LS-WECS
CO-OPERATION IN THE DEVELOPMENT OF LARGE SCALE WIND ENERGY CONVERSION SYSTEMS

SECOND ANNUAL REPORT (1979)

A Report of the Executive Committee of the Implementing Agreement for Co-Operation in the Development of Large Scale Wind Energy Conversion Systems
IEA
International Energy Agency

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FOR COOPERATION IN THE DEVELOPMENT
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A report of the Executive Committee of the
Implementing Agreement for Cooperation in the
Development of Large Scale Wind Energy Conversion
Systems

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on behalf of the Federal Minister of Research and Technology

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1. FOREWORD

The first annual report (1978) on the implementing agreement for co-operation in the development of large scale wind energy conversion systems (LS WECS) includes not only the report of the actual national activities in the four participating countries Denmark, Germany, Sweden and the United States. Furthermore, the general possibilities and limitations of LS WECS are evaluated basically and in more detail. Fundamental or rapid changes in these evaluations are not expected. Therefore the executive committee (EC) of the LS WECS agreement decided to concentrate the annual report on the actual status of the co-operation and the development of the LS WECS in the four countries. These activities should be summarized on the basis of the four national reports in an annual report of the EC to the IEA. This is the aim of the annual report 1979.

2. STATUS OF COOPERATION

2.1 At the two annual EC meetings

Copenhagen        April 3, 1979
Washington        November 2, 1979
detailed information on the national LS WECS activities was exchanged. The minutes of these meetings were distributed among the EC members and to the IEA secretariat.

2.2 The LS WECS Expert Committee which was installed by the EC as an additional subsidiary body of experts in 1978 carried through the following two meetings

Copenhagen, April 3/4, 1979
"Control of LS WECS and adaptation of wind electricity to the network"

Blowing Rock, North Carolina, USA, Sept. 26/27, 1979
"Data Acquisition and Analysis for LS WECS".

2.3 The EC meeting in Washington was held in connection with the Fourth Biennial Conference and Workshop on WECS from October 28 to 31. The primary objectives of this conference were to

- discuss the progress and significant results of the research and development activities in the US Federal wind energy programme and in the programmes of other countries,
- facilitate the exchange of information and the transmittal of new ideas relating to WECS technology.

Concerning the LS WECS the discussion and feedback on issues related to this field were intensive. Furthermore, most of the LS WECS EC members took the opportunity to visit the 2 MW MOD1 WECS at Boone, North Carolina.
3. DESCRIPTION OF THE ACTIVITIES IN THE PARTICIPATING COUNTRIES

3.1 Denmark

The year 1979 was the third year of the wind power programme of the Ministry of Energy and the electric utilities in Denmark. In 1979 the main efforts were concentrated on the continuation of the ongoing projects, so only a few new activities became initiated.

Objectives

The purpose of the Danish large scale wind energy development programme is through measurements and operational experience to increase the knowledge on technology and economy of wind power, and to search for practical solutions for some of the technical problems.

In 1979 the programme was composed of the following projects (ref. 1, 2 and 3):

- the final testing of the refurbished 20 years old Gedser turbine. (This project is carried out in cooperation with US Department of Energy.)

- the construction and initial operation of two new WECS, the Nibe windturbines.

- a test programme for the new WECS

- investigation of the prospect of wind energy in the electricity supply system with special concern to environmental aspects

- theoretical investigations concerning aerodynamics etc.
Management

The programme is carried out by the Danish electric utilities with DEFU, The Research Association of the Danish Electricity Supply Undertakings, as programme coordinator. The total programme budget for 1977 - 80 is 36 mill. Dkr. (about 7 mill. US $), of which 28 mill. Dkr. is sponsored by the Ministry of Energy, 6,7 mill. Dkr. is sponsored by the utilities and 0,8 Dkr. is a contribution from US DOE to the Gedser test project.

Plants

The 200 kW Gedser wind turbine (ref. 4) is 24 m high and with a rotor diameter of 24 m. It represents with the three blades, the stall controlled upwind rotor and the brake flaps a quite different design philosophy than most recent foreign designs. The turbine has been in limited operation from 1977 to April 1st 1979, but is now again stopped, because of the high operational costs for this single, old turbine.

