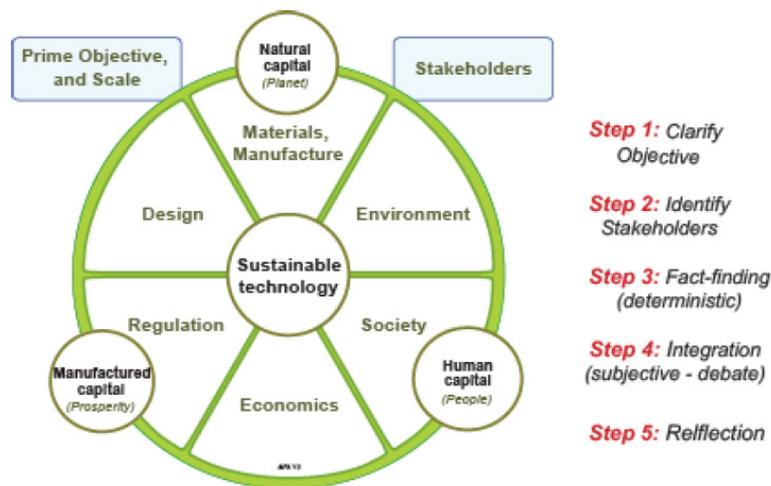


Figure 5. The five-step sustainability analysis of technology

The method is designed to help teachers introduce students to sustainability analysis in a simple, progressive way. The Sustainability database, described next, provides initial background information for the fact-finding step, guided by a check list. The Case Studies of Section 6 illustrate it in operation.

4. A database to support the teaching of sustainable materials technology.

The Granta EduPack Sustainability database package provides a computer-based resource for assessing articulations of sustainable technology and the place of materials in them. There is an Introductory and an Advanced version. The first gives access to a limited body of information; it is useful as a lead-in. The second is more comprehensive and allows in-depth studies like those of Section 6.

The Introductory version is an expansion of the **Granta EduPack Level 2** database to include three major additions. The first is a data-table of **Regulation**, listing legislation, regulations, and incentives to encourage or restrict the use of materials or of practices such as recycling that relate to material use. The second, the **Nations of the World** data-table, contains records for the world's 210 nations, with data for population, governance, economic development, energy use, and engagement with human rights, together with information that may bear on security of supply and the ethical sourcing of materials. The new data-tables are linked to the pre-existing Materials and Process Level 2 data-tables, allowing individual materials to be linked to legislation that affects them and to the nations from which they are sourced. The materials records themselves have been expanded to include a ranked list of the **Countries of Origin** and a **Critical Material status**. The upper part of Figure 6 shows the structure.

The Advanced version links the new **Regulation** and **Nations** data-tables to the much larger pre-existing Level 3 Materials and Processes data-tables. Here, too, materials records have been expanded to include a ranked list of the **Countries of Origin** and a **Critical Material status**. The Materials data-table has further links to two further data-tables relating to energy: one with records for **Electric-Power generating systems**, the other for **Energy Storage systems**. The lower part of Figure 6 shows the structure.

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 concerns, etc.). The individual data-tables shown in Figure 6 are explained in the paragraphs that follow.

Materials and Processes data-tables. These are expanded versions of the standard *Granta EduPack Level 2 with Eco properties* database and the *Granta EduPack Level 3 Eco Design* database. There are two additions to the Materials records. First, each of the Metals records now contains a ranked list of the principal nations from which it is sourced and the annual production of each source-nation. The records are linked to records in the nations of the World data-table from which they are sourced. The second is a material-criticality rating. The mineral resource bases from which most metals are drawn are so large and widely distributed that the health of the supply-chain is not a present concern. The resource bases supporting the steel and aluminum industry are examples—both are vital to the economy, but it is the resource of energy rather than that of material that could limit their production. The supply-chain for others, however, gives cause of concern for one or more of the following reasons.

- The material suffers from supply-chain concentration or constraint, meaning that a large part of global production derives from one or a small number of nations, or is produced as a by-product of the production of another metal, making it difficult to scale-up production.

- The material is sourced from nations from which supply might be withheld for political reasons.
- The production of the material causes unacceptable environmental damage.
- Revenues from material production are used to fund conflict or oppression ("conflict minerals").
- The price is unusually volatile.

Governments classify materials as “strategic” and stock-pile them if they are critical in the ways just described and are of national importance for the economy or national security.

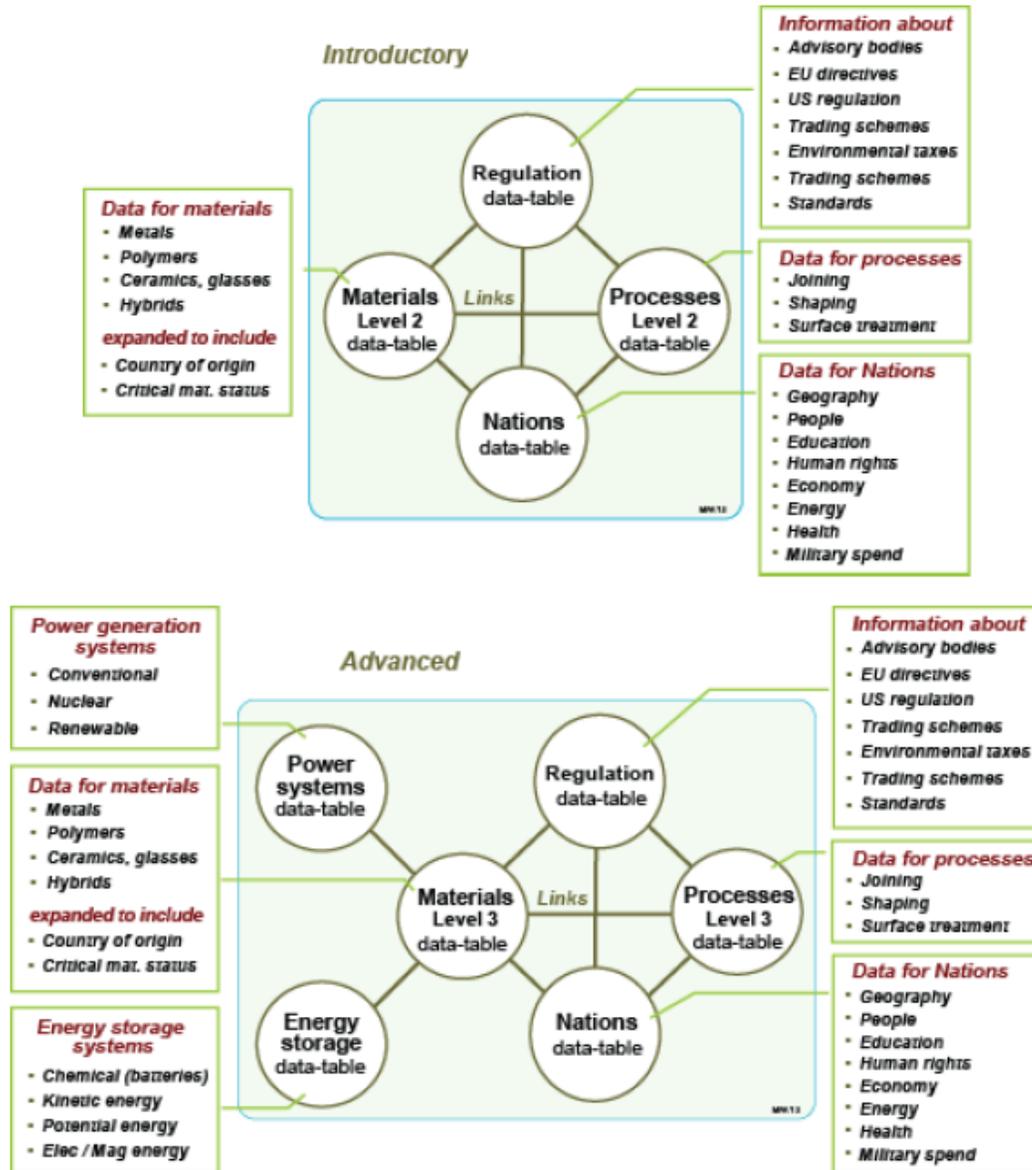


Figure 6. (top). The structure of the Introductory Sustainability database; **(bottom)** the structure of the Advanced Sustainability database

The Regulation data-table. The upper-right text box on Figure 6 lists the folder headings in the Regulation data-table, which summarizes legislation, standards, and taxation and incentive schemes that might influence the use and disposal of products and materials. Figure 7 shows a typical record: here, a summary of the European ELV Directive mandating recycling targets for vehicles. Other records include the US CAFE rules, which impose upper limits for the fleet-average emissions from vehicles. The VOC directive of the EU restricts the ways in which paints with volatile organic solvents are used. The Waste Electrical and Electronic Equipment (WEEE) Directive sets collection, recycling and recovery targets for electrical goods; it requires producers to finance the collection, recovery and safe disposal of their products and meet certain recycling targets. Projects that fail to conform to legally binding legislation are not sustainable.

End-of-Life Vehicles (ELV)

Summary of legislation

End-of-Life Vehicles (ELV, 2000). The European Community Directive, EC2000/53, establishes norms for recovering materials from dead cars. The initial target, a rate of reuse and recycling of 80% by weight of the vehicle and the safe disposal of hazardous materials, was established in 2006. By 2015 the target is a limit of 5% by weight to landfill and a recycling target of 85%. The motive is to encourage manufacturers to redesign their products to avoid using hazardous materials and to maximize ease of recovery and reuse.

Relevant sector

Automobile industry. (European Union Directive requiring take back and recycling of vehicles at end of life.)

Enacting Country

European Union

Reference

ELV (2000) The EC 2000/53 Directive on End-of-life vehicles (ELV) Journal of the European Communities L269, 21/10/2000, pp. 34 - 42.

<http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:2000L0053:20050701:EN:PDF>

Figure 7. A record in the Legislation and Regulations data-table.

The records cover Materials-related standards, legislation, regulation, taxation and incentives.

The Nations of the World data-table⁴. The Nations data-table contains information for the 210 Nations of the World. Figure 8 shows a typical record. It opens with a map and flag. This is followed by data for geography and population, indicators of wealth, well-being, economic development, and respect for law and human rights. Each field-name is linked to an attribute-note explaining its relevance and source. The use of the Nations data-table is demonstrated in Section 5.3 and the case studies of Section 6.

⁴ The Nations data-table is expanded from one first compiled by Wanner (2008).

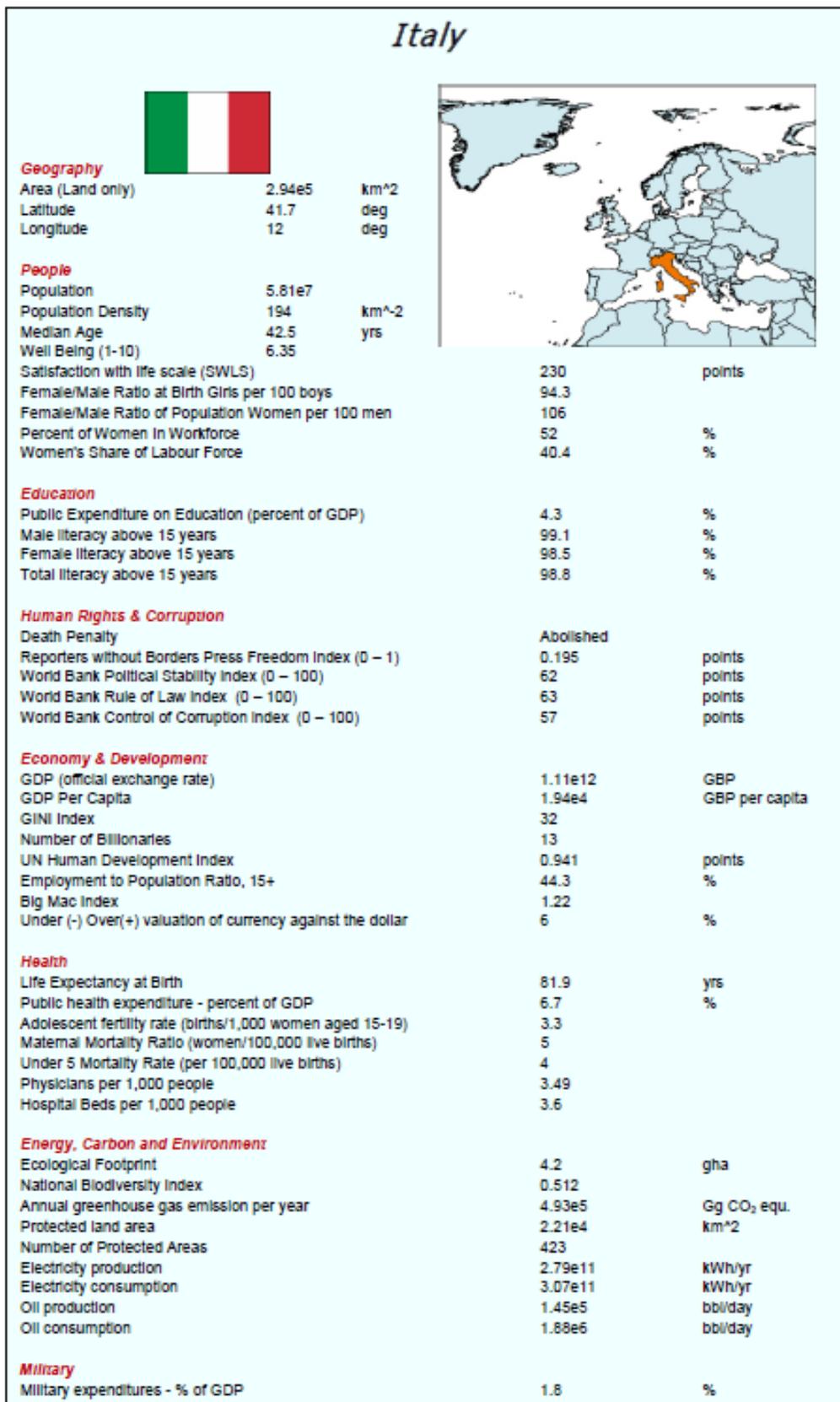


Figure 8. A typical record for a State, including a map and flag. Explanations of the field names are accessed by double-clicking on the field name.

