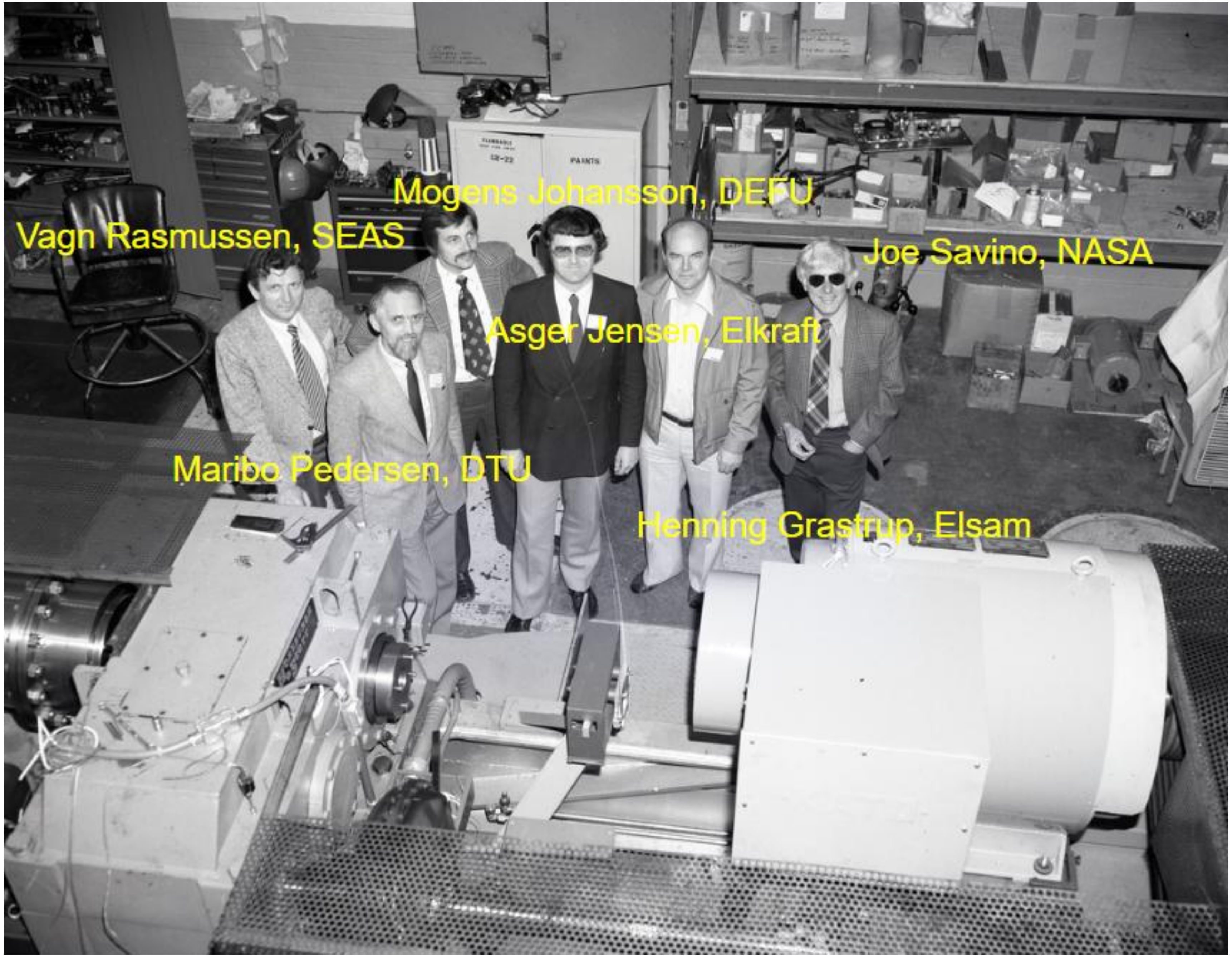
in May 1977, a Danish delegation visits NASA on a "study tour": they come back with the firm idea that Danish engineering firms needed to build their own calculation tools and blade manufacturing facilities....