The two new 630 kW machines - the Nibe windturbines - have the following main data:

- 3-bladed upwind horizontal axes rotor, rotor diameter 40 m
- Blade tip speed 71 m/s
- Rotor revolution 34 rpm
- Blades with steel (inner 8 m) and fiberglass spars and fiberglass sheets
- 3-step gearbox, ratio about 1:44
- 630 kW induction generator (connected to the local medium voltage grid)
- Concrete tower, hub height 45 m.
The main difference between the two systems is in the rotor design and control. The first rotor has a stayed hub and a limited range of pitch control (fig. 1), the other is designed without stays and has a fully pitch change mechanism.

With normal operation, the expected annual production of each turbine will be about 1.5 mill. kWh, corresponding to an annual fuel reduction of about 300 tons of oil.

Results

The results of the Gedser turbine test programme is reported in ref. 4. This report describes both the experiences with the testing procedure and the testing equipment - experiences, which are now utilized in the design of the test programme for the Nibe windturbines - and the experiences concerning the load on the response of the windturbines, - information which will be compared to corresponding information from the new Danish and foreign windturbines.

The first of the new Nibe windturbines was connected to the electricity grid for the first time on September 11th 1979 and had in the following weeks several successful runs at both high and low wind speed. Because of problems with the main supplier, the turbine has been standing still in the last quarter of 1979, but is expected to be operational again in the beginning of January 1980. The second Nibe windturbine is expected to be put on the grid for the first time in February 1980.

References

3.2 Germany

As already described in the first annual report 1979, the German LS WECS activities are covered by the GROWIAN programme. The aims of this programme are the development and testing of LS WECS up to the MW scale for electricity production while also assessing the technical, economic and institutional requirements for their widespread use, and stimulating their commercial utilization. In 1979, the GROWIAN programme came up to about 25 projects. Beside the development, construction and testing of LS WECS these projects also cover measurements of the wind characteristics for LS WECS, the development of large rotor blades, research for a better control of system vibrations and profitability analysis. Some of these projects are now finished. They support the basic assumption that the utilization of wind energy by LS systems is one of the promising ways of using renewable energy sources in Germany.

In particular, one of the important projects "Elaboration of final plans for GROWIAN I", showed that advanced LS WECS in the MW scale range could be technically realized. Fig. 2 shows a view of GROWIAN I which has the following system data:

- Two-blade rotor with pendulum hub
- Down wind operation
- Blade construction: steel-spar design with glassfiber
airfoil
- Single guyed tower
- Controlled orientation of the nacelle and rotor into the wind

Performance
- Rated capacity 3 MW
- Mean annual energy output 12 GWh
- Power-to-area ratio 380 W/m²

Wind
- Rated wind speed 11.8 m/s
- Cut-in speed 6.3 m/s
- Cut-out speed 24 m/s

Dimensions
- Rotor diameter 100 m
- Rotor speed 18.5 rpm ±15%
- Hub height above ground 100 m
- Mass of tower head with rotor 240 t

The following phase of the GROWIAN I project "Construction and test of GROWIAN I" started in 1979. The contractor is the GROWIAN-Bau und Betriebsgesellschaft mbH, a company consisting of the three German electrical supply utilities HEW, RWE and Schleswag. The plant will be operated at the Kaiser-Wilhelm-Koog which is located at the mouth of the river Elbe near the North Sea. At this location, the plant, which has a hub height of 100 m, will operate at rated capacity 27% of the time; 48% of the time the
output falls below the rated capacity. The basis of these calculations was the study "Wind conditions in the Federal Republic of Germany in view of the use of the wind energy" carried out by the German Meteorological Service. The mean annual energy output of GROWIAN will be 12 GWh.

First promising results were also produced in 1979 by projects which run parallel to the GROWIAN I project. For example, the assessment of the technical and economic potential of wind energy for the Federal Republic of Germany was investigated by the University of Regensburg. This project was carried out in cooperation with the International Energy Agency (IEA) within the R+D/WECS agreement and will be extended to include other IEA countries. The investigation showed that the fuel savings and the capacity displacement of farms of LS wind power stations depend essentially on the penetration $p$;

$$p = \frac{N_{\text{wind}}}{N_{\text{conv}} + N_{\text{wind}}}$$

where $N$ denotes the total installed capacity of wind and conventional power plants. At a penetration of 5%, 10%, 15% the savings then amount to 4%, 9%, 14% of the fuel which would have been used without wind utilization. 1.7%, 2.6%, 3.2% of the conventional capacity can be displaced without increase in the loss-of-load probability. Furthermore, another result was that storage systems dedicated exclusively to the LS wind power system are not appropriate in the framework of a national electricity supply system.

