Faculteit der
Technische Natuurkunde

Vakgroep Transportfysica

FIELD TESTING OF WATER PUMPING WINDMILLS BY CWD

* Meel, J. v., *Smulders, P., *Oldenkamp, H.
* Nat, A. v.d., °*Lysen, E.

October 1986 R 816 D

FIELD TESTING OF WATER PUMPING WINDMILLS BY CWD

* Meel, J. v., *Smulders, P., *Oldenkamp, H.
*Nat, A. v.d., **Lysen, E.

October 1986 R 816 D

Paper of the 6th European Wind Energy Conference, October 1986, Rome

* TECHNICAL UNIVERSITY EINDHOVEN
Faculty of Physics
Laboratory of Fluid Dynamics and Heat Transfer
WIND ENERGY GROUP
P.O. Box 513, 5600 MB Eindhoven, Netherlands

CONSULTANCY SERVICES WIND ENERGY DEVELOPING COUNTRIES
P.O. BOX 85
3800 AB AMERSFOORT
THE NETHERLANDS

**DHV Consulting Engineers, P.O. Box 85,
3800 AB Amersfoort, Netherlands

FIELD TESTING OF WATER PUMPING WINDMILLS BY CWD

J.J.E.A.v.MEEL*, P.T.SMULDERS*, H.OLDENKAMP*, A.L.J.M.v.d.NAT*, E.H.LYSEN**

CWD, Consulting Services Wind Energy Developing Countries, Amersfoort, The Netherlands

ABSTRACT

Field testing of water pumping windmills is an important part of CWD's activities. Measurements are performed by means of Apple II computers and thereafter elaborated by means of the same computers, using software developed by the Wind Energy Group. This article discusses some aspects related to the hysteresis behaviour of windmills driving piston pumps.

The behaviour of a windmill in the hysteresis region depends on the history of the wind speed. Therefore the average curves measured according to the generally accepted IEA recommendations depend on the frequency distribution and time history of the wind speed during the measurements. The IEA practices were conceived to provide a means of measuring output curves in a reproducible way. The underlying assumption is that an output curve is a characteristic of a wind machine, valid at any site, in any wind regime. As indicated above, this is not the case for windmills driving piston pumps, or for that matter for any wind machine, having hysteresis behaviour. Two examples are presented of output curves, measured for one machine at one site under different wind conditions. Considerable differences were found. Annual water outputs calculated on the basis of the two curves can differ as much as a factor of two!

Procedures for output prediction of water pumping windmills will have to involve three steps instead of two. The procedure must start by determining an output curve, including hysteresis effect, which only depends on characteristics of the wind machine. Subsequently the curve must be converted into a simple but site specific curve by means of probabilities derived from the site's wind speed frequency distribution. The third step is the conventional multiplication and integration of output curve and frequency distribution. A simple theoretical model has been developed including these three steps. Procedures for field measurements based on this concept will need to be developed.

* J.J.E.A.v.Meel, P.T.Smulders, H.Oldenkamp, A.L.J.M.v.d.Nat
Technical University Eindhoven, The Netherlands

** E.H.Lysen
DHV, Consulting Engineers, Amersfoort, The Netherlands

List of symbols

A	rotor area	(m^2)
C_E	energy production coefficient	(-)
C_P	power coefficient	(-)
C_Q	torque coefficient	(-)
D	diameter	(m)
E	energy	(J)
k	Weibull shape factor	(-)
N	number	(-)
P	power	(W)
	probability	(-)
p	probability of running in hysteresis region	(-)
p'	idem, including wind speed variations within 10 minutes	(-)
q	pumping rate	(l/s)
T	time	(s)
V	wind speed	(m/s)
v	relative wind speed in hysteresis region $(V-V_{stop})/(V_{start}-V_{stop})$	(-)
η	efficiency	(-)
λ	tip speed ratio	(-)
ρ	air density	$(1.2\ kg/m^3)$

Subscripts

d design, i.e. the point for which $C_p\eta$ reaches its maximum

max maximum

1. INTRODUCTION

CWD (Consultancy Services Wind Energy Developing Countries) is an organization initialized and funded by the Netherlands' Ministry of Development Cooperation. It aims to help governments, institutes and private parties in the Third World in their efforts to use wind energy and in general to promote the interest for wind energy in developing countries. The emphasis of the activities of CWD is on water pumping windmills, coupled to single acting piston pumps. Participants of CWD are DHV Consulting Engineers (Amersfoort), Eindhoven University of Technology, Twente University of Technology and ILRI, Institute of Land Reclamation and Improvement (Wageningen).
CWD-designed water pumpers are in operation in Sri Lanka, Pakistan, Tanzania, Mozambique, Sudan, Mauretania, Tunesia, Peru, Cape Verde and Ghana.

