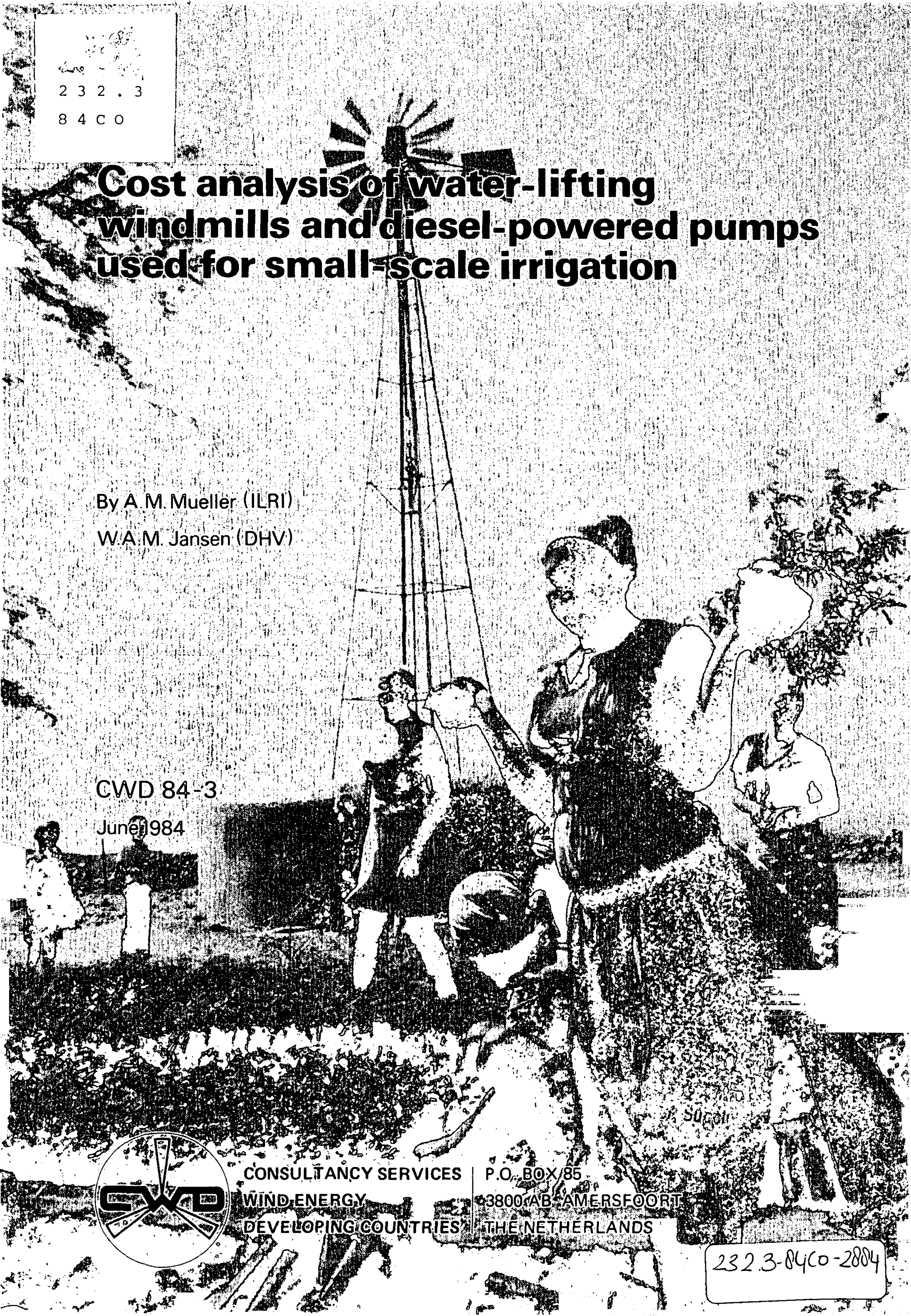

Cost analysis of water-lifting windmills and diesel-powered pumps used for small-scale irrigation

By A.M. Mueller (ILRI)
W.A.M. Jansen (DHV)

CWD 84-3
June 1984

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CWD promotes the interest for wind energy in developing countries and provides professional advice and assistance to governments, institutes and private parties.

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LIST OF SYMBOLS AND CONVERSION FACTORS

Symbol	Description	Units
A	Rotor swept area of wind pumps	m^2
AAC	Average annual cost	\$/year
AAC_{ds}	Average annual cost of diesel suction pumps	\$/year
AAC_{dd}	Average annual cost of diesel deep-well pumps	\$/year
AAC_f	Average annual cost of diesel fuel	\$/year
AAC_{wp}	Average annual cost of wind pump	\$/year
AAC_{ps}	Average annual cost of pump shed	\$/year
AAC_{st}	Average annual cost of storage	\$/year
C	Water costs	\$ct/m^3
CA	Command area	ha
CIF	Cost, insurance, freight (price)	\$
CWD	Consultancy Services Wind Energy Developing Countries	
D	Rotor diameter of wind pumps	(m)
FOB	Free on board (price)	\$
$\bar{E}$	Average hydraulic energy output of wind pumps	kWh
$\bar{E}d$	Average daily energy output of wind-pumps	kWh/day
H	Static lift	m
H_d	Total lift of diesel pump system	m
H_{wp}	Total lift of wind pump system	m
MC	Maintenance costs	% of investment
$\bar{P}$	Average hydraulic power output of wind pumps	W
P	Hydraulic power output of wind pumps	W
P_d	Design hydraulic power output of wind pumps	W
P_r	Rated hydraulic power output of wind pumps	W

Q	Daily irrigation requirement	m^3
$	US dollar	
$\bar{V}$	Average wind speed	m/s
V_d	Design wind speed	m/s
V_{in}	Starting wind speed	m/s
V_{out}	Cut out wind speed	m/s
V_r	Rated wind speed	m/s
Y	Year	

foot	=	0.3048 m
acre	=	0.4 ha
US gallon	=	3.8 l
Imp. gallon	=	4.5 l
cubic foot	=	28.32 l
acre inch	=	100 m^3
acre foot	=	1200 m^3
mile per hour	=	0.444 m/s
km/hour	=	0.28 m/s
Knot	=	0.52 m/s
Horse Power	=	0.75 kW

1. SUMMARY AND MAIN CONCLUSIONS

In many developing countries the use of wind energy has become an interesting option. Whether or not to use this renewable energy source, depends amongst others upon economic aspects.

The purpose of this study was to develop a method for making a quick economic comparison between wind pumps (water-pumping windmills) and diesel pumps (diesel powered water pumps) intended for use in small-scale lift irrigation.

Specifically, this study compares the CWD wind pumps as developed by CWD Consultancy Services Wind Energy Developing Countries for local production in developing countries and the commercially available, traditional wind pumps which will henceforth be referred to as 'American' wind pumps.

As the economic comparison is determined by many parameters, the values of these parameters had to be assumed. For this study, we used average values. A sensitivity analysis was carried out for the most important parameters.

Based on average economic costs, excluding taxes and subsidies, the comparison takes the economic life of the pumping systems into account.

The data required for comparison are: static lift, daily water requirement and average wind speed, during the period of irrigation.

The main conclusion was that, for farmers engaged in small-scale lift irrigation on areas of up to 1 ha (2.5 acres), CWD wind pumps are economically more attractive than diesel pumps if the average wind speed during the irrigation season exceeds 3.5 m/s (7.8 mph).
With 'American' wind pumps the average wind speed during the irrigation season must exceed 4.5 m/s (10.1 mph).

This study cannot be but general. If the application of wind energy for water lifting is considered seriously in a particular country or area, we suggest a detailed feasibility study which takes into account all local circumstances that influence the introduction of wind energy.

2. INTRODUCTION

A sound economic comparison of water-lifting wind pumps and diesel pumps considers the specific advantages and disadvantages of both pumping systems and shows all assumptions and calculations on which the analysis is based. The method of comparison, however, should be kept as simple as possible so as to reach as wide an audience as possible.
For the sake of reaching a compromise this study has been divided into two parts. Part I, with the help of some examples, describes how wind pumps and diesel pumps can be compared economically.
It is intended for the policy maker and all those who want to know the relative economic potential of wind pumps versus diesel pumps for farmers in an area where the static lift, the daily water requirement*, and the average windspeed during the irrigation period are known.
Part II presents all the underlying assumptions and methods of calculation in detail, along with a sensitivity analysis for some key variables.
The calculations are presented in the Appendices.

* 1 ha (2.5 acres) needs about 60 m^3 a day

PART I

ECONOMIC COMPARISON

3. ECONOMIC COMPARISON OF WIND PUMPS AND DIESEL PUMPS

The economic comparison of wind pumps and diesel pumps is presented in graph form. In these graphs, the average annual costs are plotted against the average daily water requirements during the period of irrigation (including equipment, transport, installation, operation and maintenance).

The graphs contain two kinds of lines:

1. The fan of lines starting in the bottom left-hand corner represents the cost of pumping with wind pumps. There is a separate line for different wind speeds. At the end of each line, the wind speed $\bar{v}$ is indicated in m/s along with the costs of water c per m^3 in dollar cents.
2. The dotted lines represent the cost of pumping with a diesel pump. For small amounts of water, there are two diesel lines: one for a diesel pump drawing from an unlimited water supply (like a lake, river, canal, or very high yield well) and another line for a diesel pump drawing from a limited water source (like a low-yield well or tubewell).

The proper use of the graphs will be illustrated with the, two subsequent examples. The wind speed used to determine the average annual costs of the wind pump should be the average wind speed during the irrigation season. This wind speed is usually different from the average annual wind speed. To form an idea of how great a command area could be irrigated with a given daily water requirement, we can assume 60 m^3/d (0.6 acre inch/day) as the average water requirement for 1 ha (2.5 acres).

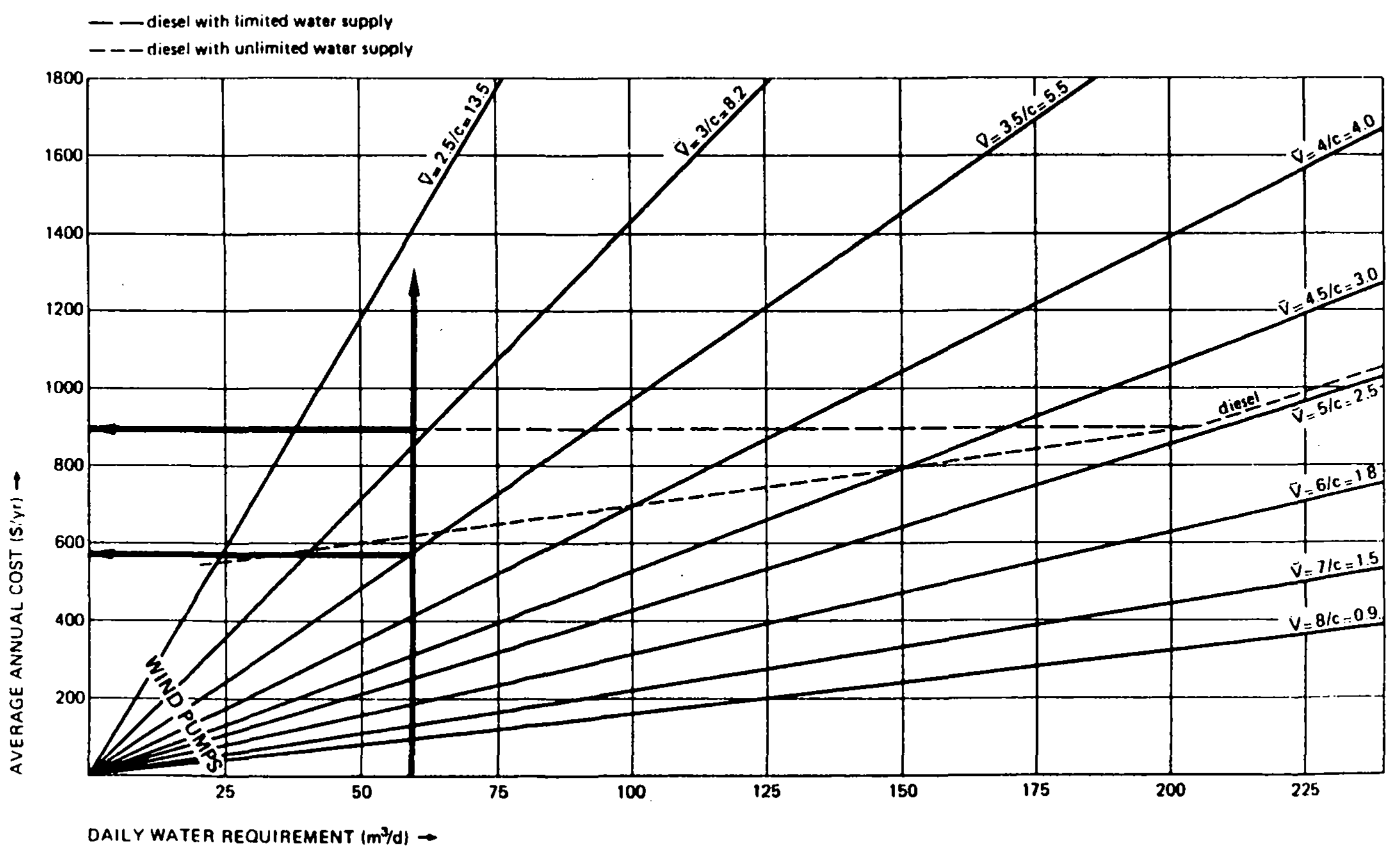
In addition, there follow two series of five graphs; one series for locally-produced CWD wind pumps and one series for imported, "American" wind pumps. Each series contains a separate graph for a static lift of 2, 7, 10, 15, and 30 m. (The static lift is the distance between the water level and the ground level).
CWD wind pumps refer to locally manufactured wind pumps and can be considered a low-cost wind option or a low-cost wind scenario.
"American" wind pumps refer to imported wind pumps and can be considered a high-cost wind option or a high cost wind scenario.
Wind pumps are compared with diesel-powered suction pumps where the static lift is either 2 or 7 m (6,6 and 23 feet). They are compared with diesel-powered deep well pumps where the static lift is 10, 15 and 30 m (33, 49, and 100 feet).

Example of CWD wind pump vs diesel-powered suction pump

In the dry zone of a given country the availability and distribution of rainwater is a serious constraint on agriculture. Farmers want to cultivate up to 1 ha of chillies and onions during the dry season, which will require about 60 m^3 of water per day. The subsoil in the dry zone consists of hard rock. Open wells are constructed in the area, but they are rather expensive and their recharge capacity is generally limited. Using a diesel-powered suction pump to draw the required quantity of water within a short time will cause these wells will to run dry.
The diesel pump must operate about six hours per day.
During the period that lift-irrigation is practiced in the area, the average wind speed is at least 3.5 m/s. The static lift is about 7 m.

