SPECIFICATION, SITING AND SELECTION OF LARGE WECS PROTOTYPES

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Introduction and Research Unit update

The Swedish Wind Energy Programme was started in 1974 with preliminary feasibility studies. These indicated that wind power could become an economic reality in Sweden, and that the technical problems would not be unsurmountable. This led to a decision by NE in 1975 to design and install a Wind Power Research Unit to study the technical problems associated with wind power at a semi-scale level. The contract for this Unit - with main characteristics as given below - was given to Saab-Scania Co.

Characteristics of Swedish Research Unit (Figure 1)

Tower:	Concrete, diameter 2 m
Hub height:	25 m
Hub type:	A) Rigid B) Flapping
Turbine diameter:	A) 18 m B) 24 m
Turbine rpm:	77
Rotor blades:	A) Aluminium B) GRP C) CRP+GRP
Rated power:	63 kW (75 kW)
Generator:	380 V, asynchronous
Grid voltage:	10 kV

The Unit was operative in April 1977, underwent delivery tests and debugging during 1977 and began giving test data for the aluminium blade/rigid hub combination late in 1977. That combination accumulated 846 hours of operation before the hub was changed in May 1978. The combination aluminium blade/flapping hub is now operative, accumulating about 1200 hours in early April 1977, total hours of operation now being above 2000. Rotor blades will be changed into a GRP-set in May 1979, and late in 1979 into a CRP+GRP-set with increased diameter (24 m).

In the first six weeks of 1979 the Unit was in remote controlled, routine "utility operation" with only weekly inspections. 400 hours were accumulated - as the winds blew - with only one snag: the temperature in the morning of January 29 was so low (-30°C) that the Unit refused to start because of -5°C in the main bearing! The technical availability during the period was 97%.

Prototype Specification Development

Continued systems analysis work, and the early experiences of the Research Unit was the basis for a decision by NE in late 1977 to develop a "Technical Specification for Design and Installation of Wind Turbine Systems in Sweden".

This specification was developed during October 1977 - April 1978, with some detail changes in September 1978. Our systems work had given the following rather clear indications:

- horisontal axis machines advantageous from most points-of-view,
- optimum turbine size in the range of 60-100 m diameter,
- hub height should be roughly equal to turbine diameter,
- concrete and steel towers roughly equal in feasibility and cost,
- blade materials and hub types should be tested in real life.

These and other deliberations led to the conclusion, that a functional Technical Specification should be written, to give a reasonably wide frame for proposals from prospective manufacturers. The frame boundaries should be given by reasonable physical restrictions, functional requirements and the electric supply network.

The Technical Specification was produced by a committee - disregarding the proverbial camel being a horse designed by a committee - chaired by the author of this paper. The committee included aerodynamics, structures and control systems consultants together with meteorologists, representatives of the two largest Swedish utilities, Vattenfall and Sydkraft, and furthermore development and engineering people from two prospective manufacturers, Saab-Scania and Karlskronavarvet.

Based on a general understanding within the committee concerning the functional approach and the indications from the systems analysis efforts, the work of the committee was organized as follows:

- the consultants were to draft all written material of the main specification, and to develop load cases and functional requirements,
- the meteorologists were to produce "best available" data concerning wind conditions (median winds, extreme winds, turbulence spectra) to be used in connection with the load cases and for performance calculations,
- the utilities were to define necessary electrical data and the requirements at the interface between WECS and grid, together with functional requirements for accessibility and maintainability,
- the prospective manufacturers were to give their comments and suggestions concerning the applicability of functional requirements and load cases, and also to develop recommendations concerning methods of calculation for certain problem areas, to be appended to the main specification.

In spite of the complexity, this scheme worked out quite weell during the few hectic months allocated for the job. Everyone engaged in this specification process took his task as a challenge, which is the only way to do it, when the task and its schedule seems impossible. The simple fact, that all those engaged knew each other from earlier projects, was probably a very helpful factor.

Summary of Prototype Specification

The final issue of "Technical Specification for Design and Installation of Wind Turbine Systems in Sweden" was published 1978-09-15. It has been distributed for information to all countries participating in the different international wind power projects of the International Energy Agency (IEA). The specification was written in English from the start, to facilitate international technological exchange.

Contents of Technical Specification

1. General
2. Definitions
3. Operational Conditions
4. General Requirements
5. Strength Requirements
6. Design, Construction, Erection
7. Instrumentation and Data Acquisition System
8. Inspection and Testing

Section "General" describes the purpose of the specification, states the encouragement of new concepts and innovations for the prototypes and the need for consideration of the visual appearence of the unit. It also states, that deviations from the specification are allowed only after negotiations with and approval by NE.

Section "Operational Conditions" gives the site wind characteristics - where we used data from Sturup Airport in southern Sweden as a common basis for the proposals, as the sites were not defined at the time. These characteristics consisted of:

- median wind velocity profile,
- wind duration during the year,
- extreme wind velocities with height profile,

- gust spectra with probability density and cross spectra definitions,

- local wind shear.

This section also deals with the general environment, access roads and transportation and the electrical network to be considered.