Implementation projects are being carried out in Cape Verde and Sri Lanka, and are in preparation for Sudan, Kenya, Nicaragua, Somalia and Mozambique. Development of prototypes is mainly done in the Netherlands.

For field testing of water pumping windmills, CWD has testfields in Eindhoven, Vriezenveen (close to Twente University) and Almere (in one of the polders in the former Zuiderzee). The three CWD testfields have different purposes:

The Almere testfield (which has a very good wind regime) is meant for functional tests, output performance measurements and endurance tests (to know the maintenance and repair requirements); only fully developed windmills are tested there. See figure 1.

Three commercially available windmills have been tested: OASIS (2 m. diameter, manufactured in France), FIASA (3 m., Argentina), Southern Cross (5.2 m., Australia). Another series of tests on three commercial windmills started recently: BOWJON (2.36 m., driving an air compressor, and air lift pump, USA), LUBING (1.50 m., W. Germany), and DEMPSTER (4.3 m., USA). Also a CWD 2000 (2 m.) was installed for endurance tests.

The Vriezenveen testfield is meant for functional tests and output performance measurements on prototypes developed by the Windmill Group of THT. The CWD 5000 (the number refers to the rotor diameter in mm) has been tested there in a version with a deepwell pump and one with a low lift/high volume pump. A newly designed 8 m. diameter prototype is being tested.

The Eindhoven testfield (figure 2) is meant for:

- functional testing of prototypes
- performance testing of prototypes
- special measurements (like short term measurements, measurements of stresses and forces)
- field testing of innovative concepts
- development and testing of monitoring systems.
- anemometer tests

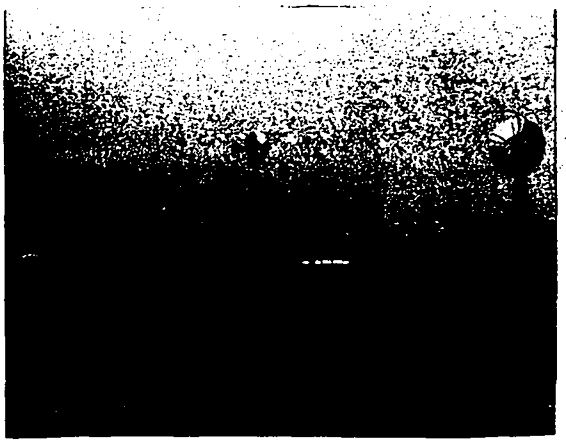

Fig. 1 Almere test site, from left to right: Oasis, Fiasa, and Southern Cross windmills

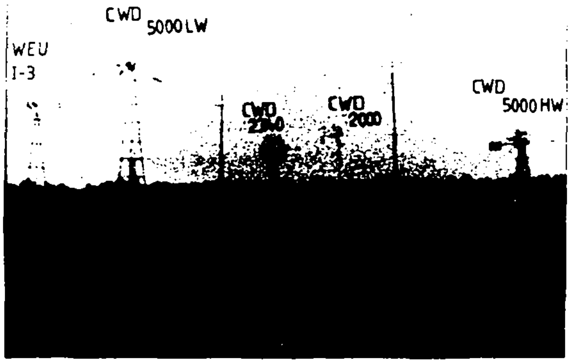

Fig. 2 Test site at the Technical University Eindhoven

In this article special attention is paid to output performance measurements for mechanical water pumping windmills. A specific problem will be presented, which is the presence of a large hysteresis loop in the start/stop region of the output curve. The consequences for output predictions will be shown.

2. STARTING AND STOPPING; HYSTERESIS BEHAVIOUR OF WINDMILLS DRIVING PISTON PUMPS

Mechanical windmills driving piston pumps have a rather peculiar starting behaviour, which is quite different from wind electric generators.

The special behaviour is due to the characteristic of the load.

A piston pump requires a torque which is in first approximation independent of the speed of operation. The torque is determined by the stroke length and by the water pressure on the piston, and only increases slightly at high speeds due to pressure losses in the valves and pipes.