Since summer 1978 a second, even more advanced LS WECS, called GROWIAN II, is under development. The contractor is Messerschmitt-Bölkow-Blohm GmbH (MBB), Munich. The objective of this project is the investigation of advanced concepts for larger WECS in the class of 135 m diameter, which corresponds to an electrical output of 5 MW, at approximately 11 m/sec wind velocity. The construction and testing of a scaled demonstration plant with a scale factor
of appr. 1/3 are important elements of this project, which will end with the preparation of the manufacturing documentation for a 1/1 prototype plant autumn 1981. Fig. 3 shows the concept which was chosen in 1979. GROWIAN II will be a single blade rotor with horizontal axis and a rotor diameter of 145 m. The hub height will be 110 m. The 5 MW-power will be produced at a wind speed of 11.3 m/sec. The results of dynamics/stability analysis, performed so far, show that this system is stable and sufficiently damped for tolerable stresses.

Looking further into the future, the study "Preparation of a final design and construction of a prototype atmospheric-thermal up-wind power plant" will be mentioned. The detailed investigations showed that even LS-power stations in the 10 - 100 MW range can be constructed with today's technology and that the largest power station will work most economically. For a 100 MW wind power station the investment costs were estimated to be 2000 DM/kW. An artist's view of such an atmospheric thermal up-wind power plant is shown in Fig. 4. In 1980 a 100 kW-experimental plant will be tested.

3.3 Sweden

Contracts for design, manufacture and installation of WECS prototypes were placed with Karlskronavarvet (KKRV) in July 1979 and with Karlstads Mekaniska Werkstad (KMW) in September 1979.

The main contractor for the first prototype (see Fig. 5) is the Karlskrona Shipyard and Hamilton Standard as a sub-contractor. The wind turbine is a two-bladed, horizontal axis system having the following main features:
<table>
<thead>
<tr>
<th>Feature</th>
<th>First Prototype</th>
<th>Second Prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>3 MW</td>
<td>2 MW</td>
</tr>
<tr>
<td>Turbine diameter</td>
<td>78 meters</td>
<td>75 meters</td>
</tr>
<tr>
<td>Hub height</td>
<td>80 meters</td>
<td>80 meters</td>
</tr>
<tr>
<td>Hub type</td>
<td>Tiltered</td>
<td>Rigid</td>
</tr>
<tr>
<td>Turbine placement</td>
<td>Downwind</td>
<td>Upwind</td>
</tr>
<tr>
<td>Blade material</td>
<td>Epoxy - GRP composite</td>
<td>Steel + epoxy - GRP</td>
</tr>
<tr>
<td>Tower material</td>
<td>Steel</td>
<td>Concrete</td>
</tr>
<tr>
<td>Generator type</td>
<td>Synchronous</td>
<td>Induction</td>
</tr>
<tr>
<td>Cut-in wind speed</td>
<td>6 m/s</td>
<td>6 m/s</td>
</tr>
<tr>
<td>Cut-out wind speed</td>
<td>21 m/s</td>
<td>21 m/s</td>
</tr>
<tr>
<td>$V_R - P_R$</td>
<td>13 m/s - 3000 kW</td>
<td>13 m/s - 2500 kW</td>
</tr>
</tbody>
</table>

The Karlstads Mekaniska Werkstad is the main contractor for the second prototype (see Fig. 6) with ERNO as a subcontractor. The main features of the two-bladed horizontal axis turbine are as follows:

Design work is proceeding according to plans. Several project meetings have been held with both contractors. Preliminary Design Reviews (PDR) are partly completed for both units, finalizing main data and design specifications. Final Design Reviews (FDR) will be held in February and March 1980.
Meteorological measurement towers are installed at both prototype sites. The met-tower at the Näsudden site on the island of Gotland (KMW site) is 150 meters high, the tower at the Maglarp site in the southern part of Sweden (KKRV site) is 120 meters. Both are instrumented at seven levels and have been giving wind and temperature data since early November 1979.

General time schedules are as earlier presented. Practical construction and installation work at the sites will begin late in 1980, with first rotation of the two units scheduled for the winter of 1981/82.

3.4 United States

The United States Department of Energy is committed to accelerating the development, commercialization and utilization of reliable and economically viable alternative energy systems.

