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Natural Resources Conservation Service

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SUBJECT: ECS - Range, Research Article on Performance and Economic Comparison of a Mechanical Windmill to a Wind-Electric Water Pumping System

FILE CODE: 190-19-

TO: State Grazing Lands Specialists

Tom Spoffard of the Water Climate Center, Portland, Oregon, recently sent me the attached research article comparing wind-electric windmills and mechanical windmills. I found it very interesting and I think it could have potential in many of your areas where windmills are used.

The bottom line is that an electric windmill is 25 percent cheaper to install and pumps more water than the mechanical windmill. Maintenance required for the electric windmill should be less also. Read on for more information. It might be the way of the future or now.

Rhett H. Johnson

Rhett H. Johnson
Director

Attachment

cc:
GLTI staff
Jim Robinson, Agroforester, NAC, NRCS, Ft. Worth, TX

Paper No. 974001
An ASAE Meeting Presentation

PERFORMANCE AND ECONOMIC COMPARISON OF A MECHANICAL WINDMILL TO A WIND-ELECTRIC WATER PUMPING SYSTEM

by

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Summary:

At a simulated 30-m (98.4ft) pumping depth, the water pumping performance of a mechanical windmill using two different size piston pumps was compared to two wind-electric water pumping systems. If the wind turbine of a wind-electric system was on a 20 m tower, it would average more daily water volume than a mechanical windmill on a 10 m tower for every month of the year at a 25% reduction in total system cost (assuming Bushland wind regime).

Keywords:

Water pumping, windmill, wind power, wind-electric

PERFORMANCE AND ECONOMIC COMPARISON OF A MECHANICAL WINDMILL TO A WIND-ELECTRIC WATER PUMPING SYSTEM[1]

B. D. Vick and R. N. Clark[2]

ABSTRACT

At a simulated 30m(98.4ft) pumping depth, the water pumping performance of a mechanical windmill using two different size piston pumps was compared to two wind-electric water pumping systems. The mechanical windmill had a rotor diameter of 2.44m(8ft) and reached a maximum of 32 strokes/minute at a 9m/s(20.1mph) wind speed. The inside diameters of the piston pumps tested on the mechanical windmill were 4.8cm(1.875in) and 7cm(2.75in) -- the stroke length on both was 19cm(7.5in). The wind turbine on one of the wind-electric systems had a rotor diameter of 2.44m(8ft) and was connected to a 0.38kW 3-phase 230V AC submersible motor via a USDA-ARS designed wind turbine smart controller. The wind turbine on the other wind-electric system had a rotor diameter of 2.74m(9ft) and was connected to a 0.75kW 3-phase 230V AC submersible motor via a controller supplied by the manufacturer. Both wind-electric systems used a 0.38kW 9-stage centrifugal pump. At a hub height of 10m, the wind-electric systems pumped more water than the mechanical systems in the winter and spring(highest average wind speed months), but pumped less water in the summer and fall(lowest average wind speed months). However, if the wind turbines were on 20m towers and the windmills were on 10m towers, then the wind-electric systems would pump as much or more water than the mechanical systems during every month of the year if the wind regime was similar to that of Bushland, TX. Even when the cost of a 20m tower for a wind-electric system was included, the total system cost for a wind-electric system was $1282 to $1414 cheaper than it would be for a new mechanical windmill system(a 25% cost reduction). The maintenance required on a wind-electric system should also be less than that for a mechanical windmill.

INTRODUCTION

A safe drinking water supply continues to be a major problem in the world. In parts of the world where there is no utility supplied electricity, the most economical solution is to use mechanical windmills, solar-PV systems, or wind-electric systems for pumping water. Which system is used depends on the pumping depth, solar radiation, wind speed, and amount of water needed. Many farmers and ranchers in this country are looking to replace their aging windmills with either another mechanical system, a solar-PV system, or a wind-electric system. Because of the high

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diameter pumps will also increase flow rate, maintenance is also likely to increase with using a larger size pump. As the pump diameter gets larger the drop pipe also should be increased which means higher cost and a much heavier system to try to do maintenance on. The total weight of the Aermotor 2.44m windmill is 161.4kg(355lb).