The Power Systems data-table. Energy is central to any discussion of sustainability. The wish to decarbonize electric power generation has stimulated interest in low-carbon and renewable-energy sources. Proponents claim that one or another such system is viable and more “sustainable” than conventional fossil-fuel based systems; opponents argue the opposite. This data-table provides facts about power-generation systems in a consistent set of units.

Figure 9 shows a typical record. The Wind Farm case study of Section 6 contains an example of its use. The data-table is documented full in the Granta White Paper on Low Carbon Power Systems, which can be downloaded from the Help menu of Granta EduPack.

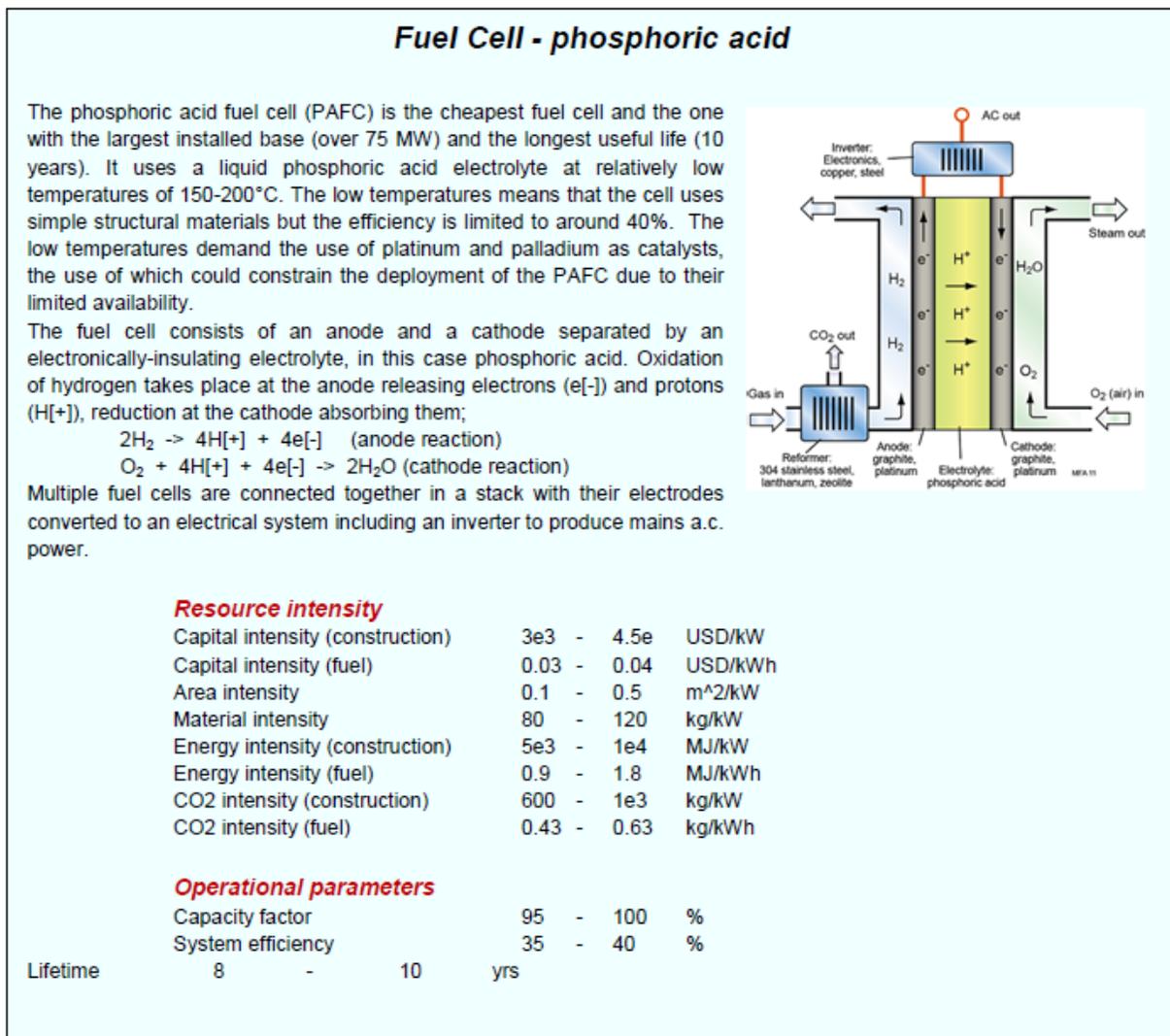


Figure 9. A typical record for a power-generation system, here a phosphoric-acid fuel cell.

The Energy Storage Systems data-table. Energy storage is of central importance in two important sectors.

- When energy is generated intermittently and its generation and consumption are not synchronized, the energy must be stored until it is needed. Grid-scale energy storage is a major challenge in deploying renewable energy systems, most of which are intermittent.
- Most transport systems carry the energy required to propel them. At present most such systems are driven by hydrocarbon fuels. Any attempt at decarbonizing transport faces the challenge of storing the necessary energy in a portable form.

This data-table contains facts about energy storage systems in a consistent set of units. Figure 10 shows a typical record. The Electric Car case study of Section 6 contains an example of its use. The data-table is documented fully in the Granta White Paper on Energy Storage Systems, which can be downloaded from the Help menu of Granta EduPack.

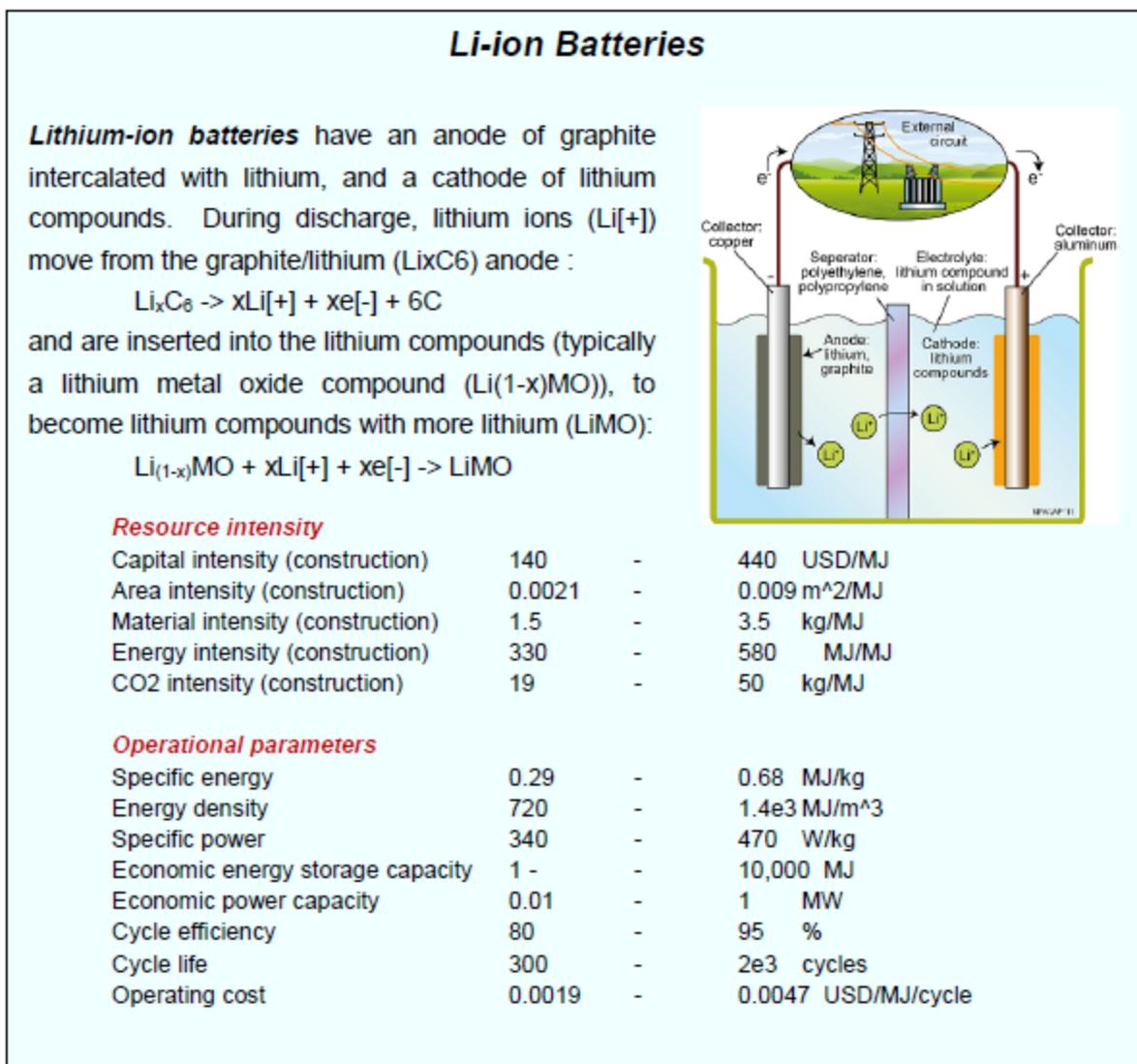


Figure 10. A typical record for an energy-storage system, here Lithium-Ion batteries.

5. Using the Sustainability database.

The Granta EduPack Sustainability database is a resource that gives rapid access to information for assessing sustainable technology. It cannot provide all the information, since some depend on local context and the details of the technology, but it provides a starting point. We start by showing what the individual data-tables can do (using the Advanced version throughout), then proceed, in Section 6, to Case Studies that use several of them. Each example is phrased as a question (Q) followed by the Answer provided by the database.

5.1 Using the expanded Materials and Processes database.

Q1. Platinum. From which nations is Platinum sourced? What is its Material Criticality status? Why does it have this status?

Answer. The table, copied from the Platinum record in the Materials data-table, lists the main producing countries. Over 72% derives from a single nation, South Africa. This is an example of supply-chain concentration, a cause for concern for users of Platinum. The Critical Material status of Platinum is very high. This is partly because of supply-chain concentration and partly because of the abundance risk. Each of the Nations in this list is linked to its record in the Nations data-table, providing economic, political, and social background.

Producing Nation	Platinum Tonnes/yr, 2011
South Africa	139,000
Russia	26,000
Canada	10,000
Zimbabwe	9,400
United States	3,700
Colombia	1,000
Other countries	2,500
World	192,000

Q2. Sourcing cobalt. You are consulted by a steel-maker who wishes to make a special steel with 5% Cobalt content. What can you tell them about the risk to supply of Cobalt? Trace the Material Criticality status of Cobalt to the nation from which the most of it is sourced. What can you discover about the stability and governance of this nation?

Answer. The table, copied from the Cobalt record in the Materials and Processes database, lists the main producing nations. More than half the world's Cobalt is sourced from the Democratic Republic of the Congo, meaning that the supply-chain is heavily dependent on a single source. Following the link to D R Congo record in the Nations data-table reveals that this nation has disturbingly poor ratings for Rule of Law and Control of Corruption. There are on-going conflicts that may be funded by mineral sales.

Cobalt-producing Nation	Tonnes/year 2011
Congo, Republic of	52,000
Canada	7,200
China	6,500
Russia	6,300
Zambia	5,700
Australia	4,000
Cuba	3,600
Morocco	2,500
New Caledonia	2,000
Brazil	1,700
Other countries	7,000
World	98,000

Minerals.usgs.gov/minerals/pubs/commodity

Q3. Critical elements. Which metals have a criticality ranking of *Very high risk*? Use the Materials data-table to find out.

Answer. The attribute-note for the “Critical material” field in the Materials data-table describes what is meant by Critical status and summarizes the applications of materials listed as “critical”. Alternatively, a search of the Materials data-table using a Limit stage to select materials ranked “very high risk” in Critical Status delivers the list shown here.

Materials with <i>very high</i> Criticality status		
Antimony	Bismuth	Cadmium
Cerium	Dysprosium	Iridium
Europium	Gadolinium	Gold
Holmium	Lanthanum	Lutetium
Mercury	Neodymium	Niobium
Platinum	Praseodymium	Rhenium
Rhodium	Samarium	Scandium
Tantalum	Tellurium	Terbium
Thulium	Ytterbium	Yttrium

Q4. Mining discarded electronics⁵. Mobile phones contain critical elements. The concentrations of five of these are listed in the adjacent table. Use the Materials data-table to retrieve the typically-mined ore grade for these elements. Do their concentrations in phones equal or exceed those of the ores from which they are currently extracted?

Answer. The table below repeats the concentrations of critical elements in mobile phones (expressed as wt%) and compares it with their concentration in their ores. The concentration of all five elements in phones is larger than the typical grade of ore from which they are at present extracted. This suggests that “mining” waste electronics might provide a viable source of critical elements. There are, however, practical problems of collection, separation, and refinement to be overcome.

