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Economic Aspects of Wind Power Generation in Developing Countries

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Economic Aspects of Wind Power Generation in Developing Countries

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Abstract

Power interruptions are a typical characteristic of national grids in developing countries. Manufacturing, processing, refrigeration and other facilities that require a dependable supply of power, and might be considered a small grid within the larger national grid, employ diesel generators for backup. In this study, we develop a stochastic simulation model of a very small grid connected to an unreliable national grid to show that the introduction of wind generated power can, despite its intermittency, reduce costs significantly. For a small grid with a peak load of 2.85 MW and diesel generating capacity of 3.75 MW provided by two diesel generators, the savings from using wind energy (based on wind data for Mekelle, Ethiopia) can amount to over a million dollars per month. While the savings from deployment of wind turbines are enormous, the variability of wind prevents elimination of the smaller diesel unit, although this unit operates less frequently than in the absence of wind power.

Key words: wind energy and development; stochastic simulation of electricity grids; economic savings from wind power

1. INTRODUCTION

Wind energy has long been used to drive mechanical devices. In The Netherlands windmills were used well into the twentieth century to grind grain and pump water from low lying areas into the sea. In Africa and elsewhere, windmills built of wood are used in rural areas to pump water from wells. For example, a windmill located on a ranch in Zambia pumps water from a well with 6-inch bore diameter and depth of more than 60 meters into a reservoir (holding tank) from which it is distributed to households and/or troughs for livestock. When the windmill breaks down or there is inadequate wind, and the storage reservoir is empty, a diesel engine is used to drive the mechanical pump.[1] Diesel generators frequently serve as backup power source in developing countries because electricity from the national grid is unreliable. Diesel power is the main source for electricity in provincial capitals in the Sahel region of Africa, with fuel transported by road over distances of 2,500 km or more (InWEnt Consulting, 2004, pp.40, 44). Disruptions in fuel supply will disrupt power supplied by the local grid, much as drought might do at certain times of the year for grids dependent primarily on hydropower (e.g., Ethiopia). Is there a role for wind power in these circumstances?

At the utility-scale level, the economic feasibility of wind energy remains paramount to the eventual success of a wind generation sector. Yet, despite its apparent advantages (Martinot et al., 2002; Gross et al., 2007), costs continue to be an obstacle to the adoption of wind generating capacity at the scale suggested by its potential, especially in developing countries. In particular, costs of constructing transmission lines to remote or offshore sites can be prohibitive, as can costs when wind profiles result in low capacity factors (see Pitt et al., 2005). The prospects for wind power in developing countries will depend on technological developments that have the potential to reduce overall wind generating costs and on developments and prospects for solar energy, costs and availability of fossil fuels, and so on. Richer countries have tipped the balance in favor of wind (and some other renewables) by offering a variety of subsidies ranging from feed-in tariffs to tax breaks, construction subsidies and guaranteed (sometimes free) access to transmission lines. Some countries have used regulations to stimulate wind investment, while some developing countries have aggressively pursued CDM investments (e.g., China, India). In many cases, regulations and economic incentives have resulted not only in large wind generating capacity, but also in a substantial industry that builds and services wind turbines.

In rich countries, utility companies may be hesitant to invest in off-grid wind energy, because the long-term costs of small, wind-driven grids are difficult to predict and rural communities may lack financial resources to make payments; thus, the off-grid electricity market is risky (Reiche, Covarrubias and Martinot, 2000). This is even more so in developing countries where the need for off-grid electrification may also a greater. The remote nature of communities in developing countries also poses potential problems. When maintenance issues arise, communities face problems due to a lack of expertise,

[1] This information was obtained from personal interview with Steve Mann, owner of a ranch in Zambia (June 8, 2008).

while accessibility to skilled workers from outside local villages is difficult. High costs and the inconvenience of operating small grids may threaten future interest in renewable power in poor countries (UNEP, 2001).

Most studies of wind energy focus on utility-scale penetration of wind, which facilitates the establishment of large wind farms. In developing countries, financial incentives are often lacking and utility-scale investments in wind generating capacity are unlikely. Nonetheless, there may remain opportunities for using wind turbines to generate electricity, particularly where a resource extraction or manufacturing/processing facility depends on reliable power. Yet, in the majority of developing countries, disruptions in power supply are quite common because:

- There is often insufficient generating capacity to meet load, especially at peak times, with the national system operator using rolling blackouts to deal with the shortfall.
- The grid infrastructure is often outdated and/or of poor quality, generally because infrastructure is below construction standards. Hence, there are frequent disruptions in power as equipment or transmission lines break down.
- Power disruptions occur because there is a lack of adequately trained technicians to manage the power grid.
- Each of the above factors is exacerbated by corruption, theft of electricity and so on.

As a result, many companies and private individuals use diesel generators as backup, especially when disruptions in electricity supply are extremely costly (e.g., companies must meet contracts, perishable goods require refrigeration, communication facilities, etc.). Likewise, remote communities that are unable to connect to the national grid because it is too far away rely on diesel generation. Companies or communities might, in such circumstances, benefit from one or several wind turbines.

