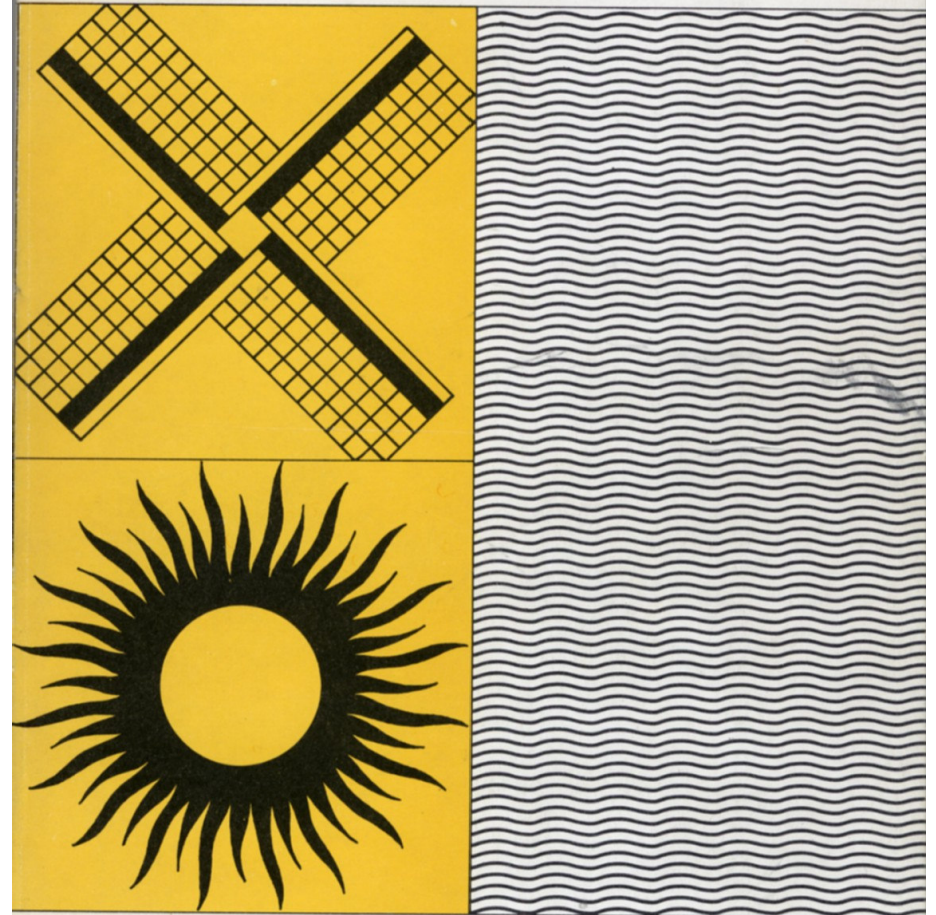


**Appropriate Technologies  
for Semiarid Areas:  
Wind and Solar Energy  
for Water Supply**



**German Foundation  
for International Development**  
Seminar Centre for Economic  
and Social Development

INTERNATIONAL CONFERENCE  
APPROPRIATE TECHNOLOGIES FOR SEMIARID  
AREAS: WIND AND SOLAR ENERGY FOR WATER SUPPLY

15 to 20 September 1975  
Berlin (West)

CONFERENCE REPORT

GERMAN FOUNDATION FOR INTERNATIONAL DEVELOPMENT  
Seminar Centre for Economic and Social Development

EFFICIENCY AND ECONOMIC COMPARISON OF DIFFERENT WEC - (WIND  
ENERGY CONVERTER) ROTOR SYSTEMS

Heiner Dörner

In order to draw a comparison between different types of WEC rotor systems it is convenient to compile a list of all the demands of such systems for all installation sites. This list which does not constitute a valuation, contains the following demands:

- simplest handling of the plant without special training of the user
- long operational life (20 to 30 years) with few maintenance intervals
- resistance of the components against all climatological conditions such as heat, cold, dryness, atmospheric humidity, salt air, rain, snow, icing up, rime, lightning and quicksand
- output at low wind velocity
- simplest construction design with easily exchangeable components (module groups)
- divisibility of the plant with regard to size and weight for the purpose of transporting the module groups
- low capital and operating costs.

The above demands require exact knowledge of construction design, as shown in a simple example.

A motor car with a mileage performance of 200,000 km has had an operation period of approximately 4000 to 5000 hours. During this time the car was frequently in the workshop and the driver was permanently present to help with breakdowns. A WEC must be in full action approximately 7,000 hours in a single year and should run, more or less, unattended.

A WEC consists of the following main components or module groups:



rotor	(rotor blades, pitch control, wind direction control, controlling mechanism)
gear unit	(cogwheel, single-stage or multistage, chain drive, tooth belt drive)
generator	(direct current-, alternating current-, synchronous- or asynchronous electrical machines)
tower	(steel, reinforced concrete, self-supporting or guyed, divisible or single part)

For a comparative examination we assume that the energy from the wind will be transformed into electrical energy to drive a water pump and also offer electricity for other purposes. The comparison is to be made between four rotor systems:

free running turbine with horizontal axis	(HAC)
shrouded propeller (aerogenerator)	(SA)
SAVONIUS rotor	(SR)
vertical axis turbine	(VAC)

Before starting the comparison, further, fundamental remarks must be made. The design of an optimal WEC has to fulfil three important qualifications:

high velocity ratio (this is the ratio of blade tip velocity  $u$  to wind velocity  $v$ , called  $\lambda$ )

high aerodynamic efficiency (according to BETZ (1926) the free running turbine can only extract 60 per cent from the energy of the air flow)

minimal expense in material.

At a given wind velocity  $v$  the swept area  $A$  of the system will determine the wind volume per unit of time. Therefore the fraction of the whole energy containing the air flow, which is changed first into mechanical rotating energy and then into electricity, is fixed. High velocity ratio reduces decisively the expense for the energy transformation. Of first order for the design of WEC is a radical structural emaciation. Only then can an optimal economic configuration be obtained.

