The Base-Load Fallacy

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Abstract

It is claimed by some that a large-scale electricity generation system cannot be based upon renewable sources of energy, because the latter are alleged to be ‘intermittent’ sources that cannot provide base-load (24-hour) power. This paper shows that there is actually a wide variety of renewable energy sources with different types of time variability. Some of these have similar variability to coal (e.g. bio-electricity, hot rock geothermal, solar thermal electricity with thermal storage) and are therefore base-load. Although large-scale wind power has a different variability, it can substitute for some base-load coal with the assistance of a small amount of peak-load power plant (e.g. gas turbine). Together, a mix different types of renewable energy sources can replace a conventional generating system and can be just as reliable.

Introduction

Opponents of renewable energy, from the coal and nuclear industries and from NIMBY (Not In My Backyard) groups, are disseminating the fallacy that renewable energy cannot provide base-load power to substitute for coal-fired electricity. Even Government Ministers and some ABC journalists are propagating this conventional ‘wisdom’, although it is incorrect. The political implications are that, if the fallacy becomes widely believed to be true, renewable energy would always have to remain a niche market, rather than achieve its true potential of becoming a set of mainstream energy supply technologies.

The refutation of the fallacy has the following key logical steps:

- With or without renewable energy, there is no such thing as a perfectly reliable power station or electricity generating system.
- Electricity grids are already designed to handle variability in both demand and supply. To do this, they have different types of power station (base-load, intermediate-load and peak-load) and reserve power stations.
- Some renewable electricity sources (e.g. bioenergy, solar thermal electricity and geothermal) have identical variability to coal-fired power stations and so they are base-load. They can be integrated into electricity grids without any additional back-up, as can efficient energy use.
- Other renewable electricity sources (e.g. wind, solar without storage, and run-of-river hydro) have different kinds of variability from coal-fired power stations and so have to be considered separately.
- Wind power provides a third source of variability to be integrated into a system that already has to balance a variable conventional supply against a variable demand.

- The variability of small amounts of wind power in a grid is indistinguishable from variations in demand. Therefore, existing peak-load plant and reserve plant can handle small amounts of wind power at negligible extra cost.
- For large amounts of wind power connected to the grid from several geographically dispersed wind farms, total wind power generally varies smoothly and therefore cannot be described accurately as 'intermittent'. Thus, the variability of large-scale dispersed wind power is unlike that of a single wind turbine. Nevertheless, it may require some additional back-up.
- As the penetration of wind power increases substantially, so do the additional costs of reserve plant and fuel used for balancing wind power variations. However, when wind power supplies up to 20% of electricity generation, these additional costs are still relatively small.

These steps are now discussed in more detail. First it is necessary to define 'base-load'.

Base-load power stations

A base-load power station is one that is in theory available 24 hours a day, seven days a week, and operates most of the time at full power. In practice, this is an ideal. In reality, even base-load power stations break down from time to time and, as a result, can be out of action for weeks. In mainland Australia, base-load power stations are mostly coal-fired – a few are gas-fired. Coal-fired power stations are by far the most polluting of all power stations, both in terms of greenhouse gas emissions and local air pollution.

Overseas, some base-load power stations are nuclear. They produce little pollution during normal operation, but much pollution (including carbon dioxide emissions) from mining, enrichment, plant construction and decommissioning, reprocessing and waste management. They also increase the risks of proliferation of nuclear weapons and have the capacity for rare but catastrophic accidents.

Renewable energy can provide several different clean, safe, base-load technologies to substitute for coal (Diesendorf 2007a):

- bioenergy, based on the combustion of crops and crop residues, or their gasification followed by combustion of the gas;
- hot rock geothermal power, which is being developed in South Australia and Queensland;
- solar thermal electricity, with overnight heat storage in water or rocks or a thermochemical store; and
- large-scale, distributed wind power, with a small amount of occasional back-up from peakload plant.

It is obvious that the first three of these types of renewable power station are indeed base-load. Efficient energy use, the natural companion of renewable energy, can also substitute directly for base-load coal. However, the inclusion of large-scale wind power in the above list may be a surprise to some people, because wind power is often described as an 'intermittent' source, one that switches on and off frequently. Before discussing the variability of wind power, we introduce the concept of 'optimal mix'.