Moreover, the torque is cyclic: during the upward stroke the piston has to lift the water, requiring a large torque, during the downward stroke the torque is practically zero. The maximum torque during one cycle is π times the average torque.

Starting from stand still in such a situation is quite difficult for a wind machine:

In order to start the load, a high torque is required. In order to lift the piston for the first time, the maximum torque is needed (π times the average).

The windmill blades are in stall, and the torque available from the windmill is relatively low.

This makes that the wind speed at which the windmill starts from stand still is relatively high: V_{start}.

Once running, the situation becomes much more favourable.

The cyclic character of the load has no influence any more due to the large inertia of the windmill rotor. Only the average torque is needed.

The windmill blades work in their normal range of operation, i.e. in lift. Hence the available torque is relatively high. This makes that a windmill, once running stops at a relatively low wind speed: V_{stop}.

Due to this start/stop behaviour one will find a hysteresis loop in the output curve as indicated in figures 3 and 4.

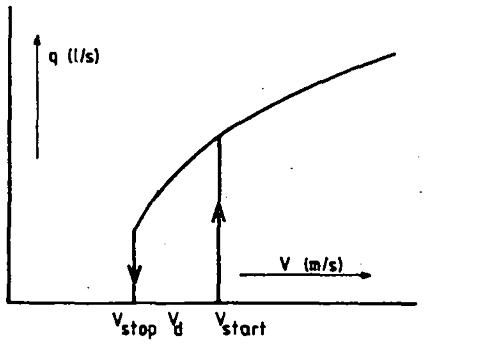

Fig. 3 Hysteresis loop due to start/ stop behaviour in output curve

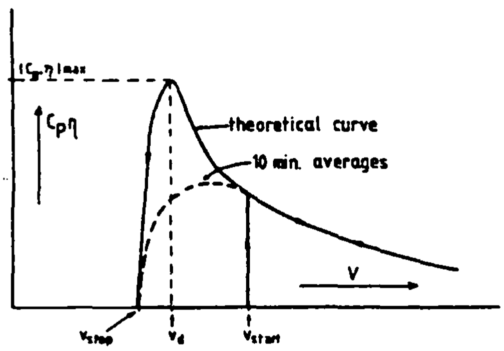

Fig. 4 Hysteresis loop in $C_p\eta$ curve

Figure 3 presents an output performance curve as pumping rate versus wind speed, which is, of course, equivalent to a power curve, i.e. hydraulic power versus wind speed. Figure 4 presents the same information in a format which is more convenient for comparison of different machines: $C_p\eta$-V curve, the overall power coefficient as a function of wind speed.

A detailed analysis of start and stop wind speeds for different types of windmills was presented in May 1986 at a conference in London, U.K., see reference 3. Measured and calculated values for V_{stop} and V_{start} proved to be in reasonable agreement. Here some more emphasis will be put on the curves as a whole, and hence on output.

As a reference for measurements and for general output predictions, it is useful to have a general expression for the output curve, or - which is equivalent - for the $C_p\eta$ curve. The overall shape of the curves can be derived rather easily, when making some assumptions (see also ref. 1).

A central role in the derivation is played by the value of various quantities at the design wind speed V_d, i.e. the wind speed for which the overall power coefficient $C_p\eta$ reaches its maximum, see also figure 4. They are indicated by an index d.

It is assumed that the windmill can be characterized by a linear torque-speed relationship (i.e. once running, beyond the region of stall):

$$C_Q = C_{Q_d}(\lambda_{max} - \lambda)/(\lambda_{max} - \lambda_d) \qquad (1)$$

The pump is assumed to demand a constant torque for all speeds, including the design wind speed, therefore the windmill will deliver a constant torque at all points of operation:

$$C_Q V^2 = C_{Q_d} V_d^2 \qquad (2)$$

From these two equations one finds λ as a function of V. Substituting the result into the first equation, and using the fundamental relationship $C_p = \lambda C_Q$, one finds an expression for C_p as a function of V:

$$\frac{C_p}{C_{p_{max}}} = \frac{V_d^2}{V^2}\frac{\lambda_{max}}{\lambda_d}\left(1-\frac{V_d^2}{V^2}\left(1-\frac{\lambda_d}{\lambda_{max}}\right)\right) \qquad (3)$$

Assuming a constant efficiency for the pump, expression 3 also represents the shape of the $C_p\eta$ curve (see fig. 4). Of course, it can easily be converted into a P(V)curve. For a windmill-piston pump system the point at which $C_p\eta$ is maximum is sharply defined, since the locus of maximum power points in the torque-speed characteristic of a windmill is a second order curve, whereas the torque characteristic of a piston pump is basically a horizontal line. The point of intersection corresponds to the design wind speed V_d.

