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Integrating Wind Power in Electricity Grids: An Economic Analysis

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INTEGRATING WIND POWER IN ELECTRICITY GRIDS: AN ECONOMIC ANALYSIS

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ABSTRACT

As a renewable energy source, wind power is gaining popularity as a favoured alternative to fossil fuel, nuclear and hydro power generation. In Europe, countries are required to achieve 15% of their energy consumption from wind by 2010 as the EU strives to meet its Kyoto obligations. Wind power is considered to be environmentally friendly and low cost. While environmental friendliness has come under scrutiny because wind turbines continue to pose a hazard to birds, are visually unappealing, affect the uses of land and change air flows, the purpose of this paper is to examine the question of its presumed low cost and effectiveness at reducing CO_2 emissions by replacing power generated from fossil fuels. To do so, we develop a mathematical programming model of an electrical energy grid that employs power generated by a base-load nuclear power plant, a coal-fired power plant and a gas facility, with the latter used primarily to meet peak-load demand. We then introduce varying levels of wind power generating capacity into the grid. The results indicate that, at low levels of penetration, wind power can provide CO_2 mitigation benefits at low cost. However, as the degree of penetrability increases, the costs of reducing CO_2 emissions rise rapidly because of the spinning reserves required in the coal- and gas-fired power plants. Fossil fuels are consumed even though no power is generated in the eventuality that wind power is suddenly unavailable. The whimsical nature of wind energy makes it a less than desirable long-term source of energy.

Keywords: renewable energy; wind and nuclear power; economics of power generation

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INTRODUCTION

Concern about climate change and rising concentrations of CO_2 in the atmosphere has increased demand for non-fossil energy sources. One approach to lowering CO_2 emissions is to switch from fuels with high carbon content per unit of energy, such as bituminous coal (24.5 tC per gigajoule) and oil (19.0 tC/GJ), to ones with lower carbon content such as natural gas (13.8 tC/GJ). However, there are limits to such substitutions because there are limits to the availability of cleaner fossil fuels (Banks 2003). The alternative, therefore, is to shift away from fossil fuels to renewable energy sources.

In 2000, global energy consumption amounted to 9,963 million tonnes of oil equivalence (Mtoe), up 65% from the 6,040 Mtoe consumed in 1973, an increase of nearly 3% per annum. Fossil fuels accounted for 79.4% of the world's energy consumption in 2000, while energy from nuclear and hydro sources accounted for 6.8% and 2.3%, respectively. Wind (0.026%), solar (0.035%) and tidal (0.004%) sources accounted for miniscule amounts of energy requirements (IEA 2003). Geothermal power generation contributed the third largest component of renewable sources of energy, after hydropower and combustibles/renewables/waste (CRW).

The IEA forecasts an increase in global energy consumption to nearly 15 Mtoe by 2030, with consumption of fossil fuels rising faster in absolute terms than that of renewables (Cozzi 2004). In relative terms, the share of natural gas in consumption is projected to rise the most (for the reason noted above), followed by non-hydro renewables. The share of other energy sources is expected to fall, while the share of non-renewables is expected to remain small – about 4% of primary energy consumption (ignoring CRWs) in 2030 compared to 2% in 2000.

Solar and wind power are often considered the best options for replacing fossil fuels. Any discussion of solar and wind power needs to address the problems of storage and transmission, and environmental spillovers. Electricity is generated by fossil fuels, nuclear power plants, hydropower generating stations, wind turbines or solar photovoltaic (PV) cells. With the exception of power generated from fossil fuels, each of the other sources has some limiting constraints. Natural gas and crude oil are highly mobile, while coal is less so, but power plants can increase or reduce fuel use according to demand, which varies substantially during the day and across seasons and regions. Nuclear power plants are difficult to shut down and are best at meeting a continuous, base-level demand; hydropower is best suited to providing a low-level of power (based on lowest river flow) or power at times of peak demand (from water stored behind a dam). While storage enables hydropower to be available at peak times, overall availability is subject to the vagaries of precipitation and competition for water with agricultural, wildlife, industrial, commercial and residential users. It is vulnerable to droughts and periods of high rainfall when water simply spills over the dam because reservoir capacity is too great. Hydro capacity can only be increased by building more dams or higher ones, something opposed by many environmental groups because of their destructive impact on fish and other wildlife habitat. Indeed, there are serious proposals to dismantle dams in some areas of the western United States in the interests of wildlife.

Solar and wind energy are similarly limited. One study of the potential of solar power concluded that all of the 1997 electrical demand in the United States could be met from a single solar photovoltaic plant in Nevada of 28,000 km^2 (Turner 1999). Neglected in the calculations were transmission, storage, timing and terrain (Love et al. 2003). Also ignored was the fact that, in order to meet electrical demands that fluctuated during the day and across seasons, some method would be required to store the energy to smooth out the peaks and troughs. Using a computer model of daily energy demand, Love et al. calculated that the smallest solar PV system would require a minimum area of 41,000 km^2 if located in the ideal location (western Texas), but much more area if located elsewhere. The analysis does not address the energy required for mobility and space heating and other needs that are currently met by natural gas, coal or fuel oil.

Love et al. (2003) also estimated the area required to satisfy U.S. demand for energy using most up-to-date wind technology. For wind power, it is necessary to store an equivalent of 108 days of average demand in addition to satisfying ongoing demand. In that case, the smallest wind farm would be 193,000 km^2, but then spread over three locations in Kansas, Texas and Wyoming.