#### The Horizontal Axis Converter (HAC)

Prof. Hütter of the FWE (Forschungsinstitut Windenergie-technik) has much experience with this type of wind energy converter. In the early 1950's Prof. Hütter developed in the ALLGAIER-WERKE, Udingen, Germany, a standard unit with a pitch-controlled three- and later just two-blade high tip speed ratio rotor. This high-speed converter, including in one block rotorhub, gear, generator and an automatic system to position the rotor perpendicular to the wind direction, has been adjusted to a tubular tower. High-speed converters are plants where the ratio of tip speed  $u$  to wind velocity  $v$  is higher than 3.5. The speed of the ALLGAIER WEC could be accurately kept at a constant rate, regardless of wind velocity, by means of a flyball governor. Provided that a sufficiently strong wind blew, the generator voltage of 220/380 volts was so accurately maintained that directly connected bulbs burned without flickering. This speed governor also reliably limited the wind pressure on the rotating wheel to the maximum value of 250 kg. (Figures 1, 2 and 3)

Thus the plant was safely protected against storms and could be left unattended even in heavy storms. The velocity of the blade tips was higher than during heavy storms.

The tower built with a safety of ten and securely anchored to the foundation was subjected to minor stress only.

The starting of the ALLGAIER WEC was extremely easy due to the carefully shaped metal blades with their automatic adjustment to highest starting torque when the plant was at a standstill. The plant operated in very low winds up to 2.5 m/s.

The automatic shifting of the wheel was achieved by means of a small side governor wheel which, through its high gear ratio with single-step back gearing and self-locking, amply-dimensioned worm, could turn the entire head smoothly and gradually into the wind. In this manner the use of vanes mounted on long arms, causing the wheel to swing and vibrate when subjected to gusty winds, was eliminated. Therefore a



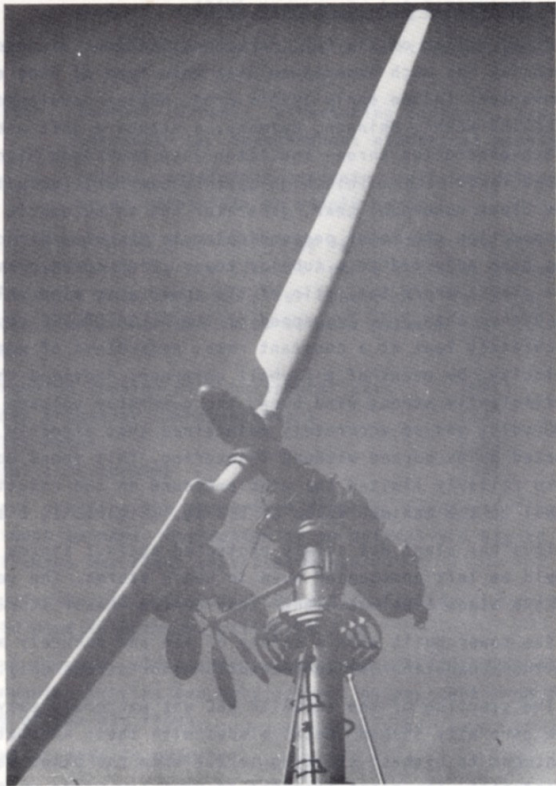


Figure 1 ALLGAIER wind energy converter WE 10, System Dr. Hütter. Composite blades

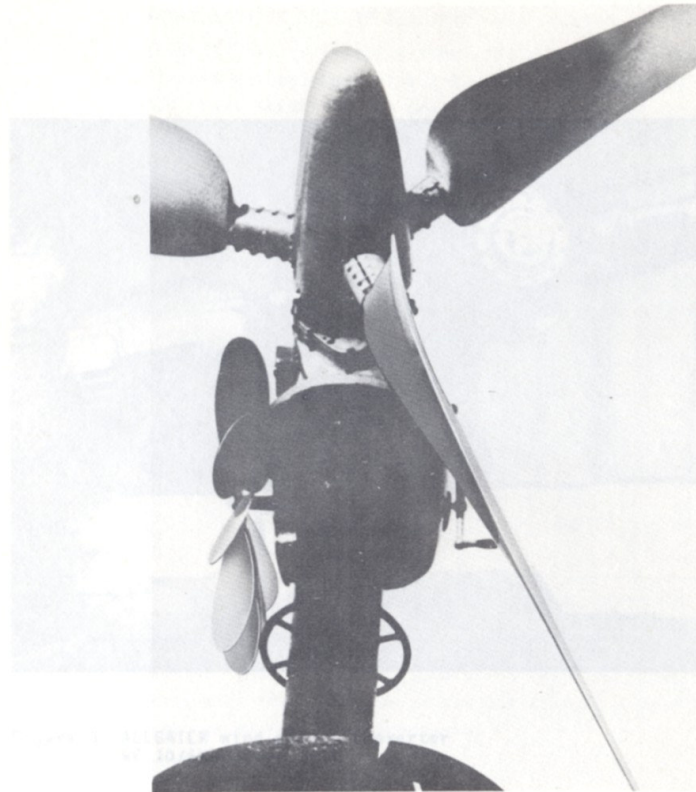


Figure 2 ALLGAIER 3-blade wind energy converter

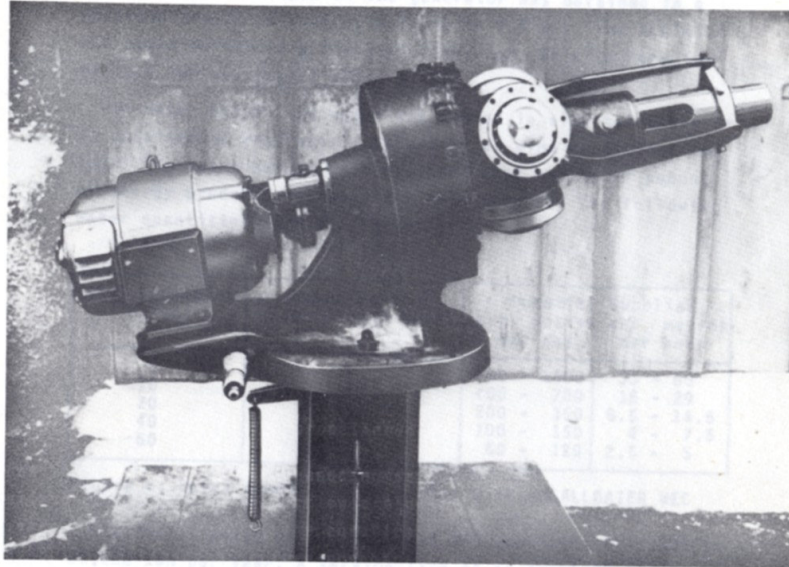


Figure 3 ALLGAIER wind energy converter  
WE 10/6KW power unit

much longer service life of the plant was assured.