Graph 2 presents the relative cost of diesel pumps and CWD wind pumps at a static lift of 7 m

$\bar{v}$ = average wind speed (m/s)
c = watercost ($ct/$m^3$)



GRAPH 2: 7m STATIC LIFT; CWD WIND PUMPS AND DIESEL-POWERED SUCTION PUMPS

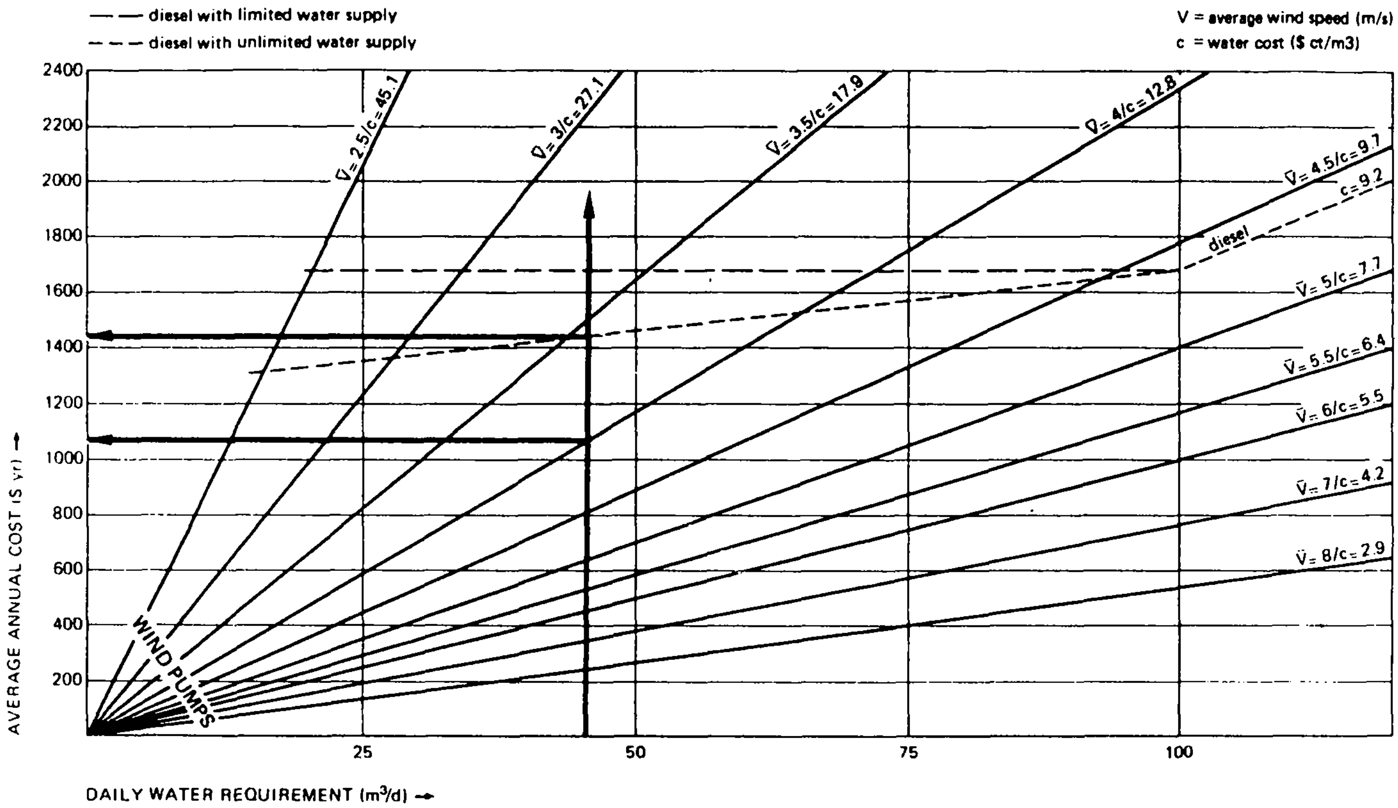
A vertical line has been drawn from the horizontal axis at the point representing 60 m^3 of water per day. At this line's intersection with the windpump line $\bar{v}$ = 3.5, a horizontal line has been drawn out to meet the left-hand, vertical axis. At the vertical line's intersection with the dotted line (diesel with limited water supply), a second horizontal line has been drawn out to meet the vertical axis. Now it can be seen straightaway that the wind pump will cost less than $ 600. per year, while the diesel pump will cost $ 900. per year. The cost of water per m^3 (5.5 dollar cents) can be found at the end of the wind pump line.
It can therefore be concluded that in this case a CWD wind pump can pump water at a lower cost than the diesel-powered suction pump. The use of wind pumps for small scale irrigation is therefore worth to be considered seriously.

Example of 'American' wind pump vs diesel-powered deep-well pump

For a given island country, the availability of water is also a serious constraint on agriculture; it lies within the Sahel Zone. One of the country's very few natural resources is wind. The wind velocity is very adequate on the tops of ridges, but diminishes considerably in the narrow valleys where the farmers have their fields.
A donor considers giving a number of 'American' windmills, but he first wants to know that they are economically a better option than diesel pumps.

Farmers want to cultivate vegetables for the nearby market. They have command areas of about 0.75 ha. The static lift is 15 m and the average wind speed is believed to be at least 4 m/s in the valleys during the irrigation season. The recharge capacity of the wells is good.

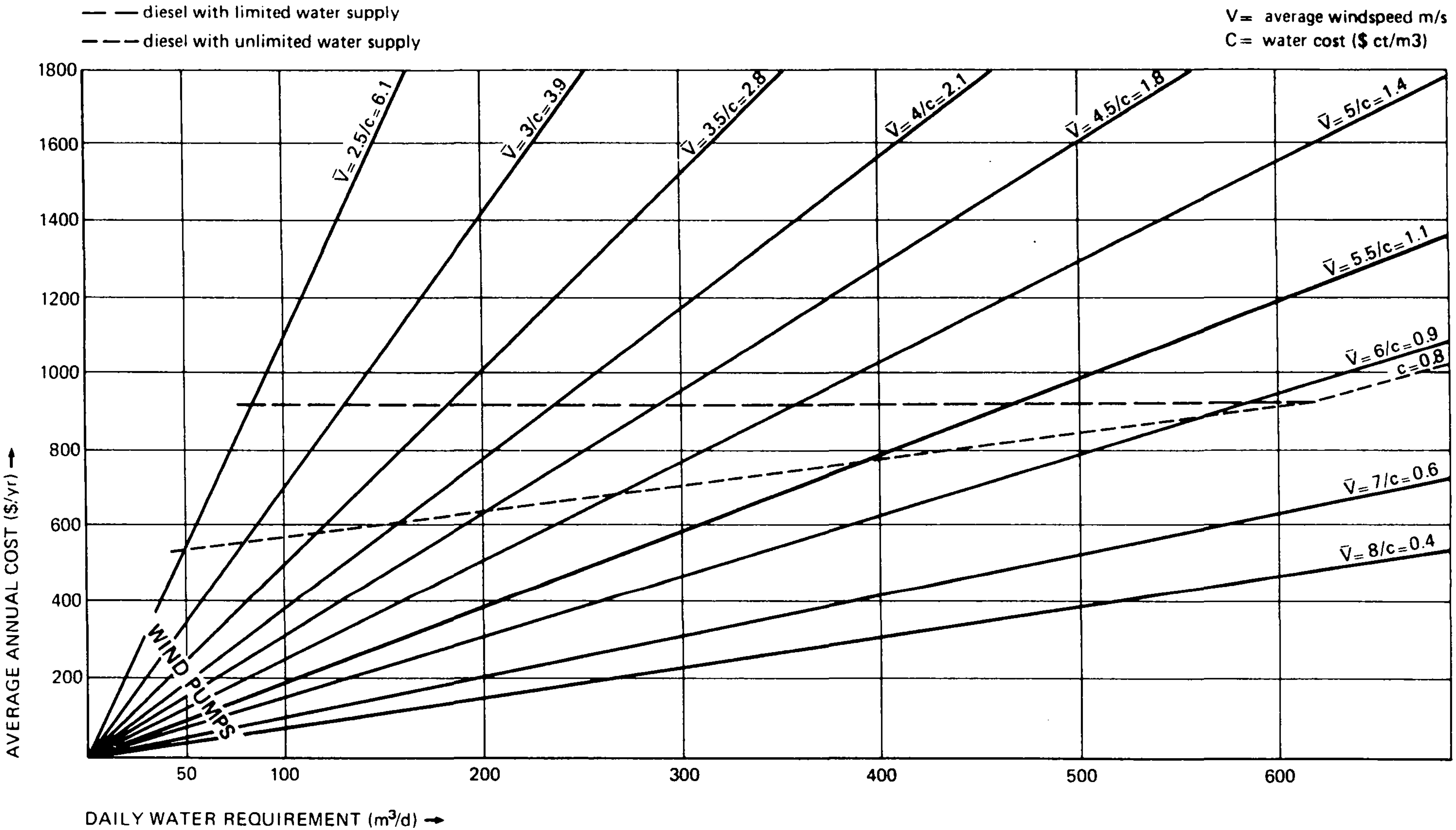
Graph 9 presents the relative cost of 'American' wind pumps and diesel pumps at a static lift of 15 m.



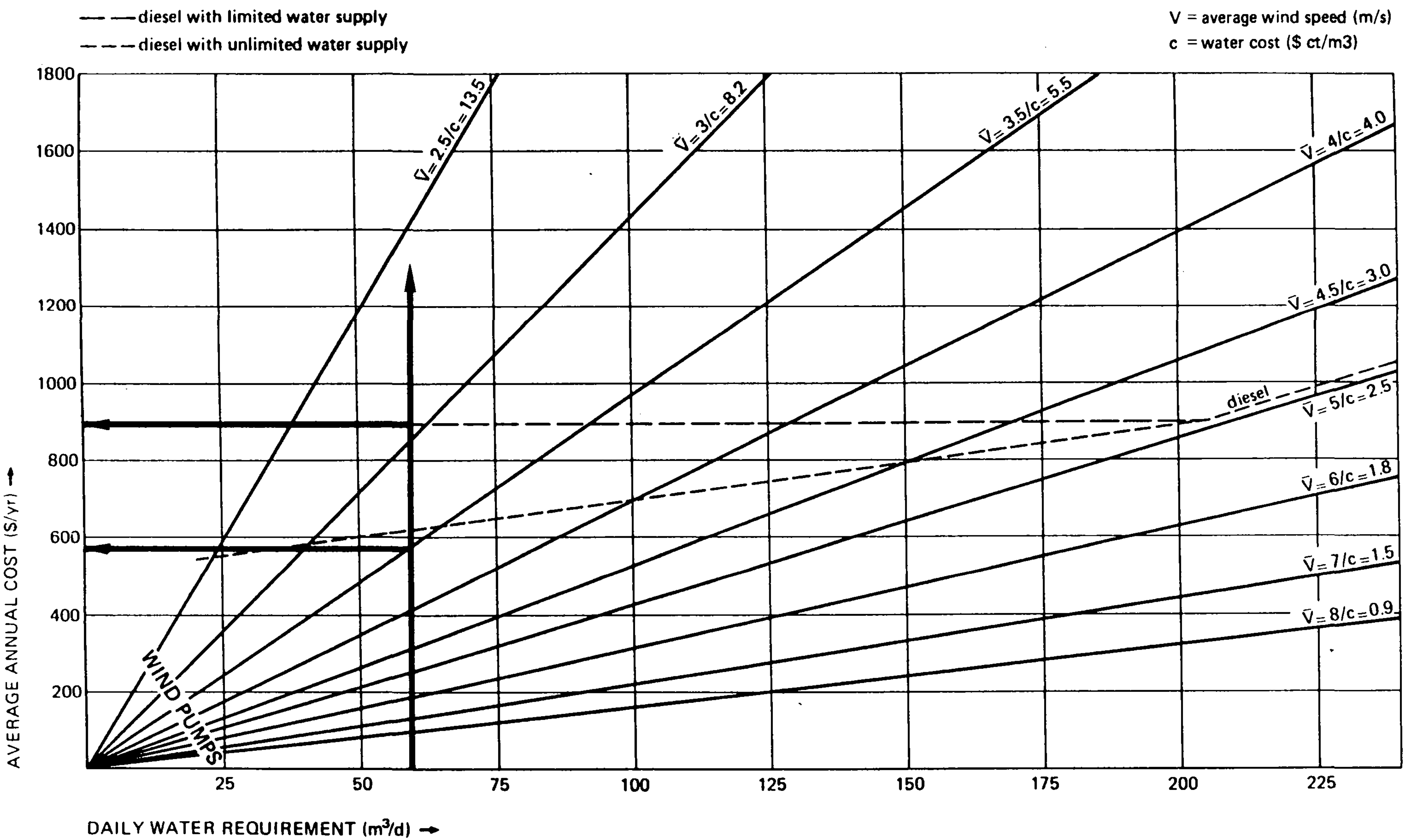
GRAPH 9: 15m STATIC LIFT; 'AMERICAN' WIND PUMPS AND DIESEL POWERED DEEP WELL PUMPS

A command area of 0.75 ha means an average daily water requirement of 0.75 x 60 = 45 m^3/d. Starting at the point representing 45 m^3 of water per day, a vertical line had been drawn from the horizontal axis. At the line's intersection with the wind pump line $\bar{v}$ = 4 m/s, a horizontal line has been drawn out to meet the left-hand, vertical axis. At the line's intersection with the dotted line (diesel with unlimited water supply), a second horizontal line has been drawn out to meet the vertical axis. It can now be seen that the average annual costs with the 'American' wind pump are about $ 1,050.-- per year and with the diesel-powered deep well pump about $ 1,450.-- per year.

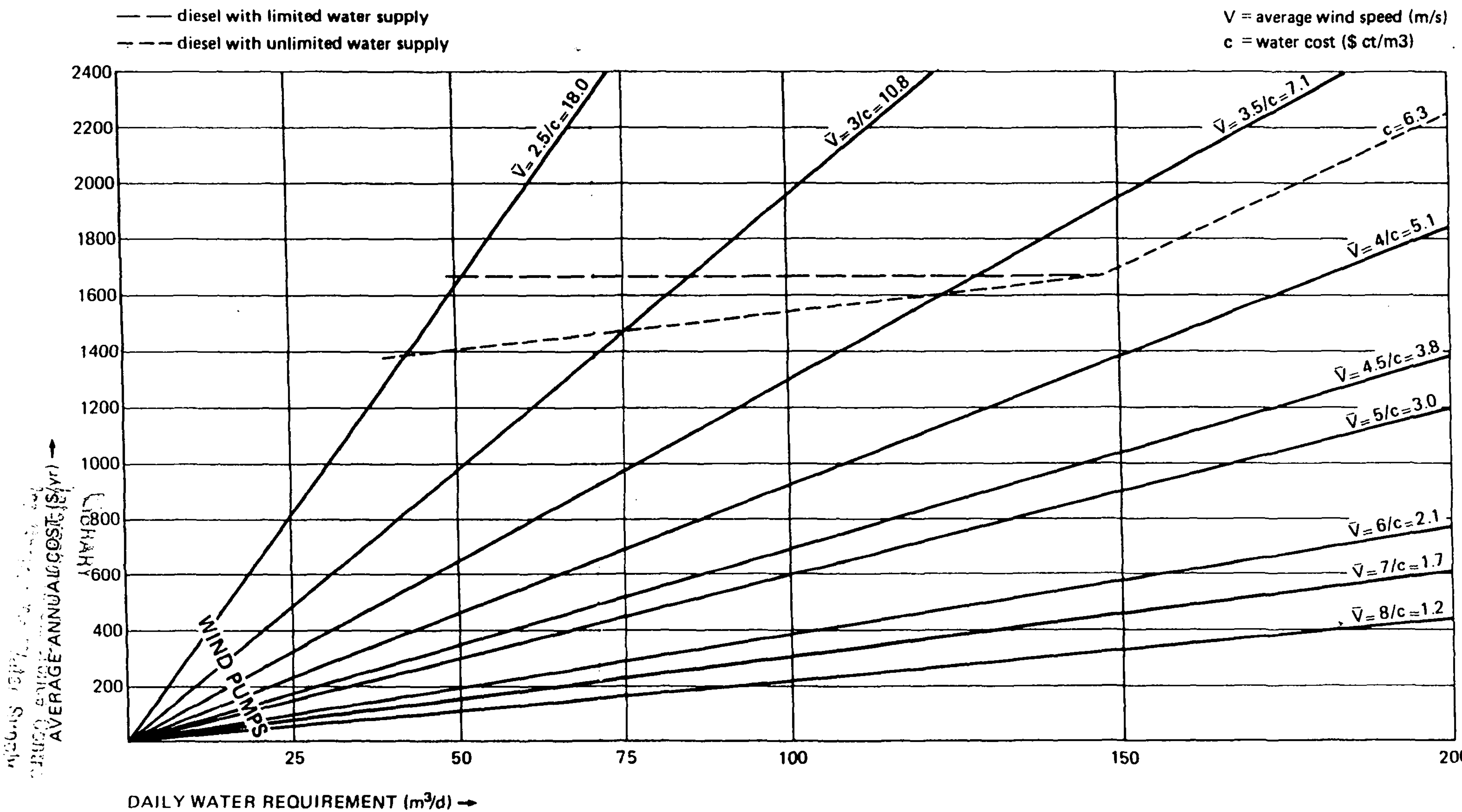
Thus the wind pump can pump water more economically than the diesel pump. The cost per m^3 of pumping water with the wind pump is 12.8 dollar cents. The cost of water, however, may be rather high for agricultural purposes. Generally, the World Bank specifies 6 dollar cents as an acceptable upper limit per m^3 [6].