In order to verify the compatibility of large Wind Turbine Generators (WTG) with electric utility distribution systems and obtain field data, integration of machines with utilities has been found necessary. Under the direction of L.V. Divone, Chief of Wind Systems Branch and the management of the National Aeronautics and Space Administration's (NASA) Lewis Research Center, the Federal Wind Energy Programme has progressed. There were several large wind turbine generators in operation or in planning as well as technological advancements during 1979.

The first MOD-OA (200 kW) WTG, Fig. 7, erected at Clayton, New Mexico and tied into an electric utility has been in operation since January 1978. By January 1979, the machine completed 3000 hours of operation and has generated 285,000 kWh of energy. In March, the fluid coupling (fig. 8) de-
Developed fatigue cracks and was replaced. During the year the blades were removed twice for repairs or modification, once without the use of a large crane. The pitch angle between the blades was changed and the control logic of the microprocessor was changed to increase annual energy yield. Several other changes were made, requiring shut-down of the machine, yet by November the unit had completed a total of 5700 hours of operation and had produced over 524,000 kWh of energy.

The second MOD-OA (200 kW) WTG (Fig. 9), erected at Culebra, Puerto Rico, was turned over to the local utility in January 1979. In May 1979 after 600 hours of operation and 83,600 kWh the machine was shut down to allow a complete blade inspection. The blade and hub were removed and replacement units substituted.

A third MOD-OA (200 kW), erected on Block Island, Rhode Island (Fig.10), was dedicated in June 1979. Due to the probability of interference with television reception a cable antenna system was approved for the homes on the island. Full scale operation of the machine has been delayed until the cable system is complete and operational.

A contract for a fourth and final MOD-OA (200 kW) was awarded to the Special Services Division of Westinghouse Electric Corp. and will be erected at Kahuku Point, on the island of Oahu, Hawaii. Site preparation was started in December, 1979.

During 1979, assembly was completed on the MOD-1 (2000 kW) at Boone, North Carolina, (Fig.11) by the General Electric Co., with first rotation in May and dedication in July. This is the largest wind energy system ever built. Synchronization was accomplished under manual control and full automatic operation in the 200-1500 kW range.
Measurements were made of television interference as well as noise levels at the site and at nearby homes. Additional studies are being initiated, particularly in the area of infra-sound. Procurement was initiated to provide systems for ice detection, crack detection and emergency braking. The machine will be subjected to additional acceptance testing before it is released to the utility company for normal operation.

Another significant accomplishment, during the year, was the acceptance of the final design review for the MOD-2 (2500 kW), (Fig. 12 / 13) with an estimated cost of electricity of less than 4c/kWh (100th unit in production). A decision was made to construct three machines (7500 kW) and locate them at a single site. Procurement was initiated for certain long lead items and electric utilities were invited to nominate sites for construction of the wind turbines. A site at Goodnoe Hills, Washington State was proposed by the Bonneville Power Administration and accepted by the Department of Energy.

Preparation of the site will begin in early 1980 with the first machine completion six months later.

Further developments, utilizing lessons learned on previous models, are planned in the forthcoming MOD-5 and MOD-6 wind turbines.

The objective of the MOD-5 project is to design, fabricate, and field test a nominal megawatt size wind turbine that can achieve a cost of electricity, for the 100th unit in production, of less than 3.5 ¢/kWh (capital and operating and maintenance costs in 1980 dollars) when operating at a site with an annual mean wind speed of 6.3 m/s (14 mph). Technical, management, and cost proposals have been received. Evaluation of proposals and contract negotiations
and award(s) are anticipated for first half of 1980.

The MOD-6 project is to design, fabricate, and field test an advanced, medium-scale wind turbine for application in utility network, farms, and industries. The project will explore innovative designs (both horizontal and vertical axis) optimized for minimum cost of energy and adapted for multiple applications. The requests for proposals will be released soon after a determination is made as to minimum performance required of the machine(s), possibly in the range of $2 \times 10^6$ kWh/yr.

In the areas of research and technology, in support of large wind turbine development, progress has been made to improve on the design and performance of existing machines. The turbine test bed (MOD-0) at Sandusky, Ohio, has been used to test concepts and hardware as well as to simulate the MOD-2 under construction.

Large leaf springs were added to the tower to simulate a 'soft' tower. The soft tower was found to be structurally and dynamically acceptable.