Nonetheless, wind energy has become the world's fastest growing energy source, partly because of advances in technology and lower production costs. According to the World Wind Energy Association, in 2003 installed wind energy capacity increased by 26% worldwide, from 31,117 MW at the end of 2002 to 39,151 MW by December 31, 2003. The most successful wind energy markets have been in Europe, particularly Denmark, Germany and Spain, and the EU now requires that 15% of all electricity be produced from wind. In Denmark, the current average penetration rate of wind energy is nearly 20%. In some areas of western Denmark, wind accounts for as much as 50% of the electrical power generation, and the Danish government's target is for wind to account for half of all power generation in the country by 2030. Although Europe accounts for 70% of world's installed wind energy capacity, other regions are beginning to emerge as substantial markets. There has also been an upsurge in the use of the technology in the United States as well as in many developing countries.

Among renewable energy sources, wind power has the reputation of being most cost effective. With improvements in technology and growth in the market for wind energy, the cost of electricity generated by modern wind farms has declined 80% since 1980 – from about 38 cents per kilowatt hour (kwh) to about 4 cents. Cost projections for 2005 are as low as 2.5-3.0 cents per kwh, making it competitive with fossil fuel energy. However, these cost estimates ignore the externality costs that wind imposes on an electrical grid – the costs of maintaining 'spinning reserves' in the event that wind is unavailable for generating electricity. In other words, because wind may not be available to meet demand at a particular time, other generators need to be up and running to provide electricity the moment the power generated by wind turbines falls below what is 'expected'. If backup electricity is produced by hydropower, this is not a problem – a hydro dam constitutes the best storage device. If backup power is provided by a coal-fired generator, as in Estonia (Liik, Oidram and Keel 2003), fuel will be consumed (burned) but no power will be generated unless that available from wind turbines falls below that required.

There are other externality costs associated with wind-generated power (e.g., noise from the rotating blades, visual dis-amenities of wind towers, impact on wildlife). The purpose of the current paper, however, is only to investigate in greater detail the externality costs associated with the vagaries of the wind. While a number of researchers have investigated this issue from a purely practical (enginerring) standpoint, to our knowledge none have examined it from an economics perspecitve. In particular, there are few estimates of the marginal value of unexpected reductions in wind. We provide such estimates using shadow prices from a constrained optimization model of an electric grid.

We begin in the next section with a more detailed discussion of the operation of an electric grid and the role of wind farms in such a grid. We also discuss problems with the whimsical nature of wind that are unrelated to the impact on other power generating sources. Then, in section 3, we provide a mathematical model of an electric grid that includes wind and other sources of power. Given that nuclear energy offers an non-fossil fuel alternative to wind power, we consider the role of nuclear energy in such a grid as well. Simulation results are provided in section 4, while our conclusions and discussion follow in section 5.

PRODUCING ELECTRICITY FROM WIND: BACKGROUND

An obvious drawback of wind energy is that wind is neither steady nor predictable. Even at the most resourceful area, there are periods when wind does not blow. The uncertainty of available wind power requires certain amount of backup generation to provide electricity when wind speed is low. The operation and maintenance costs of these backup power plants dramatically reduce the benefit of introducing free energy – wind. The fluctuation of wind power naturally leads to the idea of storage. When the total output exceeds current demand, the surplus energy is put into storage. The stored energy can be withdrawn to make up the deficit during periods when the wind does not blow strongly. However, a storage system imposes an energy penalty in both the input and output conversion processes. A typical battery system has a roundtrip efficiency of about 80%, and this number is about 35-40% for fuel cell systems. As a substantial fraction of the energy is wasted in the storage system, the capacity of the wind power plants needs to be increased to overcome these losses.

More and more people are starting to realize that opportunity cost of land used by wind farms plays an important role in determining the true cost of electricity from wind energy. Still, it is rare to come across discussion of land area requirements of utility scale wind farms and the associated costs of those lands. Conventional power plants such utilizing nuclear, coal or natural gas require much less land to generate the same amount of electricity. In order to generate a thousand megawatts, which can provide electricity for 1 million houses or a mid-size city in the

United States, the land requirement for a thermal plant such as coal or nuclear power plant is around $0.5x10^3$ to $1x10^3$ square meters compared to $0.3x10^6$ to $1x10^6$ square meters required for a wind power plant. According to the United States Department of Agriculture, the average farm real estate value, a measurement of the value of all land and buildings on farms, was $1,270 per acre as of January 1, 2003. That is, in order to supply electricity for a mid-size city in the United States, the cost of land for a thermal power plant will be $157-$314 on average compared to $104,608-$313,823. Therefore, although wind power plants are cost competitive based on daily production and maintenance, the cost of land requirements will highly affect the profitability of the wind power plants.

A MODEL OF THE ELECTRIC GRID: INTEGRATING WIND POWER

The approach for assigning electricity production to generators is a two-step procedure. First, a day-ahead, unit commitment (DAUC) model is used to schedule next-day delivery from various power sources on an hourly basis. A projection or forecast of hourly demand is used to determine the amount of total power that needs to be delivered in each hour. Engineers employ simulation models to determine how next-day power needs are to be assigned to each generator (Hirst and Hild 2004b). It works as follows: In the simulation model, the Integrated Systems Operator (ISO) will announce prices at which it will purchase power for each hour in the next day. Generators will offer to supply power for each hour in the next day at those prices. The prices that the ISO is willing to pay will be readjusted up and down until enough power will be offered to meet anticipated demand in each hour of the next day. Although the output from DAUC models focuses on the next day, the simulations need to take into account what happens over several days so that capacity, ramping-up, ramping-down and other constraints between days can be appropriately taken into account.

