2 Scale, uncertainty and estimation

What would make a big difference?

If we are creating big problems, we need to look for big solutions: just putting our newspapers in the recycling bin won't be enough. So we need to answer the question "what really matters?" However, we can't give a precise answer to that because we won't know till after the event, so how should we deal with uncertainties about future impacts, and about the effect of different options for change?

In 2007 Gordon Brown, the UK Prime Minister, announced that the UK would now get serious about climate change, and we would cut down on the use of carrier bags in supermarkets[1]. In making this statement, he was following the leadership of some UK supermarkets, who had already begun to charge for bags, and now, in most shops when we reach the checkout, we're asked if we want a bag or will use our own. Apparently our use of carrier bags has reduced by 41% as a result[2]. Good news, and now we've all done our bit, so can fly off to sunny Spain for the weekend with a clear conscience. "Sin bolsas el sol es más sabroso. ¡Adiós bolsas!, ¡Hola sol!"

13 plastic bags for the weekly shop...

... and the rest of the plastic that was inside the bags

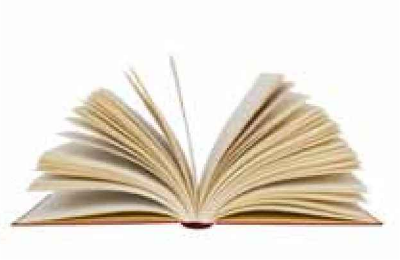
Well, maybe, but let's check. Firstly we'll do an informal experiment: imagine we have a typical family of five, who live in Cambridge for example, and buy most of their food at a supermarket in a weekly shop. The two photos to the left show (a) that their weekly shopping requires 13 carrier bags weighing around 100 grams, and (b) that the weight of the other plastic brought home in the carrier bags (two-thirds of which was bottles) was ten times greater at about 1 kg. So carrier bags are a small fraction of the plastic we purchase in supermarkets. Does our use of supermarket packaging form a significant part of the country's total use of plastic? If we look at the total use of plastic in the UK, carrier bags account for less than 1%. So, as plastic accounts for around 1% of the UK's total CO_2 emissions, if we all stopped using all plastic carrier bags, we would reduce our national emissions by less than 0.01% (less than one 100th of 1%). This is a step forwards, but it is a small step. Roughly, it is equivalent to avoiding driving 4 miles per year each, or turning off one 60 W light bulb each for one day, once a year.

It turns out that the problem with plastic carrier bags is actually about litter—when they blow around after use, they get caught in hedgerows and railings. We don't like to see them, and it is a shame to throw out 65,000 tonnes of carrier bags when landfill space in the UK is tight, but they're almost irrelevant to our search for responses to climate change.

We've started with this story, not because we have any particular interest in carrier bags, but because it illustrates three major challenges as we look for a sustainable materials future: scale, uncertainty and estimation. If we want to make a big difference to our environmental impacts, we need to make big changes. Many small changes, if they each apply in different areas, do not add up to a big change. It is very difficult for us to be certain about exactly how much impact any action will have, not only because of a lack of data (exactly how many carrier bags did you use last year?) but also because we don't know precisely how one change to our behaviour leads to other consequences. (How many straw baskets were flown in from the Caribbean to allow us to go shopping without using carrier bags?) As a result, we can only make sensible decisions by estimating the scale of change they cause, and of course estimates are imperfect.

These three issues are linked, but we can't defer action until we have perfect data, because by then it would be too late to make effective changes. If we can make sensible estimates of what's big and small, we can start to take actions leading to big changes knowing they will make a significant difference, even if we don't know exactly how big that difference will be. So the aim of this chapter is to identify the key 'bigs' of sustainable materials, make clear why we're uncertain about how big they are, and then explain how we're going to use estimates to predict likely big actions.

Scale



This book uses more than ten different materials

This book is made from more than ten materials: the paper is mostly wood fibres, but also contains kaolin clay, calcium carbonate, titanium dioxide, silica or talc; the print on the page may be made from polymers (styrene/acrylate, polyethylene, or others), wax, resin and silica, with colours made with iron oxide or other pigments; the cover is coated with varnish, aqueous coatings or film lamination; the pages are bound by stitching, stapling or glue, requiring a further nine or more materials. Remarkable. A book made mainly of paper, which we consider to be a relatively natural material, contains numerous engineered materials. Glance up from the book, and start counting the number of materials you can see around you and whether you're looking at the inside or outside of a building, some furniture, the toaster, or your computer you'll probably lose count within a minute or so. Our lives depend on a cornucopia of materials, so much so that our colleague Professor

Tom Graedel at Yale has shown that a typical mobile phone now uses more than two thirds of the periodic table of elements[3]. So, if we're concerned about finding a more sustainable material system, where on earth should we start? What should be our priorities?

Fortunately, we can give a rather simple answer to this question, based on the three pie charts to the side. We've drawn the charts using data published by the International Energy Agency (IEA), who collate the most comprehensive global data set on energy use and consequent emissions[4], and they give us a great basis for identifying priorities. The IEA data is extensive, covering all greenhouse gas emissions including CO_2 emissions, details for the three main sectors (buildings, industry and transport) and importantly for our purposes, giving details for 13 industry categories including direct emissions (from burning fuels for energy), process emissions (from chemical reactions) and indirect emissions (from upstream electricity generation). The pie charts all show fractions of 'equivalent' annual CO_2 emissions, i.e. they show the effects of other greenhouse gas emissions translated into units equivalent to CO_2, and we drew them using data from 2005. Total global emissions are rising year by year, but the fractions change more slowly, so the breakdown in our three pie charts is likely to be a useful predictor of proportions in future years.