The rigid coned hub was replaced with a teetered non-coned hub. Testing of the new hub has resulted in finds that

- the measured and calculated teeter angles agree for steady wind conditions
- the measured teeter angle increases in turbulent winds
- yaw loads are reduced by a factor of ten
- blade loads are reduced by 30%
- loads during yaw are greatly reduced
- a major benefit is a smoother running wind turbine
- this configuration provides benefits of a 3-blade without an additional blade and lower RPM
Another modification of the test bed involved the replacement of the full-span pitch control rotor with a tip-control rotor. Testing of this change resulted in findings that:

- The tip control provides dual emergency shutdown as well as power and speed control
- The cost of pitch change mechanism and blade interface is reduced
- The cost and weight of large blades is reduced
- There appears to be little, if any, degradation in aerodynamic performance
- Startup in low winds is slightly more difficult
- Cyclic pitch reduced teeter angle

The desire to develop components with lower cost, improved reliability and increased energy capture prompted several positive actions. The search for a low cost blade included contracts to develop blades 60, 100 and 150 feet long made of various materials. A summary is provided in the following table:

<table>
<thead>
<tr>
<th></th>
<th>Weight</th>
<th>Second Unit</th>
<th>Production</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pounds</td>
<td>cost $/lb</td>
<td>cost $/lb</td>
</tr>
<tr>
<td>60'</td>
<td></td>
<td></td>
<td>100K</td>
</tr>
<tr>
<td>Aluminium</td>
<td>2.400</td>
<td>40 18</td>
<td>10 4-5</td>
</tr>
<tr>
<td>Wood</td>
<td>2.200</td>
<td>50 17</td>
<td>15 5</td>
</tr>
<tr>
<td>Fiberglass</td>
<td>3.000</td>
<td>75 25</td>
<td>12 4</td>
</tr>
<tr>
<td>Spot weld spar</td>
<td>3.000</td>
<td>55 15</td>
<td>30 8</td>
</tr>
<tr>
<td>Utility pole spar</td>
<td>3.600</td>
<td>50 17</td>
<td>15 5</td>
</tr>
<tr>
<td>60' Steel</td>
<td>20.900</td>
<td>500 24</td>
<td>- -</td>
</tr>
<tr>
<td>100' Fiberglass</td>
<td>23.000</td>
<td>300 12</td>
<td>130 5-6</td>
</tr>
<tr>
<td>150' Steel***</td>
<td>88.000</td>
<td>440 5</td>
<td>180 2</td>
</tr>
<tr>
<td>150' Fiberglass</td>
<td>41.000</td>
<td>410 10</td>
<td>185 4-5</td>
</tr>
</tbody>
</table>

* Design with wood ribs and razorback covering may reduce costs
** Includes hub
4. CONCLUSION

The objective and the scope of cooperation established in the Implementing Agreement for cooperation in the development of LS-WECS were successfully attained in 1979 by an intensive exchange of information through the EC Committee and the LS-WECS experts. In particular, each of the four contracting parties performed national projects on the design construction and operation of at least one LS-WECS with a rated power of approximately 1 MW or more. In 1979, first of these LS-WECS went into operation, the largest one with 2,500 MW in the United States (see figures).

All these LS-WECS projects follow the aim of the IEA countries to make new energy resources accessible technically, economically and environmentally. In 1979 the activities in the four participating countries demonstrated clearly that the utilization of the renewable energy source wind by LS-WECS could provide a new potential energy source.
Fig. 1. One of the Nibe Windturbines (with stayed hub).
Fig. 2: LS - WECS GROWIAN I,
3 MW at 11.8 m/sec, rotor diameter: 100 m
Fig. 3: LS - WECS GROWIAN II
5 MW at 11.3 m/sec, rotor diameter: 145 m
Fig. 4: LS Atmospheric - thermal up-wind power plant:
Artist's view of two 100 MW plants,
tower height: 600 - 800 m,
tower diameter: 100 m,
collector roof diameter: 3000 m
Fig 5 The prototype in southern Sweden built by Karlskronavarvet. Mounted on an 80 meter steel tower, the two-bladed turbine measures 78 meters in diameter and is made of epoxy - GRP composite. Rated power is 3 MW.
Fig 6 The prototype on the Swedish island of Gotland in the Baltic Sea built by Karlstads Mekaniska Werkstad. Mounted on an 80 meter concrete tower, the two-bladed turbine measures 75 meters in diameter and is made of steel and epoxy - GRP.
DOE/NASA 200kW EXPERIMENTAL WIND TURBINE