Expression 3 describes the upper branch of the hysteresis loop (see figures 3 and 4). It is similar for a wide range of mechanical water pumping windmills. Only the values of start and stop wind speeds are different for different types of windmills.

3. FIELD MEASUREMENTS OF OUTPUT CURVES WITH HYSTERESIS LOOP

In this section some problems of field measurements are presented which are caused by the hysteresis effect. This is done on the basis of measurements performed at the Almere test facility for the Argentina manufactured FIASA windmill.

The FIASA is a typical example of a classical "American" windmill. The rotor is 3.06 m. in diameter (about 10') and has 18 blades. It is back geared (1:3.29). During the test it was driving a piston pump (diameter .101 m. and stroke .243 m. This configuration was specified by the manufacturer. This corresponds to a design wind speed V_d of 2.5 m/s.

A complete report of the tests and measurements is available, see reference 4. Some of the results were already published at a conference in London, reference 3.

Complete and reliable measurements were performed in the period October, November 1985. The measurements were performed according to the recommendations of the

IEA (see reference 2). No selection of measurements was applied except for selection of wind directions as recommended by IEA.

3.1 Measured and calculated $C_p\eta$ curves

When performing 10 minutes average measurements according to the IEA recommendations, the results in the hysteresis region will be some average of the upper and lower branch of the hysteresis loop (see figure 4). Sometimes the windmill is running (upper branch), and sometimes it is standing still (lower branch). For this region one expects to find average values below the theoretical curve, as well as a considerable spread in the measurements: a large standard deviation. This was indeed the case as can be seen in figure 5.

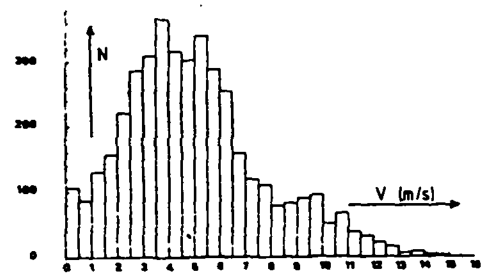

Fig. 5a Wind speed frequency distribution
Average wind speed 5.0 m/s

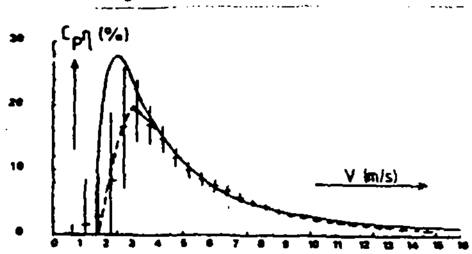

Fig. 5b $C_p\eta$ curve
Crosses: measurements
Drawn curve: theory (3)
Dotted curve: correction (5)

Fig. 5 Results of measurements of FIASA windmill October-November 1985, 4143 measurements (ref. 4)

Figure 5a shows the frequency distribution of the wind speed during the measuring period, which will prove to be an important reference.
Figure 5b shows the measured $C_p\eta$ curve as crosses. The centre of a cross represents an average value, the length of the crosses corresponds to the standard deviation. The drawn curve corresponds to the theoretical $C_p\eta$ relationship derived above (equation 3). The dotted curve corresponds to a correction which will be presented in section 4 of this article (equation 5). In the hysteresis region between V_{stop} and V_{start} (2 and 4 m/s respectively) one sees that the measured values are far lower than predicted by the simple theoretical formula (3). As expected, a large standard deviation is found in this region. Below 2 m/s one finds some low, but non zero values for $C_p\eta$. This is due to wind speed variations within 10 minutes. Even in a 1.5 m/s wind, one will have some moments with a wind speed over 2.0 m/s.
Between 4 and 9 m/s the measurements coincide very well with the theory. At high wind speeds the measured values are lower due to the safety system which limits the output.