DESCRIPTION OF WIND-ELECTRIC SYSTEMS

The two wind-electric systems selected in this study were a Bergey Windpower[3] 850 and a World Power Technologies[3] Whisper 1000. The Bergey 850 is currently being sold for battery charging, but the manufacturer made a new winding for the stator so we could test it for powering a 3-phase AC submersible motor and centrifugal water pump. Since this is a prototype, the final Bergey 850 water pumping system that is sold will perform better than this one. The Bergey 850 has a rotor diameter of 2.44m(8ft) and reaches 850W at a 12.5m/s wind speed. There currently is no controller commercially available for using this wind turbine for water pumping, but a smart controller was designed for the Bergey 850 by USDA-ARS (Ling and Clark, 1997). The controller uses a 6V, 5A-hr rechargable battery and has the usual high/low frequency cut-in/cut-out capability of a wind turbine pump controller. In addition, this controller also has:

1) solid state instead of mechanical relays for shorter response time and longer life.
2) a dump load cut-in and cut-out frequency which can be used for adding a resistive or a capacitive load for improving the performance at higher wind speeds.
3) a battery charging circuit which can limit the maximum charging current to protect a fuse from being blown due to low battery voltage. Low battery voltage can be caused by low wind days or wind turbine being braked for long periods.
4) CPU logic that will protect the turbine if it begins to get too hot.
5) CPU logic that determines the proper dump load cut-in/cut-out frequencies if the turbine goes offline repetitively due to gusty winds.

The wind turbine uses 3 pultruded fiberglass blades which have an airfoil developed by Karl Bergey. The blade's chord and twist are constant in a static condition, but a pitch weight will alter the twist at higher wind speeds. The generator is a permanent magnet alternator with 18 poles and has increased stator insulation(compared to the battery charging stator) to reduce the risk of the stator shorting due to high voltage. This wind turbine uses horizontal furling for overspeed protection. This wind-electric system used a Grundfos[3] 0.38kW(0.5hp) 9-stage pump driven by a Franklin Electric[3] 0.38kW(0.5hp) 3-phase, 230V submersible motor. The variable voltage and frequency from the generator was connected to the controller which in turn was connected to the submersible motor. No inverter was needed because additional capacitance is added in parallel(via controller) with the inductive motor which keeps the voltage-to-frequency ratio around 3 to 4 and keeps the voltage and current waveforms in phase (i.e. improvement in power factor). The capacitance used is 35μF until the dump load frequency is reached whereupon an additional 20μF is added. The total weight of the Bergey 850 wind turbine is 38.6kg(85lb).

The Whisper 1000 has been sold for about four years for water pumping. The Whisper 1000 has a rotor diameter of 2.74m(9ft) and reaches 1000W at a wind speed of 11m/s. Its controller is energized by power from the wind turbine and therefore doesn't require a battery. This controller has a low frequency cut-in/cut-out, but no high frequency cut-in/cut-out. The wind turbine used 2 epoxy fiberglass blades which were made using a hand layup. A Wortmann airfoil with a variable chord and twist distribution were used in the blade design. The generator is a permanent magnet alternator with 10 poles. The wind turbine furls vertically for overspeed protection. This wind-electric system used a McDonald[3] 0.38kW(0.5hp) 9-stage pump driven by a Franklin Electric[3] 0.75 kW(1hp) 3-phase 230V submersible motor. As was true for the Bergey 850, the Whisper alternator generates 3-phase AC variable voltage and frequency electricity and was connected to a controller which in turn was connected to a submersible motor without the use of an inverter. A capacitance of 35μF was used to improve the power factor. The total weight of the Whisper 1000 wind turbine is 31kg(68.2lb).

RESULTS

The windmill and wind-electric systems were evaluated at a simulated pumping depth of 30m. The pumping depth was simulated by using a back pressure valve. For further discussion on the experimental apparatus see (Clark and Vick, 1994). The flow rate for both the windmill and wind-electric systems is shown in Figure 1. This graph shows that the windmill systems cut-in at a lower wind speed (2.5 to 3m/s) than the wind-electric systems (5 to 5.5m/s). This is due to the high solidity of the windmill with its 18 blades compared to the low solidity of the wind-electric systems with two or three blades. If the wind speeds always stayed between 3 and 5m/s the windmills would pump water, but the wind-electric systems would not. However, the wind-electric systems substantially outperform the windmill systems at higher wind speeds. From this graph it is evident that the windmill systems are beginning to furl at a windspeed of 9 m/s(20.1mph). While it appears the wind-electric systems are beginning to furl at 13m/s (because of the decrease in flow rate with increasing wind speed), in actuality the wind turbines are losing synchronization with the motors at these wind speeds and therefore running offline part of the time -- especially when there are gusty winds.