The ALLGAIER WEC generated a three-phase current of 220/380 volts and was equipped with a 3, 6 or 8 kW synchronous generator. Full output of the generator was obtained in a moderate breeze at wind velocity 6 to 7.5 m/s. The ALLGAIER WEC could be termed a low-wind converter. This is very important for all installation sites.

For water supply the water was stored in elevated tanks or in underground reservoirs. Depending on wind conditions and total conveying height, and provided that the total amount of energy produced was used for this purpose, the following water quantities were available:

Total Conveying Height	Water Depth under Ground Level	Quantity Supplied	
		cub. metres per day	cub. metres per hour
5	1	800 - 1000	33 - 63
10	5	400 - 700	16 - 29
20	15	200 - 350	8.5 - 14.5
40	32	100 - 150	4 - 7.5
60	50	60 - 120	2.5 - 5

Figure 4: Water quantities available with an ALLGAIER WEC

The total energy of the ALLGAIER WEC amounted to 12,000 to 20,000 kWh per year. A service life of at least 20 years was guaranteed; with the exception of two oil changes a year the plant required no further maintenance.

Some technical data on this WEC:

Diameter of wheel . . . . .	10 metres
Surface area of wheel . . . . .	78 sq. metres
Area of each blade . . . . .	1.3 sq. metres
Standard height of tower . . . . .	8.4 metres
(higher towers on request)	
Height of platform above ground . . . . .	7.2 metres
Standard speed of wheel . . . . .	100 rpm
Speed of generator . . . . .	1500 rpm
Power of generator . . . . .	7.5 kva = 6 kw

Figure 5: Technical data on the ALLGAIER WEC



Units of this type have been produced in small quantities and delivered mainly for the energy supply of farms in 12 countries of four continents in the world. (Figures 6, 7 and 8) (1)

For the comparison of the different rotor systems we chose a WEC of this conventional type. All the experiences made in two decades are taken into account. The comparative converter has a horizontal axis and a pitch-controlled two-blade high-speed rotor. It uses a generator with 1500 rpm, which means that a gear unit with a gear ratio of 1:15 must be connected to the rotor shaft, because the rotor shaft has, regardless of all wind velocities, a constant rate of revolutions equal to 100.

The technical data on this two-blade rotor are:

rotor diameter $D_{HAC}$	11.28 m
swept area $A_{HAC}$	$0.785 D_{HAC}^2$ 100.0 m <sup>2</sup>
area of each blade $F_{HAC}$	1.6 m <sup>2</sup>
area of blade material $F_{HAC}$	$0.025 D_{HAC}^2$ 3.2 m <sup>2</sup>
depth of profile $\bar{e}_{HAC}$	0.25 m
ratio $D_{HAC}/\bar{e}_{HAC}$	45
output at 5.6 m/s wind velocity	3.3 KW
output at 7.7 m/s wind velocity (and more)	6.0 KW
power coefficient $c_{PmaxHAC}$	0.48
at tip speed ratio $\lambda_{maxHAC}$	14
area number $P_{HAC} = \lambda_{HAC} \cdot c_{PmaxHAC}$	48 m <sup>2</sup>
comparison number $V_{HAC} = \lambda_{maxHAC} \cdot c_{PmaxHAC}$	6.72
rotor rpm, constant	100
rotor tip velocity	60.0 m/s

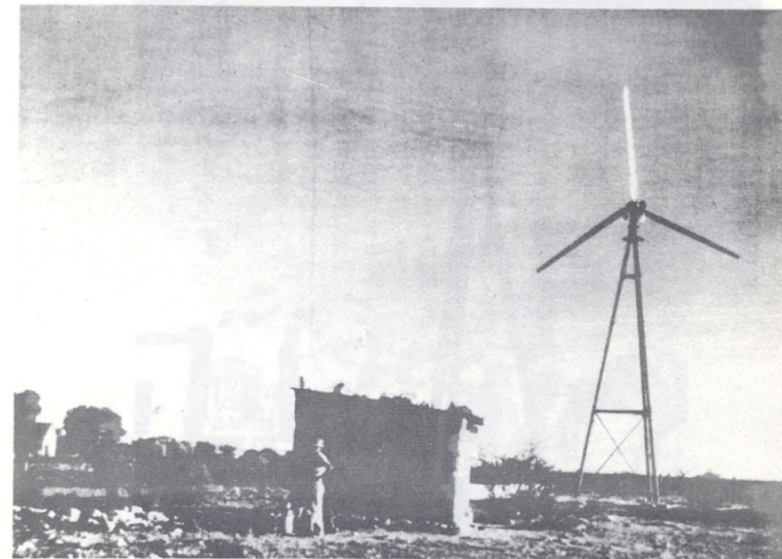


Figure 6 ALLGAIER/HOTTER 6 KW standard unit on Becker's farm, Gungams, Southwest Africa, 1951



Figure 7 ALLGAIER/HOTTER wind energy converter, Africa

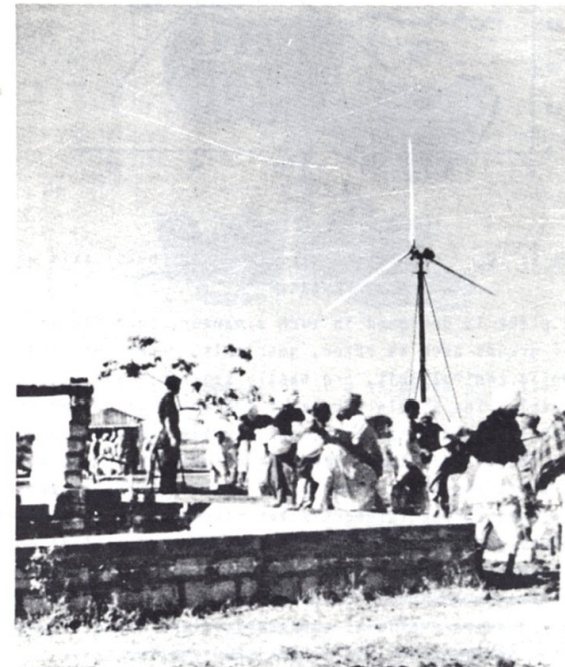


Figure 8 ALLGAIER/HOTTER WE 10 Installation for waterpumping, India 1960



The power coefficient-characteristic is shown in Figure 9.