3.2 Reproducibility of output curves

As indicated before, a windmill-pump system may operate either in the upper, or in the lower branch of the $C_p\lambda$ curve (figure 4). What exactly happens depends on the history: Once the windmill is running it will continue doing so when it enters the hysteresis region. Once standing still, it will remain standing still when entering the hysteresis region. Therefore, the probability of either situation depends on the wind speed distribution. In a period of strong winds the windmill will be running most of the time and the system will follow more often the upper branch of the hysteresis loop than the lower one. In a period of weak winds the opposite is expected.
In order to verify this, two different data series were chosen from the total data base on which figure 5 was based. One series was chosen so as to have mainly high wind speeds. Another one was chosen so as to have mostly low wind speeds. For these two series, graphs were made of frequency distribution, and power coefficient, see figures 6 and 7. It is to be noted that the full data series were used, no selection of data was practised, except for selection of wind direction as recommended by IEA.

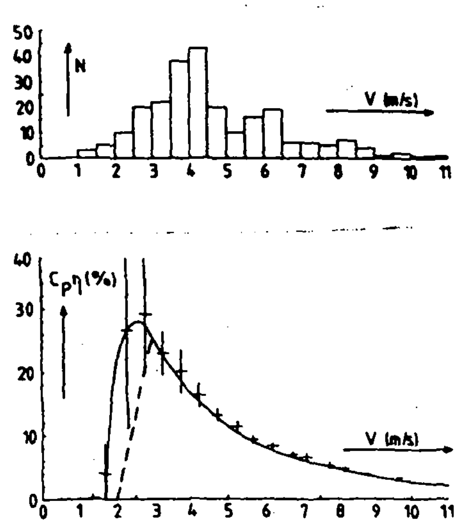

Fig. 6 Results of measurements of FIASA windmill November 1 until November 4, 1985, 239 measurements. High wind speeds prevail, average wind speed 4.6 m/s
Drawn curve: theoretical $C_p\eta$ curve, formula (3)
Dotted curve: correction according to (5)

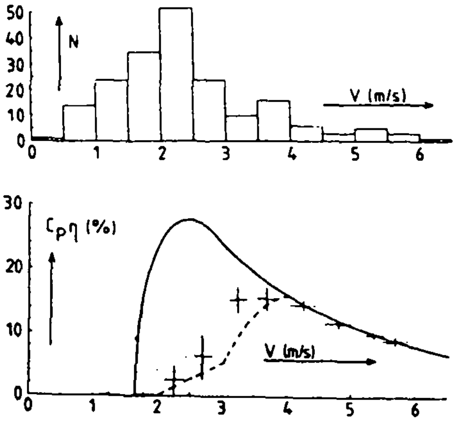

Fig. 7 Results of measurements of FIASA windmill October 17 until October 21. 1985, 194 measurements. Low wind speeds prevail, average wind speed 2.4 m/s
Drawn curve: theoretical $C_p\eta$ curve (3)
Dotted curve: correction according to (5)

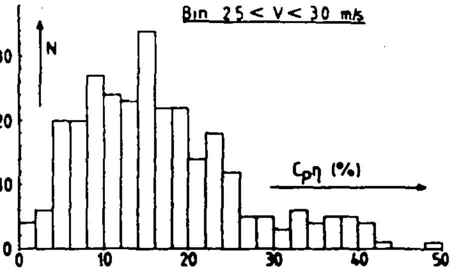

Fig. 8a Bin of 2.5 to 3.0 m/s

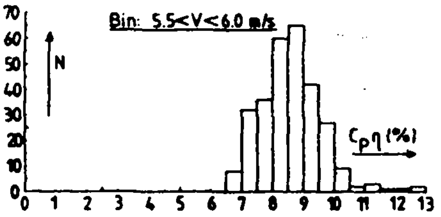

Fig. 8b Bin of 5.5 to 6.0 m/s

Fig. 8 Distribution of measured $C_p\eta$ values within one bin Measurements of FIASA windmill October-November 1985

Indeed, the two curves of figure 6 and 7 are quite different. For the first series, having mostly high wind speeds the measured values approximate closely the simple theoretical relationship (3).

It is concluded that, following the recommendations of IEA, completely different $C_p\eta$ curves can be obtained for one and the same wind machine. This procedure of measuring output curves does not yield reproducible results if the output curve has a hysteresis loop!

In order to judge how seriously this affects output predictions, yearly average outputs were calculated, both on the basis of the measurements of figure 6 and of figure 7. Especially for low average wind speeds, in which water pumping windmills are often applied, very large differences were found: 50% to 100%, see reference 3.