1979 – NIBE turbines operation by ELSAM

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I/S	Skærbækværket	(SV)
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Fabrikant Vagn Iversen (til 18.6.1979)
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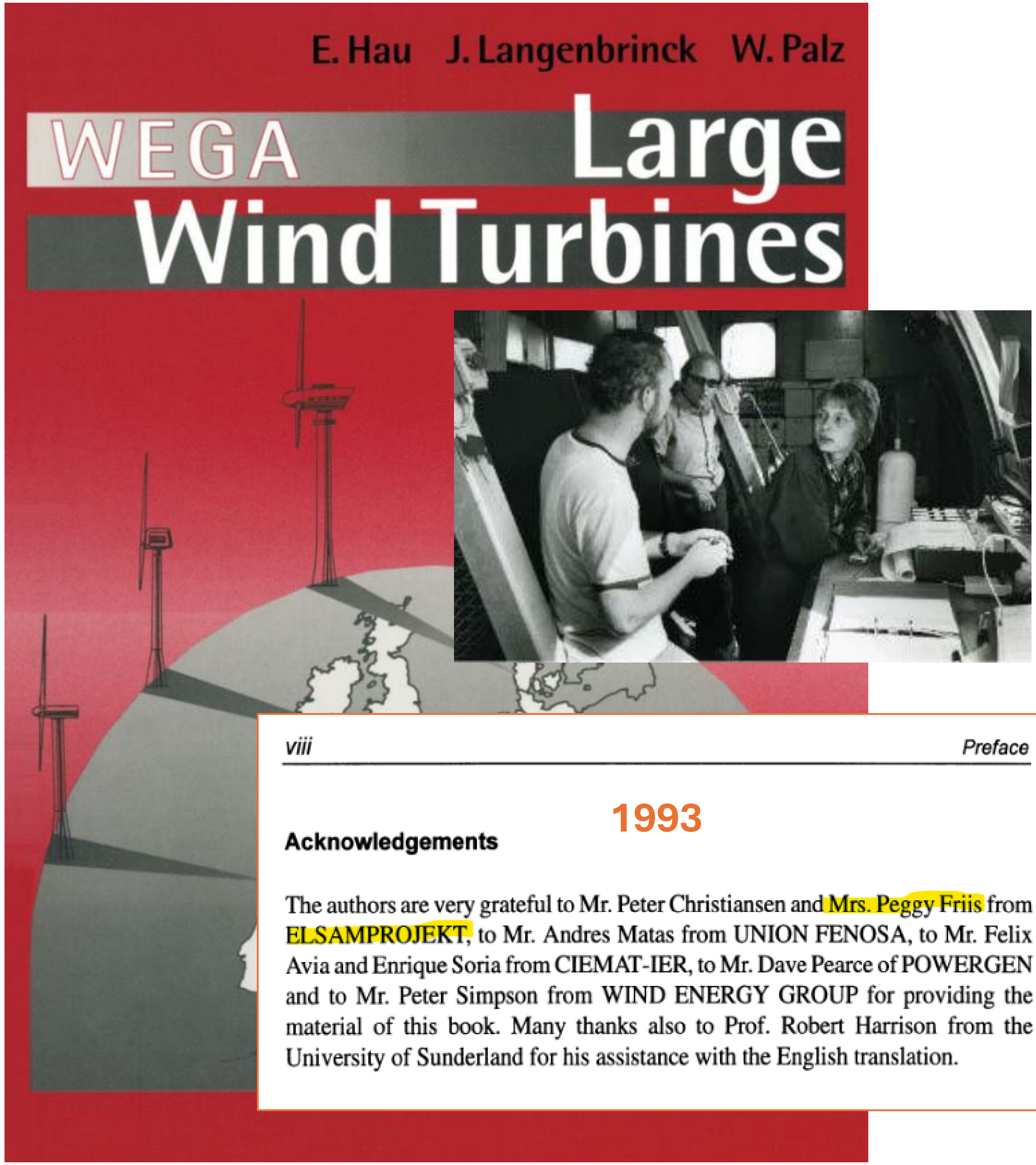

1993

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The Tjæreborg Wind Turbine

NEI-DK--1018
DE93 752793

Final Report

CEC, DG XII contract EN3W.0048.DK

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Summary:

This Final Report is prepared under CEC contract EN3W.0048.DK as part of the contractual obligations of the contractor, I/S ELSAM, represented by I/S VESTKRAFT.