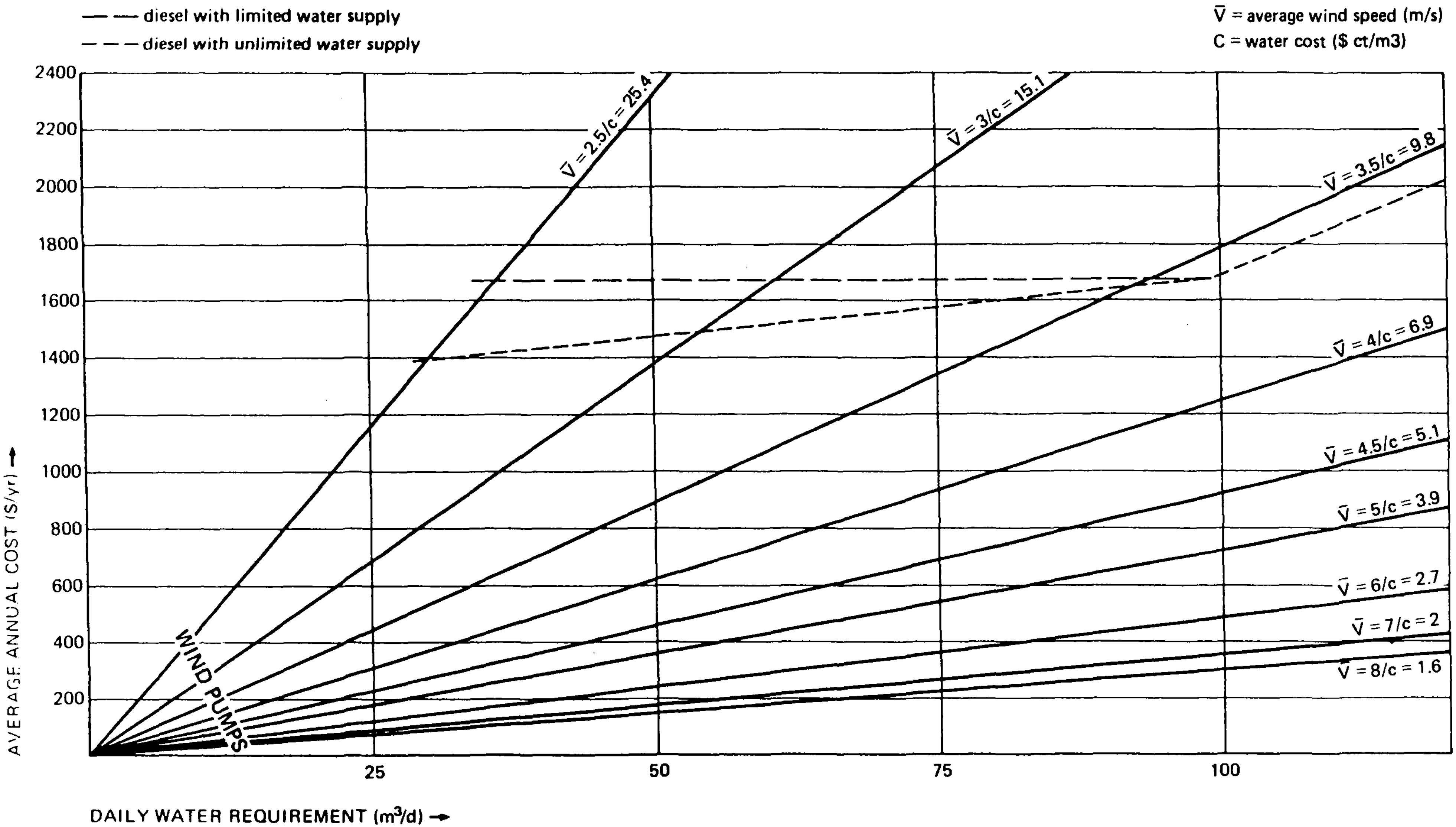
GRAPH 1: 2m STATIC LIFT; CWD WIND PUMPS AND DIESEL – POWERED SUCTION PUMPS



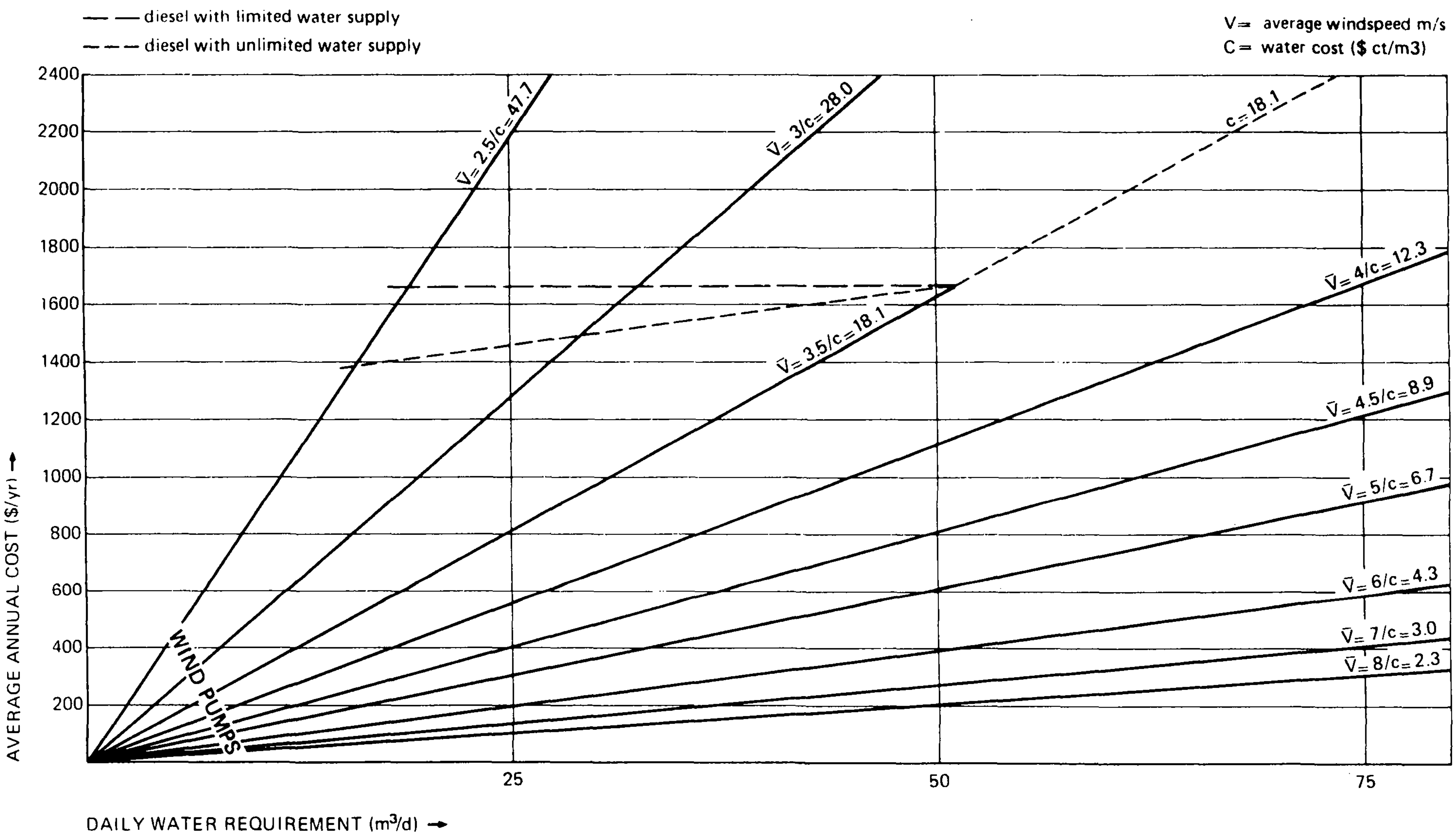
GRAPH 2: 7m STATIC LIFT; CWD WIND PUMPS AND DIESEL-POWERED SUCTION PUMPS



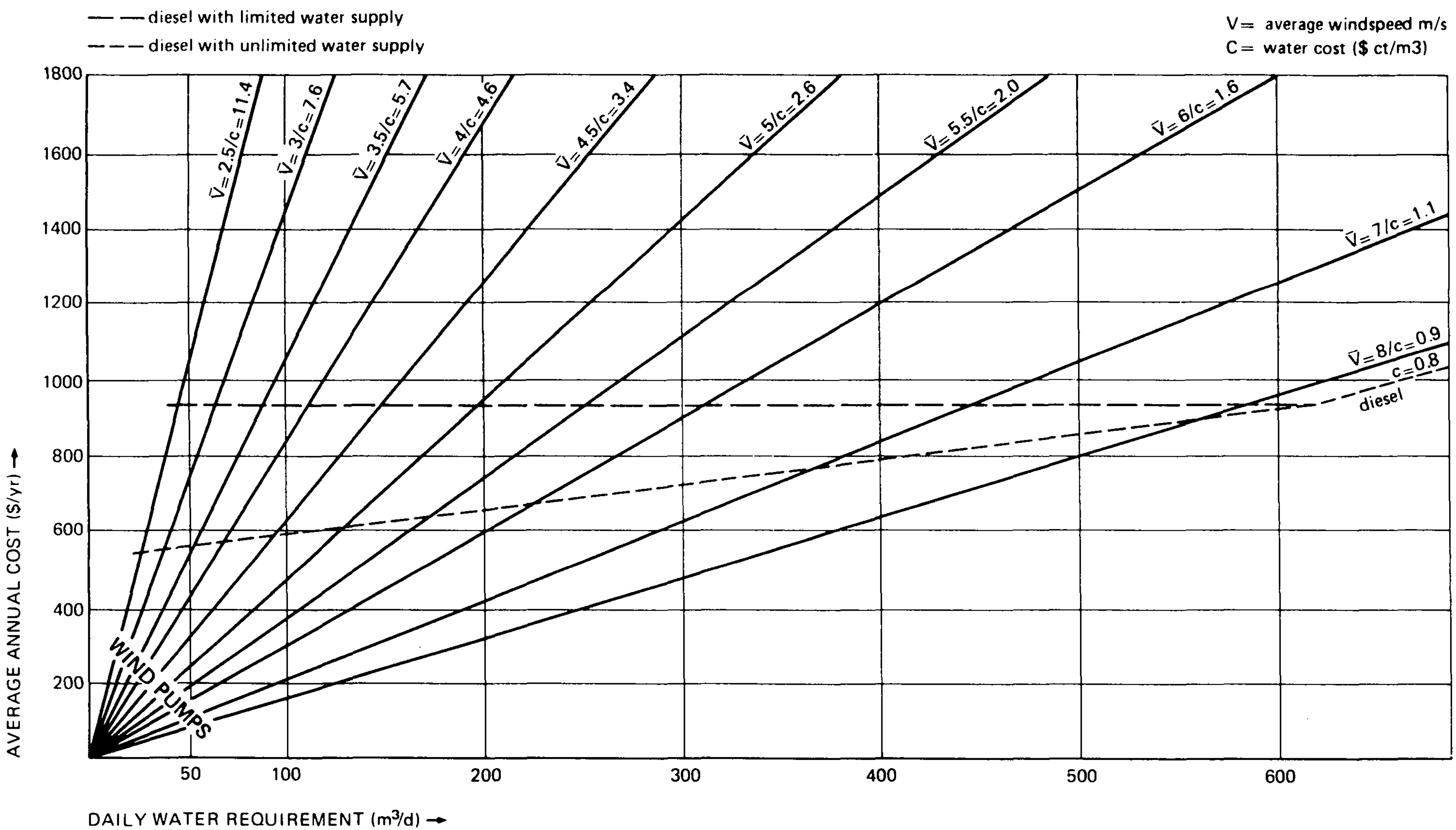
GRAPH 3: 10m STATIC LIFT; CWD WIND PUMPS AND DIESEL-POWERED DEEP WELL PUMPS



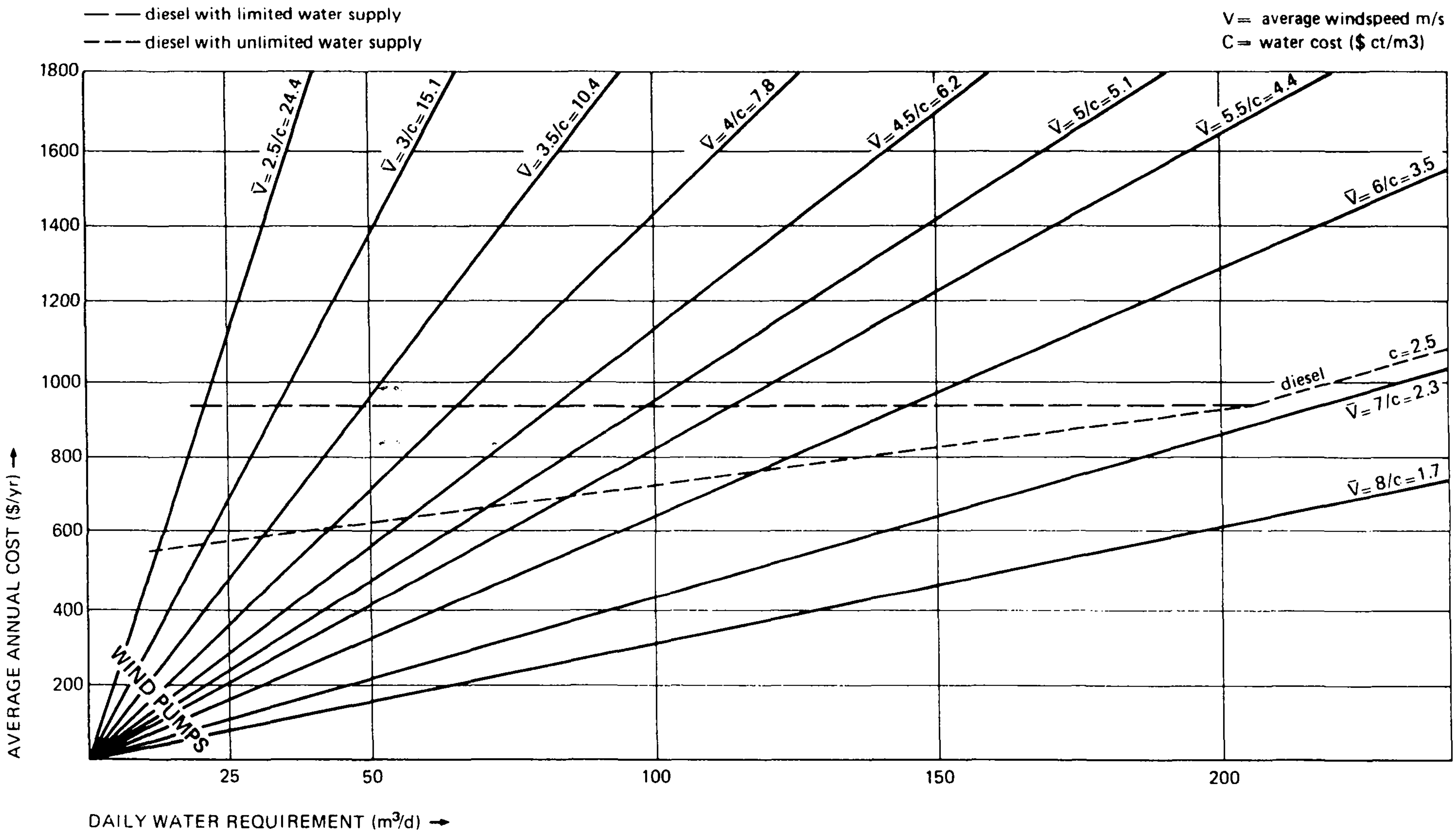
GRAPH 4: 15m STATIC LIFT; CWD WIND PUMPS AND DIESEL-POWERED DEEP WELL PUMPS



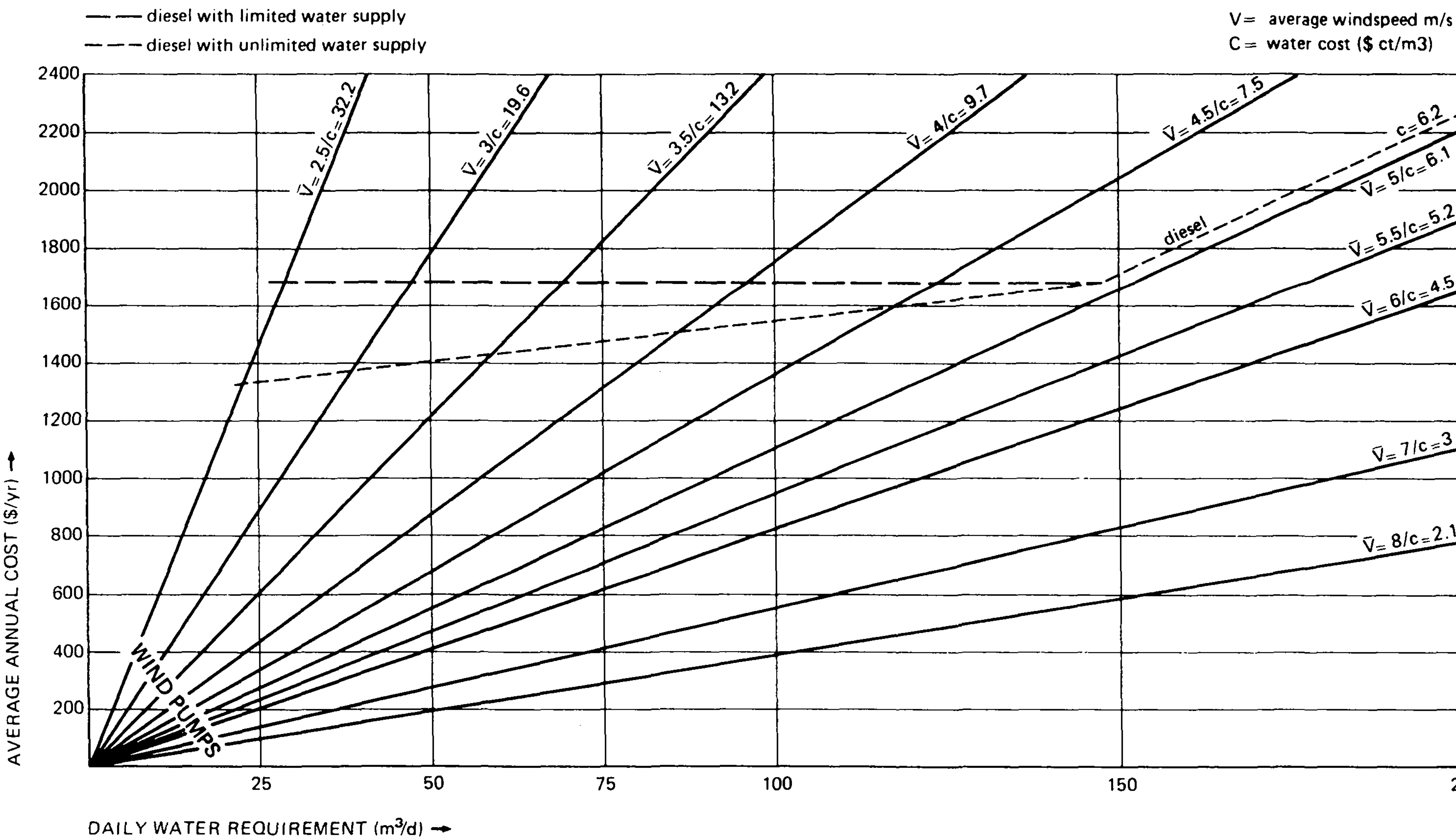
GRAPH 5: 30m STATIC LIFT; CWD WIND PUMPS AND DIESEL – POWERED DEEP WELL PUMPS



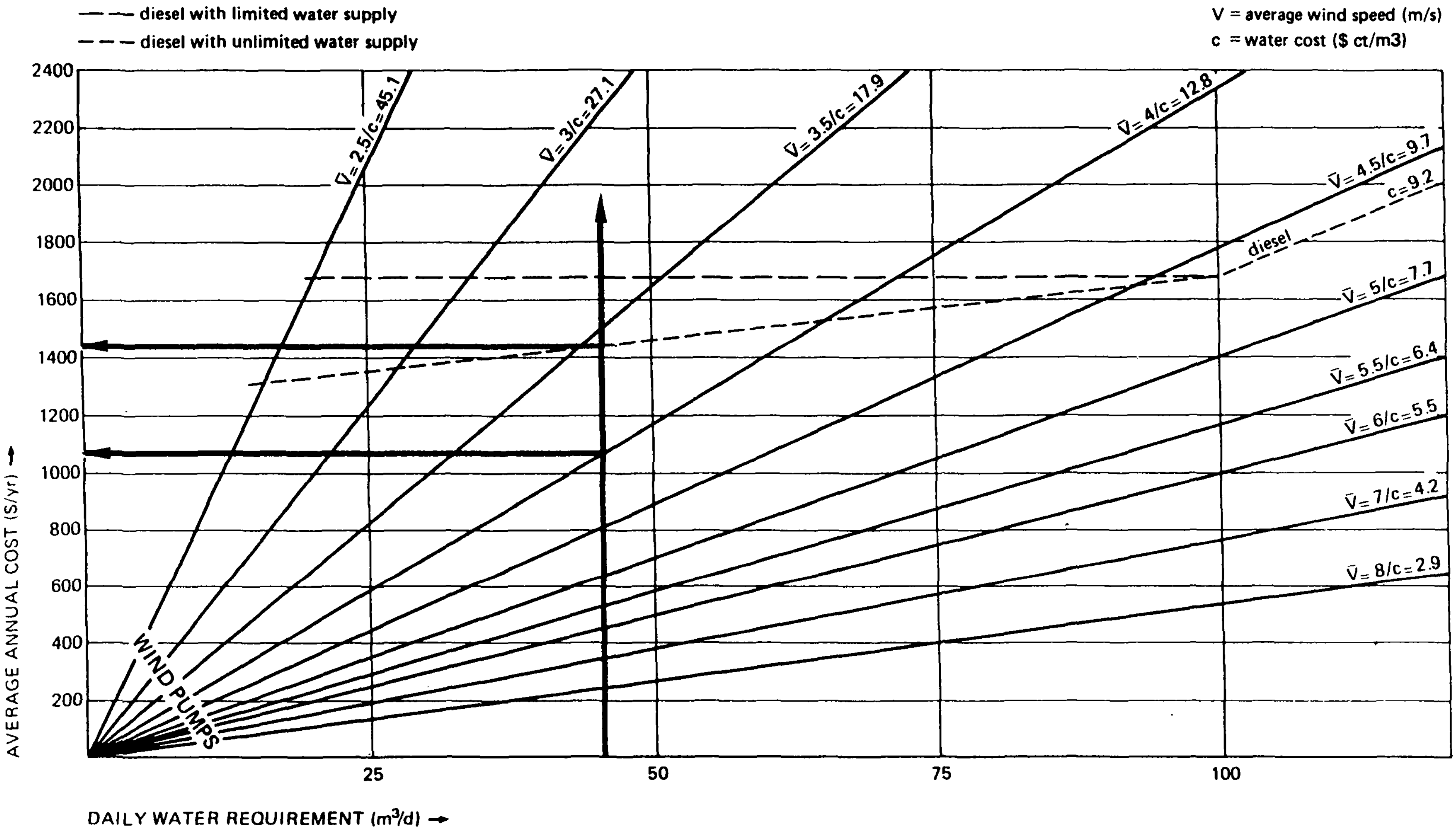
GRAPH 6: 2m STATIC LIFT; 'AMERICAN' WIND PUMPS AND DIESEL – POWERED SUCTION PUMPS



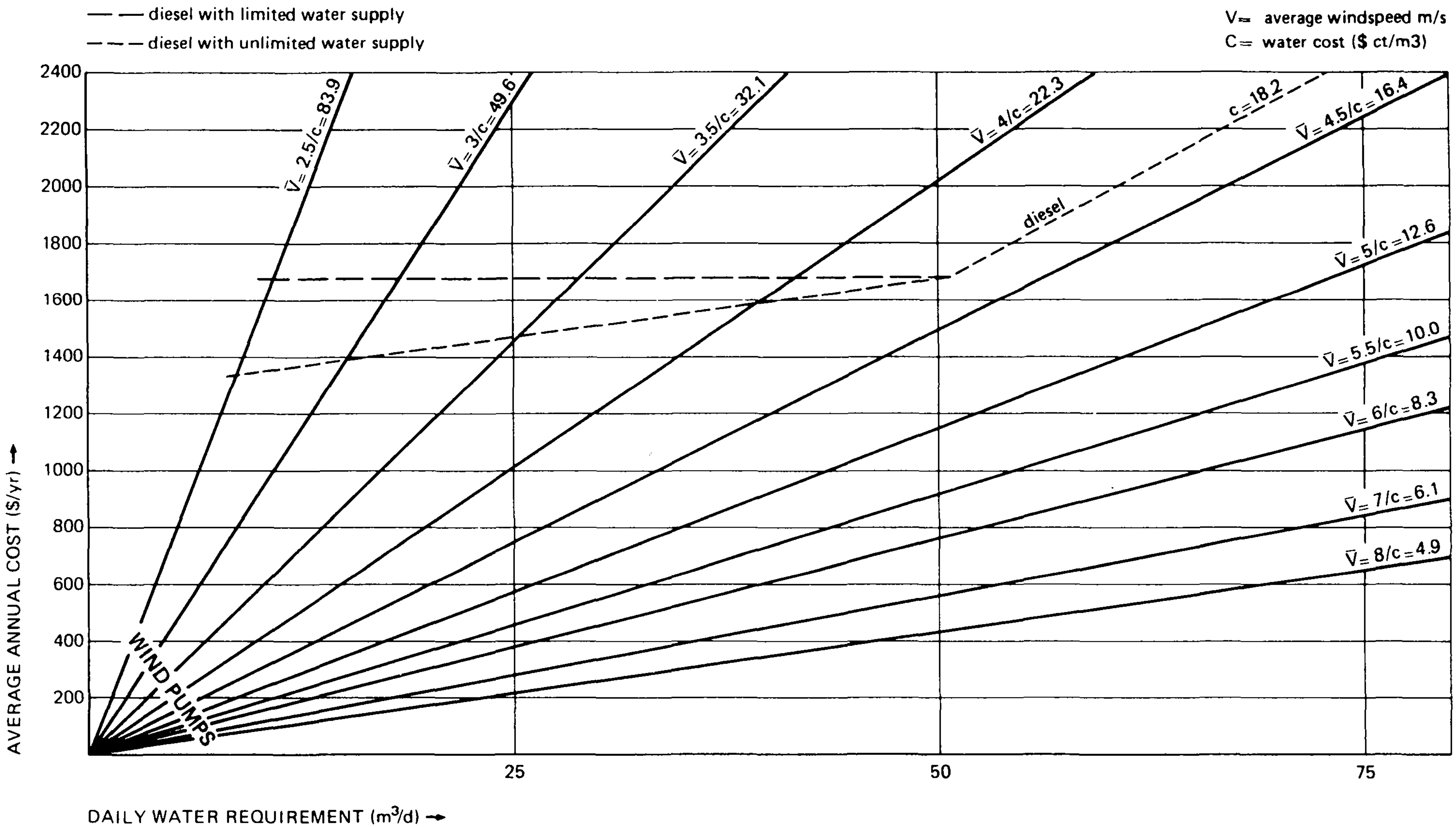
GRAPH 7: 7m STATIC LIFT; 'AMERICAN' WIND PUMPS AND DIESEL – POWERED SUCTION PUMPS



GRAPH 8: 10m STATIC LIFT; 'AMERICAN' WIND PUMPS AND DIESEL – POWERED DEEP WELL PUMPS



GRAPH 9: 15m STATIC LIFT; 'AMERICAN' WIND PUMPS AND DIESEL POWERED DEEP WELL PUMPS



GRAPH 10: 30m STATIC LIFT; 'AMERICAN' WIND PUMPS AND DIESEL – POWERED DEEP WELL PUMPS

4. GENERAL CONCLUSIONS

This study enables a quick, economic comparison of wind pumps combined with storage tanks and diesel pumps intended for use in small-scale irrigation. Some general conclusions reached during the course of the study are presented below.

- For farmers engaged in small-scale lift irrigation on areas of up to 1 ha (2.5. acres), CWD wind pumps are always economically more attractive than diesel pumps if the average wind speed during the irrigation season exceeds 3.5 m/s (7.8 mph). For 'American' wind pumps this value increases to 4.5 m/s (10.1 mph).