3.3 Distribution of observations within a bin

Because of the large standard deviations of the $C_p\eta$ measurements in the hysteresis region, it seems of interest to study in more detail which values have occurred, and with what frequency. Figure 8 shows two distributions of observations in typical bins: one within the hysteresis region (2.5 to 3 m/s), and one outside the hysteresis region (5.5 to 6 m/s). The figure was derived from the same series of measurements as figure 5. The difference between the two bins is quite clear. Inside the hysteresis region one finds a wide variety of values, ranging from 0 to 40%. Outside the hysteresis region one finds a distribution, which is nicely centered around one well defined value.

Figure 9 shows the influence of the wind regime on the distribution of $C_p\eta$ values inside the hysteresis region (again for the 2.5 to 3 m/s bin). Figure 9a refers to a period of high wind speeds (same period as figure 6), figure 9b to a period of low winds (same as figure 7).

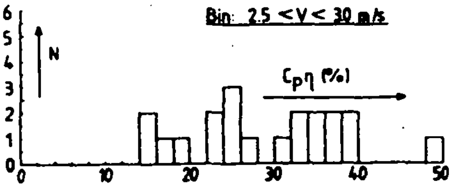

Fig. 9a High wind speeds, same period as fig. 6

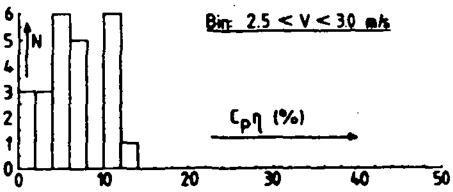

Fig. 9b Low wind speeds, same period as fig. 7

Fig. 9 Distribution of measured $C_p\eta$ values within a bin in the hysteresis region (2.5 to 3.0 m/s)

Basically, the two figures show again the same range of values, but the frequencies have shifted. In the period of low wind speeds (figure 9a) one finds only $C_p\eta$ values close to zero. For high wind speeds, one finds higher values.

These results again confirm to the remarks made earlier concerning the probability of pumping in the hysteresis region. It is to be noted that one does not only find $C_p\eta$ values corresponding to the upper and lower branch of the hysteresis loop (see figure 4). but one finds instead a whole range of intermediate values. This is due to variations of the wind within the 10 minutes averaging period used for the measurements: The windmill may run for a few minutes (upper branch) and stand still during the remainder of the 10 minutes period, resulting in some intermediate 10 minutes average.

From figures 8 and 9 it may be concluded that it does not make much sense to take a simple arithmatic mean of all observations in a bin within the hysteresis region. Doing this, would not result in a unique $C_p\eta$-V relationship. If high wind speeds prevail, the frequency distribution of observations is distorted in favour of high $C_p\eta$ values, and a high average value would be found. If low wind speeds prevail one would find a low average value.

4. CONSEQUENCES FOR OUTPUT PREDICTION

The total energy output of a wind machine over a longer period of time depends both on characteristics of the wind machine, and the site where it is installed. It is usual to separate the wind machine's characteristics and the site characteristics in the following way:

- Output curve of the wind machine, the relationship between power output of the machine and wind speed. This is assumed to be a unique characteristic of a given wind machine (with load), independent of site characteristics, universally applicable.
- Wind speed frequency distribution, summarizing information on the wind regime of a certain site.

The IEA recommendations for output performance testing (reference 2) are based on this concept. They describe how to measure an output curve during a relatively short period of time. Total output at a certain site is to be calculated by "multiplying" the output curve, and the frequency distribution, i.e. multiplying corresponding points and integrating the result.

For long it has been attempted to conceive of output prediction models for water pumping windmills along the same lines. However, problems occurred with respect to the calculation of an unambiguous probability of pumping in the hysteresis region, which was needed to determine a unique output curve in this region.

On the basis of the experience with output measurements presented above, the solution to the problem has become quite obvious: one must leave the concept of a unique output curve, which would be generally applicable for any site.

Instead, a three step procedure will be required for the calculation of total output of a water pumping windmill:

- An output curve is determined including the two branches of the hysteresis loop. A theoretical model to do this can be rather simple (see section 1 of this paper). A measuring procedure will be more complicated and is being developed.
- Using the actual wind speed frequency distribution of a certain site one calculates the probability of pumping in the hysteresis region and corrects the output to find a curve which is valid for this particular site only.