Second, there is a real time (RT) assignment. Again, a simulation model is used to make these assignments on a real-time basis. These models are run every few minutes to ensure that the electrical demands of consumers are met and the system does not 'crash'. At this level, actual ramping-up and ramping-down constraints are real and any shortfall or oversupply needs to be dealt with. Generators that have the greatest variance between what they commit to and what they actually deliver (viz., wind turbines and PV cells) create the largest problems in real time, and this problem is not resolved if the operator makes an arbitrary adjustment of the generator's day-ahead commitment.

In this paper, rather than use a simulation model, we use mathematical programming methods to determine the allocation among generators/power plants and the shadow prices of various constraints on the system. This is a more appropriate method for determining shadow prices than simulation modeling. At this stage, we only describe a DAUC model. While this qualifies our conclusions, it is important to recognize that our hourly time step is arbitrary. Indeed, we use one-hour intervals only for descriptive convenience, as any length of interval could be envisioned. A smaller time step may be more appropriate because, by reducing the time step to a real-time level (a 15-minute or even one-minute interval), the rates at which power plants/generators can change their production become more constraining.

In our model, we assume that the grid will take all the available electricity produced by the renewable energy sources. The grid operator chooses the outputs from all available sources (generators) to maximize total profit subject to a number of technical and economic constraints. Mathematically, the objective is to maximize profit:

$$\underset{Q_{t,i},I_{t,i}}{MAX}\ \pi = \underset{Q_{t,i},I_{t,i}}{MAX}(TR - TC) = \underset{Q_{t,i},I_{t,i}}{MAX} \sum_{t=1}^{24\times d} P_t \left[\sum_{n=1}^{N} Q_n + \sum_{r=1}^{R} Q_r \right] - \sum_{t=1}^{24\times d} \left[\sum_{1} F_i + b_i \left(Q_{t,i} + I_{t,i} \right) + \sum_{r}^{R} b_r Q_{r,t} \right],$$

where π denotes profit (\$), *TR* is total revenue (\$), *TC* is total cost (\$), *n* denotes a generator/power plant using fossil fuels, nuclear or hydro power (of which there are *N*), *r* refers to a generator/plant using a renewable source of energy such as wind (of which there are *R*), *d* is number of days, *t* refers to the hour since the system started, *F* is fixed cost (\$), *Q* is quantity of electricity (KW), *P* its price (\$/KWh), *b* is variable cost (\$), *I* is idle capacity (KW), *D* refers to demand (KW), *A* is a specified safety allowance factor, *C* total capacity (KW), and T_i is the time it takes to ramp up production from generator/ plant *i* (= 1, ..., *N*+*R*). The profit function is maximized subject to the following constraints:

1. Demand is met in every period (hour): $\sum_n Q_{t,n} + \sum_r Q_{t,r} \geq D_t \ \forall t = 1,\ldots,24 \times d$
2. A safety allowance is satisfied every period: $\sum_i^{R+N} I_{t,i} \geq A \times D_t, \forall t = 1,\ldots,24 \times d$
3. Ramping-up constraint: $Q_{t,1} - Q_{(t-1),i} \leq \frac{C_i}{T_i}, \forall i = 1,\ldots,R + C$
4. Ramping-down constraint: $Q_{t,i} - Q_{(t-1),i} \geq -\frac{C_i}{T_i}, \forall i = 1,\ldots,R + C$
5. Capacity constraints: $(Q_{t,i} + I_{t,i}) \leq C_i, \forall i = 1,\ldots,R + C$
6. Non-negativity: $Q_{t,i} \geq 0$, $I_{t,i} \geq 0$

If output price is assumed to be constant in every hour, the profit maximization objective can be re-specified as a cost minimization problem.

In our specific application, the electricity demand plus safety allowance is satisfied by available wind power and the production from three other power plants (generators) – a nuclear power plant and ones that are fired by natural gas and coal. The safety allowance factor is assumed to be 15% of the demand. In this system, wind power is modeled as a uniform random variable with values between zero and the generating capacity of the wind power plant. Since wind output is known beforehand, rational expectations are assumed. The choice variables of this optimization problem are the electricity outputs of the three conventional power plants. If the available electricity produced by the renewable energy sources is more than enough to satisfy the demand in any given period, the excess electricity produced is lost as there is no provision for storage (because it would be too expensive).[1]

The cost functions represent the ranking of the marginal costs of the four power plants (gas>coal>wind>nuclear). The ramping constraints are meant to represent a ranking of how fast a power plant adjusts its production. From the fastest to the slowest, the ranking used in this model is wind>gas>coal>nuclear. The model is solved for 48 hours, but can potentially be solved for any number of days and/or periods of arbitrary length.

Four scenarios are designed based on different potentials for generating wind: a base case where all power is generated from existing thermal (fossil fuel and nuclear) power plants, a low wind scenario, a moderate wind scenario, and a high wind scenario. The base case assumes that wind energy is absent from the system, so that the hourly demands plus safety allowances are satisfied by the natural gas, coal and nuclear power plants. These three thermal power plants are assumed to have equal generating capacities. The low wind scenario assumes that the 'name-plate capacity' of the wind power plant is 10% of the total capacity from the other three power plants. In this scenario, the potential wind energy penetration rate turns out to be around 9%. This penetration rate gradually increases in the moderate and high wind scenarios. The moderate

[1] If any generator produces power that cannot be used by the grid because there would be an oversupply, it is a simply matter of throwing a switch to prevent the power from entering the grid.

wind scenario assumes that the capacity of a wind farm is equal to the capacity of each of the other power plants. In this case, the potential wind energy penetration rate is 25%. The high wind scenario assumes that the capacity of the wind power plant is double the capacity of the other power plants. Therefore, the potential wind energy penetration rate is 40%.