Critical elements	Grams per tonne in mobile phones
Platinum	70
Gold	140
Silver	1,300
Cobalt	19,000
Copper	70,000

Critical elements	Concentration in mobile phones, wt %	Typically mined ore grade, wt %
Platinum	0.07	0.00025
Gold	0.014	0.0018
Silver	0.13	0.055
Cobalt	1.9	0.5
Copper	7	2.6

5.2 Using the “Legislation and Regulations” data-table.

Q5. European Directives. What does the WEEE Directive of the European Commission say? Use the **Browse** or the **Search** facility of the Sustainability database to query the Regulations data-table to find a summary. Then follow the link to the web site that presents the Directive itself.

Answer. The WEEE Directive (EC 2002/96 and 2003/108) sets collection, recycling, and recovery targets for electrical goods. It is part of a legislative initiative to solve the problem of toxic contamination arising from waste electronic products (www.environment-agency.gov.uk/business/topics/waste/32084.aspx).

⁵ http://www.electronicstakeback.com/wp-content/uploads/Facts_and_Figures

Q6. REACH. What is the REACH Directive? Which Nations apply this Directive or one like it? Search on REACH in the Legislation and Regulations data-table to find out.

Answer. The Search facility of Sustainability database brings up two relevant records, one for the European Registration, Evaluation, Authorization and Restriction of Chemical Substances Directive (REACH) and one for the Chinese equivalent known as China REACH. The Directive places responsibility on manufacturers to manage risks from chemicals and to find substitutes for those that are most dangerous. Manufacturers in Europe and importers into Europe who use a restricted substance in quantities greater than 1 tonne per year must register the use. The list is long—it contains some 30,000 chemicals, many of them used in materials extraction and processing.

Q7. Landfill tax. What is a land-fill tax? Approximately how much does it cost to send building waste to landfill in Europe? Use either the **Browse** facility or the **Search** facility (search on *Landfill*) to find out.

Answer. Landfill Tax is a tax on the disposal of waste. It aims to encourage waste producers to recover more value from waste, for example through recycling or composting, and to use more environmentally friendly methods of waste disposal. The UK landfill tax in 2012 stands at £64 per tonne.

Q8. CAFE rules. What are the US CAFE rules? Is there a European equivalent?

Answer. The CAFE rules are found by **Browsing** the Regulation data-table or by **Searching** on the word CAFE. Here is what is found.

The US Energy Policy Conservation Act of 1975 established the Corporate Average Fuel Economy (CAFE) standards, penalties, and credits. The motive was to raise the fuel efficiency of new cars sold in the US from an average of around 15 mpg (miles per US gallon) to 27.5 mpg by 1985. The Energy Independence and Security Act, passed 22 years later (2007) raised the bar, aiming for a progressive increase to 35 mpg by 2020.

A further search for Regulations relating to Transport brings up both the CAFE rules and the equivalent European Regulation, the EU Automotive Fuel Economy Policy Directive (EC) No 443/2009 of the European Parliament, which sets emission standards for new cars.

5.3 Using the Nations data-table

Q9. Corruption and human rights. At the time of writing Julian Assange, founder of Wikileaks, is resisting extradition to Sweden where he faces criminal charges and has sought asylum in Ecuador to avoid them. In an article in the *Times* (*Monday 20 August 2012*), he is quoted as praising Ecuador for being a “courageous Latin American Nation that took a stand for justice.” Research the justification of this statement by comparing the World Bank *Control of Corruption index* and the Reporter without Borders *Press Freedom Index* of Ecuador with those of Sweden. (Similar methods can be used to investigate Nations from which materials are sourced.)

Answer. The table shows the rankings for Sweden and Ecuador. Sweden ranks No 3 for control of corruption and No. 12 for press freedom. Ecuador, by contrast, ranks much lower. It appears that, by these two measures at least, Sweden has a rather better record of justice and free speech than Ecuador.

State	Control of Corruption Index (0 = poor, to 100 = excellent)	Press Freedom Index (0 = free, to 1 = constrained)
Sweden	99	0.03
Ecuador	20	0.1

Q10. Wealth and Natural capital. Globally, affluence is increasing. What influence does this have on the drain of Natural Capital? The Gross Domestic Product (GDP) per capita is one measure of affluence per person. The Ecological Footprint is measure of the human impact on Natural Capital, per person. It is measured in “global hectares” (gha), thought of as the productive land area per person if all was shared equally. The productive capacity of the Planet can provide the present population (7 billion) 2.1 gha per person. A Nation with an average ecological footprint greater than this value greater than 2.1 gha is consuming more than its fair share. Plot Ecological footprint against GDP per capita to find the answer.

Answer. Increased affluence, if shared and appropriately invested, has the potential to increase Human and Manufactured capital but the plot of Ecological Footprint against GDP per capita, shown in Figure 11 strongly suggests that increased affluence causes a greater drain on Natural capital.

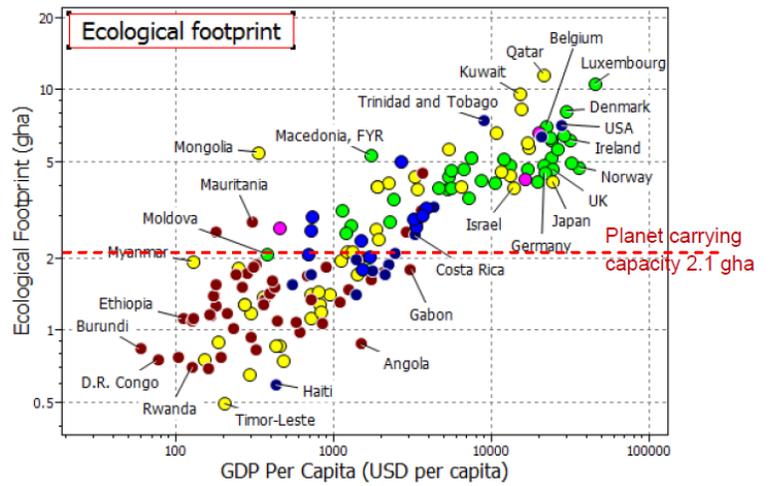


Figure 11. The ecological footprint of Nations (the globally productive area in hectares required per person) plotted against GDP per capita. The planet’s productive capacity is 2.1 gha per person.

Q11. Wealth and Provision of Healthcare. Does the drain on Natural capital with increasing GDP per capita, demonstrated in the previous example, allow a compensating increase in human capital, as measured by education or length of life? Plot Life expectancy against GDP per capita, using a linear scale for Life expectancy, to find out.

Answer. Figure 12, made with the Nations data-table, shows that increased GDP increases at least one aspect of Human Capital—here measured by life-span.

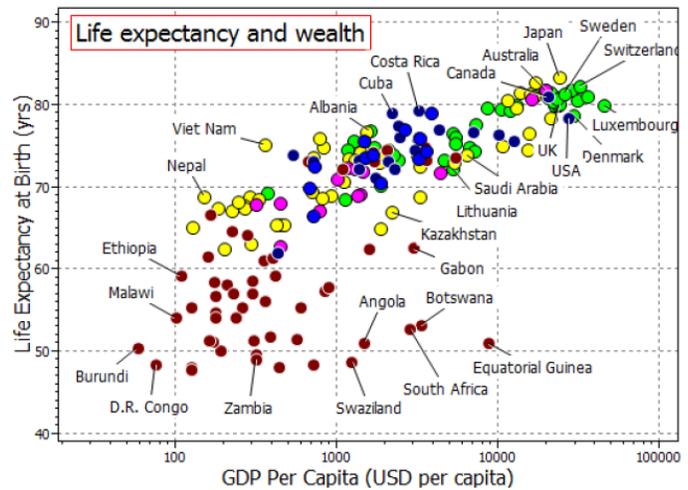


Figure 12. Life expectancy of Nations plotted against GDP per capita.

Q12. Wealth and happiness. Does money buy happiness? Plot the Satisfaction with Life Scale against GDP per capita, using a linear scale for Satisfaction, to find out.

Answer. Figure 13 shows the plot. Globally, the correlation is poor. But if the data for Europe, the green dots, is examined, a clear correlation emerges. It is interesting to ask why Austria is so happy and France and Japan so miserable on almost the same per capita GDP. Also to ask why the Satisfaction with Life in Butan, Malta and the Bahamas (all with GDP per capita below \$20,000) is the same or better than that in Luxembourg, with GDP per capita of \$70,000.

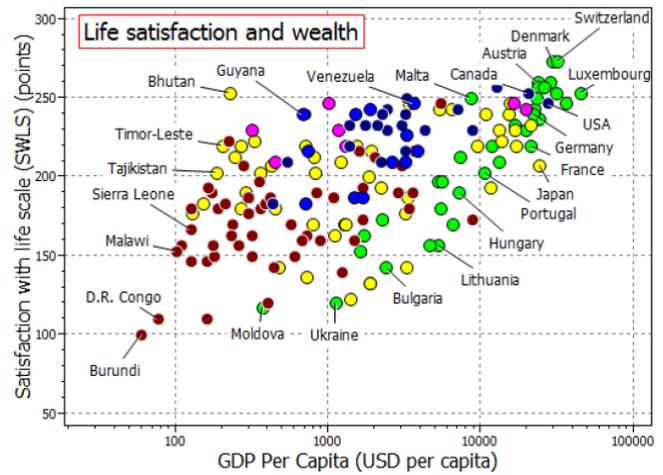


Figure 13. Satisfaction with life and GDP

Q13. Wealth and Human Development. Does increased Manufactured Capital enable Human Development? The UN Human Development Index (a combined measure of health, education, and welfare) is a measure of Human capital; GDP per capita is a measure of Manufactured capital. Plot one against the other to find out.

Answer. Figure 14 shows the plot. It would seem that the growth in per capita GDP up to about \$40,000 (in 2008 \$) enables human development; beyond that, it flattens out.

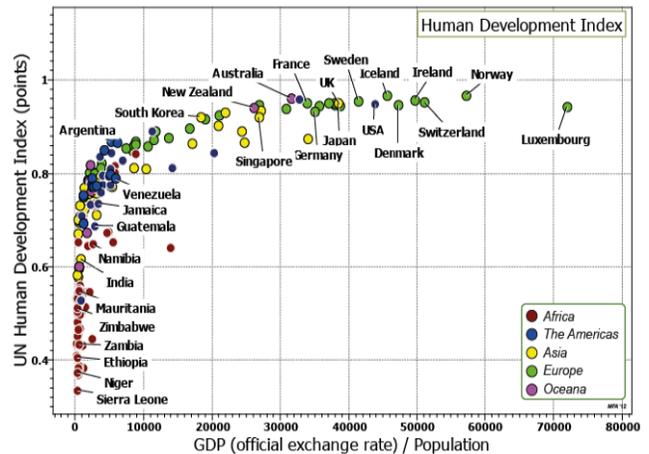


Figure 14. The UN Human Development Index, plotted against GDP per capita.

Q14. Global financial resources. Dealing with emerging global challenges—energy provision, provision of fresh water, emission reduction, desertification, or climate change—will be expensive. To get the word “expensive” in perspective, use the data in the “THE WHOLE WORLD” record of the OTHER ENTITIES folder in the Nations data-table to work out the amount that we, globally, spend each day defending ourselves from each other.

Answer. Figure 15 shows the military spend per country per day. At the top left is the Whole World. Globally, we spend about \$2.6 billion each day on defense. The positive side of this number is that, if the world were faced

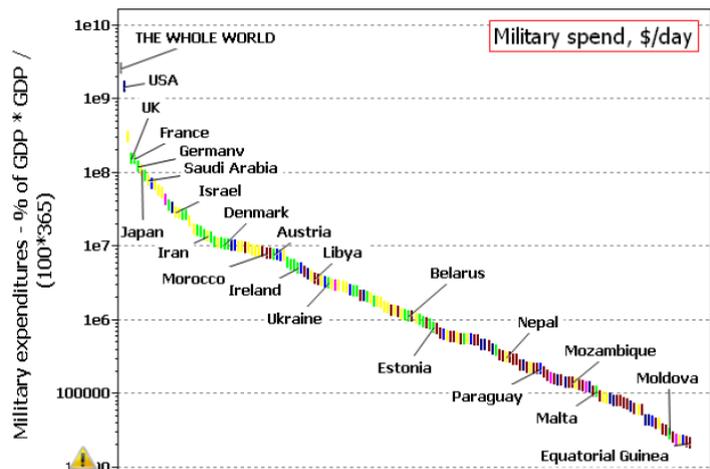


Figure 15. Military spend per day for the Whole World and its Nations

some major global threat, considerable resources could be diverted from the military spend to deal with it if agreement could be reached to do so.

5.4 Using the Power Systems data-table

Q15. Carbon footprint of electrical power generation. Governments invest in alternative power systems to reduce dependence on imported fossil fuels and to reduce the national emissions of green-house gases, particularly carbon as CO₂. How do the carbon footprints of these alternative power systems compare with that of power from conventional coal or gas-fired power stations? Use the Power Systems data-table to find out.

Answer. Figure 16 shows the sum of the carbon per kW.hr released by the fuel and that of construction and maintenance of the plant, prorated over a design life of 20 years. The alternative power systems all have a carbon footprint, but all are lower than that of conventional power systems. (This may not be quite fair. Coal and gas-fired power stations have a design life of 40—50 years. But the dominant source of carbon is the fuel, not the structure, so it makes little difference to the plot.)

