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Efficiencies and load factors in electricity production

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This briefing sheet will examine the concept of efficiency as it applies to different electricity generating technologies and wind turbines (wind farms) in particular. It will try to answer how efficient are current fossil fuel technologies in terms of converting fuel into electricity; and, also, in what sense is this measure of efficiency applicable to technologies which don't rely on thermal conversion (burning) of fuels.

Introduction

- Concept of **efficiency** is often confused with **load factor**. However, load factor is a ratio of average output over theoretical maximum output over a period of time (usually a year). According to 2008 Digest of UK Energy Statistics load factors for offshore wind were 34.9%, hydro 35%, nuclear 49%, etc.

- For instance, if the presumed **theoretical maximum** output of a 1 gigawatt (GW) rated nuclear power station is 8,760 gigawatt hours per annum (1GW station working at full tilt for 8760 hours in a year), but it actually produces 4,380 gigawatt hours (GWh), we would say that its load factor was 50% in that year. Note that 8,760 hours equals 24 hours x 365 days.

- **Load factors** are useful for predicting quantities of electricity a power station, or a pool of power stations can produce. This has implications for balancing projected supply and demand. For example, load factors for wind, hydro and solar energy installations rarely deviate more than a few percentage points from the historical annual mean, so we can predict with a great degree of certainty how many units of electricity we will be getting from these technologies every year.

- **Efficiency**, as we will see bellow, is a different criteria: it measures how well the plant converts thermal energy contained in the fuel into units of electricity. It helps us answer the question of, for instance, how much coal or gas we need to burn on average to get a certain amount of units of electricity. This has major implications for the cost of electricity.

- **Efficiency** in this context can be further extended to examine the so called 'life cycle' energy costs of a certain generation technology. For instance, coal needs to be mined using an energy intensive process. It then needs to be transported to the power station. After use, the ash needs to be disposed. All of these processes use energy and decrease the overall efficiency of the technology, on top of the heat dissipation during generation itself.

- In the context of **wind energy**, however, **efficiency** would mean something different. Wind is readily available at the point of generation and as a fuel has no cost. In this sense efficiency is taken to mean how much of the kinetic potential, or the force of movement of air, can be converted into units of electricity. This information is useful, for instance, in optimising size of turbine in relation to electrical output, thus making wind turbines more productive while minimising installation and build costs.

Efficiency and load factors

As seen above, efficiency is a measure of how well power plants convert the energy in their fuel into electricity. Load factor is the ratio of average power to full output, or rated, power, usually averaged over a year. The two parameters are generally unrelated.

Coal-fired power stations have efficiencies in the range 35-40% (36% in the UK in 2009). The corresponding figures for gas and nuclear power were 47% and 39%, respectively. Wind turbine efficiencies have received little attention. As the “fuel” is free, the efficiency is, to a large extent, unimportant.

Thermal power stations generally achieve their maximum efficiency when delivering their full rated output but wind turbines are different. They operate over a wide range of wind speeds and this means that peak efficiency rarely coincides with peak output. As efficiency varies with wind speed, the question arises as to what is the overall efficiency of conversion from wind to electricity. The definition used here ‘the total electricity production over a year divided by the total energy content of the wind during the same period’. This is similar to the definition for other types of plant.

Life-cycle efficiencies in electricity generation

The wind that ‘fuels’ a typical wind turbine does not have to be mined, nor travel any distance in order to reach the turbine. The same is not true of the fuels used for conventional power stations. When the energy associated with fuel extraction and transport is taken into account, together with the needs of power station auxiliaries, estimates can be made of the complete life-cycle efficiencies of such plant.

The basic definition of efficiency is (Energy output)/(Primary energy input). The more precise life-cycle definition used here applies corrections to both terms.

(Power output*derating factor to allow for auxiliaries)
(Heat content of fuel+heat equivalent of processes used in mining and transport of fuel)

Coal

There are three stages in the production, transport, and usage of coal in the power stations, all of which consume energy. These are:

Mining: the energy requirements for deep-mined coal have been quoted as 60 kWh per tonne of coal . Assuming an overall thermal efficiency of 33% for the electricity generation, this corresponds to 180 kWh of primary energy. The energy requirements of opencast mining are less and the same source suggests 8 kg of diesel oil per tonne of coal. That corresponds to about 100 kWh of primary energy. If it is assumed that all UK power station coal is deep mined and that imports comprise equal quantities of opencast and deep-mined coal, that leads to an estimate of 140 kWh per tonne for mining.

Transport: most coal is transported by rail, either from the mine to the power station, or to and from the ports where it is shipped and delivered in the case of imported coal. Reference 2. suggests rail transport uses 0.6 MJ (0.167 kWh) per tonne-km and shipping 0.05 MJ/tonne-km (0.014 kWh)

Power station use: the auxiliaries in power stations use significant amounts of electricity and this is not ‘netted off’ in the calculation of thermal efficiency. ‘ Works power’ for the electricity system as a whole accounts for just over 4% of generation (1), but the coal-fired power stations have above average needs and appear to be just over 7%, the derating factor is therefore 0.93.