SIMULATION RESULTS

The mathematical programming problem is solved using GAMS. Demand data are from Reliant Energy's hourly demand data for the first two days of 2000, but then standardized so that the greatest demand during these 48 hours is set to 1000 megawatts (MW). For the base-case scenario, therefore, each of the gas, coal and nuclear power plants is assumed to have a maximum capacity of 400 MW to cover demand and the safety allowance. As noted earlier, the power available from a wind generator (farm) is modeled as a uniform random variable, with values between zero and the name-plate capacity of the wind farm. For different capacities, the amount of wind power available for each hour of the study period is plotted in Figure 1. The proportion of a wind farm's generating capacity that is available to the grid is the same for each of the three wind scenarios because the same random number sequence is used to generate each.

From the figure, it is clear that the low wind scenario has little ability to meet demand in any significant way, with available wind power never exceeding 10% of the demand at any time. When the name-plate capacity of the wind farm increases to 25% (moderate wind scenario) and, particularly, to 40% (high wind scenario), the effect of fluctuations in the amount of wind power entering the grid becomes dramatic. At times, wind can meet 40% of hourly demand in the moderate wind scenario, while it can exceed demand in the high wind scenario (hrs 28 and 29 in Fig 1).

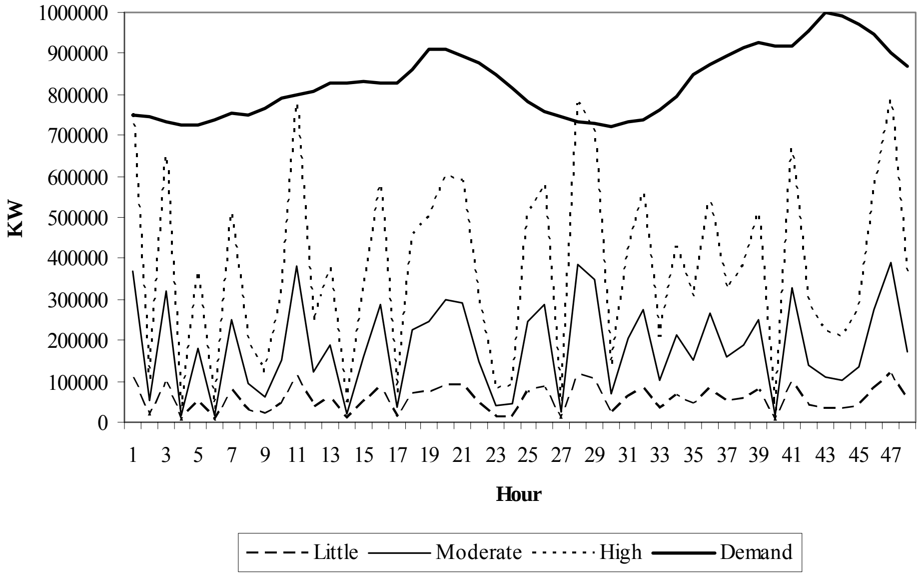


Fig 1: Demand and available wind power for different wind farm capacities

If available wind power exceeds demand in a given period, it is easy to shut off some deliveries to the grid, or use the excess power to 'drive' a storage device. The greater problem occurs when there is insufficient wind – when a wind farm cannot deliver the amount of power that the grid operator expects. To maintain the power grid's integrity, a spinning reserve is required to provide electricity in case wind delivery is below expectation. The costs of maintaining this spinning reserve could potentially reduce the overall benefit of introducing wind energy (as noted in the previous section). In Fig 1, for example, the available wind power at hour 27 is nearly zero, so the three 'conventional' power plants will need to cover the shortfall, with the amount each provides to this shortfall in supply determined by their respective marginal costs during that hour.[2] At hour 28, on the other hand, available wind power is nearly 800 MW, which is almost enough to satisfy the electricity demand plus safety allowance for that hour. Ideally, all

[2] The mathematical programming solution will equate the shadow marginal costs across each of the conventional power plants at each hour.

other power plants should be nearly shut down during hour 28, but, as we see below, because conventional power plants cannot adjust production quickly enough, the real output at hour 28 will be much higher than what is needed. Hence, power plants will be 'on line' even though their power is not required – fossil and/or nuclear fuel will be consumed. Unless this electricity can be stored or sold into another grid, it is wasted.

Total production in each hour from all power plants in each of the four scenarios is plotted in Figure 2. In the base case, the solution to the profit maximization problem is that the total output from the three conventional power plants is equal to the electricity demand from the grid plus the safety allowance. Electricity generation and demand track each other nearly perfectly. When wind power is introduced into the system, the potential for waste arises. Unless the amount of power provided by the wind farm exceeds demand, all wind-generated power is consumed and/or used to satisfy the safety requirement. That is, any adjustments to changes in the difference between demand and available wind power are made by the conventional power plants.