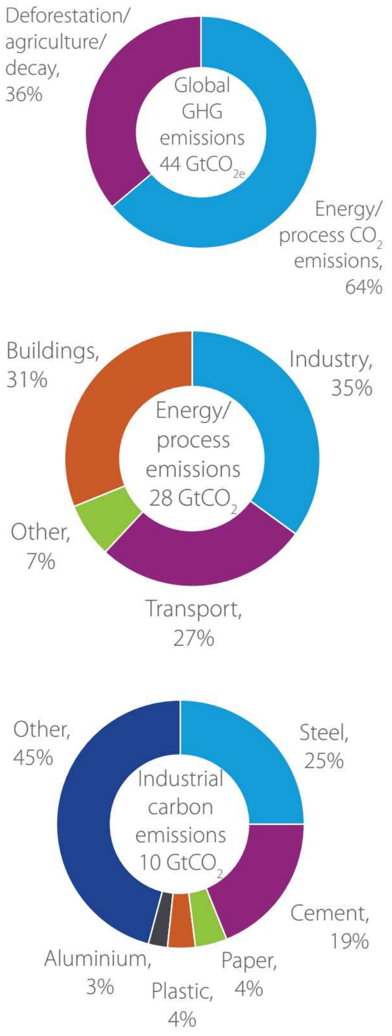


Figure 2.1—**Pie charts showing the sources of global CO_2 emissions**

The first chart shows that emissions arising from burning fossil fuels to generate energy, and those released directly by industrial processes, form about two-thirds of the world's total "man-made" greenhouse gas emissions (i.e. those which are in addition to the natural cycle, in which plants and animals absorb and release CO_2 during growth, life and death). The other third of the first chart represents emissions which arise from changes in land-use (particularly deforestation) and from agriculture. As CO_2 is invisible, and of course we can't accurately measure all releases either, these numbers are estimates. However, the estimates from fuel combustion and processes are likely to be quite accurate, because our colleagues in chemistry know how much CO_2 is released from burning fuels and we can measure the amount of CO_2 emitted from a car or power station to verify our estimates. In contrast, it is much more difficult for our colleagues in biology, plant sciences and agriculture to predict the remaining third, because there are so many different and complex processes involved. The second pie chart explores the largest segment of the first one. It shows the main drivers of CO_2 emissions arising from energy production and industrial processes. Roughly one third of these emissions come from the use of buildings, a quarter from the use of transport, and one twentieth in "other" relates to upstream emissions from fuel processing. But the largest segment, just over one third, arises in industry in making the goods, buildings and infrastructure with which we live our lives.

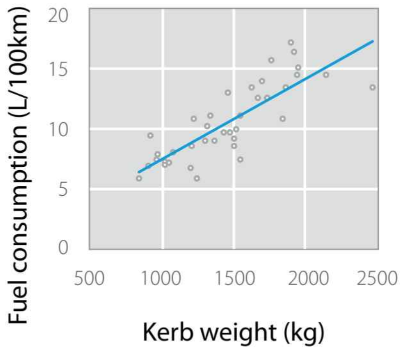


Figure 2.2—**Vehicle fuel consumption against mass for a typical range of cars in use in the UK at present**[15]

Most public debate about energy efficiency in the past 5–10 years has focused on the first two segments we mentioned, the use of buildings and transport, both because of their significance on this pie chart, and because we have many options for making them much more efficient. The two graphs to the side illustrate this for cars and houses. For cars, there is a strong correlation between fuel consumption and the weight of the car, so if we want efficient cars, we need to make them lighter. This is hardly surprising as on average our cars in the UK weigh 1.5 tonnes, but with an average contents of 1.5 people, the ratio of car weight to passenger weight is around 10:1. The second graph shows a recent history of CO_2 emissions for houses, per square metre of floor area, projected forwards to the targets we now have in UK law for future efficiency. The graph shows rapid improvement of the emissions arising from use (for heating, cooling and powering electrical goods), but little change to embodied emissions (those associated with constructing and maintaining the building). The three key design options that drive the improvements in use are better insulation, better sealing so that all exchange of air (and hence heat) with the outside world is controlled, and better design for natural air flow. The fact that we have already built 30,000 “passive houses” worldwide, without regular heating or cooling, is confirmation that the governments targets for future ‘zero energy’ buildings can be achieved[5].

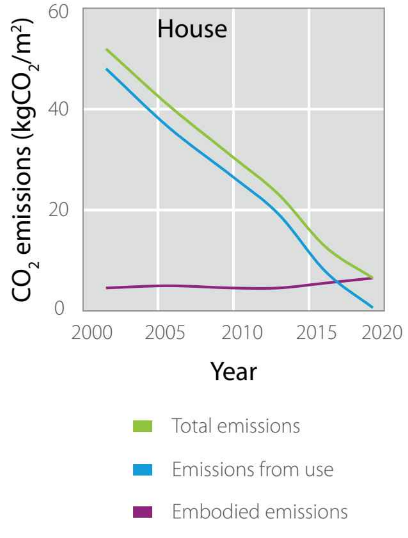


Figure 2.3—**CO_2 emissions per square metre for buildings**[16]

So, we have good options for making a significant impact on two of the three big segments in the second pie chart. But what about the biggest one: industry? The third pie chart shows the major contributors to this industrial segment, and here we find a very useful simplification of our question about priorities: production of just five materials accounts for 55 % of industrial emissions, so this gives a clear focus to our exploration of sustainable materials. The five key materials are steel, cement, plastic, paper and aluminium, with the first two of these, steel and cement, the materials with which we construct buildings, roads, bridges and tunnels, accounting for nearly half of all industrial emissions.