The first task is to establish the probability of pumping in the hysteresis region. Once in the hysteresis region one must go back in time until finding a wind speed outside the hysteresis region. If this wind speed happens to be higher than V_{start}, the windmill is running all the time; if it happens to be less than V_{stop}, the windmill is standing still. Writing the probability of a wind speed greater than V_{start} as $P(V>V_{start})$, and writing the probability of a wind speed outside of the hysteresis region as $P(V>V_{start}) + P(V<V_{stop})$, one may express the probability of the windmill running as follows:

$$p = \frac{P(V>V_{start})}{P(V>V_{start}) + P(V<V_{stop})} \qquad (4)$$

The probabilities P can be simply calculated from measured wind speed frequency distributions or estimated from assumed Weibull distributions.

The probability expressed by (4) is constant throughout the hysteresis region. Applying this factor as a correction, would result in a rather strange output curve, with a steep step at V_{start}. Also, a constant probability is not very realistic.

The probabilities defined above refer to 10 minutes average wind speeds, whereas a windmill will react on a much shorter time scale: it may start or stop due to a gust or a lull of a few seconds only. For a 10 minutes average wind speed just below V_{start} the probability of running must be practically unity; within the 10 minutes one will soon observe a gust above V_{start}: the windmill starts and keeps on running. For a wind speed just above V_{stop} the probability of running will be practically zero for a similar reason.

Analyzing this process would be very complicated. For the time being, as a first guess, simple linear relationships are assumed. At V_{stop} a probability of zero is assumed, in the middle between V_{stop} and V_{start} a probability equal to p (see above), at V_{start} a probability of 1. In between the probability is assumed to vary linearly with wind speed, summarizing:

$$\begin{array}{lll} v<0 & p'=0 & \text{with } v = \dfrac{V-V_{stop}}{V_{start}-V_{stop}} \\[2ex] 0<v<\frac{1}{2} & p'=2vp & \\[2ex] v=\frac{1}{2} & p'=p & \qquad\qquad (5) \\[2ex] \frac{1}{2}<v<1 & p'=2(1-v)p + 2(v-{}^{1}/_{2}) & \\[2ex] v>1 & p'=1 & \end{array}$$

This correction has been indicated with dotted lines in figures 5, 6, and 7. The probabilities were derived from the measured distribution. It corresponds reasonably well to the measurements.

Now, it is also possible to

calculate the total output rather [illegible] the $C_p\eta$ curves (3) with the corrections according to (5) must be integrated after multiplication with a Weibull distribution. The results can be presented in a general format by defining an energy production coefficient, which is the ratio of energy produced and a reference energy:

$$C_E = \frac{E}{\frac{1}{2} \rho A \bar{V}^3 C_p\eta_{max} T} \qquad (6)$$

This coefficient will be a function of the ratio of the design wind speed of the windmill and the average wind speed at the site of installation: V_d/V.
Figure 10 shows some results.

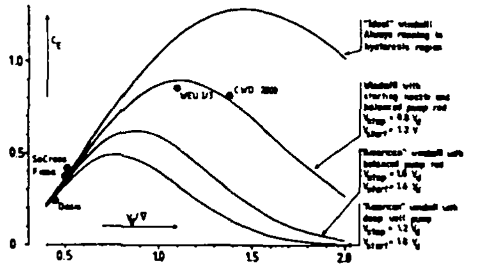

Fig. 10 Energy production coefficient as a function of design wind speed average wind speed

Drawn curves: theoretical model *presented here*
Dots: results of measurements, see table below

Of course, important parameters are start and stop wind speeds. Figure 10 shows as an upper limit the integration of the complete $C_p\eta$ curve, i.e. assuming that the windmill is always running in the hysteresis region. Three more curves are indicated which are believed to be typical for three classes of windmills: classical "American" windmills with and without balancing of the pump rod weight, and windmills having a starting nozzle in the pump and a balanced pump rod (like the CWD designs). For the start and stop wind speeds, values were assumed as indicated in figure 10. These values were derived from earlier work, see reference 3.

Some more assumptions, of minor importance were necessary for calculating the graphs. The shape factor of the Weibull distribution was taken to be 2, a usual value. The parameter λ_{max}/λ_d, see expression (3) was taken to be 1.8, a usual value (except for $V<V_d$, where a value of 2 was taken, since otherwise the maximum of $C_p\eta$ would not occur at V_d). It was assumed that the windmill's safety system limits the output to a constant value for wind speeds above three times the design wind speed (i.e. $V_{rated} = 3\ V_d$), and that it shuts down the windmill completely above six times the design wind speed ($V_{out} = 6\ V_d$), yielding a correction of not more than 10% of C_E.
For the windmill with starting nozzle the $C_p\eta$ relationship was corrected for losses through the nozzle, according to reference 1. At V_d this loss is [illegible].