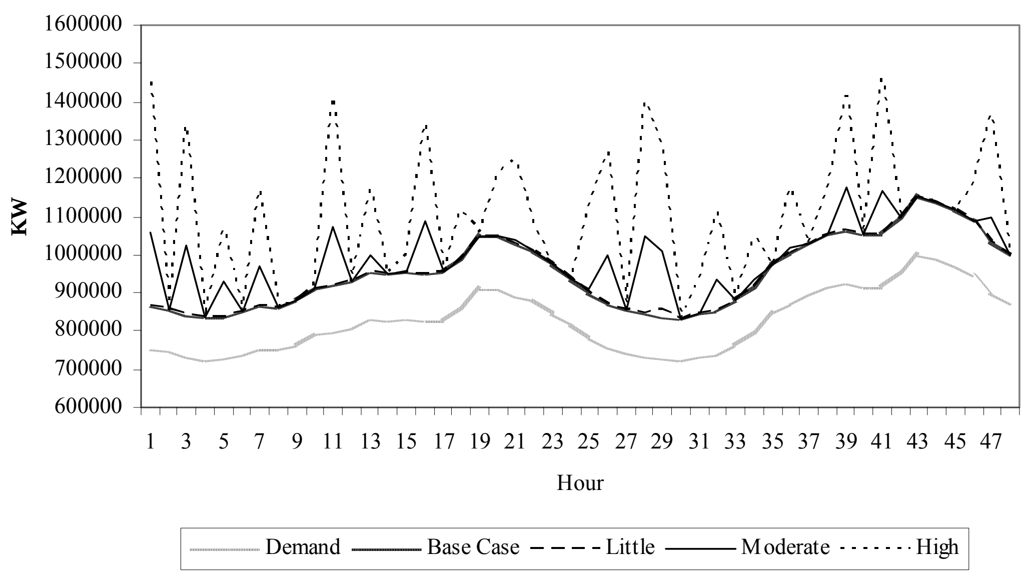


Fig 2. Total production of power from all generators

When the capacity of the wind farm amounts to 10% of the total capacity of conventional plants (low wind scenario), there is little difference between this scenario and the base case. This is primarily due to the fact that, since we assume the grid operator to know beforehand how much wind to expect in a given hour (even though it is a random variable), the adjustments to conventional power deliveries between one period and the next resulting from the whimsical nature of the wind are well within the 'ramping' factors for the power plants. That is, when a small amount of wind capacity is included in an electrical grid, the grid operator is able to adjust plant outputs in an optimal fashion. We suspect that relaxing the rational expectations assumption (which is not modeled here) will result in the generation of excessive power, reducing the benefits of wind power.

In the moderate and high wind scenarios, however, the fluctuations in wind power exceed the ability of conventional power plants to pick up the slack. Thus, in order to satisfy system and physical constraints the amount of power generated by the system exceeds demand plus the required safety allowance, sometimes by a substantial amount, by more than 30% in some cases in the moderate wind scenario and more than 50% in some cases in the high wind scenario. Even though the system operator has perfect foresight regarding the availability of wind power and adjusts output from the three conventional power plants in the most economically optimal fashion, significant amounts of excess power are being produced. It is simply not possible to ramp up or ramp down production in conventional power plants quickly enough to take into account the variability in power supply from the renewable source. The problem is one of adjustment. Clearly, the longer the time required for power plants to adjust to changes in output needs, the more difficult it is to operate such plants without waste.

As the name-plate capacity of a wind farm increases relative to the power generated from conventional plants, the variability in available wind power becomes so large relative to hourly demand that the ability of conventional power plants to adjust production is adversely affected. The reason is that conventional power plants must satisfy the demand left after all available wind power is used. While demand varies across periods and seasons, it is relatively stable and predictable compared with wind volatility. It is the volatility introduced by wind to which conventional power generators cannot adjust quickly enough. This results in fuel wastage as conventional power plants continue producing unnecessary electricity as a spinning reserve because they cannot raise or lower output quickly enough. Since 'conventional' power generators differ, however, it is necessary to investigate what happens at the individual generator/plant level.

In the base-case scenario, production from the coal plant is equal to its capacity at every hour. However, as indicated in Fig 3(a), as the size of the wind farm increases, there will be a decline in the electricity produced by the coal power plant.

In the base case, the gas-fired power plant takes on the role of 'peak provider'. In the model (as in the real world), the gas plant can adjust quicker to changes in demand than either coal or nuclear power, while it also has the highest marginal costs (due to high fuel costs). Thus, the gas plant never produces at capacity but is used as a peak-demand power source. As a result, the production level from the gas power plant is lower than the other two conventional power plants in every scenario, as indicated in Fig 3(b). The introduction of wind leads to greater volatility in the electricity supplied by natural gas. For example, between hours 18 and 20 in the moderate- and high-wind scenarios, the gas plant is shut down, but in hours 27 and 30 electricity supplied by gas is even higher than in the base case. As a peak demand power source, the production from the gas power plant is low when wind power is peaking and high when wind power is low or unavailable.