We seem to have five clear priority materials, but let’s just check that we haven’t missed anything. The ‘other’ segment still represents 45 % of industrial emissions, and the segments related to the five key materials describe the energy and emissions required to produce the materials as stock products (such as plates, sheets and bars), not the total energy for delivering final goods. Are there other important materials in ‘other’ or are we actually under-representing the five key materials, by not showing the emissions associated with converting stock materials into goods?

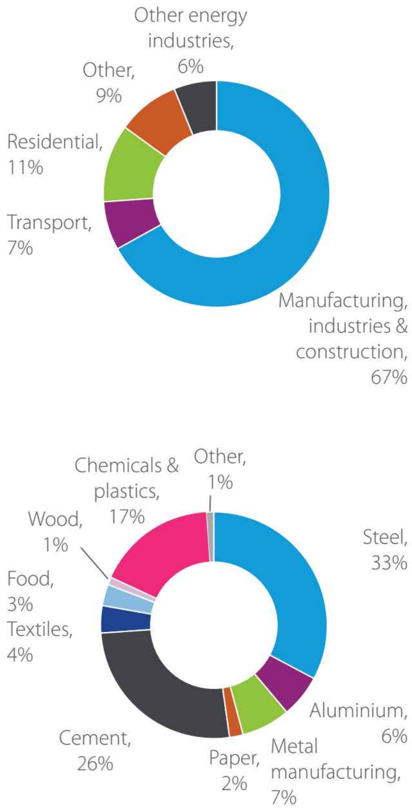


Figure 2.4—**Sources of Chinese CO_2 emissions**

To answer this question, we need to know more about the 'other' segment, and to find out whether any downstream activities connected with our five materials are hiding in the data. The IEA gives only a broad analysis of the 'other' sector but we can find out more by looking at data from particular countries. Both the UK and the US have more detailed data, but manufacturing in both countries has declined recently so the proportions would not be globally representative. However, fortunately the Chinese government publishes excellent data on their own energy use, and China is 'the workshop of the world' so spans all manufacturing activity. The two pie charts in Figure 2.4 recreate the second and third of our global charts from Figure 2.1, for China[17].

The first chart for China shows that around two thirds of all energy used in China is for industry. However, the bottom chart is the key one: if we're right that China's industrial activity is a good proxy for global industrial activity, then this is the best insight we can gain into the global 'other industry' segment. The same five materials—steel, cement, plastic, paper and aluminium remain dominant, but they are now followed by other materials—textiles, food, and wood. We can also see that converting metal stock into products requires significant energy input, around 7% of the industrial total. (Incidentally, although these numbers are clear and widely agreed, it's remarkable how much variety you can create by presenting them in different ways. Take a look at our box story on the next page, 'Fun with numbers 1', to see how you can correctly argue that steel drives any fraction between 4% and 35% of the world's emissions.)

In exploring scale, we've now come up with five priority materials to examine in our search for a sustainable materials future. We've come a long way, but we need to address one other key issue before moving on. To illustrate it, let's say that I currently drive 9,000 miles per year in a car that does 30 miles per gallon, so each year I purchase 300 gallons of fuel. If I swap my car for one that does 60 miles per gallon, I will halve my fuel purchases and save 150 gallons per year. Alternatively, if I decide to drive half the distance each year, I will also halve my required fuel and save 150 gallons per year. So, what if I do both: swap the car, and also halve the annual distance? Clearly, I've now taken both savings, so I buy 300 gallons per year less, so that's .... no gallons at all to drive 4,500 miles! Perfect, all solved. But of course it's not true. The two options are not independent, and if I adopt both of them then firstly, I halve my consumption with the new car, and then I halve the remaining consumption by reducing the distance, so I arrive at 75 gallon per year to drive 4,500 miles. However, we find that errors like this, where energy efficiency options are wrongly added up has permeated debate about future energy use and emissions, so we need to clear it up completely.

When we started looking at global energy use, we found that the excellent data of the IEA is collected by country and by economic sector, but not by the technologies in which fuel is converted into services. If we have data on energy use in economic sectors, we can address the question "who should I blame?" for energy consumption but we can't ask "what can I change?" To do so we need to know how many electric motors are involved, for instance, or how much gas is burnt in boilers, and how efficient they are. So, we ran a major project to develop a map of global energy use, to show how energy sources (mainly fuel, but also renewable sources) are transformed by technologies to deliver the final services required by consumers. Our key map is to the right, showing this transformation. The map is in the form of a Sankey diagram in which the width of the lines are proportional to annual use of energy. (The box story on Riall Sankey describes the origin and uses of this diagram. We'll be developing several other Sankey diagrams later in the book.)

Fun with numbers 1

How significant is steel as a driver of global emissions? We need to answer the question with a ratio dividing the top number, the numerator, by the lower denominator. On the top, we can choose emissions associated with making liquid steel only (2 $GtCO_2$/year), with making the stock products that are sold by steel makers for manufacturing (2.5 $GtCO_2$/year), or the emissions associated with final goods made from steel (3.5 $GtCO_2$/year). On the bottom, we could include all possible emissions due to mankind, including agriculture and land-use change (44 $GtCO_2$/year), or we could use total emissions from the use of energy and processes (27 $GtCO_2$/year), or the emissions of the industrial sector (10 $GtCO_2$/year). So the unique and clear answer to the question is 4.5 %, 5.7 %, 7.4 %, 8 %, 9.3 %, 13 %, 20 %, 25 % or 35 %—all of which are true! But this is just the beginning. Here are some other recent suggestions about the 'real value' of the numerator in our ratio: steel can be recycled, where cement cannot, so the emissions in making steel the first time should be reduced by a third to account for the benefit of using it in 40 years time; making a tonne of steel leads to production of about a quarter of a tonne of unwanted by-product called blast furnace slag, which can be used to reduce requirements for cement, so the true emissions of steel should be reduced by a quarter; new cars are more fuel efficient than older cars, so we should use more steel to make more new cars, and credit the resulting 10 % emissions savings to the steel.