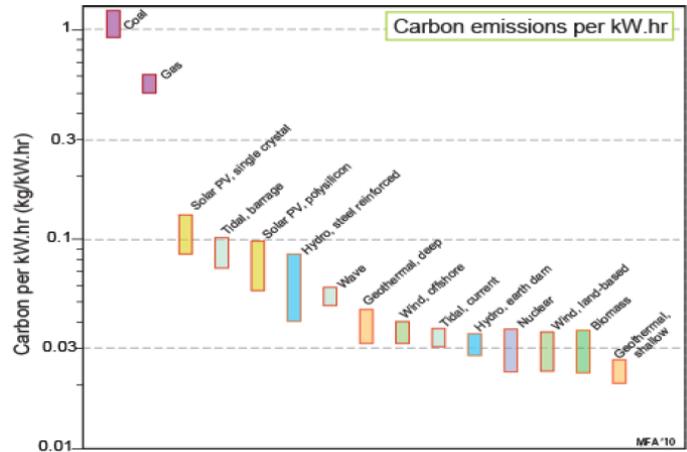


Figure 16. The carbon footprint of power from alternative generation systems.

5.5 Using the Energy Storage data-table

Q16. Energy storage systems for transport. Most transport systems carry the energy they need for propulsion with them. Most are powered at present by oil or gasoline. What alternative energy reservoirs might replace fossil fuels? Use the Energy Storage data-table to find out.

Answer. Figure 17 shows the specific energy of energy storage systems. The energy per kg of gasoline far exceeds that of any alternative system. Lithium-ion or sodium-sulfur batteries, candidates for electric car propulsion, are almost 100 times heavier for the same energy provision. Compressed air, attractive because it is clean and safe, has a still lower energy density.

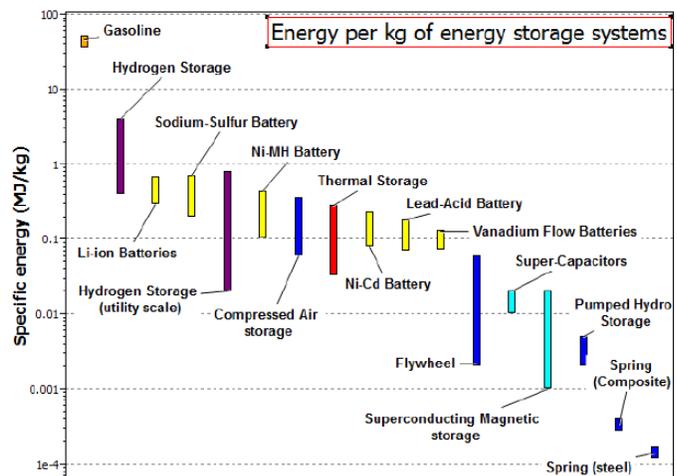


Figure 17. The specific energies of alternative energy storage systems.

6. Case studies assessing technology for sustainable development

These case studies require a more comprehensive way of thinking. There is no “right” answer—instead there is a thoughtful, well-researched response that recognizes the many conflicting facets of sustainable development. Each follows the approach developed in Section 3: a statement of Objectives (Step 1), an identification of Stakeholder concerns (2), a Fact-Finding search (3), Integration of facts to explore their influence on Human, Natural, and Manufactured capital (4), ending with reflection on possible priority changes (5). The first three steps are objective and deterministic; the last two are subjective, and therefore open to debate.

6.1 Wind farms⁶.

Many nations have undertaken to reduce the carbon emissions arising from electric power generation and to seek at the same time to diversify their sources of electrical power. One strategy is to encourage 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.



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—their composition is shown in the adjacent table. Annual construction of 50,000 new turbines per year each requiring 25 kg of Nd creates a demand for 1,250 tonnes of Neodymium per year.

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

Apply the method of Section 3 to analyze the sustainability aspects of wind farms, using the Sustainability database as a source for the Fact-finding step. What are the Prime Objectives and Scale? Who are the stakeholders and what might be their concerns? What materials, design, environmental, regulatory or social issues involved? With this information as background, what opinion can be formed about the effect of wind farms on Human, Natural, and Manufactured Capital? To what extent have the Stakeholders’ concerns have been addressed? Given this information, can a judgment be made of the contribution of wind farms to a more sustainable future?

⁶ Image of wind farm courtesy of www.windjobsuk.com/wind-farm-jobs.cms.asp

The assessment.

Step 1: Prime Objectives and Scale.

They are defined in the project-statement. There are two: to reduce national carbon emissions; and to provide a more diverse portfolio of electric power sources. To make any real difference to emissions, power from wind farms must have a lower carbon footprint than that of conventional power, and it must make a significant (20%, say) contribution to the total, setting an approximate target on the desired scale, at present seen as 50,000 new units per year.

**Prime Objective
and Scale**

Step 2: Stakeholders and their concerns (see Appendix 1 for a check-list).

Stakeholders

The national press reports initiatives to promote wind-farms and the reactions these provoke. The reports identify most of the stakeholders and their known concerns. Here are two examples.

- *“Government and industry slam ‘spurious’ anti-wind farm headlines.”* (The Times, 16 April 2012.) The British government defends its policy of encouraging wind farms.
- *“Strike a blow against wind-farm bullies.”* (The Times, 25 February 2013) A columnist calls for protests against the siting of wind farms in Cornwall, the Lake District and other landscapes he loves.

Stakeholders need to be heard, reassured, persuaded, or compensated if large-scale wind power is to be sustainable. Among them are:

- *National and Local Government.* Many Nations have made commitments to reduce carbon emissions over a defined time period and see wind farms as able to contribute. To encourage their construction, some Nations impose taxes on carbon emissions and subsidize renewable energy projects. The erection of wind farms also creates jobs, attractive to government.
- *Energy providers.* Electricity-generation from fossil fuels releases carbon to the atmosphere. 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.* Developing a manufacturing base for wind turbines requires considerable investment. 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.* There is opposition to land-based wind turbines from communities from which the turbines are audible or visible. Even off-shore wind farms are found objectionable by some. Feed-in tariffs for small-scale generation and compensation for acoustic intrusion aim to make turbines more acceptable.
- *The public at large.* To some, wind turbines are both necessary and beautiful, but others object to them and their associated power distribution systems because the power they generated is intermittent and expensive, because they are visually and acoustically intrusive and because they harm wildlife. They point out that the scale of deployment of wind farms has to be very large if they are to generate a significant fraction (say, 20%) of the nation’s electrical power, and that energy-storage systems to deal with intermittent power generation add cost and require space.

Step 3: Fact-finding.

The Sustainability database can help with some of these concerns. Its Materials data-table provides information about the countries of origin of elements, Neodymium among them. The Nations data-table provides background on the economy and governance of countries from which materials are sourced or manufacture is based. The Regulation data-table identifies government incentives and restrictions that relate to renewable energy. The Low Carbon Power data-table includes the carbon footprint of electrical power systems, including wind. They yield the following information, summarized in Figure 18.

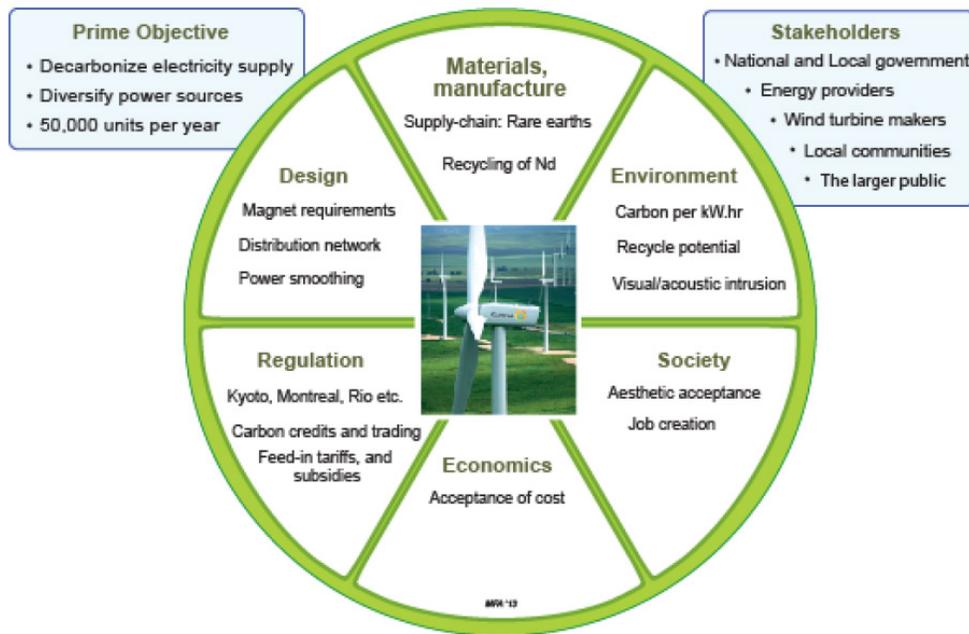


Figure 18. Fact-finding for Wind farms

Materials and Manufacture. Neodymium, Nd, is important in the manufacture of turbines. From which Nations is it sourced? What proportion of global supply will be needed?

Neodymium is co-produced with other rare-earth metals, of which it forms 15% on average. The record for Nd in the Materials data-table lists the main Rare-earth producing countries and the quantities they produce. The global production of Rare earths is 133,600 tonnes per year, giving an annual production of Nd of 20,000 tonnes per year. Over 95% derives from a single Nation, China.

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

Minerals.usgs.gov/minerals/pubs/commodity

The same record lists the Critical Material status of Neodymium as very high risk, meaning that its uniquely desirable properties (for high field permanent magnets) and its supply-chain concentration give cause for concern. The current rate of building wind turbines, given in the question, carries a requirement of 1,250 tonnes of Neodymium per year. This is 6% of current global production. Following the link from Neodymium to the countries that produce it allow their quality of governance, record of human rights observance and freedom from corruption to be explored.

Design. The Materials data-table includes records for magnetic materials. Permanent magnets for electric turbines require high remanent induction with high coercive force. The generated chart of Figure 19 (generated with Granta EduPack) shows these two properties. 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 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 force.

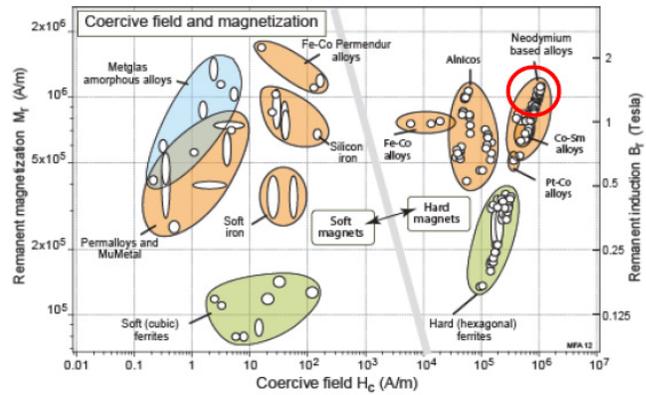


Figure 19. The remanent magnetization and coercive force of magnets, using the Materials data-table. Nd-B magnets are ringed.

The Environment. The Prime Objective of a wind farm is to generate electrical power with low carbon emissions. It meets this objective only if the carbon emissions associated with its construction are more than offset by the low carbon emissions during life to give net emissions per kW.hr that are lower than a conventional fossil-fuel power station. The Low Carbon Power Systems data-table of Sustainability database allows comparison of the carbon emission per kW.hr of delivered power for alternative systems (Figure 20). 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. 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.

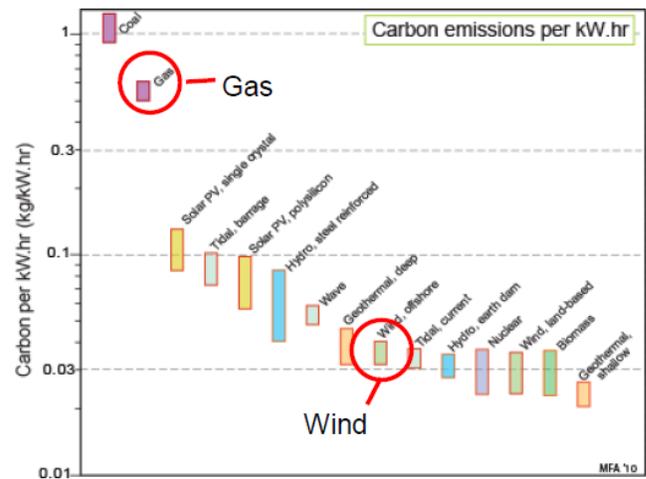


Figure 20. The carbon footprint of electrical power from the Low Carbon Power data-table.

Regulation. The Regulations data-table in the Sustainability database is indexed by industrial sector (automotive, electrical and electronic, energy, etc.) allowing those relevant to renewable energy generation to be located. Those that have relevance for wind farms are listed in the table—see the adjacent table.

Relevant Regulation and Legislation
Carbon off-setting
Carbon tax
Carbon trading
Carbon Trust
Energy Efficient Buildings Directive
Feed-In Tariffs
US Business Investment Tax Credit
US Recovery Act 1603 Program

From these we learn that making and installing wind farms is made financially attractive by “green” subsidies and feed-in tariffs but these have changed (usually down-graded) at short notice, making the market unpredictable.

Society. The manufacture of wind turbines creates jobs. In Europe these jobs are mainly in Denmark, Germany and Spain. The Nations data-table of Sustainability database shows that all three have a relatively high standard of living (GDP/capita), favorable rankings by the Rule of Law index and the Control of Corruption index, and that women make up over 40% of the labor force in all three countries.

Per unit of generating power, wind farms require a land-area that is almost 1000 times greater than a gas-fired power station (see adjacent figure) and while this land can still be used for agriculture the scale of the visual 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 km²).