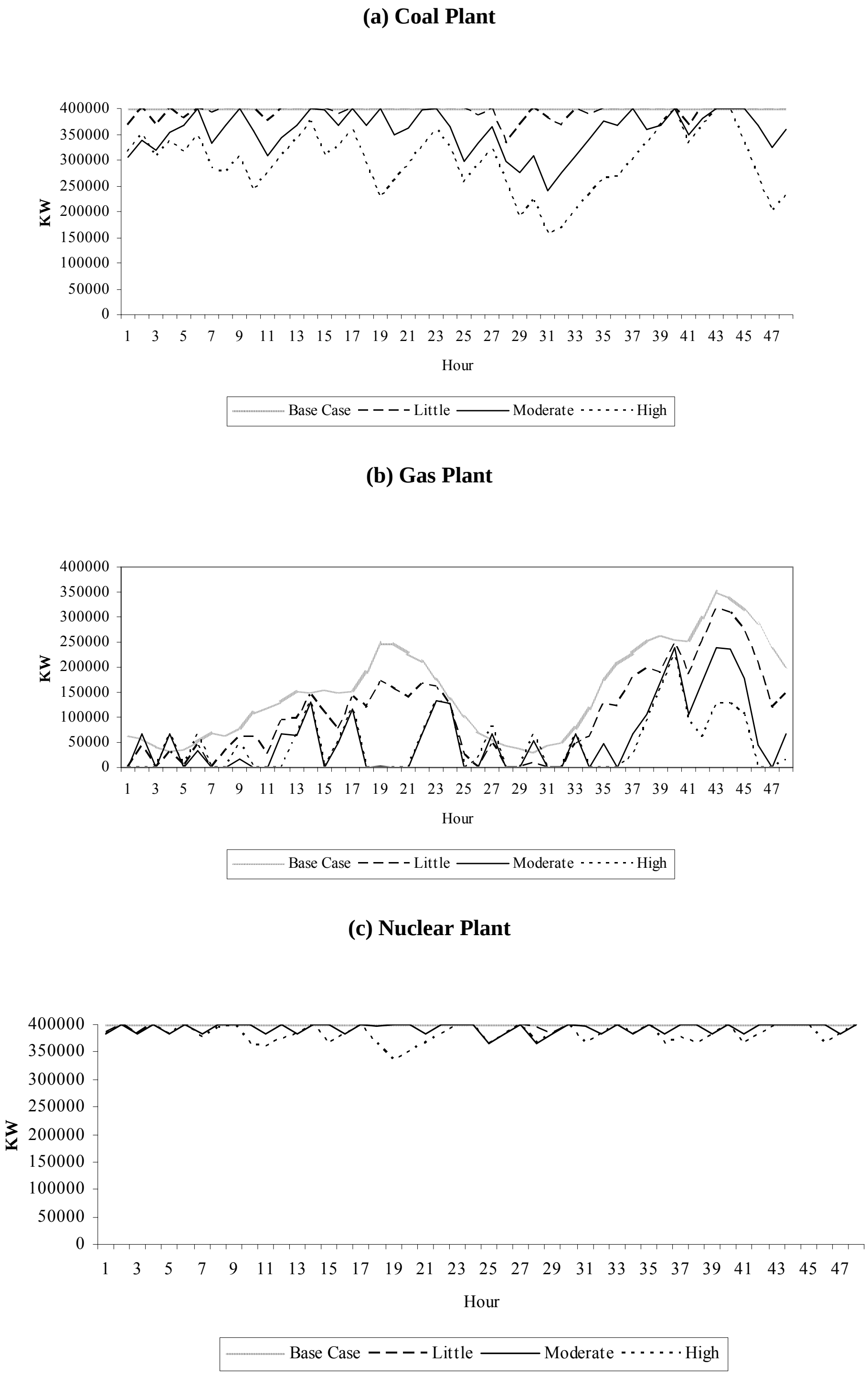
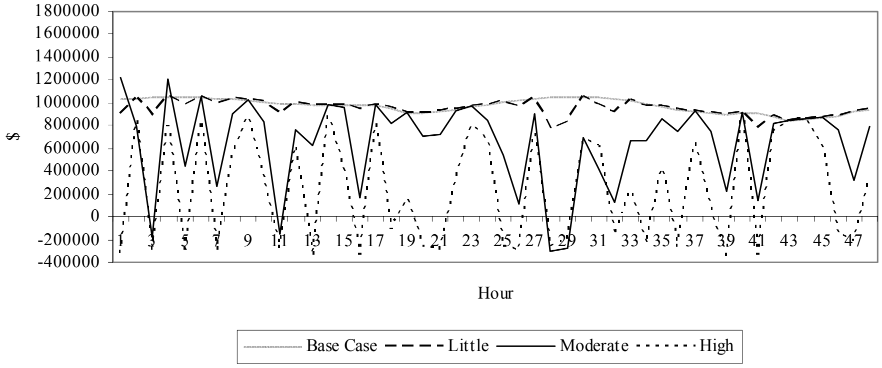


Fig 3. Electricity productions from each power plant in different scenarios

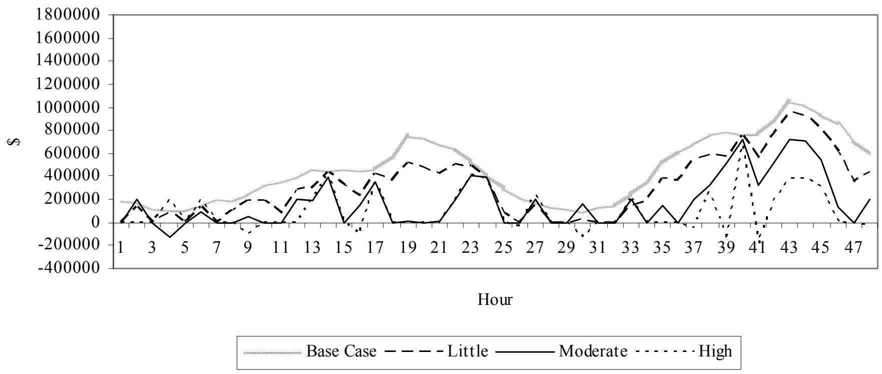
As indicated in Fig 3(c), the nuclear power plant always produces at capacity in the base-case scenario. Since the nuclear power plant is designed to deal with base load, the reduction in the amount of nuclear energy produced as wind is introduced is very small. The nuclear power plant has the lowest marginal cost among the three conventional generators, and it cannot adjust production as quickly as the conventional plants. The system operator will always prefer to use nuclear power to meet any demand not satisfied by wind power.