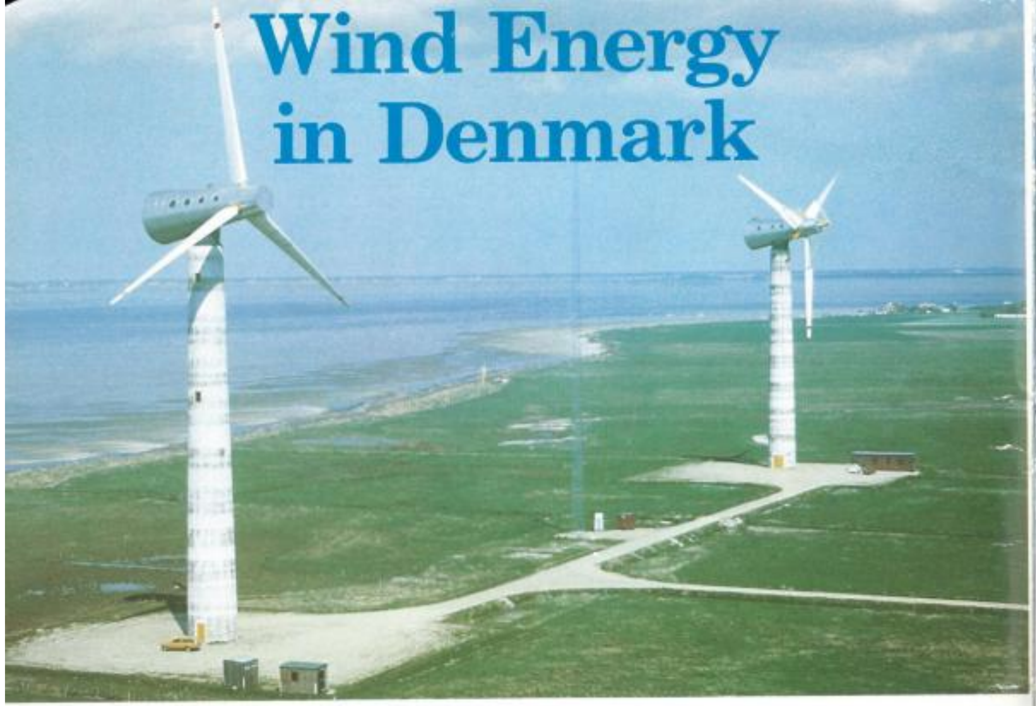
The project was initiated in 1981 as a feasibility study under the wind power programme of the Danish Ministry of Energy and the electric utilities. In 1985 I/S ELSAM decided to build the turbine and the contract with DG XII was signed in late 1986. Construction of the turbine commenced in 1985 and it was connected to the grid for the first time i March 1988. It finally came into stable operation in late 1990 after severe technical problems with control system and gearbox. By the end of 1991 the turbine had been released to automatic unmanned operation for 10117 hours and had thus fulfilled the contractual obligation towards DG XII of one year of availability.

The general conclusion that can be drawn from the project is that electricity producing wind turbines in the multi MW class is a viable technical possibility even though the Tjæreborg Wind Turbine represents the wind turbine technology of the early eighties.

The total project cost up to the date of the acceptance test was 74,846,000 DKK. The CEC, DG XII, contributed with 16,800,000 DKK to the construction costs, The Danish Ministry of Energy with 20,600,000 DKK and I/S ELSAM with the rest. The 10% bonus (1,680,000 DKK) obtained from CEC, DG XII, for passing the acceptance test before June 1, 1989 was transferred to the budget for the measurement phase following the acceptance test.

1990

Wind Energy in Denmark



The two 630 kW Nibe wind turbines.

B. Maribo Pedersen,
Department of Fluid Mechanics,
Technical University of Denmark

Introduction

The present publication surveys the developments in wind energy technology that have taken place over the last twelve years in Denmark.

By addressing a number of various issues in detail it is hoped that a clear picture will emerge of how far we have come in identifying and understanding the problems, where we are at present in implementing wind energy and how we hope to be able to proceed in the future.

In 1974, shortly after the first "oil crisis", the Danish Academy for the Technical Sciences took the initiative of establishing a committee with the task of making a first assessment of the possibilities for utilizing wind energy as part of the Danish energy supply system.

In 1975 the committee concluded in a report that the conversion of kinetic energy of the wind into electric energy for the end user, was the more favourable alternative to conversion of wind energy directly into heat or mechanical energy for water pumping or similar uses.

Secondly, it was found that probably up to 10% of the Danish electricity consumption could be covered by wind energy without causing any noticeable problems of regulation, and without any need for energy storage.

Thirdly, for evaluating the economics of wind energy conversion, the committee calculated the break-even price for wind turbines, i.e. the amortised capital costs for which the cost of electricity produced from wind turbines would match the cost of fuel (coal or oil) saved when an equal amount of electricity was produced in a conventional power plant.

The parameters which influence this calculated break-even price were varied so that the sensitivity of this price to interest rate, inflation, development in fuel prices, annual mean wind speed, etc. could be seen.

The actual capital costs for various types of wind turbines were difficult to estimate at that time, of course. Only one larger wind turbine had been built in Denmark since World War II, the 24 m diameter, 200 kW Gedser wind turbine, which was operated in the years 1957-1967. Hence, a cost estimate was made by calculating the cost of this machine in 1974 kroner.

On comparing the range of estimated actual costs of a wind turbine with that of calculated break-even costs an overlapping region was found. It was thus fair to assume that it would be possible to develop machines that would be cost effective. But it was also concluded that in order to come to that point several measures had to be taken by government. In particular, a publicly funded research and development (R&D) programme had to be established.

A Danish 55 kW windmill.

As a consequence and follow-up of this first report, another report was submitted in January 1976. In this second report an action plan was outlined for a 5-6 year R&D programme. The programme encompassed basic research in aerodynamics and structural dynamics as well as the design, construction and testing of wind turbines of various sizes. Also, the establishment of a test station was proposed.

The Danish Effort

In January 1977 the Danish government adopted a programme following the broad lines of this proposal. The programme covered a few years, but each year since 1980 it has been updated for the following three years, thus being a continuous, "rolling" plan, with the important advantage of avoiding a stop-and-go pattern which would have had a negative effect on the efficiency of the work. Thus, over the last twelve years a continuous effort in R&D in wind energy has been accomplished.