- For farmers cultivating several ha, CWD wind pumps are always more advantageous economically than diesel powered deep well pumps if the average wind speed during the period of irrigation exceeds 3.75 m/s (8.4 mph).

- As they can be made up in very small sizes, wind pumps have the general advantage of presenting no "small-scale diseconomics". The smallest diesel engine, on the other hand, is 2 kW (2.67 HP) rated power.. This makes wind pumps attractive, even at low average wind speeds, in situations where only a small amount of water is required.

- Unlike diesel pumps, wind pumps produce no sharp difference in price between low-lift and high-lift pumping.

- Wind pumps require using a storage tank, which is a rather expensive item. The tank, however, increases the pumping head by 1 m, which means a rather substantial relative increase at low static lift.

- CWD wind pumps combined with intermediate technology storage tanks compare very favourably with diesel-powered deep well pumps. When pumping from wells with a limited recharge, wind pumps also compare favourably with diesel-powered suction pumps. It is more difficult for wind pumps to compete successfully with diesel-powered suction pumps when they are pumping from open water or from wells with a very good recharge capacity.
  For pumping small quantities of water where there are reasonably good winds, CWD wind pumps are still an attractive alternative.

- 'American' wind pumps combined with high technology storage tanks are rather expensive. They can compete successfully with diesel-powered deep well pumps operating at high static lifts with reasonably good winds, especially in cases where only small quantities of water are required. However, water pumped in this way is far too expensive for irrigation. 'American' wind pumps can only be used economically for irrigation when pumping at very low lift from wells with a limited recharge capacity (tube wells) in reasonably good winds.

The above conclusions are valid under the assumptions made for this study. If the application of wind energy for water-lifting is considered seriously in a particular country or area, we suggest a detailed feasibility study which will take all local circumstances into account.

PART II

ASSUMPTIONS AND METHODOLOGY

5. BASIC ASSUMPTIONS

The ten graphs for economic comparison of wind pumps and diesel pumps as presented in Part I are based on the following assumptions:

5.1. Wind pumps

In this study two types of wind pumps are considered: imported commercial 'American' wind pumps and locally produced CWD wind pumps as designed by CWD Consultancy Services Wind Energy Developing countries.

Presently, the 'American' wind pumps are commercially produced in industrialized countries (such as the USA, Australia, and South Africa), in large foundries, using heavy machinery. Generally, gearboxes are included in the design to reduce the number of strokes per minute of the piston pumps. These windmills are multi-bladed, with high starting torques at relatively low wind speeds, but with low efficiences at medium and high wind speeds.
These wind pumps have been, and still are mainly used for pumping drinking water for humans and cattle from depths of more than 15 m. They are rarely used for irrigation.
The investmest costs for the American wind pumps are rather high and can increase considerably when used in developing countries because of the international transport costs required. The maintenance costs of these wind pumps are rather low, but spare parts have to be imported. In developing countries, this often poses problems. 'American' wind pumps are available in a rotor of 1.8 to 9.1 m. 'American' wind pumps need no operator and have an automatic safety device to prevent damage from storms. This type of wind pump is assumed to have an economic life of 20 years and to require an annual maintenance budget of 1% of the investment costs.

To enable the construction of graphs as intended in this study continuous cost functions for all items are required.

The FOB price of 'American' wind pumps (rotor, tower, and pump) is taken as \$ 350. per m^2 of rotor area. The CIF price in developing countries is taken as \$ 438 per m^2 of rotor area, which is the FOB price plus 25%. The costs of local transport, laying the foundation and installation are estimated at \$ 70 per m^2 of rotor area, which is 20% of the FOB price. The total costs of 'American' wind pumps therefore amount to \$ 508 per m^2 of rotor area.

CWD wind pumps are designed for local production in small and medium size workshops in developing countries. These wind pumps combine well engineered technology with materials and techniques available in those countries. They require no operator, and they have an automatic safety device to prevent damage from storms.

The CWD wind pumps are made of angle iron, galvanised sheet, steel and PVC piping. An expensive gearbox is eliminated by using direct-drive piston pumps designed for a relatively high number of strokes per minute. The result is a much lighter and cheaper construction. The CWD wind pumps are designed to pump large amounts of water for irrigation or smaller amounts for drinking water.

The CWD wind pumps require more maintenance than the 'American' wind pumps, but spare parts are manufactured locally. The investment costs of the CWD wind pumps are kept as low as possible. No international transport is required. Presently, CWD wind pump designs are available with rotor diameters of 2, 3, and 5 m. An 8 m diameter wind pump is in the design stage.

CWD wind pumps are assumed to have an economic life of 10 years and to require an annual maintenance budget of 5% of the investment costs. The total price of the locally produced CWD wind pumps (rotor, tower and pump), local transport, foundation-laying and installation is taken as $ 175 per m^2 of rotor area.

In this study, it is assumed that the 'American' and the CWD" wind pumps are matched to their piston pumps in such a way that they run at their maximum efficiency at the average wind speed of the period for which irrigation is considered*. Furthermore, it is assumed that the American and CWD wind pumps are designed approximately according to the following specifications:

$V_{in} = 2/3\ V_d$

$V_r = 2\ V_d$

$V_{out} = 3\ V_d$

Where

V_d = design wind speed; wind speed at which the wind pump runs at its highest efficiency; V_d should be approximately equal to the average wind speed of the period under consideration

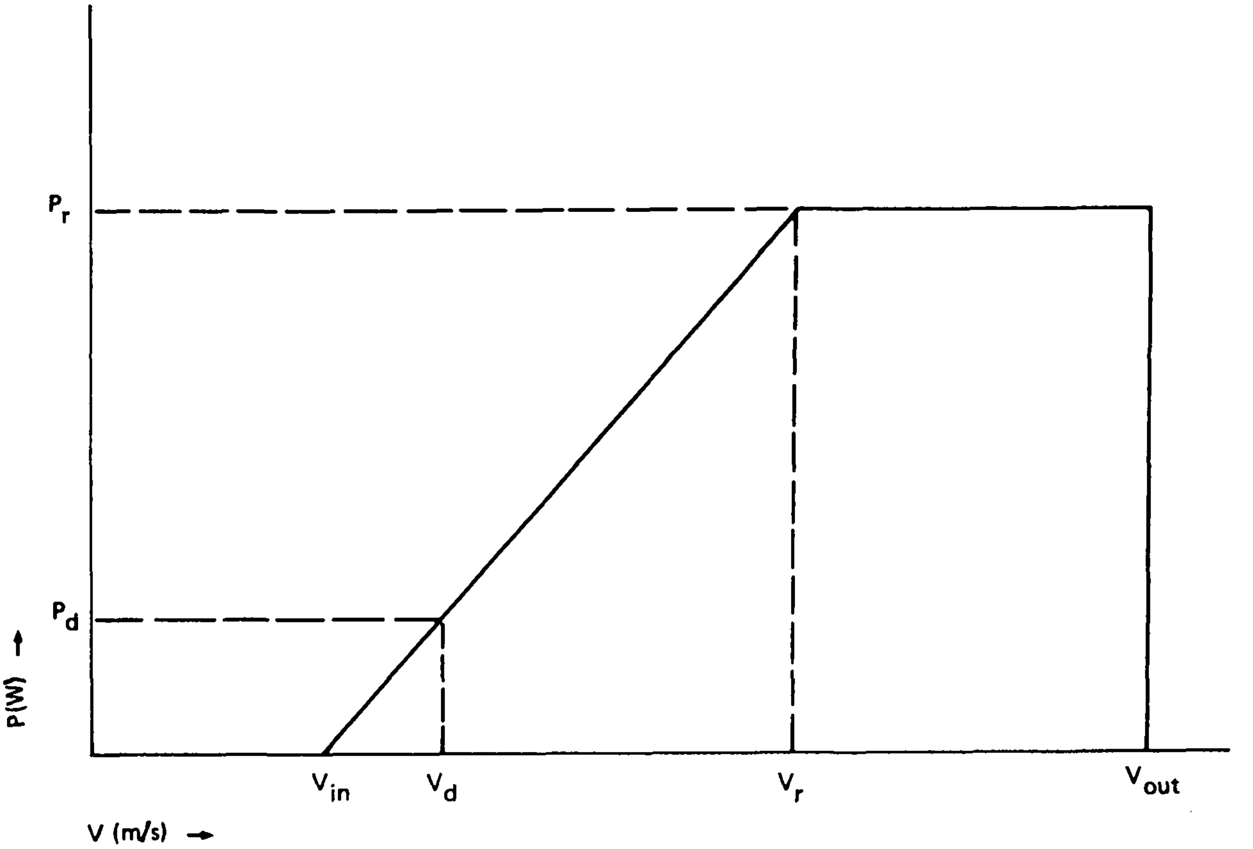
V_{in} = wind speed at which the wind pump starts pumping

V_r = rated wind speed, at which the wind pump reaches its highest output

V_{out} = wind speed at which the wind pump is stopped by its automatic safety device

Note: the wind speeds meant here are not instantaneous values but 10-minute averages or hourly averages.

* In practice, 'American' windpumps are often installed with an under-sized pump.



The average seasonal or yearly power output over a season of a wind pump that operates according to the above mentioned specifications is fairly well approximated by the relation

$$\bar{P} = 0.1\ \bar{V}^3\ A \qquad (W) \quad [3]$$

where

$\bar{P}$	=	average seasonal or yearly power output	(W)
$\bar{V}$	=	average seasonal or yearly wind speed	(m/s)
A	=	rotor swept area	(m^2)

It is supposed that for wind pumps the water supply poses no constraint to the pumping rate since these pumping rates are low, but more or less continuous over a 24 hour period.

5.2. Storage tanks

Generally, ground level storage tanks are proposed in combination with wind pumps for irrigation. These tanks have two main functions:

1. to absorb the short term fluctuations of the wind pump output and to enable irrigation with a somewhat higher, and more constant flow

2. to store the water pumped by the wind pump during the night and during other hours when water cannot be used directly

The first reason is a rather technical, but still practical, one. A small tank of about 10% of the average daily water output would probably be enough. The second reason is, in fact an economic reason. A tank that can store the water pumped during the night (in cases where this water would be lost otherwise) helps to increase the useful output of the wind pump and it is expected that the tank will contribute to lowering the unit cost of water. Such a tank covers automatically the minute to minute fluctuations of the wind pump output. Generally, a tank with a capacity of about 75% of the average daily output will be sufficient. This capacity corresponds to about 50% of the average daily output during the month with the highest output in the irrigation season. Although the farmer cannot be expected to spend 12 hours per day in his fields, this 50% is justified by the fact that in most cases the wind pump pumps considerably more water during the day than during the night.

In fact, there is an alternative to a wind pump having a tank with a capacity of 75% of the average output during the irrigation season. This alternative would consist of a wind pump with a rotor area twice as large as before, combined with a storage tank of only 10% of the average daily output during the irrigation season. Whether this alternative is attractive is ultimately an economic question, with the parameters of:

- the average annual cost of the wind pump per m^2 rotor area;
- the average annual cost of the tank per m^3 storage;
- the average wind speed during the irrigation season;
- the pumping head.

In this study the lowest of the two alternatives will be selected in each particular case. Break even windspeeds are calculated in Appendix E.

Generally speaking, there are two classes of storage tanks used in combination with wind pumps: the high technology tanks and the intermediate technology tanks.

The <u>high technology tanks</u> are made out of steel, concrete, or shaped rocks. Their economic life is estimated at 30 years; their required annual maintenance budget is assumed to be 1% of the investment.

The <u>intermediate technology</u> tanks are made out of ferro-cement, ferro-soil-crete or brick-lined earth bunds [2], [4], [7], [8]. These tanks are much cheaper to construct than the high technology tanks, but their designs are less proven.
Their economic life is estimated at 10 years and their required annual maintenance budget is assumed to be 5% of the investment.

In this study high technology tanks are used in combination with 'American' wind pumps, and intermediate technology tanks in combination with CWD wind pumps. Other combinations are, of course, possible, but are they not considered here.

The price of high technology storage tanks (materials, labour, transport, and supervision) is taken at $ 50 per m^3 [1].
The price of intermediate-technology tanks (materials, transport and supervision) is taken at $ 10. per m^3 [2].

5.3. Diesel pumps

Diesel pumps consist of a diesel engine coupled to a water pump. It is assumed in this study that this combination of engine and pump has an economic life of five years and requires an annual maintenance budget of 8% of the investment.

In this study two types of water pumps combined with diesel engines are considered:

1. The suction pumps , which are usually assembled with the diesel engines to pump sets. These pump sets are installed at ground level. The limitation of these pump sets is that the maximum static lift against which they can pump is 7 m. These pump sets are cheaper and easier to install and to maintain than the deep-well pumps.

2. The deep-well pumps , which consist of a rotating shaft which drives a submerged pump in the well. The shaft is coupled to a diesel engine via a bevel gear or a belt. These deep well pumps can pump water against large pumping heads. They are used mainly in tube wells with a pumping head of 7 m and greater.

The suction and deep-well pumps have an efficiency of 50%. This means that the shaft power of the diesel engine driving these pumps has to be two times higher than the required hydraulic output.

The actual shaft power output of a diesel engine is about 70% of the rated power.
If the engine is loaded at very low power levels, efficiency decreases, maintenance increases and the life will become shorter.
A problem of small diesel engines is that they are not manufactured in smaller sizes than 2 kW (2.67 HP) rated power.
For small scale lift irrigation, power requirements will be considerably less than 2 kW, especially when diesel-powered pumps are applied to wells with a poor recharge capacity.

The total diesel to water efficiency of the diesel pump combination is taken in this study as 7.5% (average between 6% and 9% as used in [6]).

It is assumed that the diesel pump should be able to pump the daily water requirement within six hours. It is also assumed that the well will yield at least this water requirement within six hours.

In this study, three cases for diesel powered pumps (suction as well as deep well) are distinguished (represented by three different lines in the graphs):

1. Diesel pump

   This line in the graphs represents a diesel pump of 2 kW or more operating at full output and at optimum efficiency. This pump is able to pump the daily water requirement in just six hours.

2. Diesel pump with unlimited water supply

   This line in the graphs represents a 2 kW diesel pump operating at full output and at optimum efficiency. But, since this pump is in fact too large for the job (there is no smaller diesel engine available), it can pump the daily water requirement in less than six hours.
   This will happen when small areas are irrigated from open water, e.g. lakes, rivers, and canals and large open wells with a good recharge and storage capacity.

3. Diesel pump with limited water supply

   This line represents a diesel pump pumping from a well with a poor recharge capacity. Although the pump could pump the required water in less than six hours, the well needs six hours to produce the required quantity.
   Therefore, the pump has to operate for six hours per day at reduced output and at reduced efficiency.
   This will occur when small areas are irrigated from small, poorly-yielding open wells or from poorly yielding tube wells.
   These tube wells have hardly any storage capacity, so it is not possible to empty them quickly and wait till they are filled up again.
   Note that in this case the pumping cost is independent of the quantity of water pumped.

The FOB price of small diesel suction pump sets is taken as $ 500 per kW. It is supposed that the smallest available diesel engine is 2 kW. The CIF price in developing countries is taken as $ 625, being the FOB price plus 25%. For local transport and installation,20% of the FOB price is estimated, bringing the total costs to $ 725 per kW.