To determine the potential of wind energy in developing countries, we develop a model of a diesel generating plant that may or may not be connected to the national electricity grid. We introduce wind power into this small-scale grid to investigate the potential benefits and costs of wind power investments in developing countries. We also consider a second issue: Is it possible to shut down some diesel generating capacity as wind penetration increases in a small grid? Similar problems arise in developed countries, but these are generally mitigated by existing infrastructure and policies, or through public action.

2. METHODS

Consider a situation where a large manufacturing facility with accompanying buildings and residences is connected to a national grid in a developing country. The peak load for this complex is assumed to be 2850 kW. Because power from the grid is highly unreliable and periods without electricity are intolerable, the owners employ a diesel unit to generate electricity whenever there is a disruption in supply from the national grid. The required capacity of the diesel unit is assumed to be 3750 kW (3.75 MW), with the diesel generating facility consisting of a 2250 kW generator and a 1500 kW generator. Assume that this is sufficient to meet any expected load (demand) when service from the national grid is disrupted, and yet leave some capacity as a reserve. The costs of second-hand diesel generating units vary from $US 375,000 to $750,000 for a 2 MW generator, and as much as $2 million for a 5 MW unit.[2] We assume that the smaller unit can be purchased, delivered and installed at a cost of $450,000 and the larger unit at a cost of $600,000, and that each is able to operate for a period of 20 years.

Operation of the diesel generators

The company purchases power from the national grid for $550 per MWh ($0.55/kWh) whenever it is available. When electricity from the grid is interrupted, which happens randomly some 5% of the time, no power is available for a period ranging from one to six hours. As soon as this happens, the diesel generator is relied upon to provide power. Diesel power is much more expensive than that available from the national grid, but is nearly 100% reliable, or at least assumed to be 100% reliability for our purposes.

The fuel costs of operating a diesel generator depend on its capacity utilization (*CU*), or instantaneous capacity factor, as indicated in Table 1, with the 1.5 MW and 2.25 MW capacity turbines used for this analysis indicated in bold. We rely primarily on the larger generator using the smaller one only when absolutely necessary. This enables us to model redundancy of this generator should sufficient wind power become available. Given the unreliability of the grid and the need to maintain a minimum amount of electrical output to keep the manufacturing facility in operation, one generator is always idling to some extent, although we do not take this cost explicitly into account. Rather, we assume the diesel units can come on-line immediately when power from the grid is not available, perhaps because the grid operator signals in advance that an off-line event will occur.

The cost of operating a diesel generator is related to the amount of fuel burned, as indicated in Table 1. Although the relationship between capacity utilization and diesel fuel consumption has a slightly quadratic trend, we assume a linear relation for convenience regardless that optimal operation appears to occur at about 75% to 85% of capacity utilization, as indicated in Figure 1. The linear trend lines for generators of capacity 1.5 MW and 2.25 MW are estimated to be as follows:

(1) 1500 kW generator: fuel consumption (liters/hr) = 23.058+372.56 CU (R^2=0.9962)

(2) 2250 kW generator: fuel consumption (liters/hr) = 33.453+559.14 CU (R^2=0.9960)

Diesel fuel consumption rises according to the above relations as power output increases, depending on the generator.

[2] This information was determined from various suppliers of diesel generators found on the internet.

Hourly Load

Lacking information on hourly load for the (hypothetical) manufacturing complex, we simply employ the July 2007 hourly load data from the Coast, East and Far West regions of the ERCOT electrical grid (ERCOT, 2008). The peak load for this region in July 2007 was 19,971 MW; we assume a peak load of 2850 kW and adjust the ERCOT series using the ratio of the two peak loads. The accompanying load duration curve for our facility is provided in Figure 2. Base load is slightly more than 1500 kW, which is why we bring the larger diesel facility on stream before the smaller one.

Table 1: Diesel Consumption by Generator Capacity Size (liters per hour)

Generator Size	Proportion of Generator Capacity (Capacity Utilization)			
(kW)	0.25	0.5	0.75	1.00
500	41.58	69.93	99.79	134.95
750	61.61	103.57	148.55	201.85
1000	81.65	137.59	196.94	268.76
1250	101.68	171.23	245.70	335.66
1500	**121.72**	**205.25**	**294.08**	**402.57**
1750	141.75	238.90	342.85	469.48
2000	161.78	272.92	391.2	536.38
2250	**181.82**	**306.56**	**439.99**	**603.29**

Source: Diesel Service and Support Inc. Viewed July 15, 2009 at
http://www.dieselserviceandsupply.com/temp/Fuel_Consumption_Chart.pdf,