And the point of raising this is that all of these ratios arise from the same agreed figures on global emissions. We can have a lot of fun creating ratios that slant the story in one direction or another, but our concern is the total environmental impact of the whole system, so blame-shifting by playing with ratios is of no interest as we look for options for change.

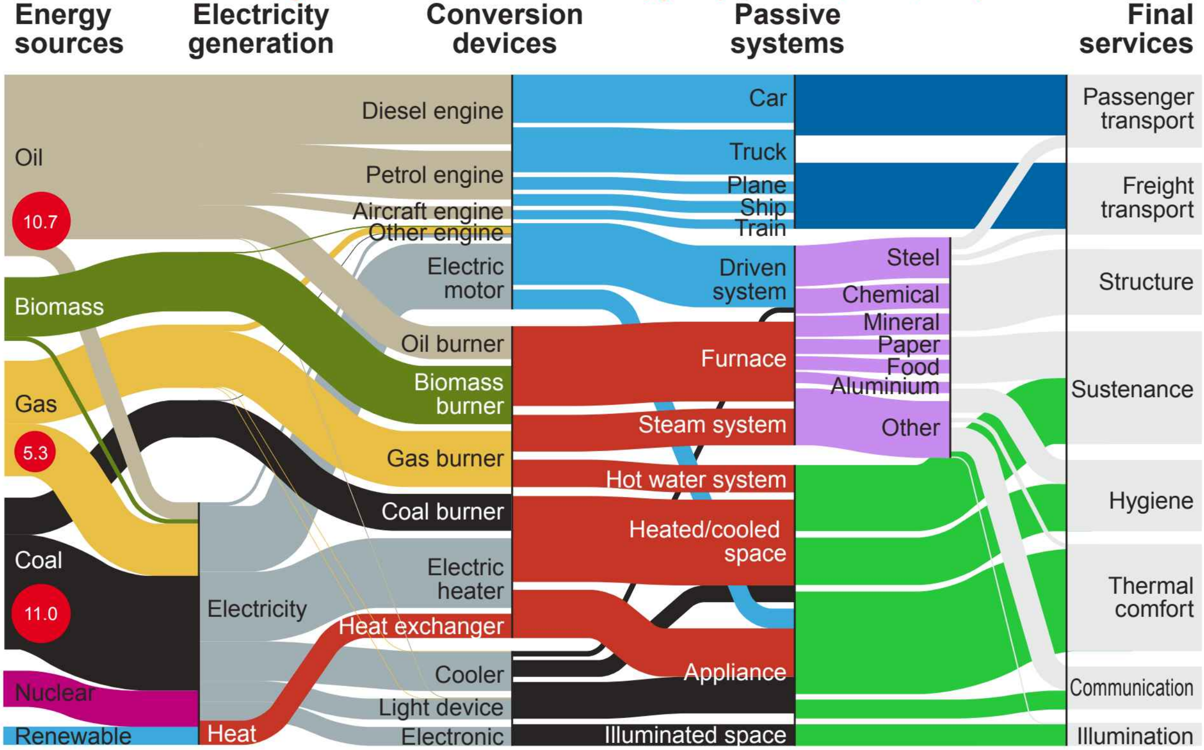


Figure 2.5—**Sankey diagram of global energy use**[18]

The origins of the Sankey diagram

Sankey diagrams were first used by the Irish engineer Riall Sankey in 1898 to compare the energy flows of a real steam engine, a Louisville Leavitt Pumping Engine, with a 'perfect' engine. Within ten years the diagrams were being used to visualise 'heat balances' for engines and industrial processes, particularly by German engineers. Following the First World War, supplies of steel were critical in Germany, prompting the use of more complicated Sankey diagrams as a tool to identify options to conserve raw materials and improve production efficiency. Sankey diagrams are now commonly used to visualise flows of mass, energy, water and greenhouse gases across systems ranging from the smallest engines, to factories, to the entire global eco-system.

The key principle of a Sankey diagram is that flows are represented by arrows or lines where the thicknesses of each line represents the amount of flow. In systems, such as those related to energy or materials, where the flows cannot be lost, the sum of the widths of the lines (the sum of flows) across any section of the diagram, must always be the same. The reason we find Sankey diagrams so useful, is because at a glance we can gauge both the scale of a flow, and see how it connects with other flows.

If we take any vertical slice through our global energy map, the width of the lines adds up to the same number, which is the total energy value of the input sources. Therefore, if we want to consider the effect of making several efficiency improvements at the same time, all of which occur in a single vertical slice, then we can simply add up the savings from each, to get a total saving. However, if our efficiency gains occur along a horizontal line in the map, an improvement in power generation and an improvement in electric heater efficiency for example, we must multiply their effects to predict the total saving in fuel inputs. In our earlier example a 50% saving through fuel efficiency multiplied by a 50% reduction in driving distance gave an overall efficiency gain to 25%.

We've emphasised this difference between vertical and horizontal slices on the energy map because it is otherwise easy to make misleading claims. Many commercial organisations currently produce 'Abatement Curves' as a way of showing the relative cost of different options to reduce emissions, but every example we have seen has misleadingly suggested that efficiencies along a horizontal path on the energy map can be added up[6]. An important example of this confusion in Europe at present is in the strong move towards electric 'plug-in' cars charged from the national grid. The energy map makes clear that even if the car itself uses less energy (in direct electricity) than a petrol equivalent, we can only compare an electric car with a conventional one if we chase back through electricity generation to the original energy source. Using this approach we quickly come to the conclusion that an electric vehicle is currently no more efficient than a comparable petrol version, and may be worse.