The FOB price of small, diesel deep-well pumps (including diesel engines) is taken as $ 1.250 per kW. It is supposed that the smallest available diesel engine is 2 kW. The CIF price in developing countries is taken as $ 1.562 being the FOB price pus 25%. For local transport and installation 20% of the FOB price is estimated, bringing the total costs to $ 1.813 per kW.

5.4. Diesel fuel

The price of diesel fuel is taken as $ 0.40 per litre.
([6] uses a low price of $ 0.40 and a high price of $ 0.80).
The energy content of 1 liter of diesel fuel is about 10 kWh of thermal energy.

5.4. Pump shed

To protect the diesel pump and the stored diesel fuel against rain and theft, a pump shed is generally required. The costs of a shed for diesel pumps is independent of the size of the diesel engine. The same shed can be used for centrifugal and deep-well pumps. The total costs are taken as $ 200. This shed is supposed to last for 30 years and to require an annual maintenance budget of 1% of its investment.

5.6. Static lift

For this study, five static lifts are considered:
2, 7, 10, 15, and 30 m.

For the diesel pumps, 1 m is added to each static lift to cover the height of the pump outlet and the friction losses. For the wind pumps, 1.5 m is added to the static lifts to cover the height of the storage tank, the height of the tank outlet, and the friction losses.

The 2-m static lift is considered the lowest lift at which pumping for irrigation is required.
The 7-m static lift is the maximum lift for suction pumps installed at ground level.
The 10-m static lift is the lowest lift at which deep-well pumps can be applied.
The 15-m static lift is typical for large open wells.
The 30-m static lift is typical for tube wells.

5.7. Irrigation period

In order to enable the economic comparison between wind pumps and diesel pumps, an assumption has to be made about the number of months per year in which irrigation is practiced.

This period depends mainly on the rainfall and cropping patterns of the area. For this study, 6 months per year are taken. This implies that the average wind speeds used should be the average wind speeds during these six months. The same applies for the static lift.

5.8. Interest rates

To enable the transformation of investment costs and economic life of an item into average annual costs, an interest rate has to be choosen
As this model aims at a general comparison of wind pumps and diesel pumps, the interest rate has to be the opportunity cost of capital. Since 10% is taken in most World Bank studies, this percentage will also be used for this model.
It is assumed that inflation is same in all sectors of the economy.

5.9. Data summary

CWD wind pumps

Investment costs per m^2 of rotor area:	$ 175
economic life:	10 years
annual maintenance costs:	5% of investment

American wind pumps

Investment costs per m^2 of rotor area:	$ 508
economic life:	20 years
annual maintenance costs:	1% of investment

Intermediate technology storage tank

Investment costs per m^3 of storage:	$ 10
economic life:	10 years
annual maintenance costs:	5% of investment

High technology storage tank

Investment costs per m^3 of storage:	$ 50
economic life:	30 years
annual maintenance costs:	1% of investment

Diesel suction pumps

Investment costs per kW of rated power:	$ 725
economic life:	5 years
annual maintenance costs:	8% of investment
percentage of rated power at which the diesel engine is normally operated:	70%

shaft power to water efficiency of suction pump: 50%
diesel to water efficiency of diesel pump: 7.5%

Diesel deep-well pumps

Investment costs per kW of rated power:	$ 1.813
economic life:	5 years
annual maintenance costs:	8% of investment
percentage of rated power at which the diesel engine is normally operated:	70%
shaft power to water efficiency of deep well pump:	50%
diesel to water efficiency of diesel pump:	7.5%

Diesel fuel

price per litre:	$ 0.40
energy content per litre:	10 kWh-thermal

Pump shed

investment costs:	$ 200
economic life:	30 years
annual maintenance costs:	1% of investment

Static and actual lifts

Static lift H(m)	Diesel pump H_d(m)	Wind pump H_{wp}(m)
2	3	3.5
7	8	8.5
10	11	11.5
15	16	16.5
30	31	31.5

Interest 10%

6. METHODOLOGY

Calculation of the average annual cost of the wind pump system AAC_{wp+st}

The AAC_{wp+st} is calculated with the following formula:

AAC_{wp+st} = wind pump rotor area * AAC_{wp} + storage tank capacity * AAC_{st}

with AAC_{wp} = average annual cost of wind pump/m² ($/yr)
AAC_{st} = average annual cost of storage tank/m³ ($/yr)

The rotor area A of a wind pump that pumps Q m³ water per 24 hours with a lift of H m at an average wind speed of $\bar{V}$ m/s can be derived as follows:

The hydraulic power generated by a wind pump is fairly well approximated by:

$$\bar{P} = 0.1 * \bar{V}^3 * A \quad \text{(W) [3]}$$

where
$\bar{P}$ = average seasonal or yearly power output of the wind pump (W)
$\bar{V}$ = average seasonal or yearly wind speed (m/s)
A = rotor area (m^2)

During 24 hours the wind pump produces

$$\bar{E}_d = 0.1 * 10^{-3} * \bar{V}^3 * A * 24 \quad \text{(kWh)}$$

where

$\bar{E}_d$ = daily hydraulic energy output of windmill (kWh)
The energy required to lift a quantity of water of Q m³ over a height of H m is equal to:

$$\rho g Q H = 10^3 * 9.8 * Q * H \quad \text{(J)}$$

or expressed in kWh:

$$\frac{10^3 * 9.8 * Q * H}{3.6 * 10^6} = \frac{Q * H}{367} \quad \text{(kWh)}$$

The daily energy demand for water lifting and the energy production by the wind pump during 24 hours are equal if:

$$\frac{Q * H}{367} = 0.1 * 10^{-3} * \bar{V}^3 * A * 24$$

From this equation the rotor area A can be calculated as:

$$A = 1.14 \frac{Q * H}{V^3} \qquad (m^2)$$

$$\text{As } A = \tfrac{1}{4} \pi * D^2 \qquad (m^2)$$

with D = rotor diameter of wind pump

$$D = 1.2 \sqrt{\frac{Q * H}{\bar{V}^3}} \qquad (m)$$

A wind pump with a rotor area A can lift the required water within 24 hours (average). Farmers, however, cannot be expected to be present in their fields day and night, whereas in most cases their presence is needed for irrigation.
This problem can be solved by attaching a storage tank with a capacity of 75% of the average daily water requirement to the wind pump. The average annual cost of the wind pump system can then be calculated as:

$$AAC_{wp+st} = A * AAC_{wp} + 0.75 * Q * AAC_{st}$$

For small lifts and good wind speeds this set up would result in a very small wind pump combined with a large storage tank. In those cases, it would be more attractive to install two wind pumps with rotor area A (or one with a rotor area 2A) and combine these wind pumps with a small tank with a capacity of 10% of the daily water requirement to level out the-minute-to-minute fluctuations of the wind pump output and to enable the farmer to irrigate with a somewhat higher and constant flow (see 7.3.). The average annual cost of the wind pump system is then calculated as:

$$AAC_{wp+st} = 2A * AAC_{wp} + 0.1 * Q * AAC_{st}$$

In the construction of the graphs, the best of the two wind pump alternatives is used. In Appendix E break-even wind speeds are presented.

The unit costs of water as indicated in the graphs on each windmill line are calculated by dividing the annual costs of a certain daily water requirement at a certain average wind speed by 182.5 (the requirement for half a year).

The required rated power is calculated as the power required to lift the daily water requirement within six hours with a rated power to shaft power ratio of 70% and a shaft power to water efficiency of 50%:

$$\text{rated power} = \frac{Q * H}{367 * 6 * 0.7 * 0.5} = \frac{Q * H}{770.7} \quad \text{(kW)}$$

This "name plate" power has a minimum of 2 kW, as smaller diesel pumps are not available.

The annual fuel cost (one season of 182.5 days) of the diesel pump is calculated by multiplying the required daily energy by 182.5 (to obtain the required seasonal energy), then multiplying by 0.1 (as 1 liter diesel contains 10 kWh thermal energy), dividing by the diesel to water efficiency of 7.5%, and finally multiplying by the price of diesel oil ($ 0.40):

$$\text{Annual fuel cost} = \frac{0.1 * Q * H * 182.5}{0.075 * 367} * 0.40 \quad (\$/Y)$$

If there is a limited water supply because of a well's limited recharge capacity, it is supposed that the diesel pump has to pump six hours per day. In this case the annual fuel costs have a minimum, which is equal to the fuel costs of a 2 kW diesel pump running at full output and at full efficiency.

What is stated above results in three diesel lines in the graphs, as explained in 5.3.:

a. A line for a diesel pump (suction or deep well depending on the lift) of 2 kW or more that runs at full output and at full efficiency for six hours a day;

b. A line for a diesel pump of 2 kW pumping from an unlimited water source at full output and at full efficiency for less than 6 hours a day. (This diesel pump is, in fact, too large for the job but a smaller one is not available);

c. A line for a diesel pump of 2 kW pumping six hours per day from a limited source of water at a reduced output and of reduced efficiency. (This pump is, in fact, too large not only for the job, but for the water source as well)

7. SENSITIVITY ANALYSIS

A sensitivity analysis is presented here to obtain an idea about the sensitivity of the results of this study to changes in key parameters. The key parameters selected are:

- investment cost of the wind pumps;
- investment cost of the diesel pumps;
- price of diesel fuel;
- interest rates.

From the 10 graphs presented in this study it can be seen that the lift of 7 m is the most critical one for the CWD and 'American' wind pumps. As small scale irrigation with wind pumps is typically practiced on command areas of up to 1 ha, a daily water requirement of 60 m^3 was selected for the sensitivity analysis. For this point (60 m^3 and 7-m lift), the break-even wind speed was calculatedfor different values of the key parameters, and it is presented along with the break-even average annual costs and the break-even water costs.

Sensitivity analysis for CWD wind pumps and diesel suction pumps for static a lift of 7-m and a daily water requirement of 60 m^3

Variation in key parameters	in break-even point		
	$\bar{V}$ (m/s)	AAC ($/Y)	c ($ct/$m^3$)
According to assumptions*	3.4	641	5.9
Investment wind pump + 10%	3.55	641	5.9
Investment wind pump- 10%	3.3.	641	5.9
Investment diesel pump + 10%	3.3	693	6.3
Investment diesel pump - 10%	3.55	589	5.4
Diesel fuel $ 0.80/liter **	3.2	761	6.9
Interest rate 12%	3.45	664	6.1
Interest rate 8%	3.35	618	5.6

* See 5.9 Data Summary
** Upper limit as used in [6]

Sensitivity analysis for "American" wind pumps and diesel suction pumps for static lift of 7 m and a daily water requirement of 60 m^3

Variation in key parameters	in break-even point		
	$\bar{V}$ (m/s)	AAC ($/Y)	c ($ct/$m^3$)
According to assumptions*	4.6	641	5.9
Investment wind pump + 10%	4.85	641	5.9
Investment wind pump - 10%	4.35	641	5.9
Investment diesel pump + 10%	4.45	693	6.3
Investment diesel pump - 10%	4.85	589	5.4
Diesel fuel $ 0.80/litre **	4.25	761	6.9
Interest rate 12%	4.9	664	6.1
Interest rate 8%	4.4	618	5.6

* See 5.9 Data Summary
** Upper limit as used in [6]

From the sensitivity tables it can be seen that CWD wind pumps are less sensitive to changes in interest than 'American' wind pumps and that the high price of diesel of which can be expected in remote areas ($ 0.80/ litre) brings the break-even wind speed down considerably.

Calculation of the average annual cost of the diesel pump, including fuel and pump shed AAC_{d+f+ps}

The AAC_{d+f+ps} is calculated according to the following formula:

AAC_{d+f+ps} = "name plate" power of diesel pump * AAC_d + annual fuel cost + AAC_{ps}

with AAC_d = average annual cost diesel pump (suction or deep well) per kW

AAC_{ps} = average annual cost pump shed

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APPENDIX A: CWD wind pumps

Calculation of Average Annual Cost of CWD wind pumps with intermediate technology storage tanks ($AAC_{wp + st}$).

<u>Wind pump/m² rotor area</u>

Investment:	\$ 175	
Life:	10 years) Annuity factor: 0.1627	
Interest:	10%)	
Annual cost/m² = 0.1627 * 175		\$ 28.47
Maintenance costs (MC): 5%/year		
MC = 0.05 * 175 =		\$ 8.75
AAC_{wm}/m^2 =		\$ 37.22

<u>Storage tank/m³ storage</u>

Investment:	\$ 10.	
Life:	10 years) Annuity factor: 0.1627	
Interest:	10%)	
Annual costs/m³ = 0.1627 * 10 =		\$ 1.63
O & MC : 5%/year		
MC = 0.05 * 10 =		\$ 0.50
AAC_{st}/m^3 =		\$ 2.13

$$AAC_{wp+st} = \frac{1.14 * Q * Hwp}{\bar{V}^3} * 37.22 + 0.75\ Q * 2.13 \qquad (\$/yr)$$

or:

$$AAC_{wp+st} = \frac{2 * 1.14 * Q * Hwp}{\bar{V}^3} * 37.22 + 0.1\ Q * 2.13 \qquad (\$/yr)$$

For each lift and wind speed the lowest AAC_{wp+st} of these two is selected to draw the wind pump lines in the graphs.
Break even wind speeds between the two formulas are presented in Appendix E.

APPENDIX B: "American" wind pumps

Calculation of Average Annual Cost "American" wind pumps with high technology storage tanks ($AAC_{wp + st}$).

Wind pump/m² rotor area

Investment:	$ 508		
Life:	20 years)	Annuity factor: 0.1175	
Interest:	10%)		
Annual cost/m³ = 0.1175 * 508			$ 59.67
MC = 1%/year			
MC = 0.01 * 508 =			$ 5.08
AAC_{wm}/m^2 =			$ 64.75

Storage tank/m³ storage

Investment:	$ 50		
Life:	30 years)	Annuity factor: 0.1061	
Interest:	10%)		
Annual costs/m³ = 0.1061 * 50 =			$ 5.30
MC : 1%/year			
MC = 0.01 * 50 =			$ 0.50
AAC_{st}/m^3 =			$ 5.80

The AAC_{wp+st} can be calculated in the same ways as for the CWD wind pumps (Appendix A) as:

$$AAC_{wp+st} = \frac{1.14 * Q * Hwp}{\bar{V}^3} * 64.75 + 0.75\ Q * 5.80 \qquad (\$/yr)$$

or as:

$$AAC_{wp+st} = \frac{2 * 1.14 * Q * Hwp}{\bar{V}^3} * 64.75 + 0.1\ Q * 5.80 \qquad (\$/yr)$$

For each lift and windspeed the lowest AAC_{wp+st} of these two is selected to draw the wind pump lines in the graphs.
Break even wind speeds between the two formulas are presented in Appendix E.

APPENDIX C: Diesel suction pumps

Calculation of Average Annual Cost of diesel suction pumps, Average Annual Fuel Cost and Average Annual Cost of the pump shed ($AAC_{ds+f+ps}$)

Pump set/kW rated power of diesel engine

Investment:	$ 725.		
Life:	5 years)	Annuity factor: 0.2638	
Interest:	10%		
Annual Costs = 0.2638 * 725			$ 191.26
MC :	8%/year		
MC = 0.08 * 725 =			$ 58,--
AAC_{ds}			$ 249.26

As the rated power to shaft power ratio of the diesel engine is 70%, the shaft power to water efficiency of the suction pump is 50%. And as the diesel pump has to lift the daily water requirement Q within six hours, the minimum required "name plate" power can be determined as:

$$\text{rated power} = \frac{Q * Hd}{367 * 0.7 * 0.5 * 6} = \frac{Q * Hd}{770.7} \qquad \text{(kW)}$$

This rated power has a minimum of 2 kW, as smaller diesel engines are not available.