Fig. 7 Clayton, New Mexico
## 200 Kilowatt Wind Turbine Specifications

<table>
<thead>
<tr>
<th><strong>Rotor</strong></th>
<th><strong>Generator</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number of blades</strong></td>
<td><strong>Type</strong></td>
</tr>
<tr>
<td><strong>Diameter, ft</strong></td>
<td><strong>Rating, kVA</strong></td>
</tr>
<tr>
<td><strong>Speed, rpm</strong></td>
<td><strong>Power factor</strong></td>
</tr>
<tr>
<td><strong>Direction of rotation</strong></td>
<td><strong>Voltage, V</strong></td>
</tr>
<tr>
<td><strong>Location relative to tower</strong></td>
<td><strong>Speed, rpm</strong></td>
</tr>
<tr>
<td><strong>Type of hub</strong></td>
<td><strong>Frequency, Hz</strong></td>
</tr>
<tr>
<td><strong>Method of power regulation</strong></td>
<td><strong>Orientation drive</strong></td>
</tr>
<tr>
<td><strong>Cone angle, deg</strong></td>
<td><strong>Type</strong></td>
</tr>
<tr>
<td><strong>Tilt angle, deg</strong></td>
<td><strong>Yaw rate, rpm</strong></td>
</tr>
<tr>
<td><strong>Blade</strong></td>
<td><strong>Yaw drive</strong></td>
</tr>
<tr>
<td><strong>Length, ft</strong></td>
<td><strong>Control system</strong></td>
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<tr>
<td><strong>Material</strong></td>
<td>Supervisory</td>
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<td><strong>Weight, lb/blade</strong></td>
<td>Pitch actuator</td>
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<td><strong>Airfoil</strong></td>
<td><strong>Performance</strong></td>
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<tr>
<td><strong>Twist, deg</strong></td>
<td><strong>Rated power, kW</strong></td>
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<tr>
<td><strong>Solidity, percent</strong></td>
<td><strong>Wind speed at 30 ft, mph (at hub):</strong></td>
</tr>
<tr>
<td><strong>Tip chord, ft</strong></td>
<td>Cut-in</td>
</tr>
<tr>
<td><strong>Root chord, ft</strong></td>
<td>Rated</td>
</tr>
<tr>
<td><strong>Chord taper</strong></td>
<td>Cut-out</td>
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<tr>
<td><strong>Chord taper</strong></td>
<td>Maximum design</td>
</tr>
<tr>
<td><strong>Tower</strong></td>
<td><strong>Weight (klb)</strong></td>
</tr>
<tr>
<td><strong>Type</strong></td>
<td><strong>Rotor (including blades)</strong></td>
</tr>
<tr>
<td><strong>Height, ft</strong></td>
<td>Above tower</td>
</tr>
<tr>
<td><strong>Ground clearance, ft</strong></td>
<td>Tower</td>
</tr>
<tr>
<td><strong>Hub height, ft</strong></td>
<td>Total</td>
</tr>
<tr>
<td><strong>Access</strong></td>
<td><strong>System life</strong></td>
</tr>
<tr>
<td><strong>Transmission</strong></td>
<td>All components, yr</td>
</tr>
<tr>
<td><strong>Type</strong></td>
<td><strong>Rating, hp</strong></td>
</tr>
<tr>
<td><strong>Ratio</strong></td>
<td><strong>Weight (klb)</strong></td>
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<tr>
<td><strong>Rating, hp</strong></td>
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<td><strong>Supervisory</strong></td>
<td><strong>Rated power, kW</strong></td>
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<td><strong>Microprocessor</strong></td>
<td><strong>Wind speed at 30 ft, mph (at hub):</strong></td>
</tr>
<tr>
<td><strong>Hydraulic</strong></td>
<td>Cut-in</td>
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<td><strong>Pitch actuator</strong></td>
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<td><strong>Ring gear</strong></td>
<td>Maximum design</td>
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<td><strong>Type</strong></td>
<td><strong>Weight (klb)</strong></td>
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<tr>
<td><strong>Three-stage conventional</strong></td>
<td><strong>Rotor (including blades)</strong></td>
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<tr>
<td><strong>Ratio</strong></td>
<td>Above tower</td>
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<tr>
<td><strong>Rating, hp</strong></td>
<td>Tower</td>
</tr>
<tr>
<td><strong>Rating, hp</strong></td>
<td>Total</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th><strong>Performance</strong></th>
<th><strong>System life</strong></th>
</tr>
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<tr>
<td><strong>Rated power, kW</strong></td>
<td><strong>All components, yr</strong></td>
</tr>
<tr>
<td><strong>Wind speed at 30 ft, mph (at hub):</strong></td>
<td>30</td>
</tr>
<tr>
<td>Cut-in</td>
<td>6.9 (9.5)</td>
</tr>
<tr>
<td>Rated</td>
<td>18.3 (22.4)</td>
</tr>
<tr>
<td>Cut-out</td>
<td>34.2 (40)</td>
</tr>
<tr>
<td>Maximum design</td>
<td>125 (150)</td>
</tr>
</tbody>
</table>
MOD-OA 200 kW WIND TURBINE
SCHEMATIC OF NACELLE INTERIOR