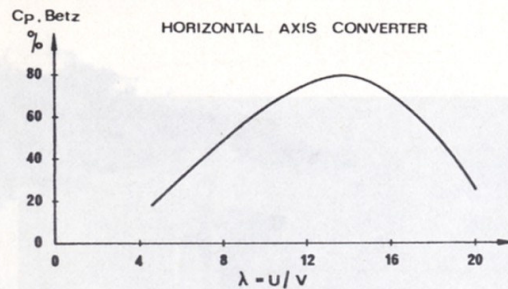
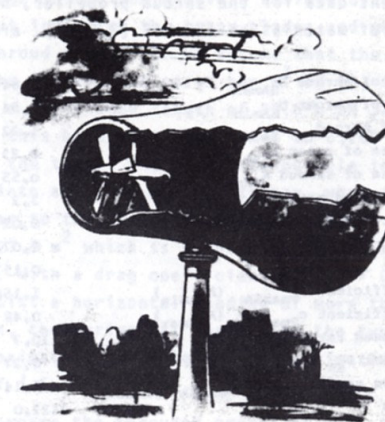


Figure 9:  $C_p$  - characteristic for a horizontal axis wind energy converter

The plant is designed in such a manner, that the single module groups such as rotor, gear unit, generator, and automatic control unit, are easily separable and interchangeable. The single pieces of the tower are dimensioned so that no one has to handle parts which are too long or too heavy. This is of utmost importance for assembling, maintenance and transportation. The rotor blades are manufactured in glass-fibre reinforced plastics (GRP), thus guaranteeing a virtually unlimited fatigue life. Each rotor blade of 5.64 m length weighs 20 kg and costs, in mass production, approximately DM 800. This price was investigated by sail-plane producers and is an empirical value. The price for the gear unit (1,500/100) is DM 1,800 and for the 6 kW generator DM 3,760. The tower of the WEC, built of reinforced concrete, is about 10 m high, weighs 2500 kg, and resists a horizontal load of 1000 kg acting on the top. Production at the installation site is possible. In mass production the cost is DM 1,100 per unit. If we use a steel tube as a tower with the same loading, the weight is only 550 kg, but the price scales up to DM 1,500. With this rough calculation of costs, a horizontal axis converter could be mass-produced for between DM 15,000 and 18,000. The specific price per kW would be, therefore, approximately DM 2,500 to 3,000.

### Shrouded Propeller (Aerogenerator) (SA)



(Figure 10: Artist's impression of a shrouded propeller)

An idea which is continually appearing is to encase turbines with a large tube to extract from the airflow a higher performance per unit area of the rotor. (2) The equation found by BETZ explains the performance of a free-running turbine in terms of the axial momentum loss of the airflow. Radial forces are neglected, an assumption which is permitted for the free-running turbine. The shroud profile produces an additional circulation around the shroud, inducing a supplementary velocity in the rotating area. These vortices also cause a higher flow rate.

If we choose the right airfoil section for the shroud, we can extract more than twice as much energy from the airflow as from a free-running turbine. Certainly these profiles are sensitive to flow separation. Detailed examinations in this field of research were made by Ozer IGRA in March 1975. (3) In these experimental tests the rotor was simulated by a sieve. The simple shroud with an airfoil NACA 4412 had a rotor diameter of 64 per cent of the maximal diameter and its length was 1,449 times the diameter. The maximum power coefficient, related to the throat of the shroud, reached the value of 1,156.



The equivalent data for the shroud propeller, built of the same area of material as the HAC ( $3.2 \text{ m}^2$ ), are:

diameter of shroud $D_{SAmax}$	0.84 m
diameter of throat $D_{SAmin}$	0.54 m
length of shroud $l_{SA}$	1.22 m
swept area of rotor $A_{SAmin}$	0.23 $\text{m}^2$
swept area of shroud $A_{SAmax}$	0.55 $\text{m}^2$
area of shroud material $F_{SA}$	3.2 $\text{m}^2$
output at 5.6 m/s wind velocity	0.027 KW
output at 7.7 m/s "	0.072 KW
output at 10.0 m/s "	0.157 KW
power coefficient $c_{PmaxSA} (A_{SAmin})$	1.156
power coefficient $c_{PmaxSA} (A_{SAmax})$	0.48
at tip speed ratio $\lambda_{maxSA}$	10.7
area number $F_{SA} = A_{SA} \cdot c_{PmaxSA}$	0.27 $\text{m}^2$
comparison number $V_{SA} = \lambda_{maxSA} \cdot c_{PmaxSA}$	5.14
rotor rpm	2122.0
at rotor tip velocity maximum	60.0 m/s

If we want the same output at 5.6 m/s wind velocity as we obtain from the HAC, the data for a shrouded propeller are:

diameter of shroud $D_{SAmax}$	9.38 m
diameter of throat $D_{SAmin}$	6.00 m
length of shroud $l_{SA}$	13.60 m
swept area of rotor $A_{SAmin}$	28.27 $\text{m}^2$
swept area of shroud $A_{SAmax}$	69.10 $\text{m}^2$
area of shroud material $F_{SA}$	400.77 $\text{m}^2$
ratio $D_{SAmin}/D_{SAmax}$	0.64
output at 5.6 m/s wind velocity	3.3 KW
output at 7.7 m/s wind velocity	8.8 KW
output at 10.0 m/s "	19.3 KW
power coefficient $c_{PmaxSA} (A_{SAmin})$	1.156
power coefficient $c_{PmaxSA} (A_{SAmax})$	0.48
at tip speed ratio $\lambda_{maxSA}$	10.7
rotor rpm	191.0
at rotor tip velocity maximum	60.0 m/s

This large shroud would have a surface of material of  $400 \text{ m}^2$ , not including the rotor blades and mounting vanes for the shroud itself. If we assume that the shroud structure weighs  $8 \text{ kg/m}^2$  and costs per  $\text{m}^2$  DM 10, this tube will cost with a calculated length of 13.6 m DM 32,000. The weight of this huge apparatus comes to 3,200 kg. To dimension the tower, the most unfavourable loading case must be taken into account, that is to say, when the air flows rectangular to the shroud's axis. Thereby we have a swept area of  $127.5 \text{ m}^2$  which is exposed to an assumed wind velocity of 60 m/s. With a drag coefficient of  $c_{DR} = 0.5$  the tower has to resist a horizontal loading of more than 13 tons. In comparison, the horizontal loading of the two-blade HAC is only approximately 1,000 kg with an estimated drag coefficient of 1.5.