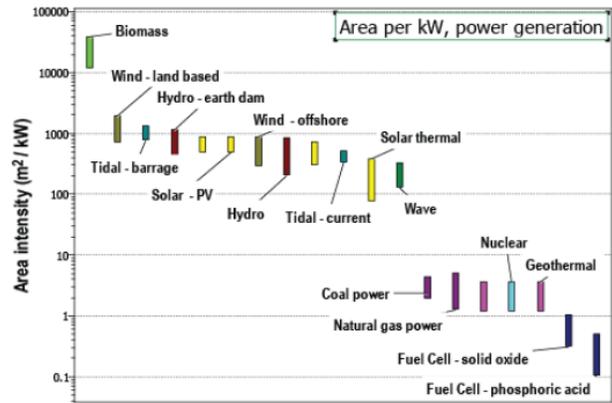
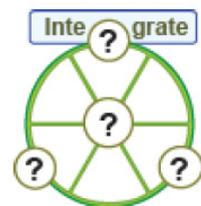


Figure 21. The area-intensity of power systems, using the Low Carbon Power data-table.

Economics. Are wind farms economic? Most of the commercial-scale turbines installed today (2013) are 2 MW (nominal) in size and cost roughly \$3-\$4 million⁷. With a design life of 20 years, a load factor of 0.25 and allowing a sum equal to the cost of installation for life maintenance, ground rent and management, the cost of wind-farm electricity is \$ 0.09 \$/kWhr, a little more than that from a 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. Interestingly, electric vehicles can contribute by introducing intelligent battery charging that draws on power when there is surplus generating capacity, turning the grid itself into a virtual storage device.

Step 4: Integration

This is the moment to reflect on and debate the relative importance of the information unearthed in the Fact-finding step, using the effect on the three capitals as a framework. It will, inevitably, require an element of personal judgment and advocacy. The function of the Sustainability database is to help inform the debate. Here is one view to set it off.



Natural Capital. The Prime Objective in building wind farms was to reduce green-house gas emissions. The studies cited above suggested that they can. Their dependence on critical elements, particularly Neodymium, might give concern but the placement of wind turbines is fixed and known, and large groups of them are managed by a single organization, 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,

⁷ <http://www.windustry.org/resources/how-much-do-wind-turbines-cost>

but we are reminded that this is not a productive way to respond to stakeholder concerns — a more considered response and exploration of mitigating measures (ultrasound, perhaps) is better⁸.

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.

Human Capital. Large-scale deployment of wind farms creates employment. If these jobs and wealth they generate are in nations that are well governed, have fair distribution of wealth and equality of job opportunity, a contribution is made to Human Capital.

Some argue that the visual and acoustic intrusion of wind turbines represents a significant loss of quality of life. Against this must be set the reduction in emissions and in atmospheric pollution that can significantly damage human health. One might compare this with the noise and visual intrusion of cars and on their questionable impact on human health (they kill over 40,000 people per year in the US alone), but we appear to accept them⁹.

There is another aspect: that of independence and national security. A 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.

Manufactured 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.

Have the Stakeholders concerns been addressed? Wind farms contribute to Governments' target of power from renewable energy. The concerns of Energy Providers and Wind Turbine Makers for long term commitment by Government is not, at the present time, met, probably constraining investment. The concerns of local residents could be addressed by a design-focus on reduced acoustic signature and the dislike of a neighboring wind farm could be alleviated by compensation or reduced energy tariffs. One of the concerns of the public at large—that wind farms really do not contribute to reduced emissions—could be removed by a definitive analysis of their performance to date by a group with sufficient authority to command wide acceptance. The broader aesthetic concerns have no easy solution.

⁸ We are grateful to Prof. Karel Mulder of TU, Delft for pulling us up on this point. He reminds us that issues of stakeholder concerns cannot be resolved by statistics. Interaction with the local population is crucial to make them feel that they are taken seriously; better advice is to set up interaction with stakeholders that may have to suffer. Remarking that "It's not so bad" just creates more negative feelings.

⁹ We are again grateful to Prof. Karel Mulder for the reminder that a more sensitive approach to concerns about visual intrusion would be more productive.

The triple bottom line: do wind farms contribute to sustainable development?¹⁰ The Prime Objective of wind farms—to generate electrical power with a low carbon footprint—appears to be met. It is less clear that they are economic (leaving a question mark over impact on manufactured capital) or acceptable on the scale required to make much difference (leaving a question mark over human capital).

Step 5: Reflection.

This is the point for broader-range thinking.

Energy is one of mankind's most basic needs and electrical energy is the most versatile and valuable. 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. Wind farms together with other low-carbon power systems (hydro, geothermal, photo-voltaic and thermal solar, nuclear) can all make some contribution, but for now the dominant source power continues to be fossil fuels. Perhaps we just have to live with wind-farms as one, perhaps transient, contribution while striving for cleaner ways to derive power from gas and coal.

Reflection

6.2 Electric cars

The global production of cars in 2011 was 60 million per year, growing at 3.3% per year. Cars account for 74% of production of motor vehicles and at present are responsible for about 20% of all the carbon released into the atmosphere¹¹. National governments implement policies to reduce this source of emissions through taxation and incentives. One of the incentives is to subsidize electric cars.



From a materials point of view, the major differences between electric and internal combustion (IC) cars are the replacement of the IC engine with electric motors that, at present, use Neodymium-Boron permanent magnets and the replacement of gasoline or diesel fuel by Lithium-ion batteries. Today's electric cars have 16 kWh batteries, and a claimed range of up to 100 km between charges. A single such car requires about 0.5 kg of Neodymium for the motors¹² and 3 kg of technical grade Lithium Carbonate, (equating to 0.57 kg Lithium) per nominal kWh for the rechargeable batteries¹³. It is estimated that the global production of electric cars—either hybrids, plug-in hybrids, or fully electric—will exceed 16 million per year in 2021 and will account for 20 % of all vehicles manufactured¹⁴.

¹⁰ A student of Class ENG 571 at Illinois makes the following point. The Nations of the World database gives numbers for specific indicators such as Freedom of the Press, but to get this one number likely involves a fair amount of “valuation” and ranking of data, which can lead to important aspects of complicated issues to be ignored. Making this fact clear might encourage engineers using the software and designing a sustainable project to seek out the involvement of social scientists, human rights activists, etc., whose knowledge on these subjects is more thorough.

¹¹ www.epa.gov/climatechange/ghgemissions/sources.html

¹² www.reuters.com/article/2009/08/31/us-mining-toyota-idUSTRE57U02B20090831

¹³ Tahil, W. (2010) “How Much Lithium does a Lilon EV battery really need?” www.meridian-int-res.com and http://www.google.co.uk/search?sourceid=navclient&ie=UTF-8&rlz=1T4ADBR_enGB321GB323&q=how+much+lithium+is+in+a+battery

Assessment

Step 1: Prime Objectives and Scale

These are defined in the project-statement. The Prime Objective is the de-carbonization of road transport. The scale is large (it has to be to make any significant difference to carbon emissions)—20% of existing car production, equating to 16 million cars per year in 2021.

Prime Objective
and Scale

Step 2: Stakeholders and their concerns.

As with wind farms, the national press reports the views of government, industry and the public about electric cars. The reports identify most of the stakeholders and their known concerns. Here are three examples

Stakeholders

- [“Bloomberg Endorses Preparing Parking Spaces for E.V. Charging.”](#) (The New York Times, 14 February 2013). The mayor says he wants New York City to be a "national leader" in electric vehicles.
- [“That Tesla Data: What It Says and What It Doesn't.”](#) (The New York Times, 14 February 2013). The New York Times reporter responsible for covering energy, environment and climate change discovers the hard way that the claimed range of electric cars is sometimes a little overstated.
- [“Are electric cars bad for the environment?”](#) (The Guardian 4 February 2013) Norwegian academics argue that electric cars can be more polluting than claimed¹⁵.

Stakeholders need to be heard, reassured, persuaded or compensated if the large-scale use of electric cars is to be sustainable. Among them are:

- *National Governments* encourage the take-up of electric cars in order to meet carbon-reduction targets and to reduce dependence (where it exists) on imported hydrocarbons.
- *Local city or state government* foresee pressure to provide charging points and specialized recycling facilities, particularly for battery materials.
- *Car makers and their suppliers* seek consistency of Government policy to support a market for electric cars and a secure source for essential materials. They are uncertain of public acceptance of electric cars, making investment decisions difficult.
- *Labor Unions* are concerned about job-creation, stable employment, and improved pay and working conditions in the automobile sector.
- *Automobile associations and the driving public* share concerns about the range, battery life and replacement cost, and depreciation of electric cars.
- *Green Campaigners* lobby in favor of electric cars because of their concerns about the impact of gasoline and diesel-powered cars on the environment.

¹⁴ http://imsresearch.com/news-events/press-template.php?pr_id=2135

¹⁵ <http://www.bbc.co.uk/news/magazine-22001356>

Step 3: Fact-finding.

The Granta EduPack Sustainability database can help here. The Materials data-table contains eco-data for materials and information about the supply-chain of elements, including Lithium. The selection tools that are part of the Granta EduPack software allow optimized material selection to meet specific design requirements—lightweighting, for example. The Nations data-table provides background on the prosperity and governance of countries from which materials are sourced or where manufacture is based. The Regulation data-table identifies government incentives and restrictions that relate to transport. The Energy Storage Systems data-table includes performance characteristics of battery technologies. The findings are detailed below and summarized in Figure 22.

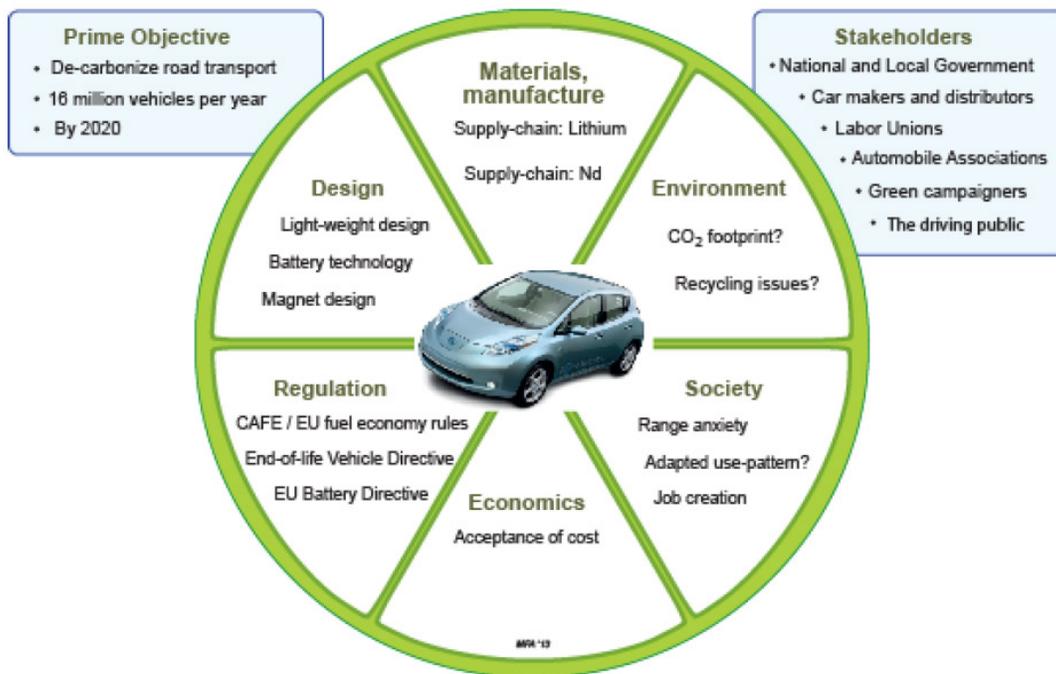


Figure 22. Issues of importance to the sustainability of electric

Materials and material sources. The supply-chain and availability of Neodymium was examined in the Wind farm case study, Section 6.1. As noted there, the present annual global production of Rare earths metals is about 134,000 tonnes per year, of which 15% (20,000 tonnes), on average, is Neodymium. Over 95% of supply is from a single nation. The envisaged production of 16 million electric cars per year, each containing 0.5 kg of Nd would require, using today’s technology

$0.5 \times 16,000,000 \approx 8 \times 10^6 \text{ kg} \approx 8,000 \text{ tonnes}$ of neodymium per year.

This is 40% of current global production. We already saw that there are no obvious substitutes for Nd-based magnets, so the constrained supply-chain is a concern.

Lithium-producing Nation	Tonnes/year 2011
Chile	12,600
Australia	11,300
China	5,200
Bolivia	5,000
Argentina	3,200
Portugal	820
Zimbabwe	470
Brazil	160
World	34,000

Minerals.usgs.gov/minerals/pubs/commodity

The other element of interest here is Lithium (Li). The record for Li in the Materials data-table provides the adjacent list of the countries that produce it. The annual production of Lithium at present stands at 34,000 tonnes per year. The supply-chain of Li is more diverse than that of Nd—67% comes from Chile and Australia, the rest from a range of other Nations.

The envisaged production of 16 million electric cars per year, each with 16 kWhr battery pack requiring 0.3 kg of lithium per kWhr, would, if battery design is unchanged, require

$16 \times 16,000,000 \times 0.3 \approx 7.7 \times 10^8 \text{ kg} \approx 77,000 \text{ tonnes}$ of Lithium per year, or 280% of current world production. If car-range is extended to meet consumer concerns the demand would be higher.

Design. The present range of all-electric cars ($\approx 100 \text{ km}$) is less than a fifth of that of conventional IC-engine automobiles. Could a re-design change this?