Three main avenues of R&D have been followed: The first, and most costly, was the design, construction and testing of two medium-size machines, the Nibe wind turbines. The second was a broad range of research projects in areas such as the properties of composite materials, aerodynamics and aeroelasticity, and structural dynamics. These studies were carried out at various Danish research institutes. The third avenue has been a very thorough study of the various problems connected with siting a substantial number of wind turbines in Denmark.

Some of the results of these studies will be dealt with in greater detail later in this publication, but a short summary is given below. However, the broad range of research projects in specialized areas are not covered by separate articles. A detailed presentation of these studies is outside the scope of this publication.

The experience gained in building the two Nibe wind turbines was very valuable. During the design phase, not many of the results from the theoretical work on aerodynamics and structural dynamics were available, so the design had to be carried out using conservative estimates of turbine loading. However, the manufacturing phase yielded valuable information particularly on the method by which the fibre-glass rotor blades were fabricated. Many of the practical problems inherent in the continuous operation of a wind turbine installation were identified and the proper solutions to these have been implemented in later designs now under completion. Finally, the extensive measuring programme which is being carried out gives results which are crucial for evaluating the calculational methods that have been, and still are, under development.

Rather sophisticated computer programmes have been developed whereby the equations of motion are solved, either in the time or frequency domain. These computations are then validated by comparison with experimental results from the Nibe turbines.

The aerodynamic calculational tools which have been developed make it possible to make accurate predictions of the energy output of the machine and provide input data for the structural calculations.

Precise knowledge of the mechanical properties of the materials used in manufacturing is essential. Knowledge of the properties related to fatigue are particularly crucial, as the components of a wind turbine experience more load cycles during its lifetime than most other comparable constructions.

Siting problems of various kinds have been studied. An accurate estimate of the wind resource itself has been made possible by using the methods brought forward in the "Wind Atlas for Denmark", published by Risø National Laboratory. The various institutional problems, problems of proper land use and other questions were considered in a number of publications from the National Agency of Physical Planning.

Finally, the utilities have carried through extensive studies of the ways in which a large number of wind turbines could be integrated in the public grid system.

By utilizing the results of these research projects it has been possible to carry out the design of the second generation of large wind turbines which now are in operation, the 2 MW ELSAM turbine and the WINDANE 40 turbines.

It is worth mentioning that the Danish electric utilities have been very active in the Danish wind energy programme. Not only did they provide partial funding, but played an important role in defining and managing the programme.

Shortly after initiation of the R&D programme, another initiative was taken which turned out to be equally important for implementing wind energy produced especially by small wind turbines. This was the introduction in 1979 of a subsidy given to the purchaser of a wind turbine calculated as a percentage of the purchase price.

This spurred the emergence of a number of manufacturers of small turbines, and over the years about 2500 small turbines have been installed. The size of these privately installed turbines has gradually increased from about 55 kW or less at the beginning up to 200-300 kW for most machines installed now. The total installed capacity now is about 200 MW. In 1979 the subsidy was 20%, in 1980 it was increased to 30%, but later it has been reduced gradually and removed from mid-1989.

The Test Station for Wind Turbines

2 MW ELSAM wind turbine at Tjæreborg, Esbjerg.

Large-Scale Wind Turbines

Henning Grastrup,
ELSAM Power Station Engineering
Poul Nielsen, Research Association
of Danish Electric Utilities

Introduction

The Danish wind power programme for the development of large-scale, electricity-producing wind turbines was initiated in 1977, and its main objective was to investigate under what circumstances and to what extent large-scale wind turbines could make a viable contribution to the Danish electricity supply system.

The programme is still running and is sponsored jointly by the government and the electric utilities. In addition, the Masnedø and Tjæreborg projects (see below) are co-founded by the Commission of the European Communities. The work is done by utility personnel, public institutions and Danish industry.

The utility involvement in the wind power programme right from the beginning was founded on the expectation that the utilities would most likely be the owners and operators of future large-scale wind turbines connected to the Danish electricity grid system. Moreover, the costs and risks involved in the development and testing of large-scale prototypes were higher than private industry was willing to accept.

Through the past two decades, the activities have been concentrated mainly on:
- Wind assessment studies
- Siting investigations
- Grid integration studies
- Technology development.

The Danish wind resources are fairly well described in the report "Wind Atlas for Denmark". The methodology presented in this report seems to be in good agreement with field data from the many existing wind turbines.

The siting possibilities within Danish territory with regard to large-scale WECS have been the topic of a general siting investigation which is now terminated. The work is described in six publications and reviewed in a concluding summary report. The latter is available in English.

A detailed grid integration study was completed in 1983. It showed that in the long run problems may arise with "surplus energy" produced by wind turbines and perhaps also load-following problems during periods when the wind velocity changes rapidly.

At present, most efforts are concentrated on technology development. Two aspects are predominant. The first is to overcome the various fatigue problems encountered in wind turbines; the second is to reduce the specific installation costs to a level which would make wind power more cost effective and, thereby, eventually more competitive with electricity produced in conventional power plants.