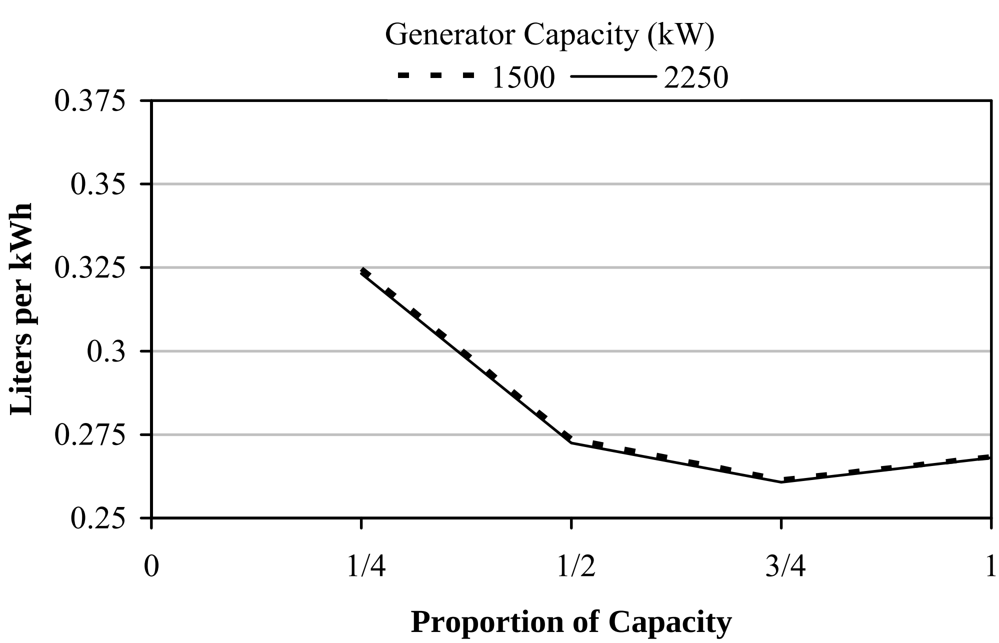

Figure 1: Diesel Generator Efficiency by Generator Capacity

Determining Available Wind Power

To determine the potential benefits of wind power, it is necessary to have some notion of available wind speeds in the region where wind turbines are to be built. Even in developed countries, there is little in the way of public data on wind speed and its variability as much of it tends to be proprietary, although hourly (or even finer) data on wind speed are publicly available for some regions. The situation in developing countries is not as good, as discussed by Knecht (InWEnt Consulting, 2004, pp.5-12). Wind data have been collected in some countries for agricultural purposes (to determine evapo-transpiration or soil loss to wind), with measurements occurring at 1 meter above the ground. However, such data are generally not available over long enough periods of time as measurement focuses primarily on the growing season. Another primary source of wind data is airports, where measurements are taken for purposes other than determining wind energy potential. As a result of the United Nations' Environmental Programme's Solar and Wind Energy Resource Assessment (SWERA), launched in 2001 to determine solar and wind energy potential in developing countries, some wind data are available for Brazil, Belize, El Salvador, Guatemala, Honduras, Nicaragua, Ghana, Sri Lanka, China and Bangladesh; wind information is also available for the oceans (SWERA, 2008). Unfortunately, this source does not provide the detailed data required for our purposes.

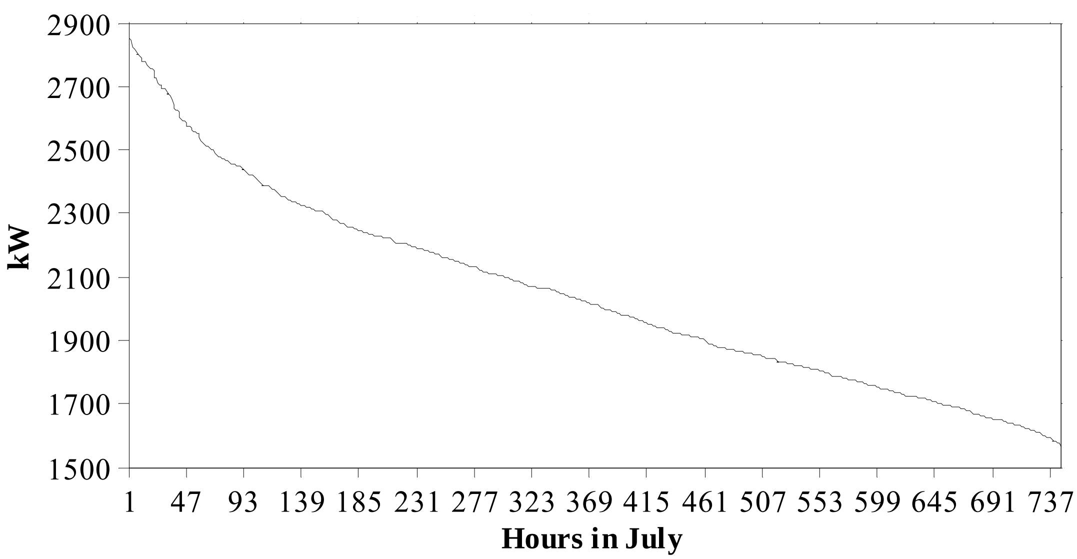

Figure 2: Load Duration Curve

We employ wind data for Africa, which appears to be a suitable candidate for wind energy development as wind potential is even greater than in Europe. Wind power information for nine countries in Africa is provided in Table 2. This information uses average daily wind speed data collected primarily at airports (and measured at a height of 10 m). The wind speed information provided in Table 2 is summarized via a Weibull distribution:

(3) $$f(x) = \left(\frac{x-\theta}{\lambda}\right)^{k-1}\left(\frac{k}{\lambda}\right)\exp\left[-\left(\frac{x-\theta}{\lambda}\right)^{k}\right], x, k, \lambda, \theta > 0,$$

where k is a shape parameter, λ is a scale parameter, and θ is a location parameter.[3]

Table 2: Wind Power Information for Africa, 2004[a]

	Annual Average Wind Speed (m/s)		Parameters of Weibull Distribution		Turbine Operating Status (%)			Capacity factor	Annual output
Country/location	at 10 m	at 45 m	k	λ	Stand still	Part load	Full load	(%)	(MWh)
Morroco									
Tangier Airport	6.17	n.a.	1.96	6.96	16.5	75.0	8.6	18.8	568.91
Kouida Blanco	10.94	n.a.	2.42	12.34	3.8	48.2	48.0	52.1	1574.39
Noin-Noinch	6.66	n.a.	2.14	7.51	12.8	77.0	10.3	22.1	669.11
Cape Verde Islands									
Airport Praia	6.66	n.a.	2.63	7.51	9.9	85.3	4.9	21.1	639.03
Windpark Mindelo	9.84	n.a.	2.85	11.10	3.6	59.2	37.3	46.9	1418.97
Brava (wind-diesel)	n.a.	9.37	3.25	10.57	1.7	67.6	30.7	43.3	1308.83
Senegal									
Met. Station St. Louis	5.06	n.a.	2.57	5.71	16.6	82.5	0.9	9.5	286.25
Mbakana	4.88	6.51	3.60	7.34	4.1	94.9	1.1	17.3	539.40
Mali									
Gao 10 m	3.87	n.a.	2.00	4.36	37.4	62.4	0.2	5.0	151.64
Gao 26 m	4.93	5.70	2.38	5.56	19.9	79.3	0.8	9.2	278.84
Egypt									
Hurghada	7.27	9.04	2.52	10.20	4.3	66.0	29.6	40.0	1250.34
Libya									
Sirt	n.a.	6.52	2.38	7.35	10.9	82.0	7.1	20.3	613.17
Ethiopia									
Met. Station Mekelle	6.30	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Airport Mekelle	6.71	8.32	2.06	9.38	9.0	66.1	24.9	34.4	1039.64
RTPC Mekelle	5.27	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Namibia									
Windhoek	1.93	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Walvis Bay	n.a.	6.54	2.11	7.37	13.7	76.7	9.6	21.3	644.38
Lüderitz	n.a.	8.36	2.57	9.44	5.0	72.5	22.5	34.9	1054.81
South Africa									
Airport Alexander Bay	4.10	5.72	1.31	6.46	32.6	55.1	12.3	18.5	560.52
Cap Hangklip	7.65	9.50	2.39	10.71	4.5	61.0	34.4	42.9	1298.72
Slagtersnek	5.10	7.04	2.16	7.94	11.2	75.6	13.2	25.0	756.70
Average	**6.08**	**7.51**	**2.41**	**8.21**	**12.1**	**71.5**	**16.5**	**26.8**	**814.09**

Notes:
[a] n.a. = not available; the Weibull distribution is given by Equation (3).
Source: Data summarized from InWEnt Consulting (2004).

The power generated by the wind depends not only on wind speed but also on the height of the turbine hub. To determine the actual power available from a wind turbine, the measured wind velocity must be adjusted to obtain wind speed at the turbine hub height. This is done using the following relationship:

[3] If k=1 and θ=0, we get an exponential distribution.

$$V_{hub} = V_{data} \times \left(\frac{H_{hub}}{H_{data}} \right)^{\alpha}, \quad (4)$$

where V_{hub} is the wind velocity (meters per second, or m/s) at the turbine hub height, V_{data} is the wind velocity (m/s) at the height it was measured, H_{hub} is the height of the wind turbine hub (m), H_{data} is the height (m) at which the data was measured, and α is the site shear component that is dependent on the type of ground surface on which the wind turbine is built. Empirical evidence suggest that $\alpha = 0.06$ for open water, $\alpha = 0.10$ for short grasses, $\alpha = 0.14$ the most common value, $\alpha = 0.18$ for low vegetation, $\alpha = 0.22$ for forested regions, and $\alpha = 0.26$ for obstructed flows. The wind velocity at the turbine hub height is used to convert available mechanical energy to electricity.