Fuel

As the cost of fuel is $ 0.40 per litre, the irrigation season is supposed to be 6 months per year (182.5 days), and the fuel to water efficiency of the diesel suction pump is taken as 7.5%. The average annual fuel cost can be calculated as:

$$AAC_f = \frac{0.1 * Q * Hd * 182.5}{0.075 * 367} * 0.40 \qquad (\$/yr)$$

In those cases where the limited water supply means that the diesel pump has to operate for 6 hours per day at low efficiency, the AAC_f has a minimum. The value of this minimum is equal to the fuel costs of a 2 kW diesel pump running at full output and at optimum efficiency for 6 hours a day:

$\frac{Q * Hd}{770.7}$	=		2
$Q * Hd$	=		1541.4
Min. $AAC_f = \frac{0.1 * 1541.4 * 182.5}{0.075 * 367} * 0.40$	=	$	408.80

Pump shed

Investment: $ 200.
Life: 30 years) Annuity factor: 0.1061
Interest: 10%)

Annual Costs = 0.1601 * 200	$	21.22
MC : 1%/year		
MC = 0.01 * 200 =	$	2.00
AAC_{ps}	$	23.22

Now the $AAC_{ds+f+ps}$ can be expressed as:

$$AAC_{ds+f+ps} = \frac{Q * Hd}{770,7} * 249.26 + \frac{0.1 * Q * 182.5 * Hd}{0.075 * 367} * 0.40 + 23,22 \text{ (\$/Y)}$$

If these is an unlimited water supply, the $AAC_{ds+f+ps}$ has a minimum of 498.50 + 23.22 = $ 521.72

If there is a limited water supply, the $AAC_{ds+f+ps}$ is constant at 498.50 + 408.80 + 23.22 = $ 930.52

APPENDIX D: Diesel deep well pumps

Calculation of Average Annual Cost of diesel deep well pumps, Average Annual Fuel Cost and Average Annual Cost of the pump shed ($AAC_{dd+f+ps}$)

Pump set/kW rated power of diesel engine

Investment:	$ 1813,--	
Life:	5 years) Annuity factor: 0.2638	
Interest:	10%)	
Annual Costs = 0.2638 * 1813		$ 478.27
O&MC :	8%/year	
O&MC = 0.08 * 1813 =		$ 145.00
AAC_{dd}		$ 623.31

with a minimum of 2 * 623.31 = $ 1.246.62

Required rated power (see Appendix C) is:

$$\text{Shaft power} = \frac{Q * Hd}{367 * 0.7 * 0.5 * 6} = \frac{Q\ \ Hd}{770.7} \quad \text{(kW)}$$

with a minimum of 2 kW

Fuel

The Average Annual Fuel Cost (AAC_f) can be calculated as (see Appendix C):

$$AAC_f = \frac{0.1 * Q * Hd * 182.5}{0.075 * 367} * 0.40 \quad (\$/Y)$$

with a minimum of $ 408.80 in case of limited water supply (see Appendix C).

<u>Pump shed</u>

AAC_{ps} = $ 23.22 (see Appendix C)

Now the $AAC_{dd+f+ps}$ can be expressed as:

$$AAC_{dd+f+ps} = \frac{Q * Hd}{770,7} * 623.31 + \frac{0.1 * Q * 182.5 * Hd}{0.075 * 367} * 0.40 + 23,22$$

If there is an unlimited water supply the $AAC_{dd+f+ps}$ has a minimum of 1.246,62 + 23,22 = $ 1.269,84

Ir kthere is a limited water supply, the $AAC_{dd+f+ps}$ is constant at 1.246,62 + 408,80 + 23.22 = $ 1.678,64 to the point where the diesel engine starts working at full capacity to full efficiency.

APPENDIX E: Break even wind speeds for wind pump cost calculations

In this study the required storage capacity of the tank attached to the wind pumps is initially assumed to be 75% of the average daily water requirement. In most cases this combination of wind pump and storage tank is the most optimum combination economically, leading to the lowest possible costs per unit of water. However, for low static lifts and fairly good average wind speeds, this combination of wind pump and storage tank would lead to a combination of a rather small windmill and a fairly large storage tank. In these cases, it would be more economical to install two windmills and a storage tank of only 10% of the daily water requirement to level out the irregular water supply of the wind pumps during the day. The water pumped during the night would, in large part, flow back into the well. In this Appendix, break-even wind speeds of the two set-ups are calculated.

Break even wind speeds CWD wind pumps with "intermediate technology" tanks

$$\frac{1.14*Q*Hwp}{V^3}*37.22+0.75*Q*2.13 = \frac{1.14*2*Q*Hwp}{V^3}*37.22+0.1*Q*2.13$$

$$\frac{42.43*Hwp}{\bar{V}^3} + 1.60 = \frac{84.86*Hwp}{\bar{V}^3} + 0.21$$

$$1.39\ \bar{V}^3 = 42.43\ Hwp$$

$$\bar{V} = 3.13\ Hwp \qquad (m/s)$$

static lift H (m)	pumping head Hwp (m)	break even wind speed (m/s)
2	3.5	4.75
7	8.5	6.38
10	11.5	7.06
15	16.5	7.96
30	31.5	9.87

This table shows that the combination of a large CWD wind pump and a small intermediate-technology tank is only cost effective in those few areas where high average wind speeds come together with low pumping heads.

Break-even windspeed 'American' wind pumps with high-technology tanks

$$\frac{1.14*Q*Hwp}{V^3}*64.75+0.75*Q*5.80 = \frac{1.14*2*Q*Hwp}{V^3}*64.75+0.1*Q*5.80$$

$$\frac{73.82*Hwp}{\bar{V}^3} + 4.35 = \frac{147.63*Hwp}{\bar{V}^3} + 0.58$$

$$3.77\ \bar{V}^3 = 73.82\ Hwp$$

$$\bar{V} = 2.70\ \sqrt[3]{Hwp} \qquad (m/s)$$

static lift H (m)	pumping head Hwp (m)	break even wind speed (m/s)
2	3.5	4.10
7	8.5	5.51
10	11.5	6.09
15	16.5	6.87
30	31.5	8.52

This table shows that the combination of large "American" wind pumps and small high-technology tanks is only cost effective in those few areas where high average wind speeds come together with low pumping heads.

CONSULTANCY SERVICES
WIND ENERGY
DEVELOPING COUNTRIES

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THE NETHERLANDS

A brief introduction to the Netherlands program for assistance to developing countries in the utilization of wind energy.

February 1984

The basis for a sound economic development of many countries in the Third World is the development of agriculture. The oil crisis in 1973 once again stressed the vital role of energy in this development process and thus caused a world-wide revival of the interest in the utilization of renewable energy sources. In the Netherlands wind energy still appeals to many people and in 1974 a study was made to analyse the possibilities of utilizing wind energy in developing countries. It appeared that in many countries wind energy could play an important role in satisfying the energy need for water pumping, particularly for irrigation purposes.

In 1975 the Netherlands government founded a national organization in order to coordinate the Netherlands activities on wind energy for developing countries.
This organization operated under the name Steering Committee Wind Energy Developing Countries until 1984. In that year the name of the organization was changed into CWD Consultancy Services Wind Energy Developing Countries.
CWD promotes the interest for wind energy in developing countries and aims to help governments, institutions and private parties in the Third World with their efforts to utilize wind energy.

The CWD pursues this aim in three ways:

1. provision of assistance to wind energy projects in developing countries
2. wind energy research, mainly undertaken in the Netherlands
3. transfer of knowledge on wind energy use.

The parties that currently participate in CWD are:

Eindhoven University of Technology (Wind Energy Group)
Twente University of Technology (Windmill Group)
DHV Consulting Engineers.

Each participant has its own, more or less well defined, field of research and the co-ordination is in the hands of DHV Consulting Engineers.

In the field of agriculture CWD closely collaborates with the Institute of Land Reclamation and Improvement (ILRI).

CWD has regular contacts with the Working Group on Development Technology (WOT) at Twente University.
Also contacts exist with the Dutch national wind energy research program, co-ordinated by the Energy Research Centre (ECN).

The installation of a ∅ 5 m windmill in Colombo, Sri Lanka; in the background the ∅ 3 m WEU-I windmill.

RESEARCH ACTIVITIES

The research activities are undertaken with the following purposes:
- to develop windmill components as well as complete prototypes
- to support the country projects
- to train future experts for country projects

Rotors

A large number of rotors have been designed and tested, both at open air test stands and in a large windtunnel. Good results have been achieved with horizontal axis curved metal plate rotors, as predicted by theory. For low Reynolds numbers (< 100,000) curved plate profiles turn out to be better than airfoils.
Designing with higher tip speed ratios ($\lambda > 1$) results in lighter rotors and thus lighter and cheaper windmills.

Pumps

The optimum matching of a pump to the quadratic torque-speed characteristic of a wind rotor has been pursued by the development of variable torque reciprocating pumps and the application of centrifugal pumps. This optimum matching results in much higher overall outputs than with the traditional (constant torque) piston pumps. The closing of valves and the operation of air chambers has been analyzed.

Generators

For deep wells electrically driven pumps are considered as a serious alternative to direct mechanically driven pumps. Two types of generators have been tested to drive these pumps:
- a self exciting induction generator
- an induction generator equipped with a permanent magnet rotor

Also two control systems for alternators have been developed.
Research is done on autonomous systems, windmills for electricity generation working in combination with diesel powered generators.

Safety Systems

A reliable safety system has been developed and tested for wind speeds up to 30 m/s. The system operates by means of a small auxiliary vane that pushes the rotor out of the wind against the normal directional vane that is hinged on a leaning axis. A complete theoretical model is being studied.

Wind measurement

An electric counter with extremely low energy consumption has been developed for contact-anemometers.

Theory

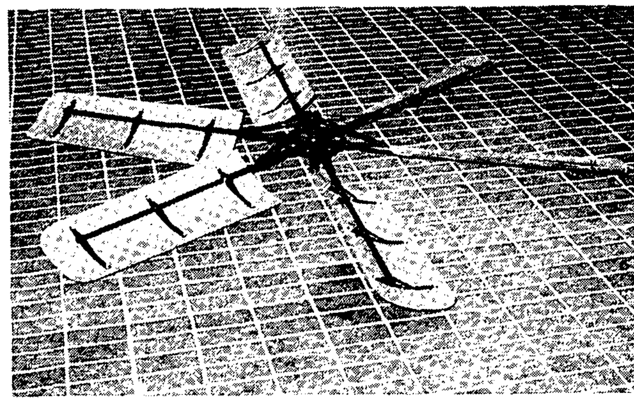
Theoretical models have been developed or refined on:
- rotor performance
- forces on rotor blades
- output in different wind regimes
- matching of rotor with generator or pump
- dynamic behaviour of pumps.

Windmill prototypes

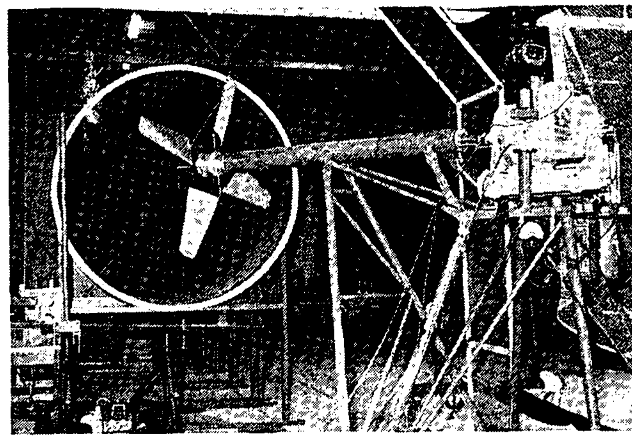
The following prototypes have been developed:

	diameter	number of blades	tip speed ratio	remarks
CWD 2740	2.74 m	6	2	piston pump
CWD 4000	4.00 m	8	2	piston pump
CWD 5000 RS[1]	5.00 m	4	5	centrifugal pump; Rotating Shaft
WEU I	3.00 m	6	2	piston pump
WEU II[2]	5.00 m	8	2	piston pump
Cretan	6.00 m	8	1	piston pump
Under development:				
CWD 5000 HW	5.00 m	8	2	piston pump; for High Wind regime
CWD 5000 LW	5.00 m	8	2	piston pump; for Low Wind regime
CWD 2000	2.00 m	6	2	piston pump
CWD 1000 EL	1.00 m	2	4	Electricity generation

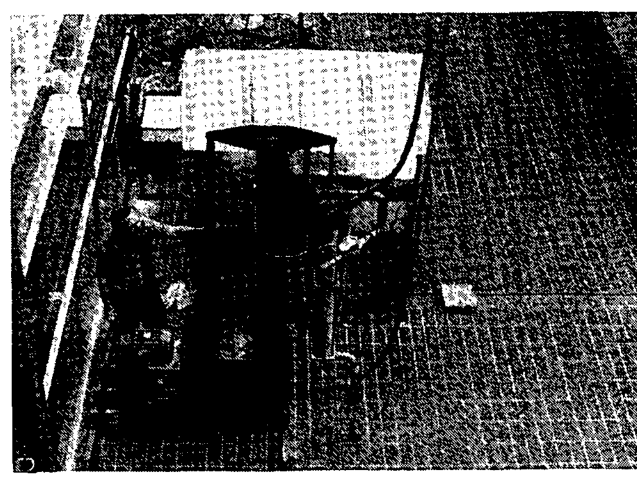
1) developed as testmodel only
2) partially based on WOT-designed 12 PU 500
3) developed by WOT with financial aid from CWD



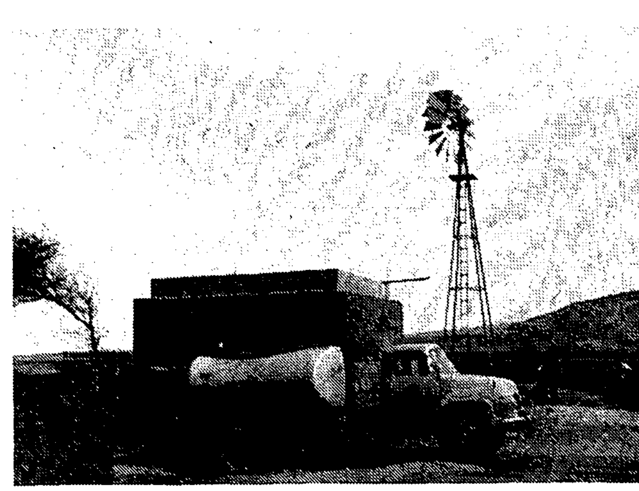
Rotor of CWD 2740 prototype



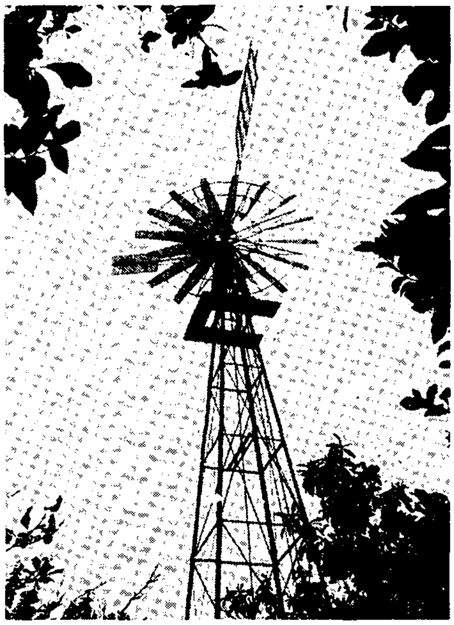
Windtunnel (∅ 2.2 m) at Delft University of Technology for testing rotor models



Pump test stand at Eindhoven University of Technology



Project for rural water supply and irrigation on the Cape Verdian Islands



Prototype installed in Hammamet, Tunisia, irrigating an orchard.