FLUID COUPLING
ANEMOMETER/WINDVANE
V-BELTS
HYDRAULIC SUPPLY
GEAR BOX
DISK BRAKE
ROTOR BLADES
YAW BRAKE
BEDPLATE
ALTERNATOR
YAW DRIVE
PITCH ACTUATOR
YAW DRIVE
40 rpm
1800 rpm
1/6 rpm
HUB
40 rpm
1800 rpm
1/6 rpm
HUB
DOE/NASA 200kW EXPERIMENTAL WIND TURBINE

Culebra Island, Puerto Rico
<table>
<thead>
<tr>
<th><strong>Rotor</strong></th>
<th><strong>Generator</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of blades</td>
<td>Type</td>
</tr>
<tr>
<td>Diameter, ft.</td>
<td>Rating, kVA</td>
</tr>
<tr>
<td>Speed, rpm</td>
<td>Power factor</td>
</tr>
<tr>
<td>Direction of rotation</td>
<td>Voltage, V</td>
</tr>
<tr>
<td>Location relative to tower</td>
<td>Speed, rpm</td>
</tr>
<tr>
<td>Type of hub</td>
<td>Frequency, Hz</td>
</tr>
<tr>
<td>Method of power regulation</td>
<td><strong>Orientation drive</strong></td>
</tr>
<tr>
<td>Cone angle, deg</td>
<td>Type</td>
</tr>
<tr>
<td>Tilt angle, deg</td>
<td>Yaw rate, rpm</td>
</tr>
<tr>
<td><strong>Blade</strong></td>
<td>Yaw drive</td>
</tr>
<tr>
<td>Length, ft</td>
<td>Control system</td>
</tr>
<tr>
<td>Material</td>
<td>Supervisory</td>
</tr>
<tr>
<td>Weight, lb/blade</td>
<td>Pitch actuator</td>
</tr>
<tr>
<td>Airfoil</td>
<td><strong>Performance</strong></td>
</tr>
<tr>
<td>Twist, deg</td>
<td>Rated power, kW</td>
</tr>
<tr>
<td>Solidity, percent</td>
<td>Wind speed at 30 ft, mph (at hub):</td>
</tr>
<tr>
<td>Tip chord, ft</td>
<td>Cut-in</td>
</tr>
<tr>
<td>Root chord, ft</td>
<td>Rated</td>
</tr>
<tr>
<td>Chord taper</td>
<td>Cut-out</td>
</tr>
<tr>
<td><strong>Tower</strong></td>
<td>Maximum design</td>
</tr>
<tr>
<td>Type</td>
<td>Weight (k lb)</td>
</tr>
<tr>
<td>Height, ft</td>
<td>Rotor (including blades)</td>
</tr>
<tr>
<td>Ground clearance, ft</td>
<td>Above tower</td>
</tr>
<tr>
<td>Hub height, ft</td>
<td>Tower</td>
</tr>
<tr>
<td>Access</td>
<td>Total</td>
</tr>
<tr>
<td><strong>Transmission</strong></td>
<td><strong>System life</strong></td>
</tr>
<tr>
<td>Type</td>
<td>All components, yr</td>
</tr>
<tr>
<td>Ratio</td>
<td><strong>Three-stage conventional</strong></td>
</tr>
<tr>
<td>Rating, hp</td>
<td></td>
</tr>
</tbody>
</table>

C-78-2874
DOE/NASA 200kW Experimental Wind Turbine

Fig. 10 Block Island, Rhode Island
### 200 Kilowatt Wind Turbine Specifications

#### Rotor
- **Number of blades**: 2
- **Diameter, ft.**: 125
- **Speed, rpm**: 40
- **Direction of rotation**: Counterclockwise (looking upwind)
- **Location relative to tower**: Downwind
- **Type of hub**: Rigid
- **Method of power regulation**: Variable Pitch
- **Cone angle, deg**: 7
- **Tilt angle, deg**: 0