Wind power is related to wind speed as follows:

$$p = \tfrac{1}{2} \rho \, v^3 \, \pi \, r^2, \quad (5)$$

where p is the power of the wind measured in watts, v is wind speed measured in m/s, r is the radius of the rotor measured in meters, and ρ is the density of dry air parameter (assumed equal to 0.94) measured in kg/m^3. This formula is generally quite useful, but it neglects information on the turbine, particularly the wind speed at which power production begins as well as the cut-out speed where the rotator blade must be stopped to avoid damage.

We construct a wind power profile using information for Mekelle airport in Ethiopia. For the Mekelle site, wind speed data are provided in Table 2 for heights of 10 m (6.71 m/s) and 45 m (8.32 m/s). Using this information, we use the velocity-height conversion (4) to calculate the ground shear value to be α=0.143 (near the most common value). For the Weibull distribution, the shape and scale parameters are k=2.06 and λ=9.38, respectively. The wind profile is constructed by sampling from the Weibull distribution (equation 3) and then converting wind speeds to the appropriate hub height using equation (4).[4] Wind speeds are then converted to power using the power curve for the Enercon E-33/330 (330 kW capacity) turbine that is an upgraded version of the E-30/300 that had been developed in 2002 specifically for export (presumably to developing countries) (InWEnt Consulting, 2004).[5]

Small-scale Grid Simulation Model

We employ a grid simulation model written in Matlab. A schematic of the model is provided in Figure 3. First, model parameters are set and cost factors are calculated. Then, random sampling from a binomial distribution with a probability of 5% is used to determine when a power disruption event occurs, followed by sampling from a uniform

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[4] The randraw.m function by Alex Bar-Guy is used in Matlab to derive a wind series (see http://www.mathworks.com/matlabcentral/fileexchange/loadFile.do?objectId=7309&objectType=file as viewed June 30, 2009.)

[5] See www.enercon.de for technical information and power curves for various Enercon turbines.

distribution to determine how long the power disruption lasts (somewhere between one and six hours). In this way, a 1×744 vector of binary triggers is created that indicates for each hour when power is or is not available from the national grid. The demand to be met in each hour by the diesel turbines is found by multiplying the load by the binary triggers; in most cases, the demand to be met by the diesel turbines is zero as power from the national grid will always be chosen over that from diesel generators because of its lower cost. As the connection to the grid is randomly determined, the demand facing the diesel generators changes with each of the 500 iterations that are modeled. An example of one such demand profile is plotted in Figure 4(a).

Next, random wind power data are generated for 744 hours using the procedure described above. Since wind power is assumed to be non-dispatchable, it is subtracted from the load facing the diesel generators. An example of the remaining demand profile to be met by the diesel generators when one wind turbine is installed is provided in Figure 4(b). This profile employs the same randomly-determined grid connection as the demand profile in Figure 4(a). It clearly shows that, when wind is installed and made available to the small grid, less demand needs to be met by the diesel generators. In essence, therefore, wind-generated power displaces diesel power, thereby reducing costs and CO_2 emissions as desired.