The at-wheel energy required to propel a small car is about 0.6 MJ/km. Figure 23, made with the Energy Storage data-table, shows that the specific energy of energy-storage systems—that of Li-ion batteries is the highest among battery systems at 0.6 MJ/kg. Thus the battery weight per unit range is roughly 1 kg/km. An acceptable range of 500 km (300 miles) would need a battery weighing half a tonne and costing, at today’s prices, about \$50,000. Thus the initial market will be for urban cars with range of about 160 km (100 miles) in families with another IC engine car.

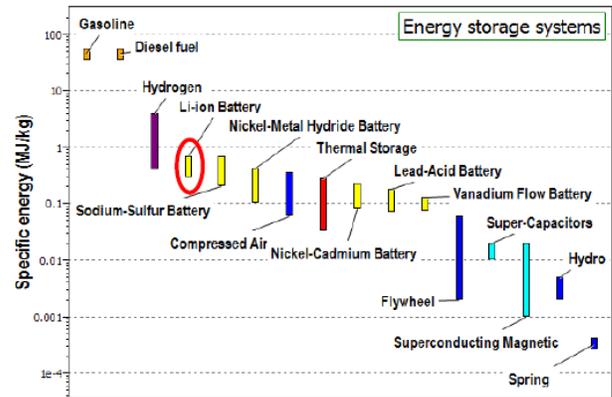


Figure 23. The specific energies of alternative energy storage systems using the Energy Storage data-table.

Regulation. The Regulation and Legislation data-table allows a search on Relevant Sector. Selecting the Transport sector gives the following list.

European legislation:

- EU Automotive Fuel Economy Policy on carbon emissions
- Fuel taxes
- EU Battery Directive
- End-of-Life Vehicles Directive (ELV)

US legislation

- CAFE rules
- Fuel taxes

All have a bearing on the viability of electric cars. We highlight one: the EU Battery Directive forbids the dumping of batteries in landfill; all must be recycled. Infrastructure for recycling Li-ion batteries on a large scale does not yet exist (but would appear in response to market forces as batteries had to be scrapped.)

Society. Automobiles give independence. Their manufacture creates employment. They also occupy space and, in conventional form, are responsible for noise and emissions.

The Environment—can the Prime Objective be met?¹⁶ The Prime Objective in promoting electric cars is that of de-carbonizing road transport. Advertisements for the Nissan Leaf (a contemporary electric car) list its CO₂ emission as 0 g/km. Is this realistic? Here a little research is necessary.

Electric cars will be charged from the National grid. Consider the carbon footprint of the car if the grid is largely fed (as now) by gas-fired power stations. Delivered electric power from such stations has a carbon footprint of 500 g/kW.hr, or 140 g/MJ¹⁷. The energy in the form of gasoline or oil required to propel an efficient small car is about 2 MJ/km¹⁸. The conversion efficiency from gasoline to crankshaft power is at best 1/3, so for equivalent performance the electric motor replacing the IC engine must deliver about 0.6 MJ/km. The combined efficiency of a lithium ion battery / electric motor set is at best 85% when the recharge cycle is included, so electrical energy of $0.6/0.85 \approx 0.7$ MJ /km must be provided from the grid. This carries a carbon penalty of

$140 \times 0.7 \approx 100$ grams per km.

The median carbon emission of today's cars is about 200 grams per km, but a number of contemporary models already emit less than 100 grams per km. Thus until the grid is decarbonize, carbon emissions from electric cars are no lower than those from an efficient gasoline or diesel powered vehicle. Power predominantly from nuclear sources (as in France) or from renewable sources (Norway, Iceland) changes the equation.

Economics¹⁹. Batteries for electric cars are still very expensive—as much as \$10,000 to \$15,000²⁰, or one third of the price of the vehicle—and can provide only limited range. The price of Lithium-ion batteries fell during the 1990s but flattened out at about \$600 per kWhr. With fuel at \$4/gallon (~\$1/liter) in the US and about \$1.8/liter in Europe, the economics of electric cars looks unattractive. However a 2012 analysis carried out by McKinsey & Co.²¹, predicts that the price for Lithium-ion batteries could fall by as much as two-thirds by 2020, down to around \$200 per kilowatt-hour. This, coupled with rising fuel price, might tip the balance.

¹⁶ Dr Jon Cullen reminds us that electric cars on this scale would require the building of a new generation of power stations that would be more efficient than the legacy generation of today. He also points out that electric cars offer certain other benefits in reduced local pollution and noise.

¹⁷ See, for example, www.defra.gov.uk/publications/files/pb13773-ghg-conversion-factors-2012.pdf Table 3c

¹⁸ An efficient small car does about 16 km/litre of gasoline. One liter of gasoline has an energy content of 35 MJ/liter.

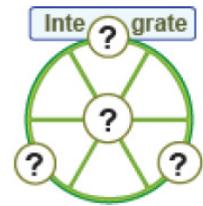
¹⁹ The Washington Post, April 2, 2013. <http://www.washingtonpost.com>

²⁰ The Wall Street Journal, April 17, 2012. <http://online.wsj.com/article/SB10001424052702304432704577350052534072994.html>

²¹McKinsey July 2012. http://www.mckinsey.com/insights/energy_resources_materials/battery_technology_charges_ahead

Step 4: Integration

What, then, is the likely impact of wide use of electric cars on the three Capitals? These are questions for debate, informed by the data generated by the Fact-finding step. Here is one view for discussion.



Natural Capital. Electric vehicles that use today’s technology rely on a least two “critical” elements: Neodymium and Lithium. The analysis of supply needs and source-nations for these elements was not reassuring. The projected demand for Neodymium for cars in 2021 is about half the current (2011) global production, most of it coming from a single nation. Some of the demand in 2021 could be filled by recycling, not at present practiced. The design life of an electric car is of order 12 years. If the vehicles are leased, so that large groups of them are managed by a single enterprise, the recovery, reconditioning, or recycling at end of life is straightforward. If they are sold, as cars are now, to individual purchasers then collection for recycling becomes more difficult but still manageable. A similar exploration for Lithium indicated a broader supply base but a demand in 2021 that far exceeds current production capacity. These facts point to a technology that makes large demands on critical elements with inadequate sources.

Does the all-electric car achieve its Prime Objective, that of helping to de-carbonizing road transport? The carbon footprint of the electric car, if charged from the national grid of a typical Western nation, is roughly 100 grams per km. An increasing number of small IC driven cars already do better than this. We conclude that the Prime Objective is not achieved until the national grid is itself de-carbonized or an independent low-carbon source of electrical power is available. Neither appears achievable in the short (10 year) term. This leaves us with the larger question: can we (will we) be able to simultaneously implement coupled goals that have a 20 – 50 year time frame?

Human Capital. A healthy manufacturing base makes a positive contribution to Human Capital: the jobs created by the automobile industry contribute to wealth and potentially to the well-being of the population of the nation in which they are built. But electric vehicles can contribute to human capital in this way only if they are widely accepted by the driving public. The limited range, at present, is an obstacle to the acceptance.

Overcoming this obstacle may require that electric cars cease to be seen (as at present) as simple replacements for those with IC propulsion, but as a different sort of transport with a changed utility, one well suited to daily short journeys. A shift from private ownership to fleet ownership by municipalities, service providers, and employers with provision of widely available recharging points at supermarkets, car-parks and place of work could make better use of the strengths of electric transport.

Manufactured Capital. Creating plants to build more than a million electric cars per year is a large investment in manufacturing technology. Is it a good investment? Some argue that it is not because, like wind-turbines, they are not competitive in cost without a government subsidy. As with all energy-using products the unknown is the price of hydrocarbon fuels over the next 20 years and the currently externalized cost of carbon-induced climate change.

Have the Stakeholders’ concerns been addressed? As of today, very few. Inconsistent government support for electric cars continues to leave car-makers unable to plan with confidence. Consumers continue to view the limited range between charges and the lack of charging infrastructure as obstacles. Local and national governments appear uncertain about investing in recharging services and do little to enable it.

The future of electric cars, at this point in time, seems uncertain.

The bottom line: is the mass-market all-electric car sustainable technology? With today's technology, it appears not. With new technology it might be. There are formidable obstacles. The low energy-density and long charge-time of present day technology are unacceptable, as is the lack of charging infrastructure. The vehicle cost is at present not competitive with conventional IC driven cars. The limited battery life and the high cost of replacement are likely to make for high depreciation. Extending range to match present-day expectations using battery technology does not appear practical.

Step 5: Reflection.

Reflection

This is the point for a broader, idea-breeding moment.

Can the Prime Objective be achieved in the way assumed in the remit—by replacing petrol-driven cars by electric cars that are used in the same way? It does not seem so. Why? Because electric cars can't provide the range, convenience of refueling or (at present) the economy that consumers expect—the energy density of even the best batteries is still far lower than that of gasoline.

That suggests two lines of thinking. Electric cars are good for short journeys. Could you (thinking as a Secretary of State or Minister of Transport) create incentives for car-users to think of electric cars in a new way, perhaps owning a small electric car for daily commutes to work and renting a larger IC car for longer journeys, vacations or employment that required one?

The central issue for electric transport is that of energy density. Suppose we accept that transport is best powered by high energy-density fuels with which batteries cannot compete. Technology exists for synthesizing hydrocarbons from CO₂. Rather than using electrical power to charge batteries, could it be used to synthesize methanol or ethanol to drive efficient IC-powered cars? The infra-structure for fuel distribution and maintenance already exists, and by drawing the CO₂ from industries that emit it such as power-stations, or cement works or from the atmosphere, true carbon-neutrality might be possible.

7. Summary and conclusions

“Sustainable technology” has many interpretations. Central to all is the concept of the value of Natural Capital (the planet’s natural resources), of Human Capital (the health, education and social development of the human population of the planet) and of Manufactured Capital (the value of man-made institutions, infrastructure and wealth). The many different articulations of sustainable technology aim to support one or another of these but few support all three. Progress is possible only with well-balanced trade-offs and compromises between them.

Introducing students to this complexity is challenging. The 5-step method and the Sustainability database described here are contributions towards meeting it. The database has the usual Granta EduPack data-tables for materials and processes, expanded to contain the counties of origin of materials and a measure of their criticality (the security of the supply-chain). The Granta EduPack search engine allows selection of materials to minimize material usage while meeting design requirements. The database has a data-table of legislation, prompting students to think about ways to meet design requirements while complying with national and international guidelines, restrictions and reporting requirements. It has a data-table of the 210 Nations of the world, providing background on the economic, political and social conditions in countries from which materials might be drawn or goods manufactured. It has data-table for Power generation and Energy storage providing necessary background about energy. The data-tables are linked, making connections that allow the complexity to be explored.

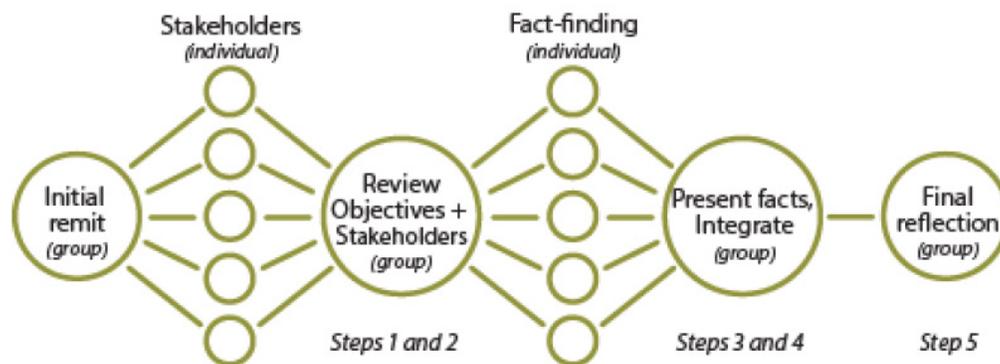


Figure 24. Running a sustainable-technology assessment project as a group activity.

The 5-step method can be used for individual or for group projects. As a group activity, the role of a stakeholder and the responsibility for one fact-finding task can be assigned to each member of the group, the individuals research their assignment and report back to the group as a whole (Figure 24). This is then followed by a group “debate” seeking consensus on the impact of each of the fact-finding searches on the three capitals. The analysis as whole has a purpose and conclusions: while the underlying problem may be complex, it is important to report the result in a simple manner, making them accessible to non-experts²².

²² Professor John Abelson (U of Illinois) raises an interesting question: do we need a higher level (systems and future development) in the integration step? Otherwise many options will seem closed or unlikely. Should “integrate” pose a set of issues to be resolved?

Acknowledgements

We wish to acknowledge the insights and helpful critical reviews of a number of colleagues, among them Dr. Jon Cullen and Professor David Cebon of Cambridge University, Professor Karel Mulder of the Technical University of Delft, Professor Peter Goodhew of Liverpool University, Professor Alexander Wanner of the Karlsruhe Institute of Technology, Professor John Abelson and the students of Class ENG 571 at the University of Illinois in Urbana, Professor Jordi Segalas Coral and the students of the Institute of Sustainability at the Universitat politecnica de Catalunya, and our many associates at Granta Design, Cambridge (acquired by Ansys in 2019), without whom this study would not have been possible.

8. Further reading

These references were accessed during the preparation of first publication this document.

Ashby, M.F. (2012) “Materials and the Environment—eco-informed material choice” Butterworth Heinemann, Oxford, UK. ISBN 978-0-12-385971-6. (An introduction to the environmental aspects of the use of materials.)

Ashby, M.F., Attwood, J, and Lord, F. (2011) “Materials for low carbon power—a White Paper”, Granta Design, Cambridge, UK.

Ashby, M.F. and Polyblank, J. (2011) “Materials for energy storage systems—a White Paper”, Granta Design, Cambridge UK.