COUNTRY PROJECTS

CWD gives assistance in the execution of wind energy programmes in close co-operation with interested ministries, institutions or private parties. The country projects encompass assistance in a number of fields:

— measurement and analysis of wind data
— selection of favourable areas
— selection and construction of prototype windmills
— training and education in the field of wind energy
— selection of application purposes
— organisation of pilot projects.
— maintenance
— agricultural application analysis
— production engineering assistance
— economic programming and
— credit systems

The guiding principles for the country projects are:

— water pumping has the highest priority
— local production of as many components as possible
— construction methods and materials must be appropriate to the local technical level.

CWD is involved in projects in the following countries:

Sri Lanka

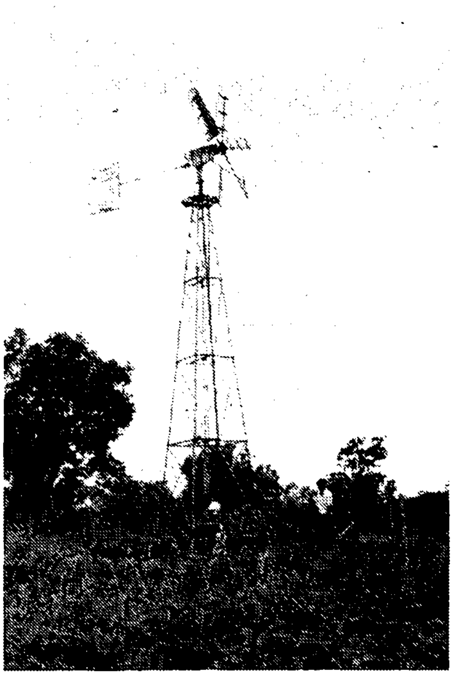
In March 1977 the Wind Energy Utilization Project was started with financial support from the governments of Sri Lanka and the Netherlands. The execution is in the hands of the Wind Energy Unit of the Water Resources Board.
The project is staffed by Sri Lanka engineers, technicians and workers, while CWD experts provide assistance. About 150 windmills were produced in the last two years, mainly by local workshops. Part of these windmills were sold at subsidized rates. Presently a small 2-m diameter windmill for irrigation by small farmers is under development.

Republic of Cape Verde

Since 1981 CWD supplies two wind experts in a large renewable energy project with emphasis on wind power, executed by the Ministry of Rural Development. The project focusses on training of staff in installation, repair and maintenance of windmills.
A high-wind-prototype for waterlifting of 5 m diameter is under development.

Pakistan

Stimulating contacts with Merin Ltd. in Karachi led to CWD's consultancy to start production of windmills. The WEU-I prototype developed in Sri Lanka was selected and in 1980 a CWD expert paid a three-month visit for technical assistance.



WEU-I prototype irrigating in Sri Lanka

Tanzania

The Ujuzi Leo Industries in Arusha have been supported in improving their windmill design via a two-month course in the Netherlands and short-term expert visits.

Tunisia

In support of the ASDEAR (Association pour le développement et l'animation rurale) CWD supervised in 1980 the construction of three CWD 4000 prototypes as a start of production in series by a local entrepreneur.
In support of the SEREPT-company CWD designs a 5-m diameter windmill for water pumping, meant for series production.

Peru

As a part of an agricultural project, supported by the Netherlands Ministry of Development Co-operation, a CWD 2740 prototype has been built. Since 1981 technical backstopping has been given to a Dutch expert in a bilateral co-operation program.

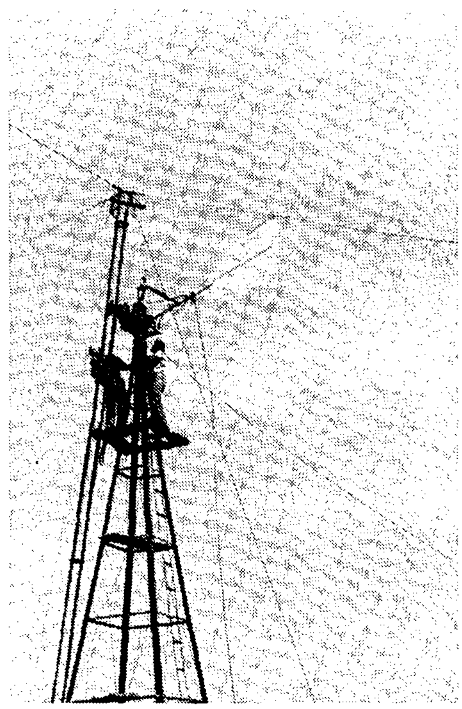
Feasibility Studies

CWD has carried out feasibility studies on the use of wind energy in the following countries or areas:
Sri Lanka (1976), Cape Verde (1980), Tanzania (1977), The Sahel (1976), Djibouti (for GTZ, 1981), Yemen Arab Republic (1980), Sudan (1980), Maldives (for ADB, 1980), Kenya (1982), Netherlands Antilles (1982).

Explaining the particulars of windmill testing at the Asian Institute of Technology, Bangkok.

TRANSFER OF KNOWLEDGE

Installation of windmills on Cape Verde.



Local knowledge is gathered in country projects and during visits of experts from abroad. Particularly the failures of windmill projects in the past deserve great attention. A first analysis of the causes for failure resulted in the following list:
- import restrictions on spare parts
- lack of funds
- lack of local know-how and of care for maintenance
- introduction of (subsidized) electric and diesel pumps
- drop of ground water table
- reduction on the number of windmills, making repair a non profitable job
- fear for repairs on top of a high tower
- termination of production and of supply of parts by manufacturers.

Knowledge in wind energy technology and related fields is transferred by CWD to developing countries by:
- publications
- drawings and construction manuals of prototypes
- visits and consultancies
- education and training

CWD also functions as a clearing-house for information and experience with wind energy systems: the experience with the WEU I windmill in Sri Lanka has been transferred to Pakistan for example.

Another facet is the supply of experts for lecturing purposes such as for the six-month UN-ESCAP Roving Seminar on Rural Energy Development in 1977. In the summer of 1980 and 1981 CWD sent an expert to the Asian Institute of Technology, Bangkok, to give introductory and advanced courses on wind energy and to coach MSc students.

PUBLICATIONS

CWD has been issueing publications on various topics related to wind energy applications: feasibility reports, theoretical aspects, design of rotors, economics of windmills, irrigation with windmills, etc. (see CWD-publications list).
CWD publications can only be ordered by letter to CWD with payment in advance. Research institutes in Third World countries may ask for a copy of three publications free of charge.

ADDRESSES

General address CWD:

DHV Consulting Engineers	P.O. Box 85, 3800 AB Amersfoort	The Netherlands, Tel.: 033 - 68 91 11 Telex 79348 dhv nl

Addresses of the other participants:

Eindhoven University of Technology Wind Energy Group	Department of Physics, Building W & S P.O. Box 513, 5600 MB Eindhoven	The Netherlands, Tel.: 040 - 47 2160
Twente University of Technology Windmill Group	Department of Mechanical Engineering P.O. Box 217, 7500 AE Enschede	The Netherlands, Tel.: 053 - 89 40 98

Address of ILRI:

International Institute for Land Reclamation and Improvement	P.O. Box 45, 6700 AA Wageningen	The Netherlands, Tel.: 08370 - 19100

Address of WOT:

Working Group on Development Technology (WOT)	Twente University of Technology Vrijhof 152, P.O. Box 217, 7500 AE Enschede	The Netherlands, Tel.: 053 - 89 38 70

Address of ECN:

Netherlands Energy Research Foundation (ECN)	P.O. Box 1, 1755 RG Petten	The Netherlands, Tel.: 02246 - 62 62

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CWD Publication list (February 1984)

For ordering instructions please read the last page.

Serial number		Prices (mail included) US $	Dfl
CWD 76-2	**Literature survey; horizontal axis fast running wind turbines for developing countries.** **By W.A.M. Jansen, 43 p., March 1976** Literature survey on theoretical aspects of rotor design and lay-out. Drag lift ratios and power coefficients are discussed.	4.-	9,-
CWD 76-3	**Horizontal axis fast running wind turbines for developing countries.** **By W.A.M. Jansen, 91 p., June 1976** Brief review of the theories that form the basis for calculation of the design and the behaviour of a windmill, together with a report on tests of several rotors.	8.-	19,-
CWD 77-1	**Rotor design for horizontal axis windmills.** **By W.A.M. Jansen & P.T. Smulders, 52 p., May 1977** Basic aerodynamical aspects of rotors are explained. With help of formulas and graphs the design procedures for blade chord and blade setting are given. (Also available in French as CWD 80-1 and Portuguese as CWD 83-2)	5.-	11,-
CWD 77-2	**Cost comparison of windmill and engine pumps.** **By L. Marchesini & S.F. Postma, 49 p., December 1978** A method to compare costs of irrigation with windmills and with conventional engines, with help of break-even and sensitivity analyses	4.-	10,-
CWD 77-3	**Static and dynamic loadings on the tower of a windmill.** **By E.C. Klaver, 39 p., August 1977** Some design considerations and the basic formulas needed for estimation of the dimensions of the tower structure.	3.-	8,-
CWD 77-4	**Construction manual for a Cretan windmill.** **By N.J. van de Ven, 59 p., October 1977 (WOT/CWD)** Detailed description for the construction of a sail wing windmill for water pumping, with wooden tower and head and steel pipe shaft. Illustrated with sketches, exploded views and photographs.	5.-	12,-

Serial number		Prices (mail included) US $	Dfl
CWD 77-5	**Performance characteristics of some sail- and steel-bladed wind rotors. By Th. A.H. Dekker, 60 p., December 1977** Report on experiments in an open windtunnel with several rotortypes. C_p-λ and C_q-λ characteristics are presented	5.-	12,-
CWD 78-1	**Feasibility study of windmills for water supply in Mara Region, Tanzania. By H.J.M. Beurskens, 89 p., March 1978.** Report on a study on wind energy potential in Mara Region, on water needs and potential windmill sites, on local production aspects and energy costs. A project proposal is elaborated.	8.-	18,-
CWD 78-2	**Savonius rotors for water pumping. By E.H. Lysen, H.G. Bos & E.H. Cordes, 46 p., June 1978.** Report on experiments with a wood and sail Savonius rotor detailing design aspects, theory on coupling to a pump and test results.	4.-	10,-
CWD 78-3	**Matching of wind rotors to low power electrical generators. By H.J. Hengeveld, E.H. Lysen & L.M.M. Paulissen, 85 p., December 1978.** Theoretical guidelines to the design of a small scale wind electricity conversion system with emphasis on the electrical part of the system and its matching to the rotor.	8.-	18,-
CWD 80-1	**Conception des pales des éoliennes à axe horizontal. (version française de CWD 77-1). Par W.A.M. Jansen et P.T. Smulders, 52 p., Décembre 1980.** Aspects fondamentales aéro-dynamiques des hélices. Procédure-modèle pour la conception des pales de l'hélice, pour les cordes et pour l'angle de calage.	5.-	11,-
CWD 81-1	**Wind energy for water pumping in Cape Verde By H.J.M. Beurskens, 162 p., February 1981.** Report on wind energy activities in Cape Verde, ground water resources, wind regime, local production possibilities and economic aspects of wind energy utilization. Proposals for a project are elaborated. (Also available in Portuguese as CWD 81-3)	14.-	34,-
CWD 81-2	**Wind energy in Sudan. By Dr. Yahia H. Hamid & W.A.M. Jansen, 71 p., July 1980.** Report on the windmill potential in Sudan detailing energy situation, wind and water situation and cost aspects, as well as a proposal for a wind energy centre in Sudan.	6.-	15,-
CWD 81-3	**Energia eólica para a bombagem de água em Cabo Verde (versao portuguesa de CWD 81-1). Por H.J.M. Beurskens, 162 p., Fevereiro de 1981.** Estudo de actividades actuais de energia eõlica em Cabo Verde, recursos de agua freãtica, utilização e aspectos econõmicos de energia eõlica. E elaborado uma proposta de projecto.	14.-	34,-

Serial number		Prices (mail included) US $	Dfl
CWD 81-4	**Aspects of irrigation with windmills** **By A.E.M. van Vilsteren, 100 p., January 1981 (TOOL/CWD)** Study on lift irrigation with windmills for smallholder agriculture in third world countries, dealing with irrigation practice, agricultural and social aspects and economic calculation methods.	9.-	21,-
CWD 82-1	**Introduction to wind energy (basics and advanced)** **By E.H. Lysen, 310 p., May 1983 (2nd edition).** Introduction to wind energy, with emphasis on water pumping windmills, dealing with a.o. site selection, wind-regime analysis, rotor design, economics.	25.-	57,-
CWD 82-2	**A model for the economics of small-scale irrigation with windmills in Sri Lanka.** **By J.A.C. Vel & L.R. v. Veldhuizen, 115 p., October 1981** Economic comparison between different cropschemes using windmill irrigation in Sri Lanka. Sensitivity analyses and differentiation between national economic aspects and farmer's viewpoints.	10,-	24,-
CWD 82-3	**Wind energy development in Kenya** **By W.E. van Lierop & L.R. van Veldhuizen** **November 1982.** A feasibility study consisting of the following volumes (may also be ordered separately):	26,-	63,-
	CWD 82-3 / ES Executive summary (21 p).	2,-	4,-
	CWD 82-3 / Vol I Main report, Volume I (81 p): Past and present wind energy activities.	7,-	16,-
	CWD 82-3 / Vol II Main report, Volume II (107 p): Wind potential.	9,-	22,-
	CWD 82-3 / Vol III Main report, Volume III (121 p): End use analysis.	10,-	25,-
CWD 83-2	**Dimensionamento do rotor de eolicas de eixo horizontal** **(Versão Portuguesa de CWD 77-1)** **Por W.A.M Jansen e P.T.. Smulders** **Traduçâo pela Universidade do Porto, Portugal, 58 p., Janeiro 1983** Os aspectos fundamentais da aerodinamica de helices ŝao tratados. Baseado em formulas e graficos, apresenta - se o metodo de calculo das cordas e dos ângulos da pá.	5.-	11,-
CWD 84-1	**Farm economics of water lifting windmills** **By A.M. Mueller, 87 p, January 1984** A guideline on economic and financial analyses for feasibility studies.	8,-	18,-

Serial number		Prices (mail included) US $	Dfl
CWD 84-2	**Catalogue of windmachines** **By D. Both & L.E.R. van der Stelt, February 1984** **(WOT/CWD) (Revised issue of CWD 83-1)** Inventory of commercially available windmills for water pumping and electricity generation, based on data of manufacturers; contains a list of addresses of suppliers (based on information upto February 1984)	5,-	12,-

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