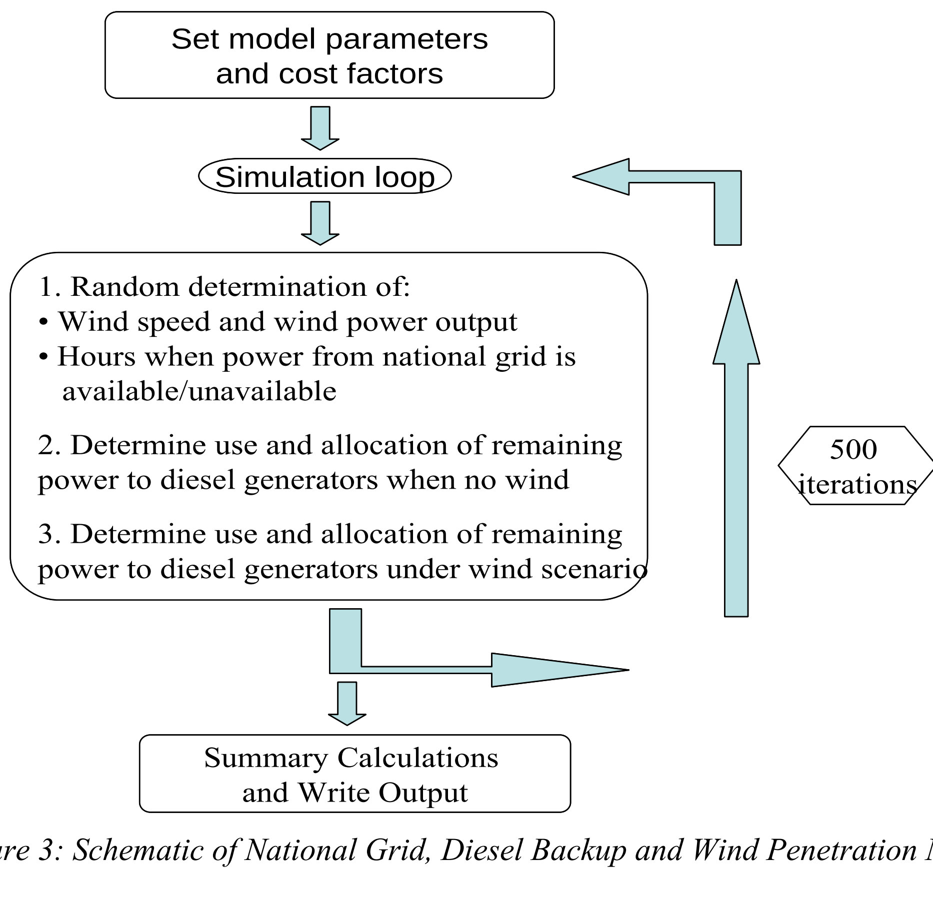
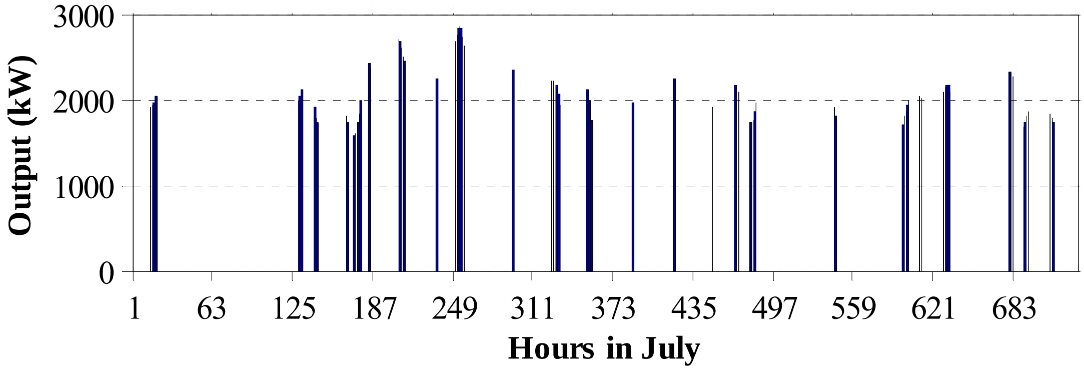
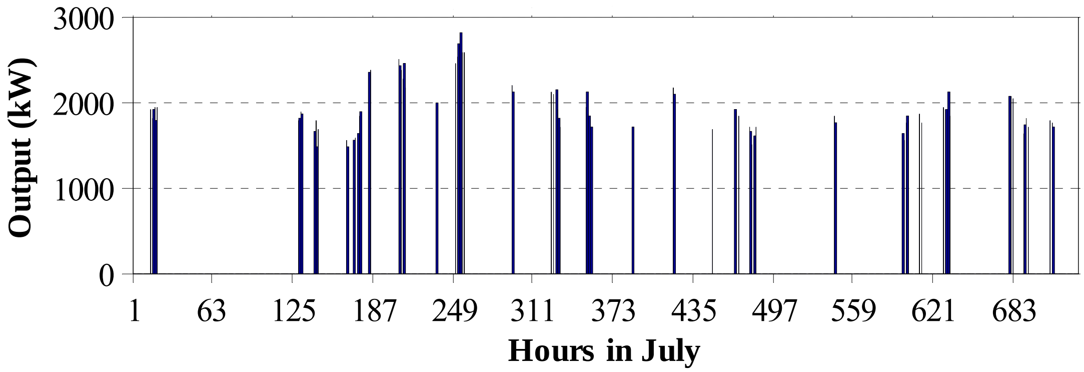


Figure 3: Schematic of National Grid, Diesel Backup and Wind Penetration Model



(a) Without Wind Power in System



(b) With One Wind Turbine in System

Figure 4: Demand Facing Diesel Generators

The extent to which costs are reduced depends on the costs of diesel versus wind. Clearly, operating costs are lower for wind, but we also take into account the component of fixed and operating and maintenance (O&M) costs that need to be covered. We assume fixed costs are $450,000 for a 1500 kW diesel generator and $600,000 for a 2250 kW diesel unit, and $1800 per installed kW of wind capacity, while annual O&M costs are $11.78/kW for diesel (we ignore O&M costs for wind).[6] Fixed costs are annualized at a discount rate of 8% over a period of 20 years. Annualized fixed and O&M costs are then simply divided by 12 to allocate them to the period in question. Finally, fuel costs are assumed to be $1.00 per liter for diesel, which turns out to be the most significant cost factor in the model.