If we compare the shrouded propeller with the free running turbine, we have to refer the power coefficient to the shroud's largest diameter and not to the throat diameter. In this case, the redefined power coefficient is  $c'_{PmaxSA} = c_{PmaxSA} A_{SAmin}/A_{SAmax} = 0.48$ . It is obvious that, if we refer the power coefficient to the largest diameter of the shroud, the SA works with the same power coefficient as the HAC. The expense in material for the shrouded propeller (125 times the area of material for the two-blade HA rotor) is absolutely beyond discussion. The tower structure has to sustain more than ten times the horizontal loading of the HAC.

For completeness it should be said that, with ring-flaps mounted at the outlet of the shroud, the power coefficient can be raised up to 1.42 with reference to the throat diameter, but only to 0.165 with reference to the largest diameter (flaps extended). The immense consumption of material for this design is even less suitable to extract energy economically from the airflow.

#### The SAVONIUS Rotor (SR)

In 1929 the Swede SAVONIUS developed a special type of rotor (4). Two or three vanes are fixed between two end



plates in such a manner that a slot remains between them. The rotor axis is vertical. The airflow acts upon the vanes in such a way that a high pressure area is created on the concave side and a low one on the convex side. It seems at first as though the SAVONIUS rotor works on the principle of drag utilization, as for instance, the cup-anemometer. Exact examinations have shown that the SAVONIUS rotor can reach a tip speed velocity above unity, because there exists an additional circular flow which increases the tip speed velocity.

If the vanes are formed in a special way a power coefficient of  $c_{pmaxSR} = 0.23$  (Figure 11) can be obtained. The SAVONIUS rotor is a low speed rotor. The construction needs a large area of material and therefore this rotor is expensive.

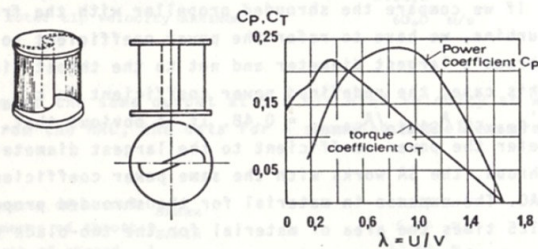


Figure 11:  $c_p$  and  $c_t$  - characteristics of a SAVONIUS rotor

If a SAVONIUS rotor is built with diameter equal to height and the same area of material is used as for the two-blade HAC, the following data result from the calculation:

diameter equal height of SAVONIUS rotor $D_{SR}$	0.96 m
swept area of SAVONIUS rotor $A_{SR}$	0.92 m <sup>2</sup>
area of SAVONIUS vane material $F_{SRV}$	1.746 m <sup>2</sup>
area of SAVONIUS end plate material $F_{SRE}$	1.448 m <sup>2</sup>
area of SAVONIUS rotor material $F_{SR}$	3.2 m <sup>2</sup>
output at 5.6 m/s wind velocity	0.022 KW
output at 7.7 m/s	0.057 KW
output at 10.0 m/s	0.125 KW
power coefficient $c_{pmaxSR}$	0.23
at tip speed ratio $\lambda_{maxSR}$	0.85
area number $P_{SR} = A_{SR} \cdot c_{pmaxSR}$	0.21 m <sup>2</sup>
comparison number $V_{SR} = \lambda_{maxSR} \cdot c_{pmaxSR}$	0.196
rotor rpm at 10.0 m/s wind velocity	176.5
at rotor tip velocity	8.5 m/s

A similar SAVONIUS rotor, but with the same output as the HAC, at a wind velocity of 5.6 m/s, must have these data:

diameter equal height of SAVONIUS rotor $D_{SR}$	11.76 m
swept area of SAVONIUS rotor $A_{SR}$	138.30 m <sup>2</sup>
area of SAVONIUS vane material $F_{SRV}$	260.70 m <sup>2</sup>
area of SAVONIUS end plate material $F_{SRE}$	217.20 m <sup>2</sup>
area of SAVONIUS rotor material $F_{SR}$	477.90 m <sup>2</sup>
output at 5.6 m/s wind velocity	3.30 KW
output at 7.7 m/s wind velocity	8.57 KW
output at 10.0 m/s	18.77 KW
power coefficient $c_{pmaxSR}$	0.23
at tip speed ratio $\lambda_{maxSR}$	0.85
rotor rpm at 10 m/s wind velocity	13.8
at rotor tip velocity	8.5 m/s

The weight of the SAVONIUS rotor would be nearly 3,000 kg for a metal structure. The price at 8 kg/m<sup>2</sup> and 10DM/kg material would be about DM 30,000. This price for the rotor alone makes this system unsuitable for a converter with this range of performance. The resulting drag on the rotor in a heavy storm (60 m/s) at a standstill would be approximately 14.4 tons, assuming a drag coefficient of  $c_{DR} = 0.5$  (as for a tube). The control of the SAVONIUS rotor is electronic so



that  $\lambda$  is constant and rpm variable. It would therefore be best to produce direct current, if any.

#### The Vertical Axis Converter (VAC)

In the year 1925 the Frenchman Darrieus took out a patent for a windmill with vertical axis. Today this concept is propagated vehemently by several institutions. Besides the NASA Langley Research Center and the European Company VFW/FOKKER in Amsterdam, the National Research Council Canada (NRC) is mainly engaged in the high-speed vertical axis converter. This institution has also published some experimental data (5,6,7). For the comparison carried out here, the papers of Peter South and Ray Rangi were used. (Figure 12) Comprising two blades, two bearings and a shaft, the vertical axis rotor was posed as the optimal system. The two-blade vertical axis rotor has constant chord, symmetric airfoil blades with their span parallel to the axis. A simple calculation shows that a high-speed rotor with straight rigid blades parallel to its axis of rotation would be subjected to a very high bending moment due to centrifugal forces and would necessitate extensive bracing. A perfectly flexible blade, on the other hand, under the action of the centrifugal and aerodynamic forces, would conform to a shape in which the only stresses would be tensile. The resultant shape of the blade would then be approximately a catenary. Hence, if we curve the blades into the form of the catenary, the bending stresses will be negligible. For simplicity of manufacture, a constant chord blade has distinct advantages and since the blades comprise the major cost item in the rotor, it is reasonable to assume that the cost of the rotor is proportional to the length of the blade. The blades of the NRC rotor model with 30" diameter were extruded from aluminum and are NACA 0012 (symmetric) airfoils of 1" chord length. Later the rotor blades for the 14 ft. diameter rotor were made from cold rolled sheet steel and were also approximately NACA 0012 with a 6" chord = 0,1525 m =  $t_{VAC}$ .