System Efficiency can be defined by the following equation:

System Efficiency = Water Power/Wind Power

Water Power is the change in potential energy of the pumped water with respect to time (the kinetic energy of the water pumped with respect to time is negligible). Wind power is the change in kinetic energy with respect to time of the air passing through a stream tube with the diameter of the wind turbine/windmill rotor and at the wind turbine/windmill hub height. The system efficiency for all the water pumping systems is shown in Figure 2. As was seen with the flow rate, the windmill systems are better at low wind speeds while the wind-electric systems do better at higher wind speeds. The maximum system efficiency is higher (15 to 20%) for the windmill systems but occurs at a lower wind speed (3.5 to 4.5 m/s). Besides the solidity, another reason for the windmill's high efficiency at low wind speeds is the chord and twist of the blades are optimized at these low wind speeds while the wind turbine blades are optimized at wind speeds around 7 to 8 m/s. Another advantage for the windmill is the wind power is directly converted to mechanical power while the wind turbines convert the mechanical power to electrical power and then the electrical power is converted back to mechanical power. The wind-electric maximum system efficiency (5.5 to 7.5%) occurs over a broader band of wind speeds(7 to 11 m/s) than the mechanical windmill because the change in rotor speed with wind speed results in maintaining a constant angle-of-attack close to the maximum lift-to-drag ratio of the airfoil.

In Figure 3 the stroke rate is shown for both windmill systems. The maximum stroke rate for both systems is about 32 strokes/minute and occurs at a wind speed of 9m/s. As expected, the stroke rate for a given wind speed is less for the bigger diameter pump. If the furling wind speed is adjusted so the maximum stroke rate is increased, the flow rate will increase, but this will increase the wear on the pumping system and is not recommended by the manufacturer.

The monthly average wind speed at Bushland, TX at a 10m height over a 14 year period can be observed in Figure 4. This graph shows that the windspeeds are normally highest in the spring and winter and lowest in the summer and fall -- this is typical of the wind pattern in much of the Great Plains. March and April are usually the highest wind months, and August is usually the lowest.

Using the flow rate data in Figure 1 and the monthly average wind speed distribution data gathered at Bushland, TX from 1983 to 1996 at a 10m height, the monthly daily water volume for all the windmill and wind-electric systems can be calculated (Figure 5). At a constant hub height (10m), the water pumping performance of the Aermotor windmill system with the 48mm pump is about the same as the Bergey 850 wind-electric system, and the water pumping performance of the Aermotor windmill system with the 70mm pump is about the same as the Whisper 1000 system. The wind-electric systems pump more water than their Aermotor windmill/pump counterparts in the spring and winter(when the winds are highest) and less in the summer and the fall(when the winds are lowest). Since August(besides being the calmest month) is also usually very hot, water for cattle or domestic use is most critical during this month. Therefore it is imperative that the wind-electric system be as good as the mechanical system which it is to replace. The size of the wind turbine could be increased, but this would result in a substantial increase in cost. However, for a relatively small increase in cost the wind turbine height can be increased by using a taller tower which will result in higher wind speeds and a higher daily water volume.

The monthly average windspeeds at Bushland, TX during 1996 at 10 and 20m heights are shown in Figure 6. Only one year of data is shown because only a few years of 20m height data have been consistently collected at Bushland, TX. Although the wind speeds in this graph vary much more than in Figure 4, it is still evident that spring has the highest wind speeds and late summer has the lowest wind speeds. The 20m height average wind speed is between 0.4 and 0.9m/s higher than the 10m height average wind speed. Since the power in the wind goes up as the cube of the wind speed, this increase in wind speed will result in a large increase in wind power and correspondingly a large increase in daily water volume.

The monthly daily water volume during 1996 of the Aermotor windmill(48mm pump) system at a 10m height and the Bergey 850 wind-electric system at 10 and 20m heights is shown in Figure 7. When comparing the Aermotor(48mm pump) to the Bergey 850 at a 10m height, the results are similar to those seen in Figure 5(average wind speed distribution over 14 years). But when the Bergey 850 at the 20m height is compared to the Aermotor(48mm pump) at the 10m height, the Bergey 850 pumps more water than the Aermotor(48mm pump) for every month.

The same results as Figure 7(wind-electric systems pump more water than windmill systems if the wind turbines are at a higher height), can be seen in Figure 8, but this time the Aermotor windmill(70mm pump) system at the 10m height is compared to the Whisper 1000 wind-electric system at 10 and 20m heights. The only difference is this time the daily water volume in August for the wind-electric system is below the windmill system but only by about 5%. Table 1 shows the system cost for the windmill and wind-electric pumping systems. The system costs have been estimated for a 30m pumping depth, but as the pumping depth increases, the windmill systems will become even more expensive when compared to the wind-electric systems due to the high cost of sucker rod and drop pipe for windmill systems. The total cost of the wind-electric systems was $1282 to $1414 cheaper than the windmill systems.