3. SIMULATION RESULTS

For the randomly chosen wind and grid connection profile represented in Figure 4 and with one 330-kW capacity wind turbine, the total costs of meeting the load with a combination of power from the national grid and diesel generators when power from the

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[6] See http://www.epa.gov/OTAQ/climate/420f05001.htm (viewed June 30, 2009).

grid is disrupted turns out to be $103.41 million. Compared with the costs of obtaining power continuously from a stable national grid, this is an enormous cost. For this particular scenario, if the manufacturing complex/small grid had been able to rely solely on the national grid, it would have incurred a cost of only $0.84 million (assuming the national grid provided electricity at a cost of $0.55 per kWh). That is, for this one scenario, a manufacturing complex with a peak load of 2850 kW would incur an added cost of $102.57 million per month because the national grid is unreliable! Thus, an unreliable power supply would constitute a major impediment to manufacturing and processing in many developing nations with erratic national electricity grids. Thus, the benefits of adding wind power to a small-scale grid in a developing country with an undependable national electrical grid can be substantial.

Does the installation of wind turbines have the potential to reduce this cost? For the single scenario investigated here, it appears that the installation of a single turbine with a rated nameplate capacity of 330 kW would reduce the cost by $142,000. The installation of two turbines would reduce costs by $688,000, while three turbines would reduce it by some $1.12 million!

One problem with an unreliable grid is that it results in frequent starts and stops of diesel generators. This is shown in Figure 5 which indicates the number of starts and the number of periods that each of the generators produces power under the no-wind and with-wind scenarios. We notice that the introduction of a single wind turbine does not affect the operating time (and number of starts) of the larger diesel generator, although its overall power output declines from 180.8 MWh to 170.0 MWh for the month of July. The smaller diesel turbine operates more like a peaking facility, with its output over the period declining from 5.9 MWh to 3.5 MWh when wind power becomes available. Importantly, the introduction of wind power reduces the number of stops and starts, thereby reducing operating costs (a component of costs not explicitly measured here). Although the results presented in Figure 5 pertain to only one iteration of the model, the averages over 500 iterations (see below) are similar: the average number times the smaller generator stops and starts falls by some 16% (from 10.26 to 8.64) and periods of operation decline by 34% (from 28.62 to 18.82), while those for the large generator are unaffected (31.6 stops/starts and 116.6 operating periods).

An important question to ask is the following: If wind penetration increases from 10% (one turbine) to 20% or more, would it be possible to do away with the smaller (or larger) diesel unit, thereby saving an upfront cost of $450,000 or more (in addition to fuel savings)?

To answer this and related questions, we need to examine the results from 500 iterations of the model. The mean, standard deviation, minimum and maximum values of the relevant outcome variables are provided in Table 3. In the table, three levels of wind penetration are considered, corresponding to the construction of one (approximately 10% level of wind penetration), two (22.5% penetration), and three turbines (35%). The capacity factor for the wind turbines in this model is some 37%.

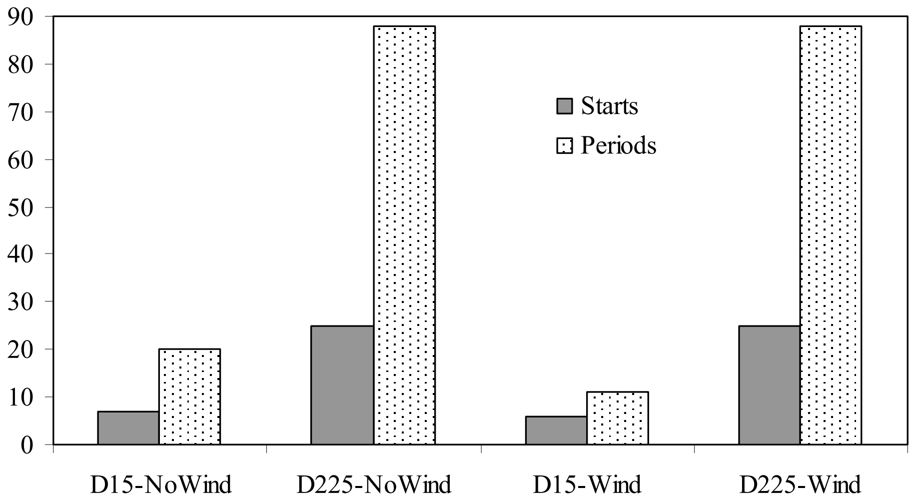

Figure 5: Operations of Diesel Generators with and without Wind Power

One important result is that, no matter how much wind is installed, it is not possible to eliminate either the small or large diesel generator. That is, even though the smaller diesel generator might not be required at any time during the month (as indicated by the zero output in the minimum column of Table 3), it is not possible to eliminate the generator entirely. Even for the highest wind penetration level, upwards of 7.1 MWh of output might be required from this generator during the month.

For the ancillary grid, wind replaces not only diesel generation but also power from the grid. When it replaces power from the grid, the financial benefit is small and would not likely benefit the private small-scale grid operator if power from the national grid was totally reliable – the costs of purchasing diesel generators likely exceed the benefits. For the simulation presented in Table 3, we find that 13.9% of the wind generated power goes to replace power that would otherwise have been generated with diesel fuel. In absolute terms, however, a greater amount of wind replaces power that would otherwise be provided by the national grid. It is clear that, as the unreliability of the grid increases, the benefit of wind power increases. Indeed, if the small grid consisted only of diesel turbines with no connection to the national grid, wind displaces diesel generated power one-for-one. This is a great benefit and holds for any grid that relies on peak-demand, fast-responding generators.