As dots figure 10 indicates the results of measurements. Table 1 summarizes these measurements and indicates the references.
The dots represent the average values during the whole measuring period. The tests of Southern Cross, Fiasa, and Oasis were performed at the Almere test site, with very high average wind speeds. *Therefore* the corresponding points are found in the left part of the graph. The tests of the WEU I/3 and the CWD 2000 *(both windmills with a starting nozzle* and a relatively high V_d) were performed at the test site in Eindhoven with rather low average wind speeds, yielding points more to the right in the graph.
The table below summarizes some information of the measurements, and the assumptions made.

Table 1. Measurements indicated as dots in figure 10.

	$C_{p_{max}}$	η*	V_d	V	C_E	ref
	(-)	(-)	(m/s)	(m/s)	(-)	
Fiasa	0.35	0.80	2.5	5.0	0.37	4
So Cross	0.35	0.80	2.8	5.5	0.42	5
Oasis	0.35	0.60	1.9	4.1	0.24	6
WEU I/3	0.35	0.60	4.1	3.7	0.86	7
CWD 2000	0.35	0.35	4.6	3.3	0.82	7

* For the mechanical efficiency a value of 0.80 was taken for high head pumps, and 0.60 for low head pumps.
For the CWD 2000 a value of 0.35 was taken because of friction in this first prototype, to which the measurements refer. Later it was improved considerably.

5. CONCLUSIONS

In a general manner it may be concluded that systematic field measurements contribute significantly to the understanding of the performance of wind machines.

More especifically field measurements of output performance have produced a much better understanding of the importance of the hysteresis behaviour in the start/stop region on the total output of water pumping windmills.
It was found that field measurements performed according to the IEA recommendations do not result in reproducible output curves for water pumping windmills having a pronounced hysteresis behaviour. The differences in measured output curves may lead to differences in calculated total output as large as a factor two, especially for low average wind speeds, in which water pumping windmills are often applied.
On the basis of the experience with field measurements, a new procedure for output predictions is proposed, involving three steps:

- Determination of the output curve including hysteresis loop, depending only upon characteristics of the wind machine.
- Conversion of this hysteresis output curve into a simple (site specific) output curve by means of probabilities

derived from the wind speed frequency distribution at the site of installation.
- Multiplication and integration of the site specific output curve and the site's wind speed frequency distribution.

A simple theoretical model was developed including these three steps. It seems to be in reasonable agreement with the measurements available so far. However, it will need further validation and refinement.
Procedures for field measurements based on this "three step" approach still need to be developed. This may eventually lead to an extension of the IEA recommendations.

REFERENCES

[1] E.Lysen "Introduction to Wind Energy" - CWD, P.O. Box 85, Amersfoort, Netherlands, CWD 82-1 - 2nd edition - 1983

[2] S.Frandsen, A.R.Trenka, B.Maribo Pedersen "Recommended practices for wind turbine testing. Power performance testing" - IEA, International Energy Agency, Roskilde, Denmark - 1982

[3] J.v.Meel, P.Smulders "Some results of CWD's test fields. Are the IEA recommendations sufficient for windmills driving piston pumps?" - BWEA conference on "Small Wind Energy Conversion Systems" - London - May 7 - 1986

[4] E.Lysen, M.Dielemans, P.Lely "FIASA Water Pumping Windmill. Output performance test results" - CWD test field Almere - CWD - DHV Consulting Engineers - Amersfoort - February 1986

[5] E.Lysen, M.Dieleman, P.Lely "Southern Cross Water Pumping Windmill. Output performance test results" - CWD testfield Almere. CWD - DHV - Consulting Engineers - Amersfoort - February 1986

[6] E.Lysen, M. Dieleman, P. Lely "Oasis Water Pumping Windmill. Output performance test results" - CWD test field Almere - CWD - DHV Consulting Engineers - Amersfoort - February 1986

[7] H. Oldenkamp "Field measurements on the CWD 2000 and the WEU I/3 performed in the period 84.11.27 until 85.01.14" - CWD - Wind Energy Group - Laboratory of Fluid Dynamics and Heat Transfer - Department of Physics - Eindhoven University of Technology - R 709 D - February 1985