Mounting of the rotor on the Nibe A turbine. 1979.

Economy of Scale

It is a well-known fact that the cost of energy produced by large-scale wind turbines is at present higher than the cost of energy from small-scale units. Therefore, this subsection briefly reviews the economy of scale problem.

For many decades, the unit size of conventional power plants has steadily grown, resulting in a lower kilowatt-hour price. This economy of scale is also known from other areas of technology, but it is not evident that the economy of wind turbines follows the same pattern. One reason for this is that the cost of major load-carrying components tends to rise rapidly with physical size. For large wind turbines, the additional cost of larger rotor blades may outweigh the value of the marginal energy capture. While it is true that the normal wind speed profile, where wind speed increases with height, favours large machines with high towers, factors such as the higher cost of erection tend to offset the gain.

On the other hand, a factor in favour of economy of scale is that the cost of some of the items - like the control system and to a certain extent also the hydraulic system - does not rise in proportion to the generating capacity. Also, land costs per kWh generated would drop with larger units.

These few examples show that it is difficult to calculate the optimal size of a wind turbine in terms of maximum energy output per unit cost. Many theoretical studies have been published on the subject in Denmark and elsewhere, and all of them show a trend in favour of large wind turbines. There is, however, no consensus on the optimal size for future wind turbines.

From the point of view of maintenance, there is some advantage in limiting the number of machines to be operated and maintained. Despite its complexity, the problem of calculating the optimal unit size is of great importance in future planning work on wind power plants.

The Gedser Wind Turbine

To a large extent, the Danish experience with wind energy in the 1940s and 1950s was based on propeller-type wind turbines with the rotor placed upwind from the tower and incorporating fixed pitch blades. Power output control was achieved either by stalling, spoilers or a combination of both.

The previously mentioned Gedser wind turbine was the final unit of the development series in this period. The first activity of the new wind power programme in the 1970s was, therefore, to reconnect to the past and study the basic concept of the Gedser wind turbine.

The Gedser wind turbine was built in 1956-57 by the Association of Danish Electric Utilities. Following a test period, the wind turbine was in regular operation from 1959 until 1967. During these years, it supplied a total of about 2.2 MWh to the public grid. In 1964 a capacity factor of 0.21 was recorded.

In November 1977, the 20-year-old Gedser machine was refurbished for a period of limited test operations. The turbine was equipped with a large number of transducers, and an extensive measurement programme was carried out until April 1979. The aim was to provide information about the essential features of this historic wind turbine. The project was financially supported by the US Department of Energy.

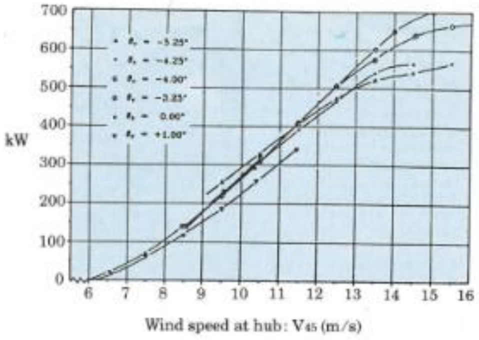


Figure 1. Nibe A. Electrical power output.

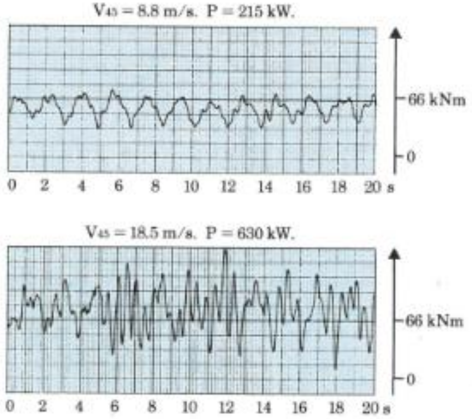


Figure 2. Nibe A. Flapwise bending moment, 8 m from the hub.

The Nibe Wind Turbines

Technical concept

As a result of thorough studies, it was decided in 1977 to build two medium-size horizontal-axis prototypes at Nibe in northern Jutland.

Main data for Nibe A and B.

Rotor diameter:	40 m
Hub height:	45 m
Rotor type:	3-bladed, upwind
Cone and tilt angle:	6 degrees
Rotational speed:	34 r.p.m.
Blade construction:	Steel/fibreglass
Blade airfoil:	NACA 44-Series
Blade twist:	11 degrees
Control mode (A):	Stall control
Control mode (B):	Pitch control
Gearbox:	3-stage, 1:45
Generator:	630 kW, induction
Tower:	Concrete, low tuned
Cut-in wind speed (at hub height):	Approx. 6 m/s
Rated wind speed (at hub height):	Approx. 13 m/s
Cut-out wind speed (at hub height):	Approx. 25 m/s

Henning Grastrup

Head of wind energy department at ELSAM Projekt.