Finally, consider the cost savings. Costs take into account the costs of buying power from the national grid, when applicable. From Table 3, we find that the shadow value of diesel ranges from \$3.44/kWh for 10% penetration to \$4.44/kWh for 22.5% penetration and then falls to \$4.34/kWh for 35% penetration. At the higher wind penetration levels, diesel serves an important back-up function for variable wind as indicated by the higher shadow prices for diesel.

Table 3: Wind Power Penetration into an Unreliable Grid with Diesel Backup: Simulation Results Summary for July

	Mean	Standard Deviation	Minimum	Maximum
Without Wind				
Diesel 1500 (kWh)	6,354	2,618	321	16,760
Diesel 2250 (kWh)	232,076	39,757	132,981	357,299
Cost ('000s)	$132,300	$22,761	$74,586	$203,324
With Wind	**Single turbine (10% penetration)**[a]			
Wind Power (kWh)	91,061	2,518	84,337	97,436
Diesel 1500 (kWh)	3,830	1,805	134	11,674
Diesel 2250 (kWh)	220,358	37,867	126,580	341,555
Cost ('000s)	$131,986	$22,692	$74,526	$202,990
Cost Difference ('000s)[b]	$313.6	$158.9	$1.1	$888.9
	Two turbines (22.5% penetration)[a]			
Wind Power (kWh)	182,123	5,037	168,674	194,872
Diesel 1500 (kWh)	2,635	1,316	52	8,330
Diesel 2250 (kWh)	207,310	35,731	120,016	324,067
Cost ('000s)	$131,491	$22,586	$74,527	$202,428
Cost Difference ('000s)[b]	$808.9	$363.1	$1.8	$2,090.3
	Three turbines (35% penetration)[a]			
Wind Power (kWh)	273,184	7,555	253,011	292,308
Diesel 1500 (kWh)	2,123	1,103	0	7,064
Diesel 2250 (kWh)	193,580	33,499	113,430	305,129
Cost ('000s)	$131,113	$22,497	$74,529	$201,841
Cost Difference ('000s)[b]	$1,186.0	$521.1	$30.7	$3,051.2

Notes:
[a] Wind penetration defined as the ratio of installed wind capacity to peak load
[b] Cost of operating small grid with unreliable power from national grid and diesel backup minus the same situation but with wind power; this is the benefit of investing in wind.

4. CONCLUDING OBSERVATIONS

The potential for wind generated power in developing countries is substantial. Both the data and simulation model indicate that capacity factors at many potential wind sites, particularly offshore in regions such as the Red Sea, are among the highest in the world. While expansion of wind generating capacity is occurring in developing countries, particularly India and China and to a lesser extent Brazil and possibly Egypt, it is clear that significant obstacles remain. The major obstacles to overcome are those well known to economists – inadequate governance structures, including lack of property rights protection and rule of law, and problems with corruption. Inadequate quality of transmission infrastructure, insufficient and poor-quality generating capacity, theft of electricity, lack of incentives, and corruption have made many national grids in developing countries unreliable. As a result, many entrepreneurs are forced to rely on diesel backup or privately-operated but very small local grids that generally also rely on diesel generation. These are very expensive to operate. Yet, it is because such grids rely on expensive fossil-fuel power that there exist such excellent opportunities to employ wind turbines.

The results of the simulation modeling exercise indicate that the operator of a small-scale, diesel-powered grid might be able to reap substantial savings by investing in wind turbines. Wind energy replaces expensive diesel power with, in the case of a grid with maximum load of 2.85 MW and diesel generating capacity of 3.75 MW, associated saving amounting to over a million dollars per month.

This conclusion is subject to several caveats. First, the main cost of operating diesel turbines is the fuel cost. We assumed a cost of $1.00 per liter, which might be somewhat on the high side. If costs are lower then savings are also reduced. However, the benefits of reduced emissions of CO_2 were not taken into account. As noted earlier, some developing countries have aggressively pursued CDM projects where Kyoto signatories help offset the costs of wind power investments and/or provide payments for each unit of CO_2 emissions displaced. Second, we calculated an average capacity factor for wind energy at Mekelle airport in Ethiopia of slightly more than 37% (compared to 34% in Table 2). Based on experience elsewhere (van Kooten and Timilsina, 2009), this might well be on the high side. In that case, the simulation results reported here are likely on the optimistic side. Finally, we have not accounted for the institutional and infrastuctural difficulties that developing countries experience in pursuing wind power developments on a large scale. These could add significantly to costs (see van Kooten and Timilsina, 2009). Despite these caveats, our results provide a strong case for the strategic deployment of wind turbines in developing countries.

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