Changes in power production provide little if nay information about how wind affects profits. It is the effect that changes in wind power availability has on the profitability of conventional, extant power plants in an electrical grid which provides information on the true cost of wind power. Changes in the profitability of the conventional power plants in our model are plotted in Fig 4 for each of the wind scenarios. Profit is calculated as the difference between the revenue from selling electricity to the grid and the cost of producing electricity, which includes the amount supplied to the grid, idle capacity to meet a required safety allowance, and any excess generation. Given that we had no data on actual costs but ranked them based on discussions with experts, absolute profit has little meaning. Nonetheless, changes in profit provide some indicator of direction and, in the future when actual data on costs become available, changes in profit magnitude can be used to determine the true cost of wind power.

(a) Coal Plant



(b) Gas Plant



(c) Nuclear Plant

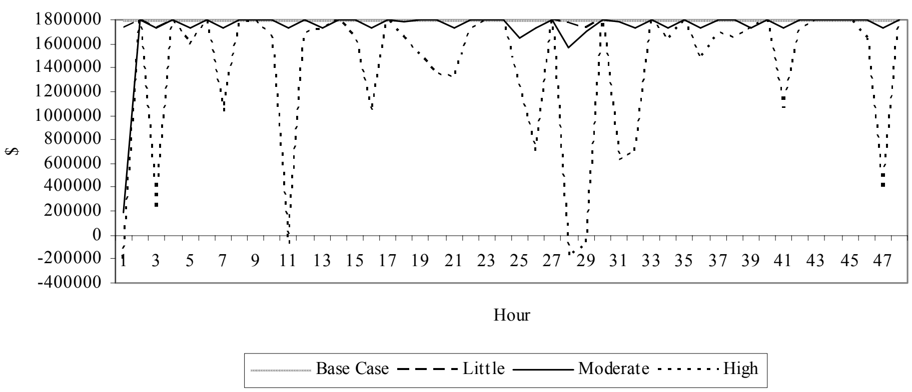


Fig 4. Profit level for each power plant in different scenarios

As the name-plate capacity of a wind farm increases, the coal plant experiences periods where net returns are negative (Figure 4a). The coal power plant is the biggest loser in the industry as the electricity generated from coal is used mainly as idle capacity to satisfy the safety allowance as gas-fired power is supplied at higher marginal cost so it is not used as idle capacity. Meanwhile, nuclear power production is too inflexible to respond as quickly to changing demand as power from coal, so it too is not used as idle capacity.

As noted in the discussion pertaining to Figure 3, gas is used mainly for peak demand due to its higher marginal cost and ability to respond quickly to demand. Thus, its profitability is affected less than that of the coal-fired plant (Figure 4). Nonetheless, as the degree of wind penetration into the grid increases, profitability of gas declines.

Profits in the case of the nuclear power facility do not change much between the base case, low wind and moderate wind scenarios, because the nuclear power plant operates at near total capacity all the time with output sold to the grid to satisfy base-load demand rather than being reserved as idle capacity. When a large wind farm is introduced into the grid, the picture changes completely (Figure 4c). Although the nuclear power plant experiences some vagary in production from one period to the next in the high wind scenario (Figure 3c), profits are affected quite significantly as a result of large fluctuations in wind power. The reason is that more nuclear power sits idle than ever before, and this imposes large costs on the system.

In the absence of actual price data, the profits shown in Fig 4 do not reflect the true profit levels for each power plant. However, with an assumed constant output price for power from each power plant and for each period, the analysis provides some indication of the direction of profit movement when integrating wind power into the electricity grid.

SUMMARY AND FURTHER DISCUSSION

When no wind power is available to an electrical grid, base-load demand will be supplied by nuclear- and coal-fired power plants, while gas-fired generators will supply peak demand as required. The marginal costs of nuclear energy are low, while it is difficult to change output from one period to the next. A great deal of advance planning is often required to change production at nuclear power plants. Gas-fired power plants are often more expensive at the margin than coal-fired plants, which is why the latter are used to satisfy peak-demand and legislated safety requirements. Coal plants also require more time to increase or decrease their output. Thus, even when nuclear, coal and gas power plants have the same capacity, nuclear power is the more profitable of the three as a result of its lower costs. However, coal is beneficial in such a system because it is able to satisfy any needs for idle capacity (whether the result of safety allowances or need to adjust power supply very rapidly). Since the idle electricity is not sold on the grid, it is a cost to the producer. Finally, gas-fired power is important because, in the absence of hydropower, it offers the only option for quickly increasing or reducing power output.

The introduction of wind energy causes problems for an electrical grid such as the one studied in this paper, because wind brings additional variability or randomness. As the results of this analysis indicate, this is generally unimportant as long as wind penetration rates are low. With low wind penetrability, the nuclear power plant still runs at full capacity, coal use is slightly reduced, and the gas plant easily covers an variability between demand and output from the other generators (although its overall production is somewhat lower than in the absence of wind).

Problems begin when the capacity of a wind farm becomes significant, as in our moderate and high wind scenarios. As wind penetrability increases, the 'effective demand' for power, defined as the difference between actual demand for electricity and that supplied by wind, becomes increasingly variable. Power plants can no longer adjust quickly enough to changes in effective demand. Indeed, at very high levels of penetrability (our high scenario), even the output of base-load, nuclear power plants is affected. With moderate and high levels of wind power available to the system, costs of operating thermal power plants increases and, importantly from an environmental standpoint, benefits of reducing CO_2 emissions are mitigated by the fact that fossil fuels continue to be consumed by coal- and/or gas-fired powered plants simply to cover the possible sudden fall down in wind output.