CONCLUSIONS

Two wind-electric water pumping systems were compared to two windmill water pumping systems for a 30m pumping depth. The windmill systems had lower cut-in windspeeds(2.5 to 3m/s) compared to the cut-in wind speeds(5 to 5.5m/s) of the wind-electric systems. However, the wind-electric systems pumped more water at higher wind speeds than the windmill systems. For the same hub height, the average daily water volume of the wind-electric systems was higher than that of the windmill systems during the spring and winter but usually was less for summer and fall. However, if the wind turbines were set on towers giving them a 20m height compared to the windmills' 10m height, then the daily water volume of the wind-electric systems was higher than that of the windmill systems for every month. It should be mentioned that using 20m towers for windmills is too expensive. When comparing the total system cost of the wind-electric systems to that of the windmill systems, the wind-electric systems were found to be 25% cheaper than the windmill systems even when the cost of the taller wind-electric towers was included. For deeper pumping depths the wind-electric systems would be even more economical than the windmill systems(due to high cost of sucker rod and drop pipe for windmill systems). The above statements imply the Bergey 850 would be a good replacement for an Aermotor 2.44m(8ft) windmill with a 48mm(1.875in) pump if the wind regime is comparable to that at Bushland, TX. Similarly, the Whisper 1000 would be a good replacement for the Aermotor 2.44m(8ft) windmill with a 70mm(2.75in) pump if the wind regime is comparable to that at Bushland, TX. If pumping too much water in the spring and winter by the wind-electric systems is a problem, then a float switch could be installed that the controller can operate.

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ACKNOWLEDGMENTS

We would like to thank Ron Davis (USDA-ARS) and Shitao Ling (WTAMU-AEI) for their invaluable help in this research.

Table 1. SYSTEM COST OF WIND PUMPING SYSTEMS
30 METER PUMPING DEPTH
Estimated by USDA-ARS

Component	Aermotor 2.44m	Aermotor 2.44m	Bergey 850	Whisper 1000
Wind Turbine/Mill	$2,400.00	$2,400.00	$1,825.00	$1,950.00
Tower[a]	$1,820.00	$1,820.00	$1,210.00	$1,210.00
Pump Controller	-------	-------	$ 300.00	$ 200.00
Pump[b]	$ 227.00	$ 403.00	$ 255.00	$ 255.00
Motor[c]	-------	-------	$ 301.00	$ 320.00
Pump Rod[d]	$ 50.00	$ 50.00	-------	-------
Sucker Rod[e]	$ 335.00	$ 335.00	-------	-------
Packer Head	$ 76.00	$ 76.00	-------	-------
Pipe[f]	$ 313.00	$ 313.00	$ 48.00	$ 48.00
Total	$5,221.00	$5,397.00	$3,939.00	$3,983.00

[a] Assuming 10m tower height for mechanical windmills & 20m tower height for wind turbines.
[b] Assuming 5cm piston pump on first Aermotor & 7cm piston pump on second Aermotor. Assuming 9-stage 0.38kW centrifugal pumps on both Bergey 850 & Whisper 1000.
[c] Assuming 0.38kW 3ϕ 230V motor on Bergey 850 & 0.75kW 3ϕ 230V motor on Whisper 1000
[d] Assuming 2.54cm square steel pipe
[e] Assuming 1.59cm fiberglass rod
[f] Assuming 5cm galvinized steel drop pipe for mechanical windmills and 2.5cm polyethylene pipe for wind turbines.