Masnedø wind farm, a well-performing project.

Wind Energy eventually “clicks” for ELSAM management.

From then: development of wind farm design consulting services:

- FLEX4 load calculations
- Siting
- Construction

The Masnedø Wind Farm

Background

After commissioning and recording data from the Nibe wind turbines, the utilities and the authorities discussed how to proceed with the development of large machines.

They decided to build both an upscaled version of the Nibe B machine (described later) and a small wind farm consisting of units close to the Nibe B machine in size and technology.

The ELKRAFT power company undertook the construction of the Masnedø wind farm, to be sited on Masnedø island near Vordingborg, and next to an existing power station.

The aim of the project was to provide Danish power companies with further technical and economic data on the construction and operation of large wind power plants.

Technical concept

The Masnedø wind farm consists of 5 turbines placed along the western shore of Masnedø island, as shown in Figure 5.

Wind resources are favourable at this location with mean wind energy contents of 4.0-4.9 MWh/m²/yr for the five turbines. Assuming 100% availability this will give an annual output from the farm of 7.55 GWh/yr.

The turbines are of the WINDANE 40 type, manufactured by "Danish Wind Technology A/S".

The main concept is adapted from the Nibe B turbine, but modifications have been made to avoid some of the problems encountered with it, such as the hydraulic pitch mechanism and the rotor blades.

The pitch mechanism has been changed to facilitate maintenance, whereas the blade material has been changed from fibreglass and steel to fibreglass alone to avoid the fatigue-strength problems.

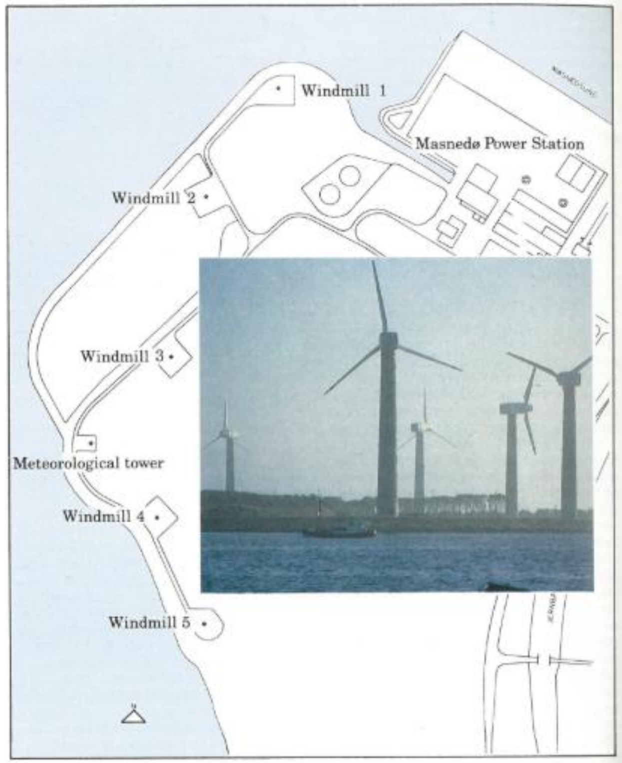


Figure 5. The five turbines and the meteorological tower on the west coast of Masnedø.

Main data for the Masnedø turbines are:

Rated power:	750 kW
Generator:	3-phase AC, 6-kV, 50 Hz
Rotor blades:	Self-supporting fibreglass
Rotor diameter:	40 m
Hub height:	45 m
Concrete tower, height:	42 m
Cut-in wind speed:	5 m/s
Rated wind speed:	15 m/s
Cut-out wind speed:	25 m/s

Table 2. Operational results in 1987 and 1988.

		Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
Hours of operation	1987	2449	1685	3492	1663	2445
Hours of operation	1988	4987	0	4003	3128	4353
Production MWh	1987	713	467	936	516	653
Production MWh	1988	1192	0	987	834	1052

Operational experience

Construction on the site started in March 1985, and the wind farm was officially inaugurated in January 1987.

The operational results during 1987 and 1988 are summarized in Table 2.

During the first years, the operation of the turbines has been influenced by only a few, but severe problems.

Unit No. 2 was destroyed by a fire in October 1987. A malfunctioning circuit breaker caused the fire which led to the total destruction of the nacelle. A new, redesigned nacelle will be mounted in 1990. The remaining turbines have suffered problems with the rotor blades and the gearboxes.

As previously mentioned, the rotor blades are made entirely of fibreglass-reinforced polyester. This has eliminated the fatigue problems encountered at Nibe, but a new problem has risen. As in the outer 12 m part of the Nibe blades, the load-carrying spar is made by transverse filament winding and the outer shells, which give rise to the aerodynamic shape, are made as a traditional sandwich structure around a foam core.

However, the bonding material used for joining the spar and shells has developed cracks which, during operation, have led to cracks in the outer shells. Although no damage has been observed in the spar, repairs have been necessary.