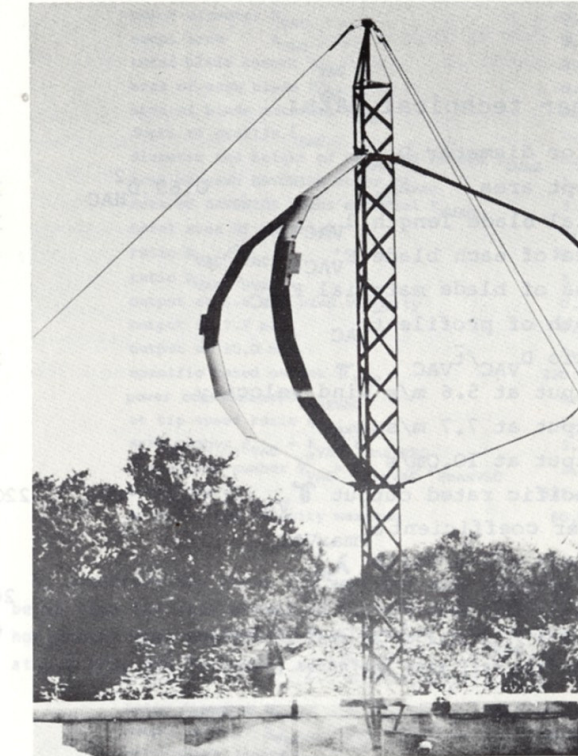


Figure 12 Three-blade vertical-axis-turbine

that is constant and rpm variable. It would therefore be best to produce direct current, if any.

#### The Vertical Axis Converter (VAC)

In the year 1925 the Franchman Savonius took out a patent for a vertical axis converter. The converter was a vertical axis converter with two Savonius rotors. The converter was a vertical axis converter with two Savonius rotors.

#### Further technical data:

rotor diameter $D_{VAC}$		4.27 m
swept area $A_{VAC}$	$0.69 D_{HAC}^2$	$12.58 \text{ m}^2$
total blade length $l_{VAC}$		12.74 m
area of each blade $F'_{VAC}$		$0.97 \text{ m}^2$
area of blade material $F_{VAC}$		$1.94 \text{ m}^2$
depth of profile $\bar{t}_{VAC}$		0.15 m
ratio $D_{VAC}/\bar{t}_{VAC}$		28
output at 5.6 m/s wind velocity		0.493 KW
output at 7.7 m/s "		1.254 KW
output at 10.0 m/s "		2.783 KW
specific rated output $\pi_{VAC}$		$220 \text{ W/m}^2$
power coefficient $c_{PmaxVAC}$		0.37
at tip speed ratio $\lambda_{max}$		6.0
rotor rpm		268.0
at rotor tip velocity maximum		60.0 m/s

To build a vertical axis converter with the same area of material as the horizontal axis converter ( $3.2 \text{ m}^2$ ), the comparative rotor has the following technical data (including two SAVONIUS rotors for starting):

rotor diameter $D_{VAC}$	2.89 m
swept area $A_{VAC}$	$5.76 \text{ m}^2$
total blade length $l_{VAC}$	8.62 m
area of each blade $F'_{VAC}$	$0.444 \text{ m}^2$
area of blade material $F_{VAC}$	$0.888 \text{ m}^2$
depth of profile $\bar{t}_{VAC}$	0.103 m
diameter and height of SAVONIUS rotors $D_{SVAC}$	0.58 m
area of each SAVONIUS rotor $F'_{SVAC}$	$1.156 \text{ m}^2$
area of SAVONIUS rotor material $F_{SVAC}$	$2.312 \text{ m}^2$
total area of material	$3.2 \text{ m}^2$
ratio $D_{VAC}/\bar{t}_{VAC}$	28
ratio $D_{VAC}/D_{SVAC}$	5
output at 5.6 m/s wind velocity	0.221 KW
output at 7.7 m/s "	0.574 KW
output at 10.0 m/s "	1.257 KW
specific rated output $\pi_{VAC}$	$220 \text{ W/m}^2$
power coefficient $c_{PmaxVAC}$	0.37
at tip speed ratio $\lambda_{maxVAC}$	6.0
area number $P_{VAC} = A_{VAC} \cdot c_{PmaxVAC}$	$2.13 \text{ m}^2$
comparison number $V_{VAC} = \lambda_{maxVAC} \cdot c_{PmaxVAC}$	$2.22 \text{ m}^2$
rotor rpm	325.0
at rotor tip velocity maximum	60.0 m/s

To ascertain how large the vertical axis converter must be to gain the same output at 5.6 m/s wind velocity as the horizontal axis converter, that is to say,  $L_{VAC} = 3.3 \text{ kW}$  at 5.6 m/s, the following technical data list applies:

rotor diameter $D_{VAC}$	11.17 m
swept area $A_{VAC}$	$86.08 \text{ m}^2$
total blade length $l_{VAC}$	33.32 m
area of each blade $F'_{VAC}$	$6.645 \text{ m}^2$
area of blade material $F_{VAC}$	$13.29 \text{ m}^2$
depth of profile $\bar{t}_{VAC}$	0.3989 m
diameter and height of SAVONIUS rotors $D_{SVAC}$	2.23 m
area of each SAVONIUS rotor $F'_{SVAC}$	$17.19 \text{ m}^2$
area of SAVONIUS rotor material $F_{SVAC}$	$34.38 \text{ m}^2$
total area of material	$47.67 \text{ m}^2$
ratio $D_{VAC}/\bar{t}_{VAC}$	28
ratio $D_{VAC}/D_{SVAC}$	5



output at 5.6 m/s wind velocity	3.3 KW
output at 7.7 m/s	8.579KW
output at 10.0 m/s	18.791KW
specific rated output $\pi_{VAC}$	220 W/m <sup>2</sup>
swept area of SAVONIUS rotors $A_{SVAC}$	9.95 m <sup>2</sup>
rotor rpm	102.6
at rotor tip velocity maximum	60.0 m/s