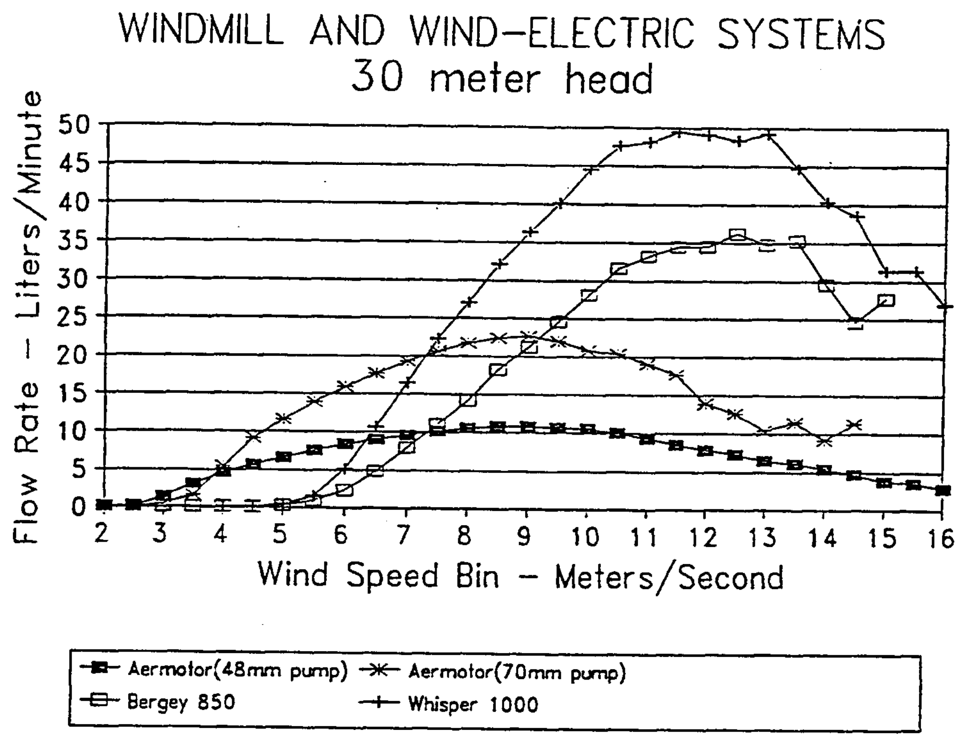

Figure 1. Flow rate at a 30 meter head for windmill and wind-electric systems.

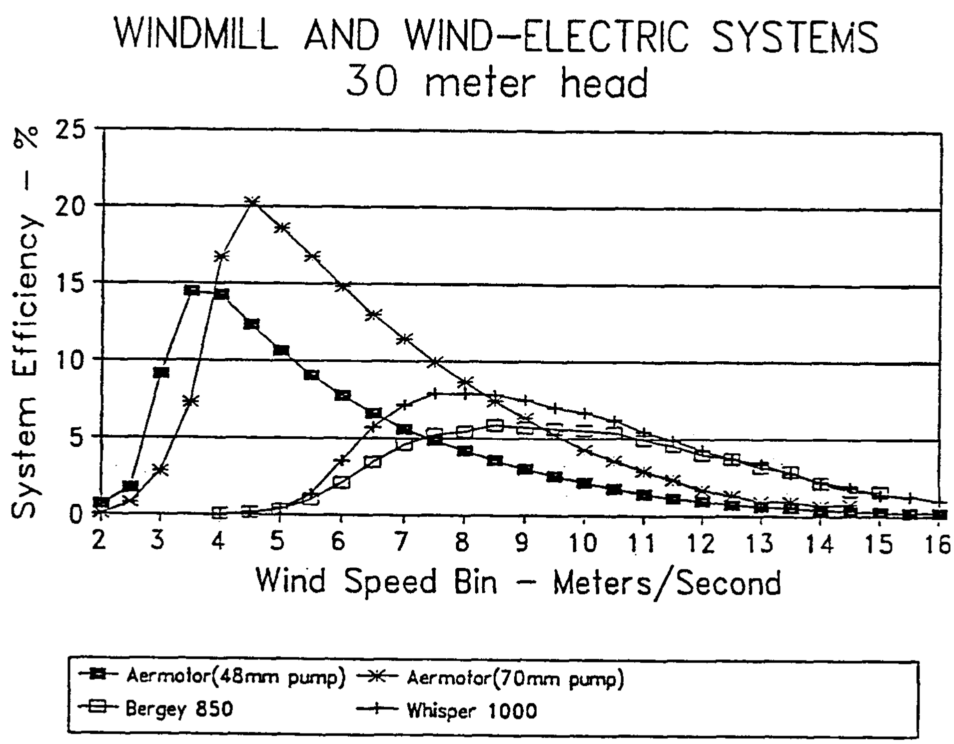

Figure 2. System efficiency at a 30 meter head for windmill and wind-electric systems.