It would be much more sensible to reduce the weight of cars first, and then change to battery power

Summarising what we've learnt about scale:

- Five key materials—steel, cement, plastic, paper and aluminium—dominate emissions from industry, and producing them accounts for 20% of all global emissions from energy use and industrial processes.
- This 20% figure relates to producing stock forms of the five materials, prior to final construction and manufacturing. Our analysis of Chinese energy use suggests that construction and manufacturing adds a further 2% of global energy and process emissions[7].
- In discussing efficiency options for producing the materials, we have to account carefully for the connection of energy transforming devices within the overall energy map as some efficiencies are additive and some are multiplicative.

Uncertainty

If only CO_2 were coloured pink, toxic releases were noisy and resource depletion caused a light to flash. It would be very much easier to address concerns about sustainable materials if all the drivers of harm and their long term impacts were instantly visible. But for most environmental processes there's a time delay between cause and effect and anyway our understanding of the causes is only partial. Here are the main uncertainties we face in exploring the impact that materials have on future sustainability:

- We do not fully understand how human activity now will affect the environment in the future.
- We do not fully understand how future environmental conditions will affect human and other life.
- We do not fully understand the environmental consequences of changes in human activity.

Specifically with regard to our five key materials, we face several other uncertainties that limit our ability to predict the consequences of future materials processing:

- We don't know how the world population will evolve or how rich we will be in future, so we don't know how demand for materials will develop or how it will be affected by environmental pressures.
- Although we have good understanding of emissions released from industrial processes and fuel combustion, we don't have a clear picture of all the uses of electricity associated with materials processing, which indirectly drives emissions.
- We don't have perfect data on the current end-uses of the key materials, because no one collects it, nor do we have good data on existing stocks of materials in use that might be re-used, recycled or replaced in the future.
- We don't know how costs will evolve, for example as oil becomes more scarce, less pure reserves of iron ore are used for normal production, or if more electricity is in future generated by renewables.

On top of this, we also have to deal with the fact that well informed organisations can make considerably different, even opposite, statements about the impacts of different choices. Two key issues have dogged our efforts to develop a clear picture of priorities:

- Materials producers naturally want to present their own material in the most positive light, so all use a different basis of comparison in order to present their particular material as "green." We've listed some examples of current claims in the sidebar, and further illustrated this problem in our second 'fun with numbers' box, which explores the much publicised information that "recycling aluminium requires 5% of the energy used in making new aluminium from ore." As the box shows, the 5% claim is factually correct if you are considering only the production of unrefined molten metal, but the can made from recycled material actually requires about a quarter of the energy required for the can from primary material. The materials producing industries are highly sensitive to the presentation of energy and emissions data and of course they can only report the most positive story. We've worked closely with them in preparing the book, and know that they would tell the story a different way, so to help them do so we have shown the basis of every number we're using in our footnotes and references.

- The processes which make materials from ore are generally much more damaging to the environment than downstream processes in which components are shaped and assembled into products. Materials processing is largely invisible to final consumers, so should we transfer responsibility from the processes onto the products which they make? Unfortunately this is an extremely difficult transfer to achieve. The most common current technique for attributing impacts to products, Life Cycle Assessment (LCA), was designed only to make relative comparisons between similar products but now is largely used to make assertions about absolute impacts of products. This is not a valid use of the technique, so the results can easily be manipulated to provide an answer that suits the preferences of whoever funded the study.

The uncertainties we've found in this section seem rather overwhelming: we're uncertain about how the environment works, we can't know the future, and much of the information provided to us is slanted. So what should we do?

We can't wait till everything is certain: there is a time delay between actions and environmental consequences, so that if we wait till all the environmental harm is visible, we will have missed the important opportunities to make change. In the

"Steel is essential to the modern world and the use of steel is critical in enabling man to move towards a more sustainable future. Steel is fundamental in a greener world … "

World Steel Association[10]

"Even fewer people are aware of the many environmental benefits that using concrete brings … Concrete, with its strength, durability and excellent thermal mass, should be a key component in eco-buildings of today and the future."

Cement Sustainability Initiative[11]

"Plastics make an immense contribution to the environmental sustainability through their energy saving potential and intrinsic recyclability and energy recovery options."

British Plastics Federation[12]

"Paper is a sustainable choice and if we only want to reduce paper consumption per se, the question is "what will we replace it with; plastic, aluminium, glass?". If we need to consider the most sustainable solution, from an energy efficiency point of view as well as from the sustainability of the raw material, then normally the answer is paper."

Confederation of
European Paper Industries[13]

"[Aluminium] is key to improving global living standards and developing a better and more sustainable world environment."

International Aluminium Institute[14]

Claims about the sustainability of materials

case of climate change in particular, CO_2 emissions released today will linger in the atmosphere for around 250 years, so our children, and many generations to come, will live with the cloud we've released.

So we need to plan ahead using estimates, making sure we're clear about the uncertainty in them, but not using uncertainty as an excuse for inaction. How do we make good estimates?

Fun with numbers 2

Making a tonne of liquid aluminium from ore uses more than twenty times as much energy as making it from scrap (168 GJ/t compared to 7 GJ/t), so can we say that making a can from recycled aluminium only uses 4 % of the energy to make it from primary aluminium?

Before aluminium cans are melted, coatings, other materials and moisture must be removed in an oven by a process called de-lacquering. De-lacquering uses about the same amount of energy as the melting process: our recycling energy is now 8 % of the primary energy.

After de-lacquering, the cans are melted, however, a can is made from two different aluminium alloys, one for the lid and tab and one for the body. Therefore the composition of the melted aluminium scrap must be 'sweetened' with primary aluminium before it has the right composition for use as can body stock. About 5 % primary aluminium must be added to correct the composition, and the recycling energy is now 13 % of the energy to produce primary liquid metal.