Ayres, R (1998), “Viewpoint: weak versus strong sustainability”.
<http://kisi.deu.edu.tr/sedef.akgungor/ayres.pdf>

Brundlandt D. (1987), Report of the World Commission on the Environment and Development, Oxford University Press, Oxford, UK. ISBN 0-19-282080-X. (A much quoted report that introduced the need and potential difficulties of ensuring a sustainable future.)

Dasgupta, P. (2010) “Nature's role in sustaining economic development” Phil Trans Roy Soc B, Vol. 365, pp 5—11. (A concise exposition of the ideas of economic, human and natural capital.)

Dow Jones Sustainability Index (2012). <http://www.sustainability-index.com/>

Elkington, J. (1998) “Cannibals with forks: the triple bottom line of 21st century business” New Society Publishers, Stony Creek, CT.

Goedkoop, M., Effting, S., and Collignon, M., (2000) The Eco-indicator 99: A damage oriented method for Life Cycle Impact Assessment, Manual for Designers (14th April 2000)
(<http://www.pre.nl>) (An introduction to eco-indicators, a technique for rolling all the damaging aspects of material production into a single number.)

Graedel, T.E. (1998) “Streamlined Life-cycle Assessment”, Prentice Hall, New Jersey, USA. ISBN 0-13-607425-1. (An introduction to LCA methods and ways of streamlining them.)

Jaffe, R. and Price, J. (2010) "Critical Elements for New Energy Technologies". American Physical Society Panel on Public Affairs (POPA) study, American Physical Soc. USA.

Janson, L (2003) “The challenge of sustainable development”, J. Cleaner Production, Vol. 11, pp. 231—245.

Kyoto Protocol (1997) United Nations, Framework Convention on Climate Change. Document FCCC/CP1997/7/ADD.1 (<http://cop5.unfccc.de>) O) 14040/14041/14042/14043, “Environmental management - life cycle assessment” and subsections, Geneva, Switzerland. (The international consensus on combating climate change.)

Materials (commodity) prices over time:
http://www.mckinsey.com/Insights/MGI/Research/Natural_Resource/Resource_revolution

Mulder, K. editor (2006) “Sustainable development for engineers: a handbook and resource guide”

Greenleaf Publishing Ltd. Sheffield UK. ISBN-13: 978-1-874719-19-9.

Mulder, K., Ferrer, D. and Van Lente, H. (2011) “What is sustainable technology” Greenleaf Publishing, Sheffield, UK. ISBN 978-1-906093-50-1. (A set of invited essays on aspects of sustainability, with a perceptive introduction and summing up.)

Norman, W. and MacDonald, C. (2004) “Getting to the bottom of the “Triple Bottom Line”, Business Ethics Quarterly, Vol. 14(2), pp 243—262.

<http://isites.harvard.edu/fs/docs/icb.topic549945.files/Canadian%20Paper.pdf>

Pava, M. (2007). “A Response to ‘Getting to the Bottom of ‘Triple Bottom Line’”, Business Ethics Quarterly Vol.17 (1) pp. 105-10.

Porritt. J. (2012) “The five capitals” <http://www.forumforthefuture.org/project/five-capitals/overview>

Transparency International (2012) <http://www.transparency.org/>

UN Global Compact (2012) www.unglobalcompact.org/

US Department of Energy (2010) “Critical materials strategy for clean technology” www.energy.gov/news/documents/criticalmaterialsstrategy.pdf (A report on the role of rare earth elements and other materials in low-carbon energy technology).

US Department of Energy (2010) “Critical materials strategy” Office of Policy and International Affairs, materialstrategy@hq.doe.gov, www.energy.gov. (A broader study than MRS 2010, above, but addressing many of the same issues of material critical to the energy, communication and defense industries, and the priorities for securing adequate supply.)

USGS (2002) Circular 2112 “Materials in the economy –material flows, scarcity and the environment”, by L.W. Wagner, US Department of the Interior (www.usgs.gov). (A readable and perceptive summary of the operation of the material supply-chain, the risks to which it is exposed, and the environmental consequences of material production.)

Wanner, A. (2008) “Wanner’s States of the World Database”, Granta Design Teaching Resources Website, www.grantadesign.com/education/resources/

WCED (1987), Report of the World Commission on the Environment and Development, Oxford University Press, Oxford, UK.

Weaver et al (2000) “Sustainable Technology Development”. Accessible in Google books [here](#) (See particularly Chapters 2 and 3)

Wiek, A., Lauren Withycombe, L. and Redman, C.L. (2011) “Key competencies in sustainability: a reference framework for academic program development”

World GDP per capita over time: <https://www.cia.gov/library/publications/the-world-factbook/geos/xx.html>

Appendix 1: Articulations of Sustainable Development

We have examined some 65 articulations of sustainable technology, drawn from journals²³ that specialize on the subject, identifying the prime objective of each. We attempted to construct a map showing how the articulations interacted with the three capitals and with each other - Figure A1 is a reduced version showing a subset of the articulations. Some of the interactions are supportive (green links), others are not (red links). The map is not entirely successful. The nature of interactions is not always unambiguous, and the picture quickly gets very complex—Figure A1 is more a schematic than an accurate representation. We include it here to bring home the point that assessing a given articulation of sustainable technology is not simple: it involves both the direct, intended, influence it has on one of the three capitals, it involves the perhaps unintended impact it may have on another of them, and it involves its interaction with other ongoing articulations.

What generalizations—meta-messages—can be distilled from maps like Figure A1? Each articulation has a motivating target that we refer to as its “Prime Objective”. Each involves a set of Stakeholders. In assessing the sustainability of project the first step is to identify these:

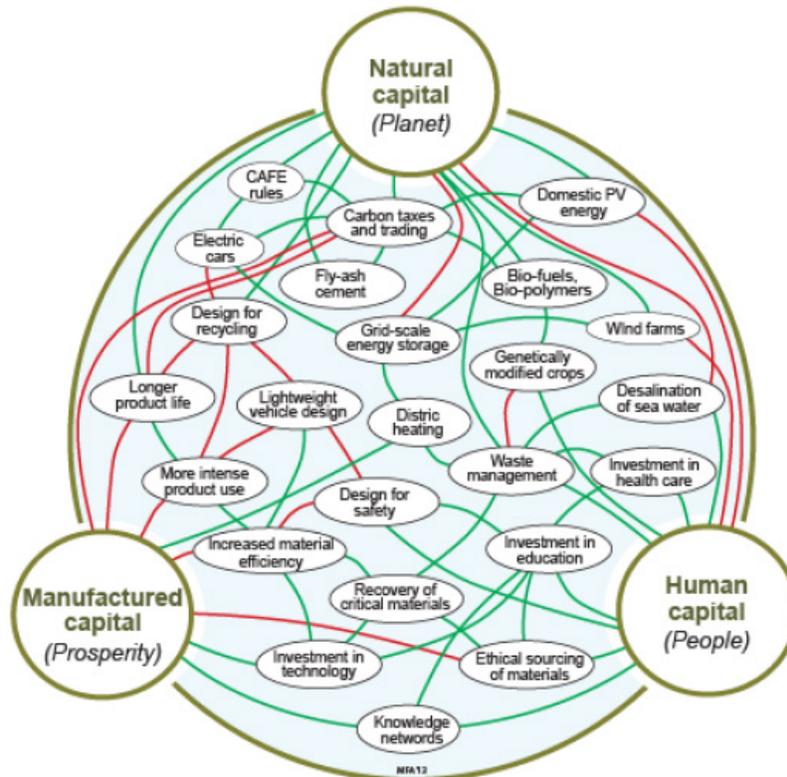


Figure A1. A few of the many articulations of sustainable development and their complex and intense interactions some positive (green) some negative (red).

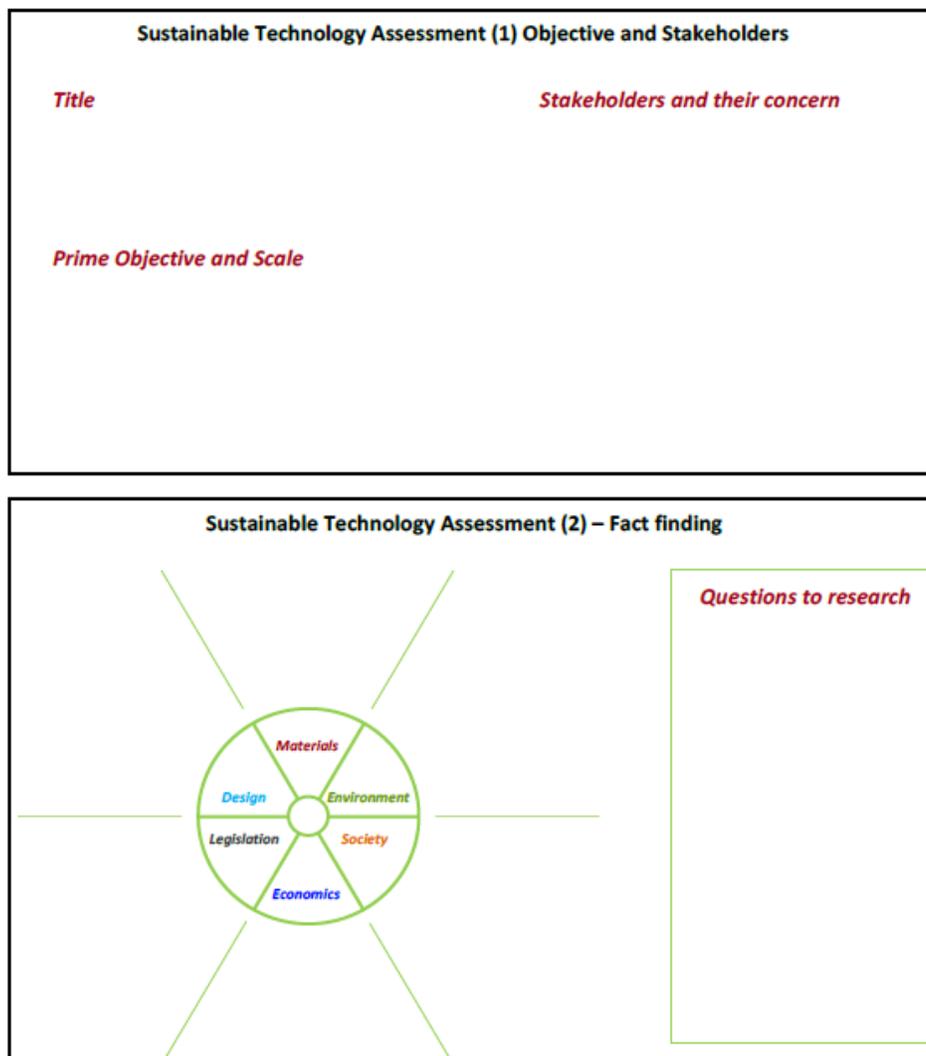
²³ *World Journal of Science, Technology and Sustainable Development*, ISSN: 2042-5945. *World Journal of Science, Technology and Sustainable Development*, ISSN: 2042-5945. *Journal of technology management & innovation*, ISSN 0718-2724. *Journal of Clean Technology and Environmental Sciences*, ISSN: 1052-1062. *Clean Technologies and Environmental Policy*, ISSN: 1618-9558.

if the Prime Objective is not achievable or major Stakeholders are left dissatisfied, the project is unlikely to contribute to sustainable development.

Examination of the 65 articulations suggests that the central issues might be grouped under the six broad headings shown in the central circle of Figure 4. Each heads a check-list for what might be called “sustainability analysis” of a design, scheme, project, or product.

- Materials and Manufacture: supply-chain risk, life-cycle recycle potential.
- Design: product function, performance, safety.
- Environment: energy efficiency, bio-efficiency, preserving clean air, water, and land.
- Regulation: awareness of, and compliance with, National and International Agreements, Legislation, Directives, Restrictions, and Agreements.
- Society: health, education, shelter, employment, equity, happiness.
- Economics: the cost of the project, the benefits that it might provide.

These form the basis of the method of analysis. We have found the template reproduced below (enlarged to A4 landscape size) serves as a useful prompt-sheet in carrying out an analysis of a given articulation.



Appendix 2. Check lists for the 5-step method

Step 1: Clarify the Prime Objectives.

Articulations of sustainability have a motive and a scale. The scale, typically, is large. It is widely accepted that our current life-style is not indefinitely sustainable. If it is to become so the technology to achieve it has to be implemented on a large scale, one that may put strain on the materials supply-chain and have political, social, and economic life.

Step 2: Identify stakeholders and their concerns.

Who are the stakeholders? What are their concerns? The stakeholders establish the context in which debate and decision-making must take place. Table A1 is a check-list, but a better way to identify stakeholders and concerns is through the National Press. A Google search on “News headlines—X” where X is the technology under study (“News headlines—Wind farms” for example) reveals a great deal.

Table A1.

Stakeholder analysis. Broadly speaking there are four groups of stakeholders: These groups are large; sub-groups within them may disagree (National and Local government, for example)

- National and Local government
- Business and Industry
- The science and technology community
- Non-government organizations (NGOs) including Trade Unions, consumer groups, advocacy groups and local communities.

Their concerns are expressed in many different ways: editorial and letters in the National Press, reports, interviews, manifestos, demonstrations, boycotts etc.

Step 3: Fact-finding

The deterministic step. The essence of this step is that it be non-judgmental and neutral. Assemble factual information under the five headings that appear on Figure 5. Table A2 is a check list.

Table A2.

Fact-finding: suggested targets for information gathering. Not all are relevant to all projects. The help provided by the CES EduPack Sustainability database, described in Section 4, appears in italics.