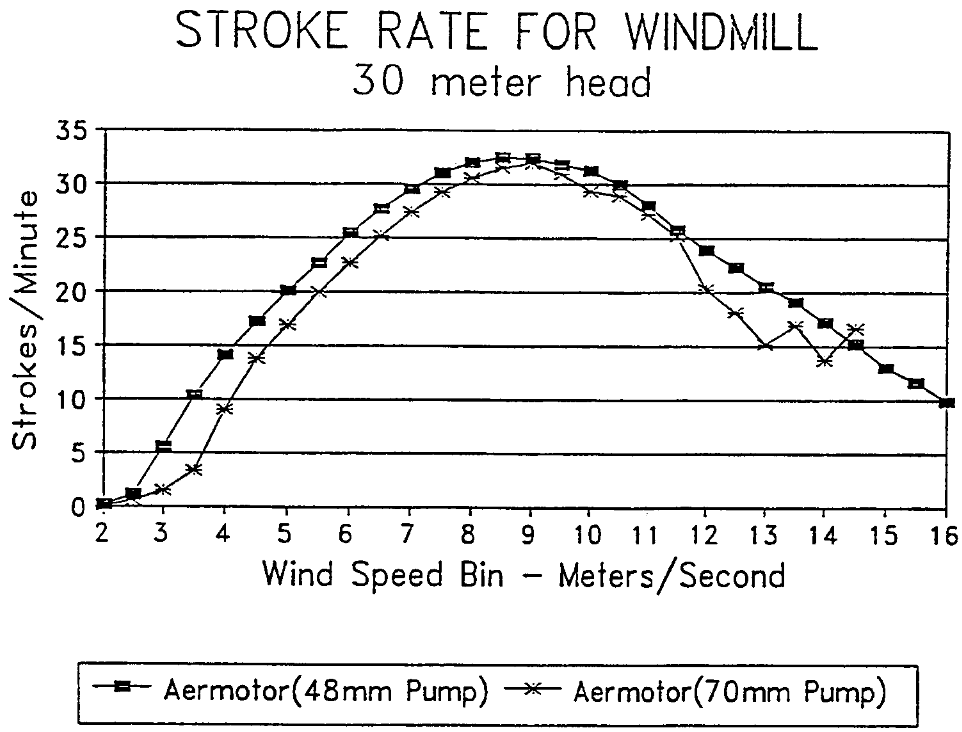

Figure 3. Stroke rate for two different size pumps on Aermotor 2.44m windmill.

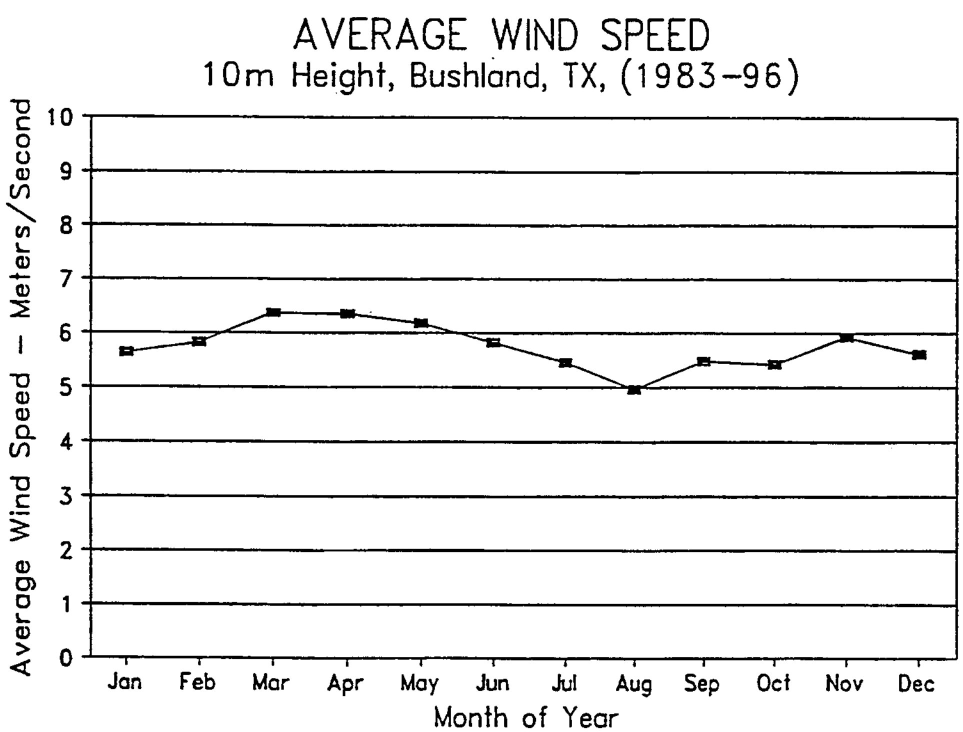

Figure 4. Average monthly wind speed at 10 meter height for Bushland,TX(1983-1996).

