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Think global, act local—a power generation case study

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Abstract
This paper describes an exercise completed by sixth form college students to compare the power output from a local coal fired power station with the potential power output from renewable sources including wind farms, solar farms, and the proposed Mersey Tidal Barrage scheme.

The phrase 'think global, act local' has become a popular mantra for environmentalists. The aim of the work presented here is to investigate how this concept may be applied to the teaching of sustainable electrical power production to college students.

With the UK's 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]. So how can we 'think global, act local'? As part of the research that underpins this paper, students were asked to investigate existing and future plans for power production in their local area. This required them to compare the power output of Fiddler's Ferry power station near Widnes, Cheshire, (photo 1)—which burns coal and biomass—with existing wind farms in the Mersey Estuary, and the proposed Mersey tidal barrage. They were also asked to consider a proposal to build a photovoltaic solar farm. The idea of collecting data and performing calculations from first principles was fundamental to this work, allowing students to apply skills and knowledge from the mechanics and electricity modules of the AS/A2 physics curriculum. Furthermore, the task gave context to many exam questions which require the derivation and discussion of power outputs from wind turbines and tidal power. By the end of the process it was hoped that students would gain a quantitative understanding of the scale of the challenge to 'keep the lights on'.

Photo 1. Fiddler's Ferry coal and biomass fired power station.

Generating power in the Mersey estuary

In this exercise, students compared the power output from Fiddler's Ferry (2000 MW) [2], with the power from local wind farms and the proposed Mersey tidal barrage. To put things into context they first asked the question 'how much

0031-9120/12/010092+04$33.00

electrical power do we need to run the country?'. The required information on UK instantaneous electricity power consumption is available from the National Grid website [3]. This may be viewed as a graph of load against time for the past 24 h, week or month. Typically the load is between 30 and 50 GW, depending on the time of day and season.

The students then investigated the power available from local wind turbines. The Port of Liverpool has four Nordex N90 wind turbines. These have radii of 45 m and are rated at 2.5 MW for wind travelling at 13 m s^{-1} [4, 5]. The equation for the power in a cylinder of air moving with a known velocity is a standard part of college physics. It is

$$P = \tfrac{1}{2}\rho A v^3$$

where P is the power in watts, ρ is the density of air in kg m^{-3}, A is the swept area of the turbine blades in m^3, and v is the wind speed in m s^{-1} [6].

Using the equation above gives an incident wind power of around 8.4 MW. Hence the efficiency of a turbine, for this wind speed, is about 30%. So what happens to the other 70%?

The students' first instinct was that this must be lost as heat and sound in the mechanical and electrical components of the turbine. Further research revealed that there is a fundamental physical limit to the power that can be extracted from the wind. This is the Betz limit and has a value of 59.3% [7].

The exercise was then repeated for other local wind farms including: six wind turbines in Seaforth, each generating 600 kW of electricity (at 13 m s^{-1}) [8]; 30 wind turbines at North Hoyle, each generating 2 MW of electricity (at 13 m s^{-1}) [9]; and 25 wind turbines at Burbo Bank, each generating 3.6 MW of electricity (at 13 m s^{-1}) [10] (photo 2). This gives a total power output of around 160 MW under ideal conditions, compared with the Fiddler's Ferry baseline of 2000 MW under ideal conditions.

Next, the students considered the proposed Mersey tidal barrage (photo 3) [11, 12]. As with wind turbines, the equation for the power can be derived from the consideration of energy—this time as stored gravitational potential energy—and the density of water. It is

$$\text{Maximum power} = \frac{\rho V g R}{2T} \qquad (1)$$

Photo 2. Burbo Bank wind farm viewed from Crosby.

Table 1. Data for low neap and high spring tides at Princes Dock Liverpool.

Volume of water trapped behind the tidal dam V	150×10^6 m^3
Tidal range R	3.2 m
Tidal period T	Approx. 6 h
	298×10^6 m^3
Tidal range R	10.0 m
Tidal period T	Approx. 6 h

where ρ is the density of water (1000 kg m^{-3}), V is the volume of the water trapped behind the dam, 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. Tidal range and period data for the Mersey estuary are readily available [13]. In this instance, students were provided with data from a 1992 study of the potential for extracting tidal power from the Mersey estuary [14]. A simplified version of this data set is given in table 1.

