Teaching about energy: from everyday to scientific understandings

Robin Millar

ABSTRACT A key challenge in designing a teaching programme on energy is in deciding how best to deal with the differences in how the word 'energy' is used and understood in everyday discourse and in science. Many of the most important decisions and choices about energy matters, both for individuals and society, can be adequately understood from an everyday perspective. This raises the question of the appropriate balance in the curriculum between the everyday and scientific views of energy, and of why, when and how we should try to move students on from an everyday understanding of energy towards the scientific understanding.

Two worlds of energy

Much of the challenge in teaching about energy stems from the differences between the everyday use of the word 'energy' (which pre-dates its scientific use by several centuries) and the associations with it that we develop, and the scientific meaning of the word 'energy'. The latter is summarised in a frequently cited passage from Richard Feynman's celebrated *Lectures in Physics* (Box 1). Feynman emphasises that 'energy' is a 'bookkeeping' quantity – a number that has to tally at the end of an event with its value at the beginning. It does not describe a mechanism and therefore cannot help us to explain how or why the event happens.

> **BOX 1 Richard Feynman on energy**
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> There is a fact, or if you wish, a law, governing all natural phenomena that are known to date. There is no exception to this law—it is exact so far as we know. The law is called the *conservation of energy*. It says that there is a certain quantity, which we call energy, that does not change in the manifold changes which nature undergoes. That is a most abstract idea, because it is a mathematical principle; it says that there is a numerical quantity which does not change when something happens. It is not a description of a mechanism, or anything concrete; it is just a strange fact that we can calculate some number and when we finish watching nature go through her tricks and calculate the number again, it is the same. (Feynman, Leighton & Sands, 1964: 4–1)

This is not, however, how many of us think and talk about energy. Every year I run a workshop for science Postgraduate Certificate in Education (PGCE) students on teaching about simple electric circuits. I ask students how they would explain what happens when you add a second identical torch bulb in series with one that is already connected to a battery. Many answer that the two bulbs are now equally bright, but not as bright as the single bulb, because 'the energy is now being shared between the two bulbs'. In fact, the energy being transferred every second from the battery to the environment is now around half of what it previously was. But my point in telling this story is not to highlight the accuracy or completeness of this response but simply the fact that many students choose to talk about energy when they are asked to explain an observation. When I then ask how they would explain the result of connecting the second bulb in parallel to the first, some are initially tempted to give the same 'explanation' but start to see that this cannot account for the different observed behaviours in the two circuits. Both circuits can, of course, be analysed in terms of energy losses and gains but an explanation of their observed behaviour has to use different ideas.

Nor can energy explain why something happens. As Ogborn (1986) points out, a quantity that is conserved cannot explain why a process or event runs in one direction rather than the opposite. So energy cannot be ‘the go of things’ – the thing that makes them happen. We all learn, however, from an early age that most events need a ‘driver’ of some kind, which seems to lose something as the process proceeds. When we add this to the meanings and everyday associations we develop for phrases like ‘having a lot of energy’ or ‘having no energy’, it is not surprising that we come to think of some objects and materials as having a tendency (perhaps even to ‘want’, or ‘need’) to lose some of their energy in order to get into a less ‘excited’ and more stable state.

An effective teaching programme for energy has to recognise, and have a strategy for dealing with, this difference between the ways in which the word ‘energy’ is used and understood in everyday discourse and within the specialised discourse of science. Successful learning builds on what learners already think and believe. This is true of any science topic but poses particular challenges for the teaching of energy because of the differences between the everyday idea of energy and the scientific idea. Among the issues and questions which a teaching programme needs to address are the following:

- There are many ideas and issues concerning our use of energy resources that are of huge, and growing, individual, social, national and global importance. [See, for example, the article by Eric Wolff on p. 17 in this issue – *Editor*.] These should form a central part of any school science curriculum – but they can be (and in the news media invariably are) discussed and explored entirely using everyday energy language and its associated meanings.
- It is not clear what, if anything, an understanding of the scientific idea of energy enables students (and adult non-scientists) to understand, or to do, that they otherwise could not. To put this another way, it is hard to identify questions about the world that a student might ask spontaneously, or be stimulated by a skilful teacher to ask, which an understanding of the scientific meaning of energy (as opposed to the everyday meaning) would help them to answer.
- At whatever point in the curriculum we decide to try to help (some or all) students to develop some understanding of the scientific idea of energy, what understanding should we initially aim for, and how can we best start to move their understanding a little way from the everyday towards the scientific?