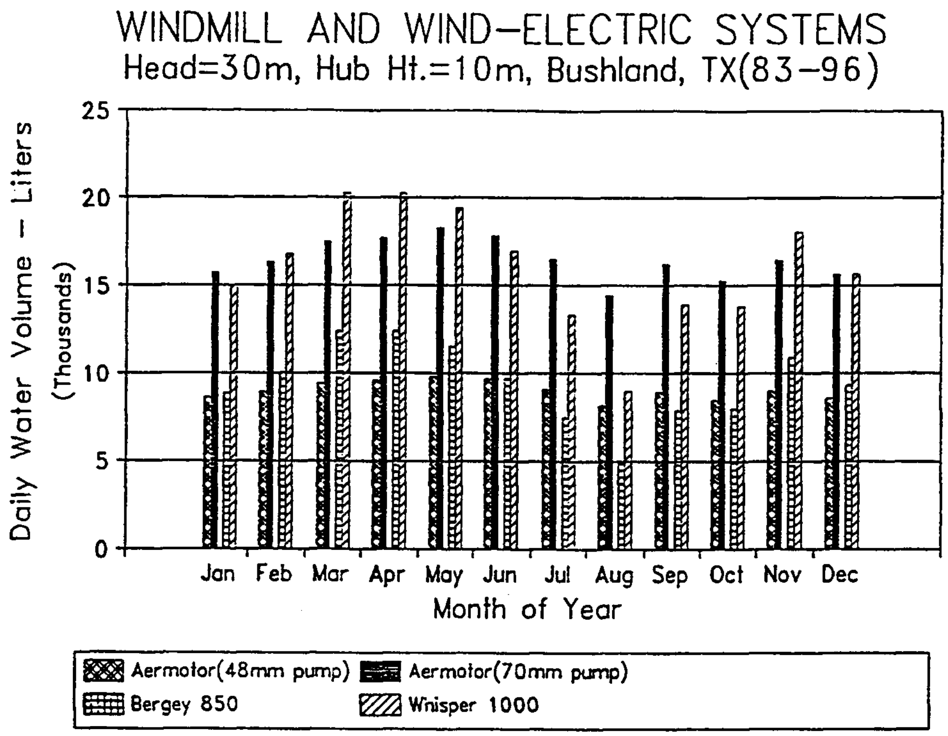

Figure 5. Monthly daily water volume at a 30 meter head and a hub height of 10 meters at Bushland, TX (1983-1996).

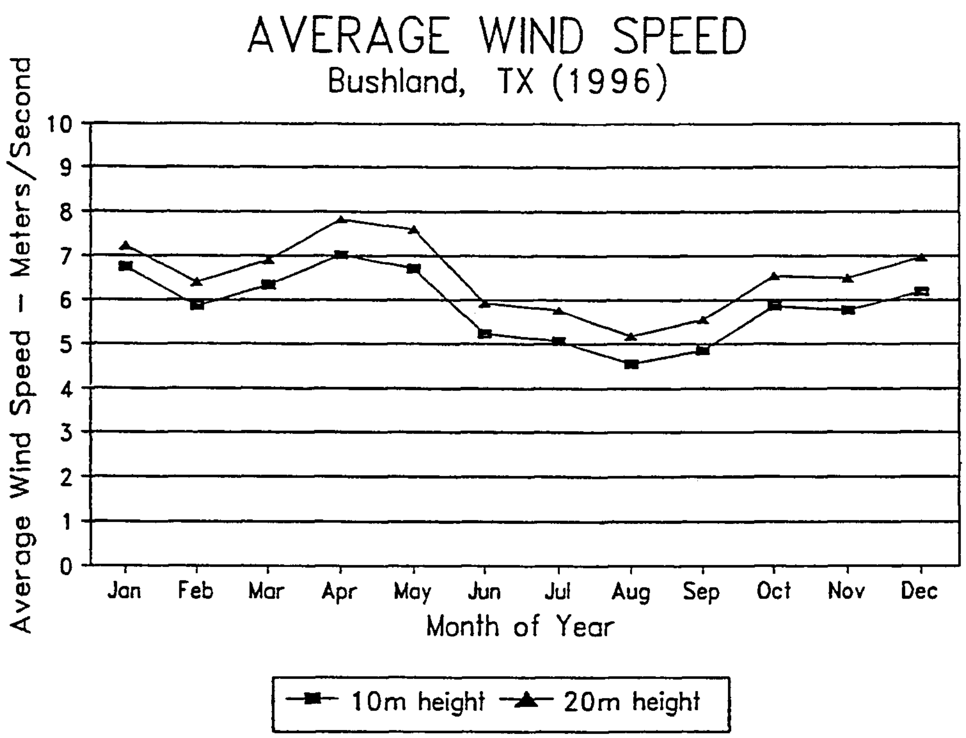

Figure 6. Average monthly wind speeds at 10 and 20 meter heights for Bushland, TX(1996).