However, we still need to make the can. The liquid aluminium from either source must be cast, rolled, blanked, stamped and coated to create can, and this requires a further 30 GJ. So making cans from a tonne of liquid aluminium from ore required 198 GJ, while from scrap it required 52 GJ, or 26%. Therefore recycled cans do save energy but require 26% not 4% of the energy used for primary cans.

The data used for this calculation is from the European Aluminium Association, EAA (2008).

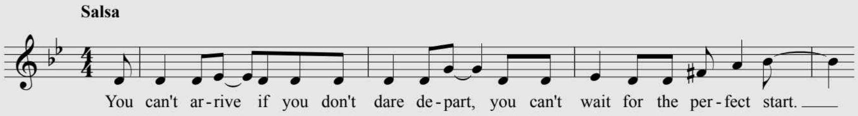
Process stage	**From ore (GJ/t)**	**From scrap (GJ/t)**
De-lacquering		7
Liquid aluminium	168	7
Sweetening		8
Can-making and coating	30	30
Total	198	52

Table 2.1—**Energy use in recycling an aluminium can**

Estimates

We started this chapter with data collected by the International Energy Agency about fuel use, which is given by country and region, and in the key sectors. These numbers are probably reasonably accurate because fuel trade is recorded with some precision, so we have high confidence in our claim to have identified five key materials.

We are less sure about exactly how much energy is used, or the level of emissions released, in processing these five materials. No one collects a complete global data set for the performance of all processes, so instead we infer data from specific cases. In some countries or regions, businesses operating in particular sectors must report their emissions at a company or site level, as required for example by the European Union Emissions Trading Scheme. But unless the site is dominated by a single process this number requires interpretation and the companies involved are understandably reluctant to reveal details because their customers could use them in negotiating future prices. Most information on processes is therefore collected by trade associations, and they in turn are only able to release information approved by their members. In future, we hope that governments will mandate more reporting on energy, just as financial reports are required of companies. But at present most reporting is still voluntary, and we must rely on estimates. The box story describes the best voluntary scheme we've found while preparing the book.

Our uncertainties increase rapidly as soon as we look at environmental effects other than those related to energy use, as the data shortage becomes more and more severe. In particular, although we know that industrial production uses over 100,000 chemicals at present, we only really understand the toxic impacts of a small fraction of them, and even then our understanding is largely about short-term impacts.

Overall, we have good data on energy and emissions by sector, but must use estimates to relate the data to particular processes. We have some data on material production volumes and use, but will need to make many estimates to predict all flows of metal into goods. Furthermore, in making estimates we've had to unpick several causes of confusion:

- Electricity or energy: we often find these two words used as if they were inter-changeable, but as we've seen on the global map of energy use, making electricity requires around one third of the world's energy sources. This is because electricity is a 'final fuel' (it can be metered by the final purchaser), sometimes called a direct energy, unlike original energy sources such as coal or gas which are called primary. To compare like with like we must always refer our numbers back to primary energy because this is the source of all energy-related carbon emissions.

- Energy or emissions: in many cases, energy use and CO_2 emissions are closely related, but not always. In manufacturing cement, for instance, roughly half the emissions arise from energy use and half are from the chemical reaction of converting limestone into cement and can't be avoided whatever energy source is used.

Data collection and reporting schemes

The Eco-Management and Audit Scheme (EMAS) introduced by the European Commission in 1995 and updated several times since, is a voluntary tool to help companies to evaluate, manage and improve their environmental performance. EMAS aims to support continuous improvement in the environmental performance of organisations and sites, through provision of transparent credible information updated at least annually. EMAS requires reporting of six key indicators, for energy efficiency, material efficiency, water consumption, waste generation, land use and emissions of greenhouse and other gases. To develop the material efficiency indicators, companies must report annual mass flows of the different materials they process.

Around 8,000 sites are now registered with EMAS, and during the many visits we made in preparing the book, we were particularly impressed by the Alunorf site near Dusseldorf, Germany, which uses EMAS to provides full public disclosure of their mass and energy flows.

- CO_2 or CO_{2e} (equivalent) emissions: we're sticking to CO_2, because making materials produces mainly CO_2, and it simplifies the problem enough for us to see a big-picture. However, CO_2 although clearly dominant, is just one of the three main greenhouse gases, alongside methane (CH_4) and nitrous oxide (N_2O). We'll need to use CO_2 equivalents, weighted over a long-time period, when we want to include the effects of the other gases in our analysis.

- Everyone uses numbers in a way that supports their interests: in gathering information about emissions and material use, we've found that authors will always choose to present their data in a way that adds weight to the argument they are making. This includes switching between giving absolute numbers (28 Mt) or ratios (32%) and, as we saw in our first 'fun with numbers' box, manipulating the terms in a ratio.

Defining the scope of the book

Given our problems with uncertainty, and the shortage of data that drives us to use estimates to anticipate the scale of key changes, we need to simplify the problem of searching for a 'sustainable' future. So we've decided to focus this book on CO_2 emissions. Climate scientists tell us that we need to cut CO_2 emissions by 50% or more by 2050. This is a massive challenge within a very short time, and unlike many of the other concerns raised in the previous chapter, governments have generally picked up on these targets and placed them into law in various forms[8].

In focusing on CO_2 emissions, we run the risk of missing other key environmental concerns such as water stress and toxic emissions to air, water or land, but having a single target helps us to clarify what is big and what small, and gives us increased confidence that our estimates can lead us to identify changes that will make a big difference. As we'll spend a good deal of the book exploring options to reduce our dependence on the production of new materials, we can also anticipate that where environmental harm is driven by intense industrial processes, reducing the demand for those processes will reduce other impacts too.