Finally, the model developed in this study is a simple representation of the allocation of power across generators in an electrical grid. While real-world electrical grids are much more complex, and operate on the basis of day-ahead unit commitments and real time allocation to generators, the current model does not consider this difference. As noted earlier, however, the distinction between DAUC and RT operations is somewhat arbitrary because it makes no difference to the analysis if the one-hour time step is reduced to a time step more appropriate to real-time operations (such as minutes). What matters is the rate at which (thermal) power plants change output to meet changes in effective demand. Ramping-up and ramping-down rates are more constraining in real time than in DAUC time, while costs of rapid adjustment are also higher.

Perhaps the most constraining assumption in the current model is that of rational expectations – that the amount of electricity demanded and the wind power available are known a priori. Although sophisticated forecasting tools can be used to forecast demand with a high degree of confidence, future projections of wind availability are much less certain. For this reason, it may be important to separate DAUC allocations of power from RT allocations in a future modeling exercise. While more realistic cost of production data for thermal power plants would be helpful, it may be more fruitful to examine alternative mathematical programming approaches, such as 'soft computing', because information on the operation of power plants and an electrical grid is never likely to be adequate.

In conclusion, it is often taken as a shibboleth that humans should harness the wind for power, and that the more wind power that can replace fossil fuels the better. At the same time, nuclear power is presumed to be a menace because of its environment spillovers (waste disposal, risk of meltdown) and potential health risk. The results of the current study indicate that some of these notions may be fallacious. In particular, we find that wind power may not be capable of delivering the environmental benefits of reduced CO_2 emissions that are attributed to it. Photovoltaic cells are expensive and gobble up land on a much larger scale than wind, because, even though solar PV produces some 10-16 watts (W) of energy per square meter compared to 1-3 W/m^2 for wind,[3] solar power is an exclusive land use while wind turbines permit other uses of land, such as agriculture (e.g., grazing, some cropping) or urban uses (e.g., commercial and industrial terrain). There are also limits to hydro, geothermal, biomass and tidal sources of power. Therefore, without major and unforeseen advances in technology nuclear power may offer the only realistic alternative to fossil fuels in the short and medium term (Scott 2004).

[3] This compares to thermal coal, nuclear or gas plants that produce 1-2 kW/m^2.

REFERENCES

Banks, F., 2003. An Introduction to the Economics of Natural Gas, *OPEC Review* **27**(March): 25-63.

Berry, Gene D. and Alan D. Lamont, 2001. Carbonless Transportation and Energy Storage in Future Energy Systems. In *Innovative Strategies for CO_2 Stabilization* edited by Robert G. Watts. Cambridge, UK: Cambridge University Press.

Cozzi, Laura, 2004. World Energy Outlook 2003 Insights: Global Investment Outlook. Economic Analysis Division, International Energy Agency. PowerPoint presentation viewed 18 September at: <http://library.iea.org/dbtwwpd/Textbase/work/2003/washington/Cozzi.pdf>.

ESB National Grid, 2004. Impact of Wind Power Generation in Ireland on the Operation of Conventional Pland and the Ecnomomic Implications. Dublin, Ireland: ESB National Grid. February. 42pp.

ETSAP, 2003. http://www.ecn.nl/unit_bs/etsap.

Hirst, Eric and Jeffrey Hild, 2004a. The Value of Wind Energy as a Function of Wind Capacity, *The Electricity Journal* July pp.11-20.

Hirst, Eric and Jeffrey Hild, 2004b. Integrating Large Amounts of Wind Energy with a Small Electric-Power System. Mimeograph. Denver, CO and Bellingham, WA: Excel Energy. April. 40pp.

International Energy Agency, 2003. *Key World Energy Statistics*. As viewed July 11 at http://www.iea.org/statist/. 78pp.

International Energy Agency, 2004. Renewable Energy Market and Policy Trends. IEA mimeograph.

Jensen, Jytte Kaad, 2002. A Balancing Act. What Demands does Wind Power make on a Grid? *Renewable Energy World* September-October pp. 57-69.

Leonhard, W. and K. Müller, 2002. Balancing Fluctuating Wind Energy with Fossil Power Stations – Where are the Limits? *ELECTRA* October.

Liik, O. R. Oidram, M. Keel, 2003. Estimation of Real Emissions Reduction caused by Wind Generators. Paper presented at the International Energy Workshop, 24-26 June, IIASA, Laxenburg, Austria. Tallinn, Estonia: Tallinn Technical University. 18pp.

Love, Murray, Lawrence Pitt, T. Niet and Ged McLean, 2003. Utility-Scale Energy Systems: Spatial and Storage Requirements. Working Paper, Institute for Integrated Energy Systems, University of Victoria, Victoria, Canada. 12pp.

Nordel's Grid Group, 2000. Non-dispatchable Poduction in the Nordel System. Report presented at the Nordel's Annual Meeting, May. 25pp. plus Appendices.

Scott, David S., 2003. Back from the Future: To Plan the Best Way Nuclear Can Get Us There. Working Paper, Institute for Integrated Energy Systems, University of Victoria, Victoria, Canada. 16pp.

Sharman, Hugh, 2003. The Dash for Wind. West Denmark's Experience and UK's Energy Aspirations. Viewed at http://www.incoteco.com on 19 May.

Söder, Lennart, 2002. Imbalance Management and Reserve Requirements. Paper presented at the IEEE-Cigre Workshop on 'Wind power and the Impact on Power Systems', Oslo, Norway, 17-18 June. 6pp.

Turner, J.A., 1999. A realizable Renewable Energy Future, *Science* 285: 687.