The remainder of this article discusses each of these in turn.

Energy resources

We meet the word ‘energy’ very frequently in everyday contexts. Foods carry labels that tell us how much energy they provide. ‘Energy companies’ sell us the fuels and supply the electricity that we use to heat our homes, cook our food and travel from place to place. The bills they send us say how much energy we have used in the previous quarter. We are advised by these companies, and by governments and various lobby groups, to save energy (and hence to save money) by insulating our homes, replacing old central heating boilers with newer ones, buying cars that do more miles to the gallon, using new types of light bulbs, switching off appliances when not in use, and so on. Government departments publish data annually on energy use and energy consumption in different sectors of the economy (industry, transport, domestic, and so on). Debates rumble on in the news media about how we can satisfy our future energy needs. (Please note that this paragraph is written in everyday energy language; there are several sentences that would be expressed differently in scientific language.)

It is important in a democratic society that as many people as possible have sufficient understanding of this energy discourse to make informed personal choices, and to recognise what is at issue in social decisions at local and national level that may have some uncomfortable practical consequences. Without this, they cannot contribute thoughtfully to these decisions and they are less likely to accept the inevitable compromises involved. Some of the things it is important to know and understand are summarised in Box 2.

In the everyday discussion of energy issues, energy is a commodity or a resource – something that we can buy and use. The fact that reserves of fossil fuels are limited and are being used up rather quickly applies equally to many other natural resources, such as copper or tin, or the rare earth metals. The economic and moral arguments for reducing the rate of use do not

BOX 2 What the general public should know and understand about energy

In a democratic society, it is important for as many people as possible:

- to know that a large proportion of our 'energy needs' is currently provided by the burning of fossil fuels, to understand how these have been formed, and to appreciate the huge difference between the rate at which they were produced hundreds of millions of years ago and the rate at which we have been using them over the past 150 years;
- to realise that, while there may be short-term fluctuations, the prices we will have to pay for gas, oil and petrol are almost certain to rise steadily over the coming years as accessible supplies of fossil fuels dwindle and governments begin to impose 'climate change' taxes on fossil fuels – and understand why this is so;
- to understand something of how electricity is generated, of the different options available for doing this, and of their implications in economic and environmental terms;
- to know about ways of reducing our demands on fossil fuels, by making greater use of wind, solar radiation, waves, tides, and biofuels that can regenerate at the same rate as they are used;
- to be aware of the link between carbon dioxide levels in the atmosphere and average global surface temperature, and its implications, and hence understand why we need to limit emissions of carbon dioxide, and the implications of this for decisions about future 'energy supply'.

require a scientific understanding. Even a key idea like 'efficiency' can be understood in terms of 'getting a job done using as little fuel as possible'. The ideas outlined above should perhaps be discussed more fully, and explored more deeply, in the school curriculum (including the science curriculum) than they currently are. Many of the ideas and issues discussed in David MacKay's important book *Sustainable Energy – Without the Hot Air* (MacKay, 2009) should be core elements of the school curriculum. But, as this book also demonstrates, they can be discussed very fully and thoroughly within the everyday discourse of energy, and do not require a deep understanding of the scientific idea of energy.

Why teach energy?

If the important issues relating to energy that affect people's lives can be grasped and discussed using everyday energy language and ideas, why do we want to teach *all* school students about the scientific idea of energy? Energy is sometimes portrayed as the most important idea in science – a conceptual 'jewel in the crown' that should be at the centre of the science curriculum. Its place is taken for granted. But what does an understanding of the scientific idea of energy, as opposed to the everyday idea, enable you to understand, or to do, that you otherwise could not? What are the questions that a student might ask, or entertain, about the natural world that require a scientific understanding of energy to answer in a satisfying way? This last question matters, as teaching is more effective when learners understand the question being explored and can see how new ideas that are being introduced might help to answer it. What are the 'hooks' to engage students with the scientific idea of energy – and make lessons about it seem purposeful (from the students' perspective) in developing their knowledge and understanding in ways which they value?