Approximately 40% the coal used in British power stations in 2009 was indigenous and most of this would have been deep-mined. About 55% of the imports came from Russia, followed by Colombia, South Africa and the United States. Much Russian coal is shipped out of Murmansk, which is about 2,500 km from the East Coast ports. Use of this figure for all imports is conservative, as other imports have further to travel. Rail shipment distances in Russia are the longest, at least 1,000 km, but this figure, again, is used as a proxy for the weighted average for imported coal. Average indigenous rail transport distances are estimated at 200 km.

These data are assembled in table 1, from which the weighted average energy consumption for UK power station coal is estimated as 284 kWh/tonne.

Operation	Indigenous	Imports
Mining, kWh/t	180	140
Rail transport, kWh/t	33	167
Sea transport, kWh/t	-	35
Total	213	332
Weighting	40%	60%

Table 1. Energy use during the mining and transport of coal

The overall efficiency of electricity production from UK coal may now be derived, using equation (1). The nominal average UK thermal efficiency is 36.4%, which needs to be multiplied by 0.93 to account for works usage. This leads to a figure of 33.9%. The average energy content of 1 tonne of coal is 7,100 kWh, to which must be added 284 kWh, to account for the energy consumption upstream, total 7,384 kWh. Adjusting the denominator in (1), this leads to a final figure of 32.6%.

Gas

An analysis by the University of Wisconsin suggests that production, processing and transmission of natural gas consumes 10% of its energy content. This means that 110 units of energy are needed to deliver the nominal 100 units on which thermal efficiency calculations are based. Taking the UK average thermal efficiency figure of 48%, this implies that the 'true' efficiency is 48/1.1, or 44%.

Data in the UK Digest of Energy Statistics supports the estimate of 10% for upstream energy use, although an additional 2.5% for losses is included. Power station auxiliaries on a gas-fired station consume less power than on coal or nuclear stations and reference 4 suggests an appropriate figure is 2.3%.

The net efficiency of the gas-fired stations is therefore estimated to be (0.48*0.977)/1.125, or 42%.

Nuclear

An analysis by the World Nuclear Association suggests that the energy inputs to a nuclear plant account for 1.35% of its output . This needs to be adjusted to take out the energy used in construction of the power station. This is small in comparison with the fuel requirements, and the adjusted figure is 1.28%.

Reference 2 suggests that mining and fuel processing together account for 0.006 kWh per unit of electricity delivered. That corresponds to about 1.7% of primary energy – somewhat higher than the World Nuclear association estimate. The average of the two figures – 1.5% - is used here.

Auxiliaries at Sizewell B Power Station account for 70 MW, reducing the gross output of 1,258 MW to 1188 MW . 70 MW corresponds to 5.6 % of the output, so the thermal efficiency needs to be scaled by 0.944.

These data suggest the net efficiency of UK nuclear is 0.39*0.944/1.015, or 36%.

Wind

Power coefficients

The 'Betz limit' of 59.3% - the aerodynamic efficiency of an ideal rotor, is often quoted, but is of little practical relevance. It assumes that the flow is uniform and does not take into account any of the aerodynamic characteristics of the rotor blades. In practice, drag and tip losses mean that the Betz limit is not achievable. The maximum achievable efficiency for a large three-blade wind turbine with efficient aerofoil sections is around 0.53, reached at a tip speed/wind speed ratio of about seven. When the efficiencies of gearboxes (if present), generators, power electronic systems and bearings are taken into account, the peak electrical conversion efficiency – termed the power coefficient - is around 0.48. This is defined:

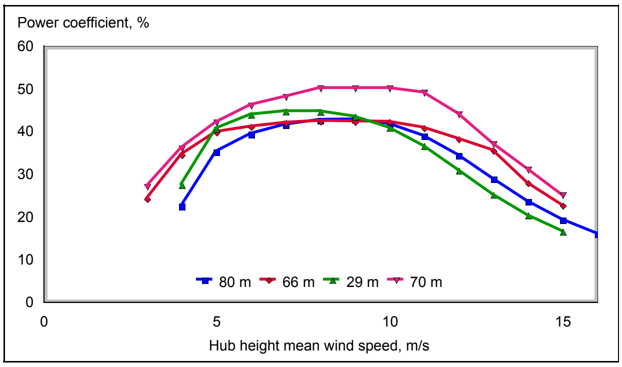
Power output
Power content of air stream, based on rotor swept area
The power content of the air stream, in turn, is:

P = 0.5*ρ*π*r2*V3

Where ρ is the air density, r is the radius of the rotor and V is the velocity of the incident air stream.