At this point a decisive problem occurs. The VAC is not self-starting. For running up this rotor needs a value of  $\lambda$  of approximately 2.6 to reach  $\lambda = 6$  and to rotate in the optimum of  $c_{pmaxVAC} = 0.37$ . If the wind velocity changes, the electronic control keeps the rotor always in the optimum point of  $c_p$ . To obtain constant rpm of the rotor shaft, the VAC has to operate with a very low, average power coefficient. This results from the distinct peak of the  $c_p - \lambda$  curve. (Figure 13)

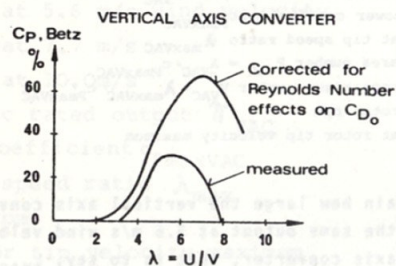


Figure 13:  $c_p$  - characteristic of a vertical axis converter

The fact that this rotor has no self-starting property, is of importance. It is necessary to establish an auxiliary drive to bring the VA rotor to sufficient rpms. At this moment the rotor turns faster and faster and in our example you can, for example, gain 3.3 kW at 5.6 m/s wind velocity. Until now the self-starting has been effected with two SAVONIUS rotors mounted at the top and the bottom of the rotor, near the bearings. For these two SAVONIUS rotors we need about 34 m<sup>2</sup> of additional material, that is to say, additional to the

blade material with an area of 13.29 m<sup>2</sup>. The diameter equal to the height of the SAVONIUS rotor is 2.23 m or approximately 20 per cent of the VAC diameter. The electronic control to  $\lambda = \text{constant}$  and therefore changing rpm points to the production of direct current. A generator for direct current with 1,500 rpm and an output of 6 kW costs DM 2,700.

The costs of extruded airfoils made from aluminum with a chord of 150 mm amount to 6 DM/kg with a 2.1 kg/m long rotor blade. The two-blade rotor for the NRC VAC with a diameter of 4.27 m would cost roughly DM 160.

The cost estimate for the comparative VAC shows that for an extruded airfoil a chord of 400 mm the weight is 15 kg/m blade length. The price for the two-blade rotor with a total blade length of 33.32 m would be nearly DM 3,000. The weight is 500 kg. If the extruded rotor blade is changed into a shell structure, we can estimate the following construction (Figure 14): The leading edge of the profile is an extruded spar from aluminum. The aft part of the section has

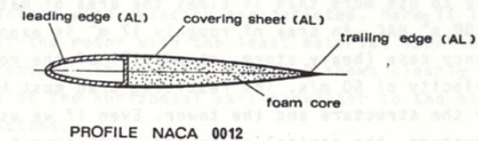


Figure 14: Possible structure of an airfoil section (8)

a foam core with a covering of Al-sheet. The trailing edge is also of aluminum. This structure weighs about 6.6 kg/m for an airfoil NACA 0012 with 400 mm chord length. Therefore this rotor weighs 223 kg. The price for this weight-saving-construction is estimated very low at 15 DM/kg. This means the VA rotor with the same output as the HA rotor would cost DM 3,350. If glass-fiber reinforced plastics are to be used for this rotor, the weight would diminish to 5 kg/m (400 mm chord). The total rotor weight is 170 kg but it costs at 40 DM/kg approximately DM 6,700. Additionally

there is the expense of the two SAVONIUS rotors, roughly DM 5,000 for 34 m<sup>2</sup> surface (GRP) and a weight of 85 kg each (2,700 DM for a metal structure, 136 kg each).

The necessary gear unit must have a gear ratio with the factor 2 compared with the gear unit for the HAC. The price for this larger unit amounts to DM 2,200.

For the tower we assume the same price as for the HAC although an additional part is needed with the length of half a diameter. Neither this increase of cost, nor the cost for an airbrake or for control flaps and the actuating rods, nor the cost for the disconnection mechanism of the SAVONIUS rotors have been taken into account.

The HA rotor with its simple automatic shifting into the wind, side governor wheel and single step back gearing and self-locking worm, never approaches this increase in cost.

The VAC is not self-starting. Below a wind velocity of approximately 5 m/s there is no output. To obtain at a wind-velocity of 5.6 m/s the same output as from the HAC, we would have to use more than 14 times the area of material as for the 100 m<sup>2</sup> HAC. An area of roughly 17 m<sup>2</sup> is exposed in an emergency case (heavy storm, standstill of the rotor) to a wind velocity of 60 m/s. The resulting drag must be supported by the structure and the tower. Even if we use a metal structure, the capital costs for a VAC cannot be reduced to the level of the HA rotor costs in GRP. If we were to take a composite rotor blade, the VA rotor would be 5 times more expensive compared with the 6 kW HAC. With regard to the fatigue life, a metal structure is not acceptable. In developing countries areas with an average wind velocity of more than 5 m/s are not found very often. Therefore with the technical standard of today it is not possible to employ the VAC economically.

### Conclusion

The history of western America, southern Africa, and many islands in the Mediterranean shows the outstanding role wind energy plays at the beginning of the development of an area. In semiarid areas where the density of energy requirement is initially very low, the energy transfer costs are so important that the WEC is in many cases, for example for waterpumping and electricity supply (light, communication, cooking, cooling), the most economic solution. The energy transportation costs include naturally the transportation of the energy carrier substance (e.g., oil barrel transportation with pack animals).

The next figure (Figure 15) shows clearly the comparison between the described WEC rotor systems with respect to the same area of material. It also indicates the proportions and the very different swept areas through which energy can be extracted from the airflow. The last figure (Figure 16) demonstrates obviously the other possible comparison. The four rotor systems and their dimensions for the same output at a certain wind velocity are depicted. Here it is evident too that the rotor with the least material expense is the most economic. The quality number Q shows clearly the superiority of the horizontal axis converter to the other examined systems.

The existing opportunity should be taken up by developed and developing countries. The former can give the knowhow, and the others can satisfy vital energy needs. This, with the aid of their own energy, will bring progress in all countries.



Comparison of different WEC rotor systems constructed with the same surface of material ( $3.2 \text{ m}^2$ ) at a wind velocity of  $5.6 \text{ m/sec}$ .

