Students to solve the world's energy problems!

An analytical approach for teaching alternatives to carbon

Pamela J Dugdale, The Mond Centre for Science and Maths, Cronton 6th Form College, Widnes, Cheshire, WA8 5WA

Our use of energy and how we generate it is of fundamental importance to society. With the UK's average electrical power consumption at around 50,000 MW and rising rapidly, our reliance on non-renewable energy to meet demand carries a clear environmental burden [1]. Tackling these problems in the long term will require the commitment and expertise of the next generation of engineers and scientists.

Most students completing a secondary education leave school with an awareness of power generation by traditional, nuclear and renewable methods. They will also have studied the potential consequences of our need for energy, and the resultant impact on climate change. While this provides them with some background knowledge as they move forward into the adult world, often it is limited to a qualitative understanding.

Post-16 college courses such as A-levels and National Diplomas in Science and Engineering give students the mathematical tools to adopt a more analytical approach. In fact, it is quite surprising how far college-level Physics will take you in the search for quantitative answers to energy problems. Time spent in lessons teaching students how to apply basic equations to real world problems can be an empowering learning experience. Even simple calculations can demonstrate the efficacy of proposed engineering solutions and allow informed decisions to be made. In some cases this may even lead to inspiring the energy engineers and scientists of the future.

The purpose of this essay is to present an overview of how this may be done, including some specific examples of renewable power generation which may be used in lessons.

Solid foundations

As a starting point, it is vital that all students grasp the standard definitions of power, energy and density, as given below.

$$Power = \frac{Energy}{time}$$

$$Kinetic\ Energy = \frac{1}{2}mv^2$$

$$Gravitational\ Potential\ Energy = mg\Delta h$$

$$Density\ (\rho) = \frac{mass\ (m)}{volume\ (V)}$$

Where m is mass in kg, v is velocity in ms^{-1} and Δh is change in height, for example the distance fallen by water in a hydroelectric system.

In addition, students must be competent in the use of units, such as the Watt and Joule, and power prefixes such as Mega and Kilo.

An introductory exercise would normally involve the students listing all of the renewable energy sources that they are aware of. The most popular response is wind power. Some students will give technical details about how wind turbines operate including the role of magnets in the generation of electricity. Most students will be more knowledgeable about the ethical and environmental implications. It is worth noting that this emphasis on ethics is even more pronounced if you ask students to describe the physics behind nuclear power generation.

A breath of fresh air

Why wind power? On a fundamental level, the 'direct' connection between rotation of the turbine and rotation of the generator make wind power conceptually more accessible to students than, for example, more physically 'abstract' photovoltaic technologies. Calculation of the power available from the wind is relatively straightforward using standard definitions for kinetic energy, power, velocity and density as shown below.

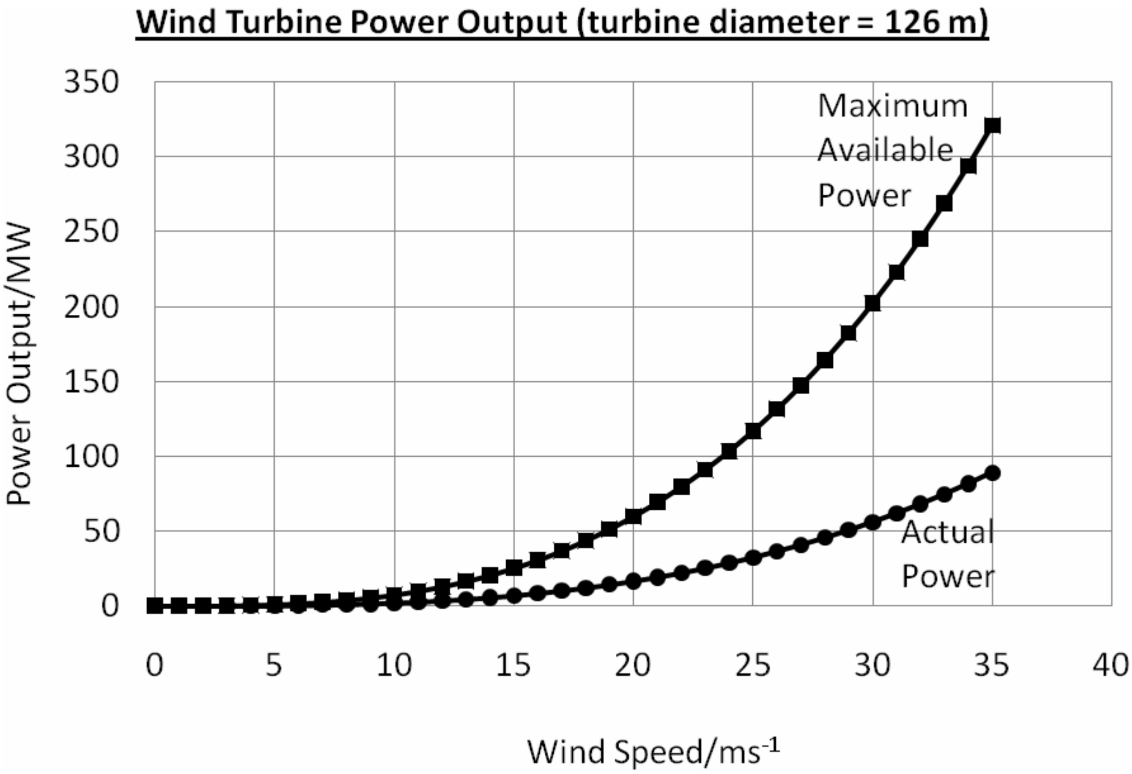
$$Kinetic\ Energy = \frac{1}{2}mv^2 = \frac{1}{2}\rho V v^2 = \frac{1}{2}\rho A l v^2$$