Using these data it was found that the maximum power that could be extracted from a Mersey Tidal Barrage scheme is about 100 MW at low neap tide and nearly 700 MW at high spring tide. Since the students completed this study, additional data have been published about the latest barrage plan, and these are given below [15]:

- Mean neap tide range 4.5 m, trapped volume 190×10^6 m^3.
- Mean spring tide range 8.4 m, trapped volume 350×10^6 m^3.

Hence, the combined maximum power available from existing wind farms and an operational

Photo 3. The river Mersey close to the site of the proposed tidal barrage scheme.

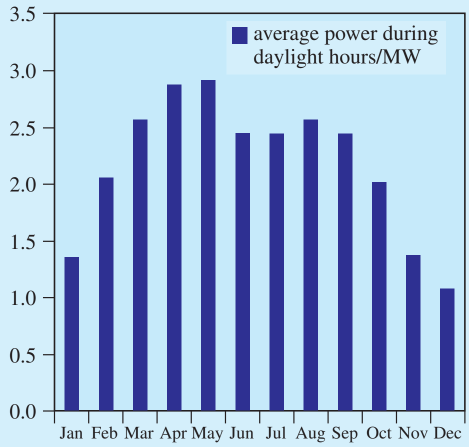

Figure 1. Students' results for PV array calculations.

tidal barrage was found to be around 860 MW, compared with 2000 MW from Fiddler's Ferry. This leaves a local power gap of around 1140 MW if Fiddler's Ferry was removed from operation.

Power from the Sun

The college students were also able to review the proposals for a solar array on farmland in NW England. The proposed site was about 10 miles from the college and covered an area of approximately 15 acres. The developers and land owner claimed power output from the planned photovoltaic (PV) arrays would be about 4 MW for a site lifetime of 25 years. The students were asked to investigate whether this predicted power output was realistic.

Using local maps and websites with conversion software, the area of the solar farm was estimated to be between 42 188 and 60 703 m^2. It was assumed that either the entire area or a fixed percentage of the area was covered with solar panels. Students were encouraged to use a wide range of approaches and data sources when tackling this task. Using a value for the solar constant 1.37 kW m^{-2} [16] gave an upper limit for power output from the farm of over 80 MW. This assumes that no energy is lost in the Earth's atmosphere, and that the solar panels and power conversion processes are 100% efficient.

More data were clearly required, and each student had a different approach to sourcing them. These included: the use of data for the irradiance on horizontal and two-axis tracked surfaces for cloudless days at 50° latitude [17]; data from manufacturers' websites [18]; real-time data from a weather station at a local university [19]; and historical data from local airports. Depending on the approach used, some students also required data for the efficiency of different PV technologies [20]. The histogram in figure 1 represents one student's results. It shows that the solar farm would generate just over 1 MW during daylight hours in winter, and nearly 3 MW during daylight hours in summer. This calculation used average solar insolation figures for St Helens which give the energy in kWh per unit area per day, and combined these with irradiance graphs and estimated light intensity thresholds (around 200 W m^{-2}) to find typical operational hours per day. These results are typical of the predictions made by the students.

Student conclusions

The most striking conclusion for students from this exercise is the difficulty involved in using alternative sources of energy to match the power output from Fiddler's Ferry. Other issues highlighted by the students included the problem of supplying power to match peak demand. For example, the wind velocity is variable and a tidal barrage may produce its maximum power at night when it is least needed. The students thought that this problem was most significant for the solar farm, which would produce its peak power on hot, sunny days when demand for electricity may be comparatively low. They also concluded that the overall power contribution from PV technology in isolation was minimal at the present time. The students also had a college visit to Dinorwig in Wales, which gave them insights into potential methods for storing energy for use in times of peak demand.

Having completed this work, the students reached a broad consensus that a diverse range of generation technologies would be required to meet future power needs. In addition, and due to the perceived problems with renewable energy generation, many of the students believed that these technologies are likely to include nuclear power. This option was then investigated subsequently as an independent study using the 'openlearn' web resource [21].

Received 4 July 2011, in final form 10 August 2011
doi:10.1088/0031-9120/47/1/92

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