Optimal mix of base-load and peak-load

An electricity supply system cannot be built out of base-load power stations alone. These stations are inflexible to operate. They take all day to start up from cold and in general their output cannot be changed up or down quickly enough to handle the peaks and other variations in demand. Base-load stations used as reserve cannot be started up quickly from cold. Base-load power stations, especially coal-fired and nuclear, are generally cheap to operate, but their capital costs are high. So they cannot be used just to handle peaks in demand. To pay back their high capital costs, base-load power stations must be operated as continuously as possible. A faster, cheaper, more flexible type of power station is needed to complement base-load and handle the peaks.

Peak-load power stations are designed to be run for short periods of time each day to supply the peaks in demand and to handle unpredictable fluctuations in demand on timescales ranging from a few minutes to an hour or so. They can be started rapidly from cold and their output can be changed rapidly. Some peak-load stations are gas turbines, similar to jumbo jet engines, fuelled by gas or (rarely) by oil. They have low capital costs but high operating costs (mostly fuel costs). Hydro-electricity with dams is also used to provide peak-load power. Because the amount of water available is limited to that stored in the dam, the ‘fuel’ of a hydro power station is a scarce resource and therefore a valuable fuel that is best used when its value is highest, that is, during the peaks.

A third type of power station, intermediate-load, runs during the daytime, filling the gap in supply between base- and peak-load power (see Figure 1). Its output is more readily changed than base-load, but less than peak-load. Its operating cost lies between those of base- and peak-load. Sometimes intermediate load is supplied by gas-fired power stations and sometimes by older, smaller, black coal-fired stations.

Clearly, if an electricity generating system has too much peak-load plant, it will become very expensive to operate, but if it has too much base-load plant, it will be very expensive to buy. For a particular pattern of demand there is a mix of base-load, intermediate-load and peak-load plant that gives the minimum annual cost. This is known as the *optimal mix* of generating plant. Figure 1 sketches how a mix of base-load, intermediate-load and peak-load generation combines to meet the daily variations in demand in Summer and Winter.

Reliability of generating systems

Even an optimal mix of fossil-fuelled power stations is not 100% reliable. To achieve this would require an infinite amount of back-up and hence an infinite cost. In practice, a generating system has a limited amount of back-up and a specified reliability. This can be measured in terms of (a) the average number of hours per year that supply fails to meet demand or (b) by the frequency and duration of failures to meet demand.

Consider an electricity generating system comprising N thermal power generation units with rated capacities c_i, where $i = 1, \ldots, N$, with total rated capacity

$$C = \sum c_i$$

where the sum is over all values of i from 1 to N.

At a given time, the available capacity (i.e. that which is not undergoing planned or forced outage) of unit i is a random variable a_i and the total available capacity at a given time is

$$A = \sum a_i$$

The load or demand at a given time is the random variable L. Measure (a) of the reliability of the generating system (mentioned above) is the Loss of Load probability (LOLP), denoted by p_0, which is the average value of the fraction of time that the load L is greater than the total available power A:

$$p_0 = Average\ [Pr\ (A<L)] \qquad (1)$$

where Pr denotes ‘probability’. The value of p_0 is determined by the electricity utility’s choice of c_i, N and hence C. Ultimately the choice is political: how many hours per year of blackouts can a government tolerate?

The economic optimal mix of thermal generating units, for a given value of p_0, is the configuration of base-load, intermediate-load and peak-load power stations that minimises the cost function

$$F = \sum c_i y_i + e_i z_i \qquad (2)$$

where the sum is again over all values of i. Here y_i is the annualised capital cost per megawatt of rated capacity c_i; e_i is the annual energy generated by unit i; and z_i is the total operation, maintenance and fuel cost per unit of energy generated. The cost function Equation *(2)* is evaluated numerically under the constraint given by Equation *(1),* as shown by Martin and Diesendorf (1982). The calculation is a non-trivial, since A and L are random variables (i.e. described by probability distributions which are obtained from empirical data).

Wind power as base-load

To replace the electricity generated by a 1000 megawatt (MW) coal-fired power station, with annual average power output of about 850 MW, a group of wind farms with capacity (rated power) of about 2600 MW, located in windy sites, is required. The higher wind capacity allows for the variations in wind power and is taken into account in the economics of wind power.

Although this substitution involves a large number of wind turbines (for example, 1300 turbines, each rated at 2 MW), the area of land actually occupied by the wind turbines and access roads is only 5–19 square km, depending upon wind speed. Farming continues between the wind turbines. For comparison, the coal-fired power station and its open-cut coal-mine occupy typically 50–100 square km.