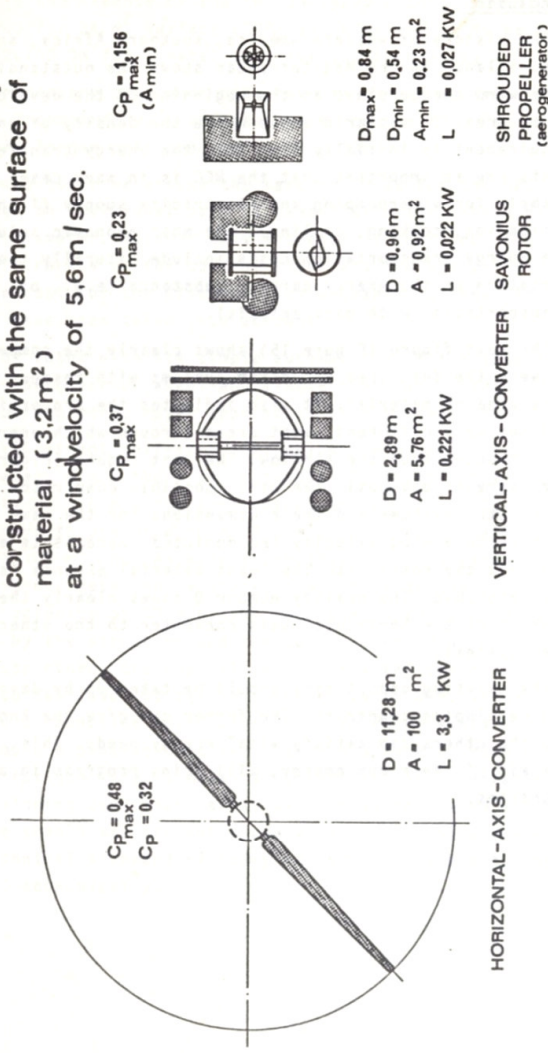
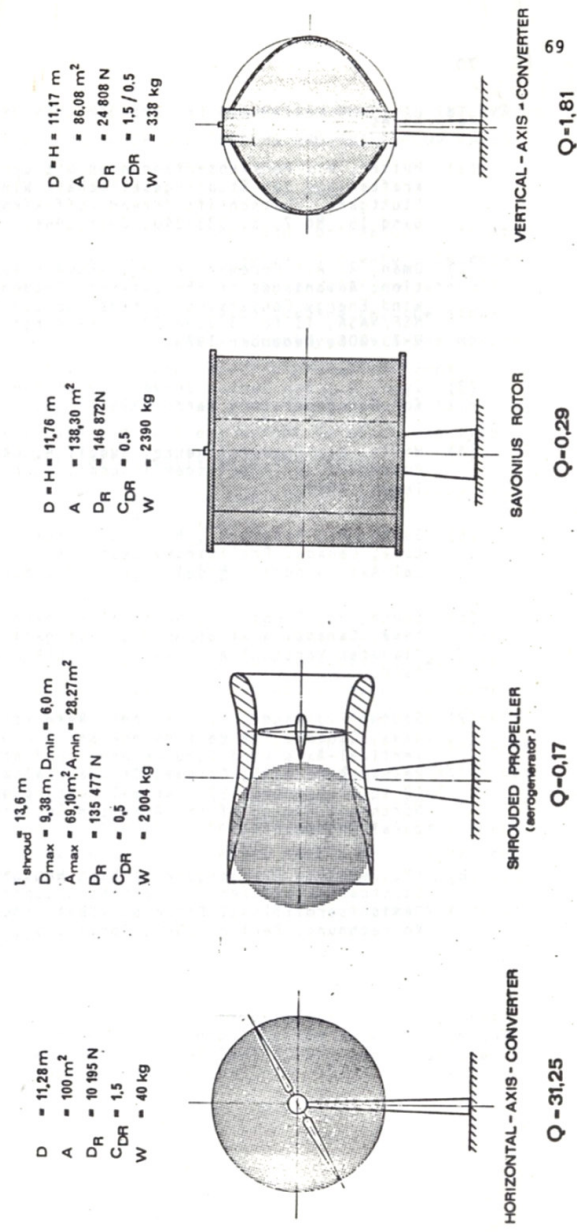


Figure 15

Comparison of different WEC rotor systems, output  $3.3 \text{ KW}$  at  $5.6 \text{ m/sec}$ . wind velocity; drag (DR) at  $60 \text{ m/sec}$ .; rotor weight (W) structure in GRP, quality number (Q) = swept area A / area of material F.



# References

- (1) Hütter, U.; Betriebserfahrungen mit der 100 KW-Windkraftanlage der Studiengesellschaft Windkraft e.V. Stuttgart. Zeitschrift "Brennstoff-Wärme-Kraft", Band 16, No 7, S. 333-340, Juli 1964.
- (2) Oman, R. A.; Foreman, K. M.; Grumman Aerospace Corporation; Advantages of the Diffusor-Augmented Wind Turbine. Wind Energy Conversion Systems, Workshop proceedings NSF/NASA, 11 to 13 June 1973, Washington, D.C., NSF/RA/W-73-006, December 1973.
- (3) Igra, O.; Ben Gurion University of the Negev; Shrouds for Aerogenerator; March 1975.
- (4) Witte, H.; Windkraftwerke. Rudolf A. Lange Verlag, Possneck, in: Arbeitsgemeinschaft Thüringischer Verleger, 1950.
- (5) South, P.; Rangi, R.; National Research Council, Ottawa, Canada. Preliminary Tests of a High-Speed Vertical Axis Windmill Model. LTR-LA-74. March 1971.
- (6) South, P.; Rangi, R.; National Research Council, Ottawa, Canada. A Windtunnel Investigation of a 14-ft-diameter Vertical Axis Windmill. LTR-LA-105. September 1972.
- (7) South, P.; Rangi, R.; National Research Council, Ottawa, Canada. The Performance and Economics of the Vertical-Axis Wind Turbine Developed at the National Research Council, Ottawa, Canada. Calgary, Alberta, 10 to 12 October 1973. Annual Meeting of the Pacific Northwest Region of the American Society of Agricultural Engineering.
- (8) NN; Deutsche Studiengesellschaft Hubschrauber e.V. Stuttgart-Flughafen. Lastenhubschrauber L-21 und L-31 Gewichtsermittlung, Schwerpunktbestimmung und stat. Vorrechnung. Bericht 28-3, April 1957.