Materials and Manufacture

- What is the bill of materials for the product?
- Are any of the materials listed as “critical”? Is the supply-chain secure? Does a recycling infrastructure exist?
- Where are the materials sourced? What is the human-rights record of the country of origin?
- Where is the product manufactured? What is the human-rights record of the country of manufacture?
- How much transport is involved in material sourcing and manufacture?

The Materials data-table contains data for the embodied energies and carbon footprints of materials and processes. The CES EduPack Eco Audit Tool accepts the bill-of-materials for a product and delivers a breakdown of the energy use and carbon footprint over life.

Design

- What is the function of the product? What service does it provide? What hazards does it create?
- Does it provide its function safely and at an acceptable cost?
- Is the design inclusive, or does it exclude some members of society?
- Are materials used efficiently? Has light-weighting been addressed?
- Is the packaging minimized? Can the packaging be reused or recycled?
- Have energy-efficiency, life-expectancy and maintenance been considered?

The rational selection methods, implemented in CES EduPack, allow material selection to meet specified design requirements and the exploration of substitute materials. Both the Materials and the Manufacturing Processes data-tables contain information about cost.

Environment

- What does an eco-audit (a cut-down life-cycle assessment) of the product reveal?
- Does the product provide its function with the least use of materials and energy?
- Can the materials of the product be recycled?
- Does the material, manufacture, use or disposal of the product pose any threat to the bio-sphere?

The Materials data-table contains data for the embodied energies and carbon footprints of materials and processes. The CES EduPack Eco Audit Tool accepts the bill-of-materials for a product and delivers a breakdown of the energy use and carbon footprint over life.

Regulation

- What legislation or regulatory measures are relevant to the production, use and disposal of the product?
- What restrictions to these impose?
- Does the product at present fail to comply with any existing or anticipated legislation?

The Regulations data-table lists the more significant Regulation that applies to materials and product. They are indexed under sector headings such as “energy” and “transport”.

Society

- Does the manufacture or use of the product create jobs?
- Does it create wealth?
- Are any aspects of manufacture, use or disposal of the product inequitable or exploitative?
- Does it contribute to human well-being, increase self-sufficiency and resilience?
- Does it clash with cultural or societal norms?

The Nations data-table provides information about the standard of living, equality, rule of law and quality of governance of the nations of the world.

Step 4: Informed integration.

The integration step aims to assess the impact of the information gathered in Steps 1, 2 and 3 on the three capitals and the actions that flow from them. Put another way, it seeks to evaluate the triple bottom line. We are dealing here with information about different things, measured in different ways, which cannot be combined in deterministic ways. Finding a balance requires holistic thinking and informed debate. The outcome is, inevitably, subjective, influenced by social, cultural, and political background. The function of the first three steps is to provide a common background of accepted facts on which the informed debate can be based.

Informed integration can, to a degree, be structured by starting with the guide-lines set out in Table A3, below.

Table A3.

Guide-lines for thought and discussion in the Integration step

Prime Objectives.

- Can the technology achieve the Prime Objectives of the project?

Human capital – People

- How are human health, education and skills affected by the technology?
- Will the technology contribute to human happiness and well-being?
- Does it increase knowledge?
- Is it culturally acceptable? Does it affect cultural identity?
- Does it promote equality?

Natural capital – Planet

- Is it resource efficient?
- How are biodiversity and eco-systems affected?
- Does it cause irreversible change? Is it viable in the long term?
- Is a rebound effect possible?
(Greater efficiency causing increased consumption.)

Manufactured capital – Prosperity

- What will it cost? What revenue will it generate?
- Will it increase industrial capacity?
- How will existing institutions be affected?
- Does it increase employment and livelihood?
- Is it creating new opportunities for development or innovations?

Finally it is important to return to the stakeholders

- How will the findings be communicated to the Stakeholders?
- Which of the Stakeholders' concerns have been addressed?
- What are the unsatisfied concerns? What could be done to allay them?
- Can the Stakeholders be involved (their stake) in the implementation of the technology?

Step 5: Reflection on alternatives.

The facts are now gathered and judgments have been made about their impact on the three capitals, and via them, on the sustainability of the technology. Now is the time to think over the findings. If all the indicators are positive, there is little more to consider. But if one or more of the indicators are negative, or if it appears unlikely that the Prime Objectives can be achieved, there is scope for reconsideration. What are the problems, the unintended consequences or the seemingly great obstacles? Could these be avoided if the Objectives were met in another way? Could change of behavior render the Objectives no longer needed or desirable?

10. Suggested Exercises

These exercises in assessing articulations of sustainable technology can be tackled with or without the Granta EduPack Sustainability database. It is much quicker to use the database than to search for the information in other ways because it is so scattered.

E1. Electric bicycles.

An electric bicycle (“e-bike”) is a bicycle with an integrated electric motor that assists or replaces pedaling. In most countries they are classified as bicycles and require no license or registration. They cost between € 425 and €1,800 (\$500 - \$2,100), are limited to about 30 km/hr and have a range between 40 and 100 km depending on the lithium-ion battery size (0.25 to 0.8 kW.hr). E-bikes are aimed at commuters—you still get some exercise yet you also don’t arrive at your destination all hot and sweaty. The case study of electric cars in Section 6 revealed that their take-up was small, inhibited by cost and range. Are electric bicycles a more sustainable option?



E2. Lanthanum in Hybrid cars.

Lanthanum is a rare earth, co-mined with other rare earths of which it forms about 25% by mass. A recent press report stated that the nickel hydride batteries powering most hybrid cars require 10 to 15 kg (22-33 lb) of Lanthanum per car. This is a lot of Lanthanum. Do nickel hydride batteries really need this much Lanthanum? Do they need any?

Let us suppose the press report is right. The current (2013) production of hybrid cars is about 1,000,000 per year and growing. Is the demand they create it to cause supply problems for Lanthanum? Use the information in the Lanthanum record of the Materials data-table, and the links from there to Nations to research the situation.

Element	Mass in a mobile phone (milligrams)
Platinum	0.077
Gold	0.15
Silver	1.4
Cobalt	21

E3. Rare elements in mobile phones.

About 1.5 billion mobile phones will be produced in (2013). The table gives approximate values for the content of four rare metals in phones. Explore the supply-chain risk associated with one of these following the approach used for Neodymium and Lithium in the text.

- Assess supply chain concentration, using data for Countries of Origin in the Materials records of the Sustainable Develop database.
- Research the Rule of Law and the Press Freedom (a measure of freedom of speech) in the Nations from which most of the metal is sourced
- (c) Find the Annual world production of the materials from the Materials data-table and compare it with the annual demand created by phone manufacture, assuming none is recovered from old phones.

E4. Bio-polymers.

It is argued that increasing the production and use of bio-polymers could reduce dependence on oil and significantly reduce carbon emissions. Explore these claims and form a basis for assessing bio-polymers as sustainable technology. The records for biopolymers in the Materials data-table will provide a starting point, but independent searches using the internet may also be needed.

- Identify the Prime Objective(s) and the approximate Scale of the proposed technology if it is to make a significant difference
- Identify the Stakeholders

For the Fact-finding step, consider the following questions.

- Materials: what are the raw materials from which bio-polymers are made? Is the necessary supply-chain viable?
- Environment: what is the carbon footprint of a bio-polymer? Is it significantly less than that of an oil-based polymer?
- Design: Do the properties of bio-polymers differ significantly from those of the oil-based polymers they would replace? What design changes might be necessary if bio-polymers were adopted?
- Regulations: What legislation, regulations or incentives bear on the use of bio-polymers?
- Society: What impact would adequate-scale production of bio-polymers have on the Nations from which they would be sourced?

E5. Material supply-chain risk assessment.

You are a supplier of components for a major second tier company producing dishwashers. High labor cost and industrial action in your country has forced you to explore to explore manufacture elsewhere. Taiwan, South Korea, Malaysia and India are possibilities. You are faced with deciding which you will first approach. Use the Nations data-table to carry out a comparative assessment.

E4. Small scale (domestic) PV solar power.

The current electricity generation capacity of the UK is 94 GW²⁴. The current (2013) solar capacity of the UK is 1.4 GW. The projected capacity by 2020 is 22 GW²⁵. Examine the issues bearing on the sustainability of this development. If the same expansion was planned on a global scale, would current material production be able to support it?

The table shows the bill of materials²⁶ for a typical silicon-based solar PV panel. The quantities are those required to generate 1 kW

Material	kg/kW
Acids + Hydroxides	7.0-9
Aluminum	15-20
Antimony	0.05-0.1
Argon	3.0-5.0
Carbon allotropes	10.0-20.0
Copper	0.2-0.3
Glass	60-70
Gold	0.05-0.1
Indium	0.02 - 0.08
Plastics	20-60
Silicon	25-40
Silicon Carbide	6.0-10.0
Tin	0.1-0.2
Wood	10.0-20.0
Total mass	150-250

²⁴ www.sse.com/EnergyPolicy/FutureEnergyNeeds/Generation/Capacity/

²⁵ Building Research Establishment figures reported in *Materials World*, February (2013).

²⁶ *Materials and quantities from Phylipsen & Alsema (1995), Keoleion et al (1997) and Tritt et al (2008).*

at peak sun activity. Governments seek to promote small-scale (< 10 kW) solar power generation.

- Who are the stakeholders? What are their concerns?
- What legislation is in place to promote or discourage the installation of small scale solar power generation?
- The bill of materials includes Gold, Indium, Antimony and Tin. Choose one of these and investigate the supply-chain, assessing supply-chain risk. What is its critical status? Does the supply-chain appear to be constrained or well distributed?

Use the Sustainable Development database to get as far as you can. This will leave you with unanswered questions. Use the internet to see how far you can get in finding answers.

E6. Geothermal power for Britain²⁷.

Energy companies are in discussion about reducing Britain's dependence on gas and coal-fired electric power by piping electric power, generated in Iceland from geothermal heat, to Britain through an undersea cable. In theory it's possible to pump low-carbon electricity from Iceland to the UK to meet up to a third of the UK's average energy consumption. The cable would be at least 1200 km long, each kilometer requiring 800 tonnes of copper. The cost is estimated at about £1,000,000,000 (one billion pounds). Does this technology make environmental and economic sense? Is it politically desirable? Carry out an assessment of this articulation of sustainable-development, drawing on data from Sustainability database's Materials, Low Carbon Power, and Nations data-tables.

E7. Bamboo as an alternative building material.

It is suggested that greater use should be made of bamboo as a structural material in housing. Investigate the world trade in bamboo. What is the present global production? Where does it come from? What is the scope for greatly increasing production? The Bamboo record in the Materials data-table provides a starting point. The Food and Agriculture Organization (FAO) of the United Nations is helpful here, particularly the book. "Non-wood Forest Products 18: World Bamboo Resources" (2005) by Maxim Lobovikov, Shyam Paudel, Marco Piazza, Hong Ren and Junqi Wu, available on line at www.fao.org/docrep/010/a1243e/a1243e00.htm.

²⁷ <http://www.theengineer.co.uk/home/blog/icelands-volcanoes-could-power-the-uk-but-at-what-cost/1012334.article>

E8. Electric hand dryers vs. paper towels.

Paper-based and electric hand-dryers compete. Many people prefer the first because it is quick (about 4 seconds) and clean. But many providers prefer the second (drying time at least 45 seconds) because it requires less attention. Explore both, viewing each as an expression of a more sustainable technology than simply wiping hands on trousers.

The British designer James Dyson produces an electric dryer that dries hands almost as fast as paper towels (10 seconds). Is it a more viable articulation of sustainable technology?



Paper towels

Power 0 kW

Drying time \approx 10 seconds

Price of fixture \approx £20



Conventional dryer

Power 2.4 kW

Drying time \approx 20 seconds

Price \approx £250



Dyson Airblade

Power 1.6 kW

Drying time \approx 10 seconds

Price \approx £700

E9. Bio-composites as non-structural parts of vehicles.

A number of auto makers are trialing bio-composites for non- structural components such as inner door panels and interior trim. The Prime Objective is to replace materials derived from non-renewable resources (steel, oil-based plastics) with those that are renewable and (possibly) lighter. But does this articulation make sense? Are the properties of bio-composites as good as those they are supposed to replace? If they are not, sections will have to be thicker, so possibly heavier. Do bio-composites have a lower embodied energy than glass fiber reinforced sheet molding compound? Will consumers accept them (some smell a bit)? See what you can find out about them and then debate their contribution to the three capitals.

E10. Alternatives light-sources for traffic lights.

Every city and town of any size has traffic lights to control traffic flow. The energy they consume is significant. Light-emitting diode (LSD) technology is now sufficiently advanced that they could replace tungsten filament technology globally. Explore this as a viable articulation of sustainable development, bearing in mind the demands this would place on the elements that are essential for LED technology. Is the present global supply sufficient to enable this development on a global scale?

E11. Nespresso.

Coffee is an important agricultural commodity in world trade. However, the coffee industry is currently in a crisis, caused by an imbalance between supply, growing at 3.6% per year, and demand, growing at 1.5% per year. Coffee prices in world markets, which averaged around US cents 120/ lb. in the 1980s, are now around 50 cents /lb., the lowest in real terms for 100 years. The drop in prices has adversely affected countries that depend on coffee export revenues as well as the livelihoods of 25 million small producers and over 125 million people who directly or indirectly depend on coffee. They welcome any stimulus to coffee consumption.



One growth area is the single-cup coffee maker pioneered by Nestlé under the name of Nespresso. The first patent application for Nespresso's process of brewing espresso from capsules containing ground coffee was filed in 1996. Nespresso aluminum foil coffee capsules are up to three times more expensive than portions of ground coffee purchased "loose". Is Nespresso a sustainable development?

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