$$Max\ available\ power = \frac{kinetic\ energy}{t} = \frac{1}{2}\rho A \frac{l}{t} v^2 = \frac{1}{2}\rho A v^3\ since\ \frac{l}{t} = v$$

Where A is the area swept out by the blades in m^2 and ρ is the density of air. Such equations appear in current A-level textbooks [1].

This equation provides a sound starting point for graphical interpretation of the potential of this renewable technology, as shown in Figure 1.

Figure1: Graphical representation of the power available for a wind turbine of diameter 126m.



The topic can be brought home to students by using real-world data, such as UK wind speeds, from sources such as Boyle [2] as shown in Table 1.

Table 1: Wind speed at various locations in the UK.

	Wind speed at 50m above ground level / ms^{-1}		
Region	Open Plain	Sea Coast	Hills and Ridges
Northern England and Scotland	> 7.5	> 8.5	> 11.5
Central England	5.5 – 6.5	6.0 – 7.0	8.5 – 11.0
Southern England and Wales	6.5 – 7.5	7.0 – 8.5	10.0 – 11.5

Manufacturers' websites are a ready source of information on turbines – including data on their diameters, which vary from a metre for domestic use, up to a record breaking 126m [3]. Students quickly realise the ease with which the potential for wind power can be estimated. Further lessons then focus on the problem of efficiency, which is limited by the laws of aerodynamics – for example, the Betz law, which states only about 60% of wind energy can be extracted by turbines [2,4] – and machine efficiency, where a range of data is available from manufacturers.

Developing potential

Having examined the physics behind energy generation from wind turbines, a natural progression is to the extraction of tidal energy using turbines. This is known as tidal stream energy and has been studied in detail by the University of Southampton, amongst others.

The students quickly realise that the same equation is applicable but that there are now different restrictions on the variables. Whereas wind speeds of 30mph, around 13ms^{-1}, are common, tidal streams are more likely to flow at between 3 and 5ms^{-1} [5]. Furthermore, with a little thinking, the students will realise that the 126m diameter turbines that can be used above land must be replaced by much smaller turbines, limited by the depth of the sea in the appropriate location. And not forgetting other factors, such as the density of water being over 830 times that of air. Again it is useful for the students to plot power against velocity or velocity cubed curves for real data. These can then be compared with the results for wind power and the students become empowered to make real engineering decisions about the efficacy of each technology.

Tidal energy is probably the largest potential source of renewable energy available to the UK. Clearly, tidal stream turbines do not extract a high proportion of the energy available. To get closer to this requires tidal dams. In this technology, water at high tide is trapped behind a dam then allowed to fall back to low tide levels. It passes through turbines in the process, converting gravitational potential energy into the kinetic energy of the turbine. Proposals such as the Severn Barrage, as discussed in Nuffield [6] and Boyle [2], have huge potential in terms of power generation. However, environmental concerns, in particular relating to habitat for wildfowl, have thus far prevented the projects from being realised. Calculation of the potential for this technology is well within the grasp of the college student, requiring only the equations for gravitational potential energy and density, to give:

$$Power = \frac{\rho A g R^2}{2T}$$

Where ρ is the density of water, A is the surface area of the water held behind the dam (around 480 km^2 for the proposed Severn Barrage), T is the tidal period and R the range i.e. the difference between the maximum and minimum height of water held behind the dam (around 7m for the proposed Severn Barrage). It has been calculated that a tidal dam system on the Severn Estuary could produce as much electricity as 2500 wind turbines with diameters of 90m. Details of other potential UK tidal sites are listed in Table 2 [2]