It is very difficult to give a convincing answer based on the practical usefulness of the ideas. A stronger rationale might be offered on more philosophical grounds: the intellectual satisfaction of a unifying perspective on events and processes in the natural world across a huge diversity of contexts and range of scales, and of the idea of conservation laws as tools for interpreting and analysing processes. The cultural argument, that '*Everyone should be given an opportunity to appreciate the elegance and power of scientific ideas and the cultural significance of science*' (Millar, 2014: 17), provides a stronger justification than arguments based on personal usefulness or democratic participation for trying to develop *all* students' understanding of the scientific idea of energy within the compulsory curriculum.

For those students, of course, who want to continue the study of science to more advanced levels, an understanding of the scientific idea of energy and the ability to analyse events and processes quantitatively in terms of energy changes is essential. Here a significant part of the rationale for introductory energy teaching is to provide a sound foundation for later study. At key stages 3 and 4 (ages 11–16), however, this needs to be balanced against other important reasons for teaching students about energy.

A teaching sequence

In the light of the issues raised in the two previous sections, how might a teaching sequence for energy ideas be designed? One general design principle that applies to the teaching of any science topic is that it should begin from ideas and contexts with which learners are familiar, and build on these rather than seeking to replace them. In the context of teaching about energy, this implies the aim of improving and extending students' understanding of the everyday discourse about energy matters, because this involves issues and choices that are of high importance in personal and social contexts, alongside the aim of helping students to move towards an understanding of the scientific idea of energy and appreciate the elegance and potential usefulness of analysing events and processes from an energy perspective.

A useful starting point is exploring and extending the ideas students bring from everyday life about the fuels we use for heating and for making things move, and about food as a fuel for humans and other animals. Students might also be taught at this stage about the origins of fossil fuels and hence that they are a fixed and finite resource. Fuels make a good entry point because they are indeed 'used up' and not conserved, in line with our intuitions. Work on fuels provides a context for introducing some numbers and doing some simple calculations, to convey the sense that energy is a quantitative variable. The energy available from the respiration of different foods can be compared with data on the amounts needed to do different jobs. Power ratings on domestic electrical appliances can be used to explore the rate at which these require energy to be supplied, and hence the cost of operating them. It is important to realise that heating is very expensive compared with using appliances that produce only movement, or light, or sound! The basic notion of efficiency (getting a job done using as little fuel as possible) can also be introduced.

Alongside these ideas, it is important to know that electricity is not a primary fuel but has to be generated using another energy resource and to have some understanding, in broad terms, of how this is done in different kinds of thermal power station and using wind- and water-driven turbines. At a later stage, it would be useful for students to gain some understanding of technologies (such as heat pumps) that are becoming more commonly used. And they should have opportunities to discuss trends in the use of energy resources over time, the inequalities in their use in different countries, and projections about future strategies for ensuring an adequate national 'energy supply'.

To make progress towards a fuller understanding of energy, students need to differentiate the ideas of heat (used here in its everyday sense) and temperature. Research studies indicate that this is a significant challenge for many learners (Driver *et al*., 1994; Linn and Songer, 1991). Some understanding of the quantity referred to in everyday language as 'heat' (and in scientific language as 'internal energy') is essential before starting to consider events and processes in terms of energy changes because almost all of these involve some transfer of energy to an object that ends up hotter than it initially was.

Identifying energy losses and gains during an event or process is the core of any qualitative introduction to energy ideas. Some care is needed, however, in the way it is done. It is useful to distinguish 'energy stores' from the 'pathways' by which energy can move from one store to another. In simple everyday events and processes, we can identify objects, or groups of objects, that have gained (or lost) energy by noticing that they:

- are moving faster (or slower) than they were;
- have reacted chemically;
- are hotter (or cooler) than they were;
- have been raised (or lowered) in a gravity field;
- are magnets (or electric charges) which have been moved apart (or closer together);
- are springy and have been distorted (stretched, compressed, bent) or allowed to spring back from a distorted state.

Shorthand labels for these various types of energy store (in order) might be:

- kinetic;
- chemical;
- internal (or thermal);
- gravitational;
- magnetic;
- electrostatic;
- elastic.