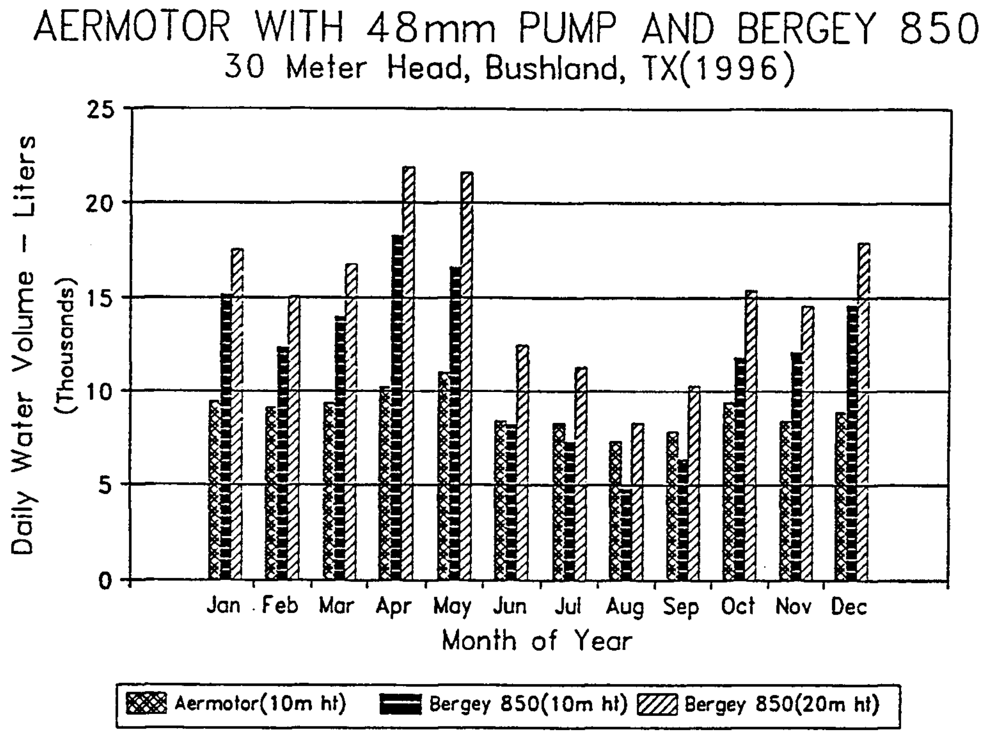

Figure 7. Average monthly daily water volume for Aermotor(48mm pump) at 10 meter height and Bergey 850 at 10 and 20 meter heights.

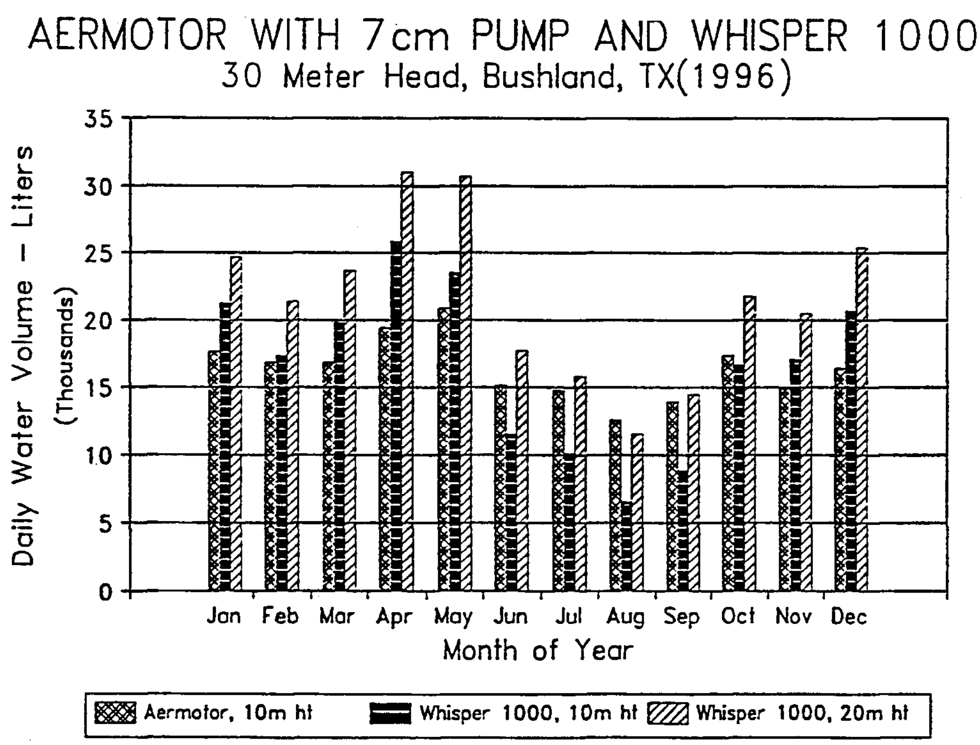

Figure 8. Average monthly daily water volume of Aermotor(7cm pump) at 10 meter height and Whisper 1000 at 10 and 20 meter heights.