The gearboxes have shown signs of structural weakness; one shaft has been broken and pitting has been observed. This has led to a general reduction in maximum output from 750 to 450 kW. Both rotor blades and gearbox internals are planned to be replaced by new, redesigned parts.

Despite these problems, the turbines had accumulated 37,000 hours of grid-connected operation by mid-1989 and had given much valuable experience to ELKRAFT, the owner.

The Tjæreborg 2 MW Wind Turbine

Background

As mentioned earlier, it was decided to follow up on the Nibe project with both a wind farm (Masnedø) and a large new prototype.

Development of the prototype began late in 1981, and in the spring of 1985 a conceptual design was completed and the theoretical and practical development work on a 30-m all fibreglass rotor blade was finished.

This part of the work was initiated and financed by the joint wind power programme of the Danish utilities and Ministry of Energy. The detailed design, construction and erection, however, were undertaken by ELSAM.

Technical concept

The Tjæreborg wind turbine is located on the west coast of Jutland, facing the North Sea where the wind energy resources are excellent. Assuming 100% availability, the annual output will be 4.1 GWh.

The turbine was procured on a multi-contract basis, as no Danish manufacturer could offer a prototype of this size. Figure 6 shows a longitudinal section of the nacelle.

Again the main concept is adapted from the Nibe B design. Major modifications are the hub-mounted blade-pitch mechanism and the use of an epicyclic gearbox. Like the Masnedø turbines, the blades are all fibreglass. Figure 7 shows the difference in the blade construction.

Main data for the Tjæreborg turbine are:

Rotor diameter:	61 m
Hub height:	60 m
Tip speed:	70 m/s
Rotor speed:	22.3 r.p.m.
Rotor type:	3-bladed upwind
Cone angle:	0°
Tilt angle:	3°
Airfoil:	NACA 4412-43
Gear:	3-stage, epicyclic and parallel 1:68
Generator:	4-pole induction, rated 2 MW
Power output control:	Hydraulic pitch
Cut-in wind speed:	5 m/s
Rated wind speed:	15 m/s
Cut-out wind speed:	25 m/s

Operational experience

Construction on the site started in September 1986, and the wind turbine was officially inaugurated in June 1988.

The operational results for the first year June 88-June 89 were:

Hours in operation:	1000
Production (MWh):	631

During the first year of operation, the control system was plagued by malfunctions. In February 1989, however, those problems had been overcome and the turbine showed sharply increasing availability.

In mid-1989 the turbine underwent a planned "1000-hour inspection" which revealed no serious problems except with the gearbox where the housing proved to be too elastic, causing deformations during operation. The gearbox housing will be replaced.

Bearing in mind the troubles encountered with the rotor blades at Masnedø, the Tjæreborg rotor blades were very thoroughly inspected, and after 1000 hours of operation they showed no signs of damage. The slight modifications made from Masnedø to Tjæreborg therefore seem to have been successful.

Future Developments

Despite the many problems encountered both in the Masnedø and Tjæreborg projects, the overall experience shows that large wind turbines can be built and operated with the same safety and reliability as the smaller wind turbines commercially available today.

The question of the most economical size is still unsolved, but during the last few years there seems to be a growing consensus in the international wind energy community that a good guess would be that the rotor diameter should lie in the 40 to 60 m range.

Experience and data from Nibe, Masnedø, and Tjæreborg confirm this, and during the next few years these plants will be major sources of new knowledge on large wind turbines.

The two power companies ELKRAFT and ELSAM still pursue the idea of large-scale wind turbines.

ELSAM is still in the early stages of gathering data from its Tjæreborg wind plant; however, from the experience gained at Masnedø, ELKRAFT has embarked upon a new project to design and construct a 1 MW machine with a rotor diameter of 50 m.

Hence, in the coming years large wind turbines will be under increased active development in Denmark.

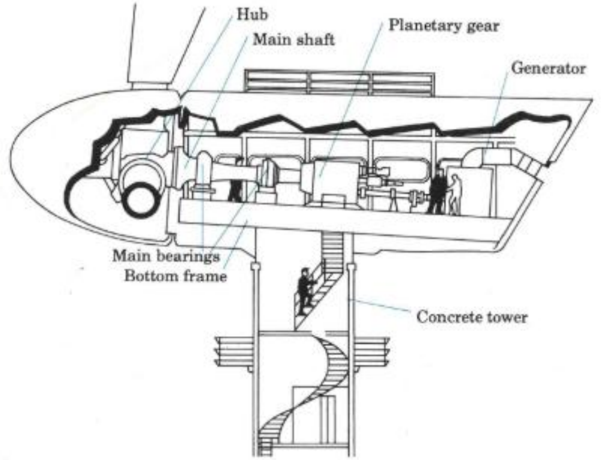


Figure 6. Longitudinal section of the nacelle.