Although a single wind turbine is indeed intermittent, this is not generally true of a system of several wind farms, separated by several hundred kilometres and experiencing different wind regimes. The total output of such a system generally varies smoothly and only rarely experiences a situation where there is no wind at any site (Sinden 2007). As a result, this system can be made as reliable as a conventional base-load power station by adding a small amount of peak-load plant (say, gas turbines) that is only operated when required.

Computer simulations and modelling show that the integration of wind power into an electricity grid changes the optimal mix of conventional base-load and peak-load power stations. The method is to include wind power as a negative load in Equations *(1)* and *(2)*. Empirical data are used for the probability distribution of wind power (Martin and Diesendorf 1982).

The result is that wind power replaces base-load with the same annual average power output. However, to maintain the reliability of the generating system at the same level as before the substitution, some additional peak-load plant may be needed. This back-up does not have to have the same capacity as the group of wind farms. For widely dispersed wind farms, the back-up capacity only has to be one-fifth to one-third of the wind capacity. In the special case when all the wind power is concentrated at a single site, the required back-up is about half the wind capacity (Martin & Diesendorf 1982; Grubb 1988a & b; ILEX 2002; Carbon Trust & DTI 2004; Dale et al. 2004; UKERC 2006).

Furthermore, because the back-up is peak-load plant, it does *not* have to be run continuously while the wind is blowing. Instead the gas turbines can be switched on and off quickly when necessary. Since the gas turbine has low capital cost and low fuel use, it may be considered to be reliability insurance with a small premium.

Of course, if a national electricity grid is connected by transmission line to another country (for example, as Western Denmark is connected to Norway), it does not need to install any back-up for wind, because it purchases supplementary power from its neighbours when required and sells excess wind energy to its neighbours. In practice it makes little difference whether a generating system installs a little of its own back-up or purchases it from neighbours.

Solar electricity

Because it is still very expensive to store electricity on a large scale, grid-connected solar electricity from photovoltaic (PV) modules is not stored. If and when advanced batteries become less expensive, PV electricity would become base-load. Meanwhile, even without storage, a large amount of solar PV can substitute for coal and/or gas combusted in intermediate-load power stations. Furthermore, by orienting the solar collectors to the north-west instead of to the usual north (in the southern hemisphere), the peak in solar generation overlaps to a large degree with the broad daily peak in Summer demand (Figure 1b). Thus, statistically speaking, even solar electricity without storage has a degree of reliability during the daytime.

Solar energy can be stored at low cost as heat in water, rocks or thermochemical systems. Therefore, solar thermal electricity with thermal storage can supply base-load and can be just as reliable as base-load coal.

New technological developments in solar electricity, coupled with expanding overseas markets, will gradually bring down prices.

Conclusion

Combinations of efficient energy use and renewable sources of electricity can replace electricity generating systems based on fossil fuels and nuclear power. With renewable sources, base-load electricity can be provided to the grid by bioenergy, hot rock geothermal, solar thermal electricity with thermal storage in water, rock or thermochemical systems, and wind power with a little back-up from gas turbines. Natural gas and coal seam methane can also substitute for some base-load coal-fired power stations, although supplies of these gases are limited in eastern Australia. Intermediate load can be supplied by solar PV electricity without storage, when it becomes less expensive. When natural gas supplies become scarce, gas turbines used for peak-load supply can be fuelled by liquid or gaseous fuels produced from biomass.

By 2040 renewable energy could supply over half of Australia's electricity, reducing CO_2 emissions from electricity generation by nearly 80 per cent (Saddler, Diesendorf & Denniss 2004; Diesendorf 2007a & b). In the longer term, there is no technical reason to stop renewable energy from supplying 100 per cent of grid electricity. The system could be just as reliable as the greenhouse-intensive fossil-fuelled system that it replaces. Taking account of the high costs of greenhouse impacts (Stern 2006), the barriers to a sustainable energy future are neither technological nor economic, but rather are the immense political power of the big greenhouse gas polluting industries: coal, aluminium, iron and steel, cement, motor vehicles and part of the oil industry.

Actually, there is one constraint on a renewable electricity future. Growth in demand has to be levelled off, or there will not be enough land for wind and bioenergy. In the long run, this would entail a change in the national economic structure and the stabilisation of Australia's population.

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Figure 1: Typical power demand (load) by time of day in (a) winter and (b) summer

In Winter the two peaks occur at breakfast and dinner time. In Summer the single broad peak occurs in early to mid-afternoon.