The topic of Material Efficiency, delivering the services we want from materials in a way that uses less material, has had very little previous attention. This is hardly surprising, because it would be much easier for everyone including those in industry and government and consumers, if our concerns about the environmental impact of materials production could be solved 'invisibly' by producers, without consumers being aware of any change. As a result, this book arises out of ongoing research, in which we're trying to gather the required information from scratch.

To increase our chances of covering all possible options in sufficient depth to be useful, our main focus has been on just two of the five key materials, steel and aluminium. We've chosen them because they're the most complicated of the five: more processes are required to make finished metal goods than goods in cement, plastic or paper. We'll describe in detail our exploration of the two metals in the first three parts of the book, and then in Part IV we'll go back to give shorter versions of the same story for cement, plastic and paper, before discussing implementation of change in Part V.

And finally, a word on units. While preparing the book we've come across energy measured in Joules, kilowatt hours, nuclear-power station years, average planet person years, Belgian household electricity years, windmills, solar square metres, Calories, British Thermal Units, cans of Coke, lightbulb years, kettle minutes, Joules per kilometre, Joules per kilogram, sheets of paper … Brilliant! Energy units are a game everyone can join, and with around seven billion people on the planet, each thinking of a new unit each day, we could generate 2.5 trillion energy units per year. If it takes one of our daughters two hours and one chocolate biscuit to make one friendship bracelet, how many friendship bracelets does it take to light the Eiffel Tower in winter?

There isn't a single convenient answer, because we often want to make comparisons, so units abound and will always do so. However, the problem we all face is that when we hear a talk in which someone introduces a new unit (standard sea level hamster vertical metres, anyone?) we spend most of the talk trying to translate them into the units in which we keep our own reference data. David Mackay included an excellent appendix in his book which is freely available online, showing a wide range of units on consistent scales and we'd recommend this as a great way to speed up conversions[9]. For our own purposes, where possible we've tried to stick to simple units for exploring energy and emissions with materials processing: for energy we'll use megajoules per kilogram (MJ/kg which, if you multiply both terms by one thousand is the same as GJ/tonne) and for emissions we'll use kilograms of CO_2 per kilogram of material processed (kg CO_2/kg which similarly is the same as tonnes CO_2/tonne.) These are manageable units for comparisons, but of course, to make sense of them, we also have to remember the total volumes of materials involved, so we can convert rapidly from relative to absolute units. The table below contains the key set of numbers we try to keep in mind whenever we're hearing other people talk about materials and energy in order to assess the scale of their suggestions. As we work through the book, we'll show that using simplified single numbers for energy and emissions ratios could be misleading. For example recycling is usually more energy efficient than producing new material. However these 15 numbers remain important as a first health check on any new presentation of data.

Table 2.2—**Useful approximate numbers for making estimates about the key materials**

Material	**Global annual production (Mt)**	**Energy intensity (GJ/t)**	**Carbon intensity (t CO_2/t)**
Cement	2,800	5	1
Steel	1,400	35	3
Plastic	230	80	3
Paper	390	20	1
Aluminium	70	170	10

It is much easier to memorise this table if, as Jeeves would advise, you eat plenty of fish, though don't forget to bring it home wrapped in used newspaper, to save that carrier bag. In fact, after a chapter of heavy thinking about uncertainties, Jeeves might well suggest that we nip off to the Savoy for a quick bracer…

Notes

1. The full speech by UK Prime Minister Gordon Brown is transcribed on the website (Politics, 2007).
2. Between 2006 and 2010 the UK's leading supermarkets reduced the total number of carrier bags given out by 41 %, according to WRAP (2011).

Scale

3. The reported Metal stocks and recycling rates, by the Global Metal Flows Working Group at the UNEP states "a mobile phone contains over 60 different metals: [two-thirds of the periodic table, including] indium in the LCD display, tantalum in capacitors, and gold on the conductor boards" (UNEP 2011).
4. The pie charts are drawn based on data from various publications from the International Energy Agency.

   Pie chart (top): Man-made (anthropogenic) greenhouse gas emissions (GHG) in 2005 were equivalent to 44.2 billion tonnes of CO_2 (IEA 2008, p.398). The 44.2 Gt CO_{2eq} includes three main gases: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O)—which account for 99 % of all GHG gases—along with small quantities of fluorocarbons (HCHF, HFC, PFC) and sulphur hexafluoride (SF_6). The emissions from different gases are totalled based on their CO_2 global warming potential over a 100-year time horizon, as standardised by the IPCC (2007). Energy-related CO_2 emissions account for 61 % of all GHGs (and 76 % of total CO_2 emissions). A further 3 % of GHGs come from non-energy related CO_2 emissions in industry, mainly from the calcination reaction cement production, giving a total of 28.2 $GtCO_2$ (64 % of GHGs) for energy-related and industrial process CO_2 emissions (note the eq subscript has been dropped, because only CO_2 emissions are included in the 64 %). The remaining 36 % of man-made GHG emissions fall under the LULUCF category (land use, land use change and forests) including activities such as "deforestation, unsustainable use of traditional biomass, burning of scrubland, decay of biomass after logging, peat fires, decay of drained peat soils and loss of organic matter from soils after cultivation" (IEA 2008c, p.399). Note that this category does not include natural flows of carbon dioxide and methane, to and from plants, animals and oceans.