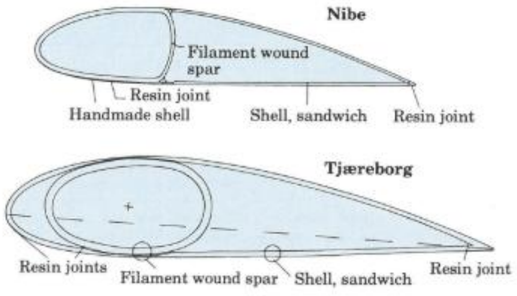


Figure 7. Blade cross sections.

1992

1. INTRODUCTION

This recommendation was made by a working group under the Energy Agency. The following persons have taken part in the work of the working group.

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Michael Brink	Danish Maritime Institute
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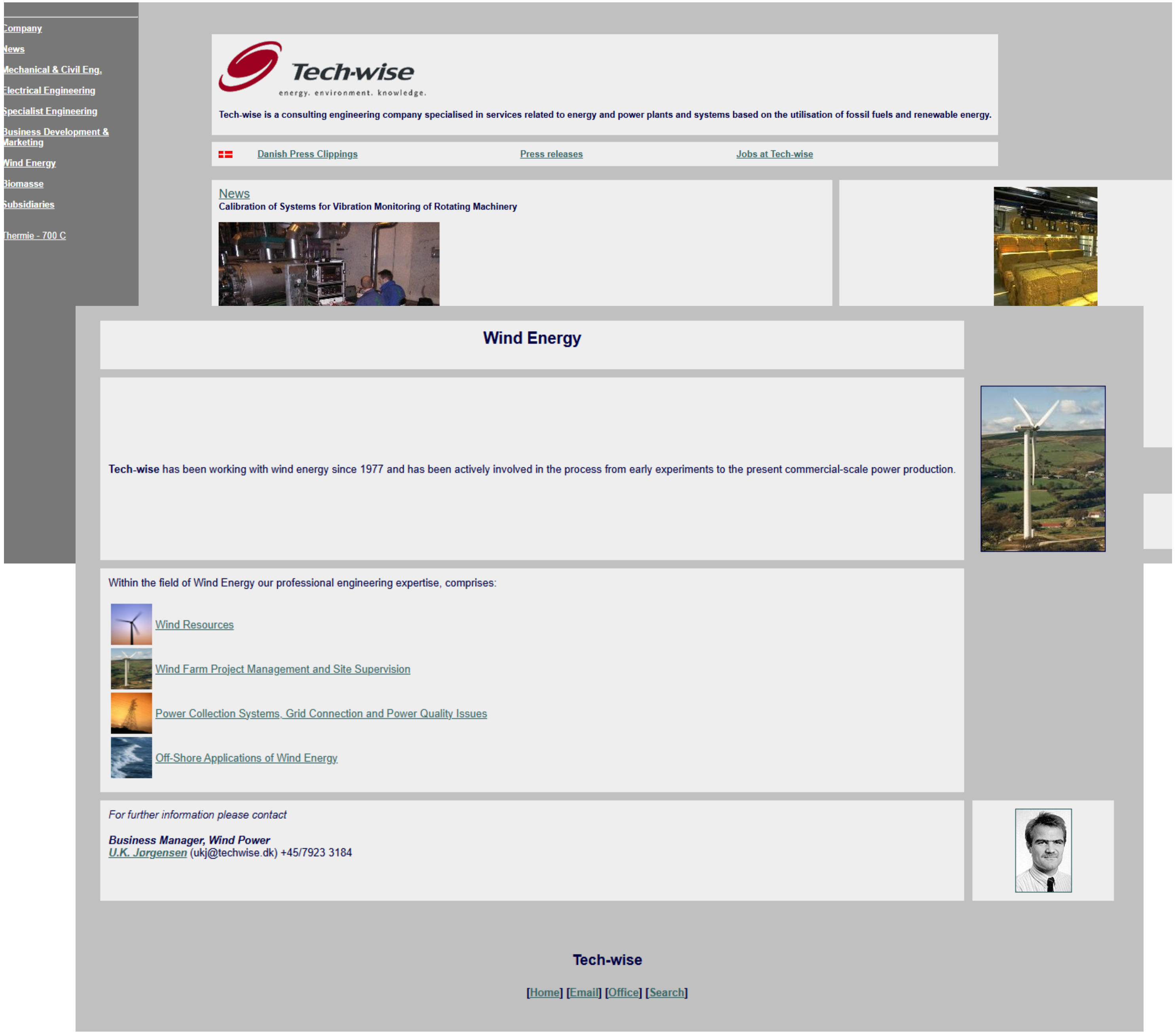
Sten Frandsen	Wind Engineering, Risø
John Olesen	Micon
Lars Budtz	Vestas
Michael Ariel Nielsen	Vestas
Henrik Stiesdal	Bonus
Klaus Ørsted Petersen	Bonus
Per Lading	Danwin/Wingineering
Lars Jørgensen	Danwin/Wingineering
Peggy Friis	Elsam Project



ELSAM Projekt (1977 – 2000)

Tech-Wise (2001-2002)

ELSAM Engineering (2003-2005)