The peak efficiency falls off either side of the optimum tip speed/wind speed ratio. Figure 1 shows power coefficients for a number of large wind turbines.

Fig 1..Power coefficients for wind turbines with diameters between 29 m and 80 m.

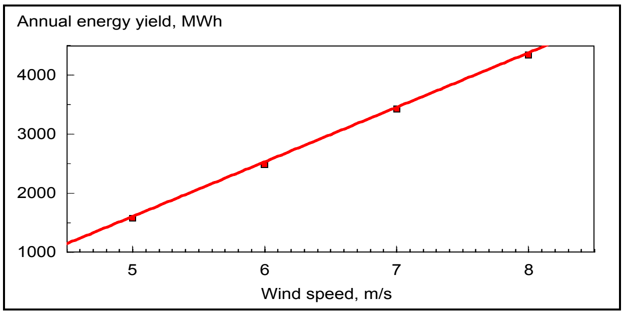


Energy production data

Manufacturers often quote the energy delivered by their wind turbines and Figure 2 shows typical data for a 62 m diameter, 1.3 MW turbine.

Wind turbine efficiencies

Fig 2. Energy yields from a 62 m diameter, 1.3 MW wind turbine

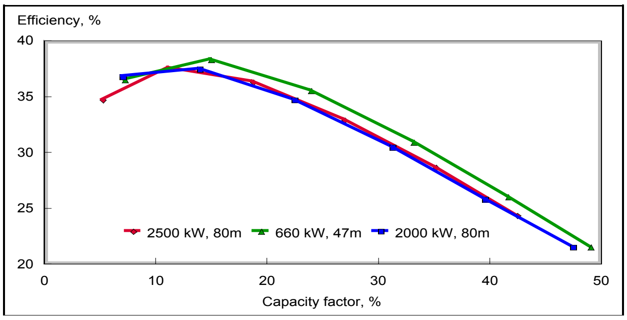


The input 'fuel' is the air, whose energy content needs to be calculated. The way in which the wind varies about its mean value is well understood. In most of northern Europe, a 'Rayleigh Distribution' typically describes the wind variations. The power in the wind is proportional cube of the wind speed and, in the case of a Rayleigh Distribution, the mean of the cubed wind speeds is equal to the cube of the mean wind speed multiplied by 1.91.

The energy inputs to wind turbines at each wind speed can then be calculated. At 5 m/s, for example, the energy content of the air is 1,279 kWh/sq m/yr.
The ratio between the energy delivered and the energy input from the air is the overall efficiency of a wind turbine. As for thermal plant, an allowance must be made for auxiliaries, which in this case, is 2% (4). Analysis – see sample calculation in Appendix - shows that wind turbine efficiencies are around 40% at sites with low mean wind speed (5-6 m/s) and that the level falls off, reaching around 25% with mean wind speeds of 9 m/s . This result, possibly counter-intuitive, stems from the fact that very little wind energy is ‘rejected’ at low wind speeds, but the amount rises with wind speed. ‘Rejected’ wind energy is the energy that cannot be used due to the need to limit wind turbine outputs once the rated power is reached.

This information is shown in an alternative form in Figure 3, which links efficiency with capacity factor. With a capacity factor of 10%, the machines deliver efficiencies between 35% and 37%. The efficiencies rise and then peak at around 38-39%, at capacity factors around 15%. With higher wind speeds – and capacity factors – the efficiencies fall off. At the UK average capacity factor of just under 30%, efficiencies are in the range 32-35%.

Fig 3. Efficiency estimates for three designs of wind turbine. It should be noted that the 47 m wind turbine has a low rating for its size and this means that capacity factors -- at any given wind speed -- will be higher than those of machines with high ratings. The apparent differences in performance are not, therefore, significant



Conclusions

This analysis suggests that the efficiencies of coal, gas and nuclear and wind in the UK are all similar, with gas slightly higher than the others, as follows:

Coal: 33%
Gas: 42%
Nuclear: 36%
Wind: 32-35%

The analysis also suggests that the relationship between efficiency and capacity factor for wind turbines is similar across a number of designs. This would change, however, if there were changes to the design philosophy; it is not necessarily a ‘universal’ relationship. It is important to emphasise that load factors, or capacity factors, and efficiencies are, in general, unrelated.

There is an important difference between wind turbines and fossil-fuelled power stations. Once the fuel has been consumed in the latter, it is lost forever. The wind that passes through a wind turbine is not lost. Wind turbines cannot be built too close together, or their output will decrease if they operate in the low-velocity wake of another turbine, but there is no fundamental change to the characteristics of the air. That is why the efficiency of wind turbines is relatively unimportant, although this analysis suggests that the efficiency of wind turbines is comparable with those of the fossil-fuelled power stations.

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