   Pie chart (middle): The 27 $GtCO_2$ of energy and process related emissions are divided into four categories, using data from the IEA's Energy technology perspectives report, (IEA 2008a): industry (9.9 $GtCO_2$, p.479), buildings (8.8 $GtCO_2$, p.519), transport (7.3 $GtCO_2$, p.425) and other (solved, 1.1 $GtCO_2$). Emissions are both direct (from the burning fuels) and indirect (from the upstream CO_2 from electricity production). The "other" category is the CO_2 emissions not covered in the three main sectors, but appears to be upstream energy use for processing fuels (extraction, refining, transportation and storage) which cannot be directly attributed to the sectors.

   Pie chart (bottom): The industry sector from the middle pie chart, is broken down further to highlight the five materials we are interested in for this book. This is not easy, as most emissions data for industry is given as direct emissions only (the metered electricity and fuel inputs to the factory), and excludes any process emissions from chemical reactions in industry and also the upstream emissions from electricity generation. So we need to find numbers for all three components of the emissions figure: direct energy-related emissions, direct process emissions, and upstream indirect emissions. Table 16.4 of the IEA Energy technology perspectives (IEA 2008a) report gives direct energy and process CO_2 emissions for 13 industrial categories and 31 regions of the world—we use only the global figures. The industrial categories still don't match our 5 materials—steel, cement, paper, plastics and aluminium—however we also know that 94 % of the non-metallic minerals category is cement (IEA 2008a, p.489), 60 % of the non-ferrous metals category is aluminium (IEA 2007, table 8.1), and Allwood et al. (2010) perform a detailed calculation to show that plastics make up 31 % of the chemical and petrochemical category. Process CO_2 emissions are associated with steel and cement manufacture, but the fluorocarbon emissions from aluminium are not included here, as they are not CO_2. Added to these direct and process emission values are the indirect emissions from upstream electricity generation, estimated from the sector graphs of 2005 baseline emissions in IEA (2008a) and scaled for cement, plastic and aluminium. The other category contains the remaining industrial emissions from table 16.4 (IEA 2008a). The table below summarises the industrial CO_2 values and references.

Sector	$GtCO_2$	Direct	Indirect	Process
Steel	2.49	1.88	0.50	0.11
Cement	1.85	0.72	0.19	0.94
Plastic	0.35	0.20	0.15	
Paper	0.42	0.19	0.23	
Aluminium	0.24	0.08	0.17	
Other	4.5	2.54	19.6	
Total	**9.86**	**5.61**	**3.20**	**1.05**

Sources—For direct and process emissions of all materials, see IEA (2008a) Table 16.4. For indirect emissions, see: Figure 16.6 for steel, Figure 16.9 for minerals, of 94% is cement (p.489); Figure 16.2 for chemicals of which 31% is plastic (Allwood et al. 2010); Figure 16.3 for paper, Figure 16.5 for aluminium; Table 16.3 for other.

5. The Passivhaus (Passive House) is the fastest growing energy performance standard in the world with 30,000 buildings already having been realised (BRE, 2011). The design standard requires a building's annual heating/cooling load to be less than 15 kWh/m^2 with particular detail paid to insulating to reduce heat loss, and sealing leaks to stop hot air escaping. The first Passivhaus residences were build in Darmstadt, Germany in 1990, and the standard has been promoted mainly in Europe by the Passivhaus Institut (2011) However, the UK's introduction of 'zero carbon' targets for housing has created more interest in the UK: BRE (2011) and the Passivhaus Trust (2011) provide excellent information on their websites. It is clearly much easier to apply the standard for new-build, but recently the first UK house retrofit was undertaken in West London, by greentomatoenergy (2011).
6. Two well known examples of abatement curves are: the Global climate abatement map by Vattenfall (2007); the McKinsey Global Institute report, Curbing global energy demand growth (Mckinsey,

2009). Neither study appears to address the problem of 'adding up' emissions savings along the energy chains.

7. Steel and aluminium make up 39% of China's industrial emissions, with an extra 7% attributed to metal manufacturing. For the world, steel and aluminium make up 28% of industrial emissions, so by the same ratio we expect that 5% of global industrial emissions arise in metal manufacturing, equivalent to 2% of all global emissions from energy and processes (LinWei, 2011).

Defining the scope of the book

8. The UK's Climate Change Act (26 November 2008) is a long-term legally binding framework aimed at tackling the dangers of climate change. The Act requires emissions reduction of 80% by 2050, measured against 1990 levels. It also sets legally binding carbon budgets limiting the total amount of emissions that can be emitted.
9. This appendix is in David MacKay's book "Sustainable Energy without the hot air" (MacKay, 2009) which is online for free at www.withouthotair.com.

Box stories, figures and tables

10. A quote from the World Steel Association's climate change position paper (World Steel Association, 2011).
11. This statement was taken from the Cement Sustainability Initiative webpages on the World Business Council for Sustainable Development's website, under the heading of "Sustainability Benefits of Concrete" (WBCSD, 2010).
12. The British Plastics Federation have published several 'position statements' on the sustainability of plastics. The extract reprinted here, was sourced from their website (BPF 2011).
13. The Confederation of European Paper Industries champions the achievements and benefits of the European pulp and paper industry. The quote was taken from their "Q&A on the sustainability of the paper industry" webpage (CEFI 2011).
14. This comment is found on the Welcome page of the International Aluminium Institute website (2011a).
15. Car data was collected from manufacturer's specifications for a wide range of makes and models in the UK.
16. The emissions for a current house are an average from 46 studies surveyed by Ramesh et al. (2010). The trend for future emissions is based on the UK's Part L Building Regulation targets and the Zero Carbon targets for new buildings, which aim to reduce use-phase emissions to net-zero by 2019 using aggressive efficiency measures complimented by onsite renewable generation.
17. These charts were compiled from government statistics (Linwei, 2011).
18. The Sankey diagram of energy flow is adapted from the paper by Cullen and Allwood (2010a)