This list does not include ‘electrical energy’, ‘light energy’ or ‘sound energy’ – because these are not ‘stores’. Rather, they are ways in which energy can be moved from one store to another. At an introductory level, we might identify four such ‘pathways’. Energy can be moved (or transferred):

- mechanically (by a force acting over a distance);
- electrically (by charges moving through a potential difference);
- by heating (as a result of a temperature difference);
- by radiation (electromagnetic or mechanical).

By clearly separating stores and pathways, it becomes possible to tell a clearer and more consistent story about events and processes from an energy perspective. The separation is not entirely unproblematic. For example, a space through which light is travelling contains a large number of photons, each of which has a measurable amount of energy. But the total energy stored at any instant in the collection of photons in a given region of space is not a quantity of any importance or interest. Also, the decision to classify an energy transfer by infrared radiation as ‘by radiation’ rather than ‘by heating’ is simply because it may be easier for young learners to see it in this way. The argument is not that a framework based on the ideas of ‘energy stores’ and ‘energy pathways’ is perfect, but that it is ‘good enough’, and significantly better than frameworks that have been widely used in the past, such as those based on lists of ‘forms of energy’ that include both stores and pathways, or which insist on talking only about ‘transfer’ and not ‘transformation’ [see also the article by Richard Boohan on p. 33 of this issue – *Editor*]. An advantage of a ‘stores and pathways’ framework is that each of the ‘energy stores’ corresponds to an equation that can be used to calculate changes in the amount of energy that an object or system has, and the pathways to equations that can be used to calculate the amount of energy transferred every second – and so it prepares the ground for a more quantitative treatment of energy ideas at a later stage.

A key idea in all of this is to notice that, in any event or process, some energy invariably ends up in one or more internal energy stores (that is, in objects whose temperature has been raised), even when this is not part of the aim or purpose of the event. So the idea of dissipation can be introduced naturally and easily, alongside conservation. The amount of energy that ends up in unwanted internal energy stores also provides an insight into the idea of efficiency.

This might seem, at first sight, very similar to the ‘forms of energy’ approach that was introduced by the Nuffield projects of the 1960s and in many textbooks and teaching schemes since. The move from ‘forms of energy’ to ‘energy stores’ is not, however, simply a cosmetic change. It focuses attention on the beginnings and ends of processes, and shifts attention away from intermediate stages and mechanisms, about which energy ideas have almost nothing useful to say. In teaching these ideas, it is important to choose examples that have a clearly specified beginning and end (or to make clear the instants in a continuing process that are being treated as the beginning and end). And it is important to make clear the boundaries of the system being considered. For example, when discussing the operation of a mains-powered electrical device, do we include the power station and its fuel and oxygen within the system, or draw the boundary closer and have an energy flow into it? It may be easier initially to consider closed systems. More complex systems, with energy flows in or out, can come later.

The approach outlined above is discussed more fully in the Association for Science Education (ASE) guide *Teaching Secondary Physics* (Millar, 2011). It is consistent, with only minor differences of detail, with the approaches taken in the Institute of Physics Supporting Physics Teaching (SPT) 11–14 project materials (www.iop.org/sep) (Lawrence, 2007) and in the materials produced by the Gatsby Science Enhancement Programme (www.nationalstemcentre.org.uk/sep) (Boohan, 2007). The stores/pathways distinction is also central to several other recent proposals about energy teaching (Papadouris and Constantinou, 2011; Tiberghien, 2000; Williams and Reeves, 2003) [see also the articles by Richard Boohan on p. 33 and Charles Tracy on p. 51 of this issue – *Editor*]. It is also strongly supported by the wording of the new National Curriculum in England documents at key stages 3 and 4 (DfE, 2013; 2014). The key stage 3 programme of study also emphasises focusing on the starting and final conditions of a system and identifying increases and decreases in the energy stored in different parts of the system. It also makes clear that physical processes and mechanisms, rather than energy, should be used to explain how a change comes about. These new regulations hold out the possibility of an improvement in the way in which energy ideas are introduced and developed in the secondary curriculum. The key now lies in how they are understood and interpreted by users: teachers, textbook authors and examiners.

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Websites

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Robin Millar is is Emeritus Professor of Science Education at the University of York. He wrote the chapter on 'Energy' for both editions to date of the ASE guide *Teaching Secondary Physics*.
Email: robin.millar@york.ac.uk