#### Blade
- **Length, ft**: 59.9
- **Material**: Aluminum
- **Weight, lb/blade**: 2300
- **Airfoil**: NACA 23000
- **Twist, deg**: 26.5
- **Solidity, percent**: 3
- **Tip chord, ft**: 1.5
- **Root chord, ft**: 4
- **Chord taper**: Linear

#### Tower
- **Type**: Pipe truss
- **Height, ft**: 93
- **Ground clearance, ft**: 37
- **Hub height, ft**: 100
- **Access**: Hoist

#### Transmission
- **Type**: Three-stage conventional
- **Ratio**: 45:1
- **Rating, hp**: 460

#### Generator
- **Type**: Synchronous ac
- **Rating, kVA**: 250
- **Power factor**: 0.8
- **Voltage, V**: 480 (three phase)
- **Speed, rpm**: 1800
- **Frequency, Hz**: 60

#### Orientation drive
- **Type**: Ring gear
- **Yaw rate, rpm**: 1/6
- **Yaw drive**: Electric motors

#### Control system
- **Supervisory**: Microprocessor
- **Pitch actuator**: Hydraulic

#### Performance
- **Rated power, kW**: 200
- **Wind speed at 30 ft, mph (at hub)**:
  - Cut-in: 6.9 (9.5)
  - Rated: 18.3 (22.4)
  - Cut-out: 34.2 (40)
- **Maximum design**: 125 (150)

#### Weight (lb)
- **Rotor (including blades)**: 12.2
- **Above tower**: 44.9
- **Tower**: 44.0
- **Total**: 88.9

#### System life
- **All components, yr**: 30
DOE/NASA 2000kW EXPERIMENTAL WIND TURBINE

Howard's Knob, Boone, North Carolina

Fig. 11
### 2000 Kilowatt Wind Turbine Specification

#### Rotor
- **Number of blades**: 2
- **Diameter, ft**: 200
- **Speed, rpm**: 35
- **Direction of rotation**: Counterclockwise (looking upwind)
- **Location relative to tower**: Downwind
- **Type of hub**: Rigid
- **Method of power regulation**: Variable Pitch
- **Cone angle, deg**: 9
- **Tilt angle, deg**: 0

#### Blade
- **Length, ft**: 97
- **Material**: Steel Spar/Foam Trailing Edge
- **Weight, lb/blade**: 21,500
- **Airfoil**: NACA 44XX
- **Twist, deg**: 11
- **Tip chord, ft**: 2.8
- **Root chord, ft**: 12
- **Chord taper**: Linear

#### Tower
- **Type**: Pipe truss
- **Height, ft**: 131
- **Ground clearance, ft**: 40
- **Hub height, ft**: 140
- **Access**: Hoist

#### Transmission
- **Type**: Three-stage conventional
- **Ratio**: 51
- **Rating, hp**: 2209

#### Generator
- **Type**: Synchronous ac
- **Rating, kVA**: 2225
- **Power factor**: 0.8
- **Voltage, V**: 4160 (three phase)
- **Speed, rpm**: 1800
- **Frequency, Hz**: 60

#### Orientation drive
- **Type**: Ring gear
- **Yaw rate, degree/sec**: 0.25
- **Yaw drive**: Hydraulic

#### Control system
- **Supervisory**: Computer
- **Pitch actuator**: Hydraulic

#### Performance
- **Rated power, kW**: 2,000
- **Wind speed at 30 ft, mph**:
  - **Cut-in**: 11
  - **Rated**: 25.5
  - **Cut-out**: 35
  - **Maximum design**: 125

#### Weight klb
- **Rotor (including blades)**: 103
- **Above tower**: 330
- **Tower**: 320
- **Total**: 650
General Configuration & Features

Wind

Controllable tip
Teetered rotor

300 ft dia. (91 m)

114 in (3 m)

288 in (7 m)

445 in (11 ft)

Nacelle
Tower

120 in O.D. (3 m)

200 ft (60 m)

Field splices

50 ft (15 m)

250 in O.D. (6 m)

804 in octagon (20 m)

Foundation
Drive Train Arrangement

- Rotor brake
- Gearbox
- Removable coupling
- Fixed coupling
- Teeter bearing interface
- Generator
- Low speed shaft assembly
- Forward bearing
- Aft bearing
- Oil inlet
- Oil outlet
- High speed shaft/couplings
- Flex mount
- Removable coupling
- Quill shaft