Table 2: Potential UK tidal energy generation sites

	Range / m	Capacity / MW	Output / GWh
Severn – outer line	6.0	12000	19700
Severn – inner line	7.0	7200	12900
Solway Firth	5.5	5580	10050
Morecambe Bay	6.3	3040	5400
Wash	4.45	2760	4690
Mersey	6.45	620	1320

In most tidal dam systems the head, or height, of water trapped behind the dam is of the order of 5m. Hydroelectric systems use dammed or trapped water at much greater altitudes, and hence can effectively store significant gravitational potential energy. The best examples of such systems are in mountainous regions such as Switzerland and Norway – which extracts almost 100% of its electrical energy from hydroelectric stations [7]. Data on hydroelectric systems, such as that shown for Scottish stations in Table 3 [2], enable the student to carry out calculations to determine the available power.

Table 3: Data for Scottish Hydroelectric Power Stations [2]

Power Station	Average Head Δh/ m	Maximum flow Q / m^3s^{-1}	Output Capacity / kW	Number of Turbines
Drumjohn	11	16	2000	1
Kendoon	46	55	24000	2
Carsfad	20	73	12000	2
Earlstoun	20	71	14000	2
Glenlee	116	26	24000	2
Tongland	32	127	33000	3

In all such calculations the concept of mass flow rate, in kgs^{-1} and volume flow Q in m^3s^{-1} prove very useful to the student, in particular when converting from energy to power, as shown below.

$$Gravitational\ Potential\ Energy = mg\Delta h - \rho V g\Delta h$$

$$Max\ available\ power = \frac{GPE}{t} = \rho\frac{V}{t}g\Delta h = \rho Qg\Delta h$$

$\frac{V}{t}$ *is the volume flow rate, sometimes given the letter Q*

Bright futures

Most students know that the ultimate source of most of the energy on Earth is the sun. Data for typical energy per unit area is readily available for various regions of the planet at different times of year [4]. Alternatively, students can make use of real time online solar radiation measurements, such as those provided on the Edge Hill University website [8]

Students are aware from early in their education that black surfaces are much better at absorbing heat than white or shiny surfaces. They also understand convection currents (easily demonstrated using potassium permanganate in a tank of water). Hence, they will quickly grasp the principles of thermo-siphon heating and solar thermal energy collection, in which fluid is heated in pipes located in sunny locations such as rooftops [2]. A particularly good demonstration of this method can be seen on a roof at the Centre for Alternative Technology in Wales [9]. At college students will encounter the concept of specific heat capacity in the form of the equation:

$$Energy = mc\Delta\theta$$

Where c is the specific heat capacity of a material and $\Delta\theta$ is the change in temperature.

Again, using the concept of mass flow rate, energy can be converted to power as shown:

$$power = \frac{m}{t}c\Delta\theta = \rho\frac{V}{t}c\Delta\theta = \rho Qc\Delta\theta$$

And with knowledge of flow rate or pumping rate, Q, and the specific heat capacities of water [10] and glycol (antifreeze), useful calculations may be performed.

Whilst studying thermal physics, students are introduced to the concept of latent heat, and can perform interesting calculations relating to heat pump and heat exchange systems, where a length of buried liquid-filled piping extracts heat from the soil [2]. Such systems operate in a similar way to domestic refrigerators.

The physics behind photovoltaic technologies (PV) tends to fall outside many of the current college syllabi. Students are generally taught basic semiconductor physics to understand the operation of a thermistor, but are rarely introduced to the concept of doped semiconductors. They will learn the IV characteristics of a diode but not the internal structure of the device. It is unfortunate that a teacher working within such a syllabus will often have to discuss these devices on a very superficial level. Yet, despite our often cloudy skies, inspiring UK-based students about the potential of solar power requires little more than an overview of the ambitious plans to connect Europe to a vast grid of PV and thermal generation technologies in Saharan Africa [11].

Future solutions

The examples discussed here cover a wide range of topics from current UK college physics syllabi. Having studied each example as an embedded part of their course, an excellent revision tool is to set students the problem-based learning task of defining a sustainable energy strategy for the UK. This is a very flexible exercise which can be used to stretch the most able students, while still being accessible to all. Real world data for wind speeds and tides, etc. is widely available, and can turn an otherwise prescriptive series of lessons into a genuinely engaging student-based learning experience.

Further to this, students with the analytical and research skills to understand the full range of energy sources and their optimal implementation, may truly develop into the scientists and engineers able to solve our current and future energy problems.

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[8] http://www.metinfo.org.uk/edgehill/ (accessed 6th December 2009)

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[10] http://www.kayelaby.npl.co.uk/general_physics/2_3/2_3_6.html (accessed 6th December 2009)

[11] Luther, J. “A Place in the Sun”. Physics World 22(11) November 2009.