The "General Requirements" describe the main physical limitations and the required operational envelope, as in the table below:

Main Characteristics of Prototypes

Rated power (generator)	2-4 MW
Turbine diameter	70-90 m
Number of rotor blades	2-3
Inclination of rotor axis	Optional
Nominal tip speed	$\leq$170 m/s
Minimum hub height	Equal to diameter
Generator system	Optional
Cut-in wind speed	6 m/s
Cut-out wind speed	$\geq$21 m/s
Rated wind speed	Optional
Blade pitch control	Required
Remote control and monitoring	Required
Access to nacelle during ops.	Required

This section also describes the minimum functional modes, control system functions and the minimum functions of the electrical system of the unit.

The section concerning "Strength Requirements" contains definitions on load categories and load character, required factors of safety and probability of failure ($\leq 10^{-5}$) during the service life (30 year). The load cases to be taken into account for structural design are furthermore defined, as summarized in table I.

Besides the definition of the different load cases, directives are given concerning the applicability of certain norms for erection loads and handling of heavy components. Furthermore some considerations on divergence and flutter speeds are given, to be above 36 m/s when in operation, and above 51 m/s when parked. A safety-factor of 1.5 regarding "toppling over" of the entire prototype on its foundation is prescribed.

The section on "Design, Construction, Erection" states that the technology used should be based on proven experience, and provide for future quantity production. It goes on to describe applicable design codes and standards, and then gives the general design considerations to apply to the different main components (wind turbine, machinery, nacelle, tower, control system and electrical installation with network connection). Blade airfoil and planform are optional. Machinery is optional, but the generator has to live with certain requirements as defined by the grid. The general functions of the electrical system are specified, and the main requirements for its connection to the grid (30 kV and 50 kV respectively for the two sites).

The same section also deals with reliability and maintenance aspects, defining a design system life of 30 years and a minimum annual availability of 90% during the system life. Personnel safety is stressed and emergency evacuation from the nacelle is required. Consequences of component failure are to be analyzed by the contractor, the only strict requirement being, that a blade failure shall not dislocate or severely damage nacelle or tower. Lightning protection is specified according to a lightning model based on Swedish lightning statistics.

The "Instrumentation and Data Acquisition System" is only specified as to its main functions, and as to what data to be measured. The latter are divided into two groups: (1) power, energy and efficiency data; (2) engineering data. The former consist mainly of RPM, torque, active and reactive power, energy, voltage and frequency data in various points of the system together with wind data from a separate mast. The latter consist mainly of stress, temperature and vibration data, qualified by correlation to wind and power data, and by high resolution transient measurements.

"Inspection and Testing" is also defined in general terms, requiring contractor-developed plans for design control, factory tests, quality control, tests on site and acceptance tests. Among the required tests to be performed are:

- simulated lightning tests in case of non-conductive rotor blade material,
- measurement of stresses at several critical points of an entire rotor blade with limit loads applied,
- simulated function tests of various subsystems including all control loops before erection of the unit,
- ground resonance test of blade and of the entire turbine and nacelle on its turntable before erection,
- ground resonance test of tower at site.

The general schedule for the various activities of the Inspection and Testing process is described in Figure 2.

Request for Proposal

In April 1978 a Request for Proposal was mailed to those Swedish companies that had showed a serious interest in developing large-scale wind power prototypes. Such a request is an official document according to Swedish law, which means that any person or company can study the RFP at NE and respond to it. However, as this procurement of wind power prototypes is what is termed a "Negotiated Procurement", NE only has to consider the invited bidders.

The RFP was sent to six companies, of which two joined forces within short, resulting in five proposals from the following groups:

- Götaverken Motor AB (part of the State Shipyard group) Gothenburg;

- Karlskronvarvet AB (part of the State Shipyard group) Karlskrona, together with Hamilton Standard;

- Karlstads Mekaniska Werkstad AB (KMW, part of the Johnson group) Kristinehamn, together with ERNO, Bremen;

- Kockums Varv AB (part of the State Shipyard group) in Malmö, together with MAN, Munich;

- Swedewind (consortium of Saab-Scania AB and Stal-Laval AB) in Linköping.

The RFP consisted of a document stating the Conditions of Tender plus the Technical Specification as described above, together with various technical backgroud material to give as comprehensive as possible common technical basis for the five bidders. The Conditions of Tender stated - among other things - that each invited bidder would be paid the sum of 1 million Sw.Kr ($ 230 000) for his design study as part of his proposal.

In September 1978 the Technical Specification was amended in some details - as agreed with the bidding companies - and a Draft Contract for the procurement was issued, the latter only to serve as a guideline for later negotiations.

Proposals, containing fairly elaborate design studies, were received from the five bidding companies at the given deadline October 31, 1978.

Siting of Prototypes

The siting process was started already in February 1978 with the formation of a siting committee, chaired by the author of this paper as representing NE and composed of representatives for the County Governments of Malmöhus, Gotland and Uppsala Counties and for the two utilities that will operate the prototypes, Vattenfall (State Power Board) and Sydkraft (South Sweden Power Co).

The Siting Committee had to consider the following main factors in the process:

- wind conditions

- terrain and ground conditions

- nature conservation limitations

- environment and safety

- local planning and building regulations.

The committee had to formulate a recommendation for the final siting and to work out a basis for the final siting decisions to be taken by the following bodies:

- NE: technical siting
- County Government: conservation and environment
- Community Council: planning and building permit.

The most important factor to be considered was the wind conditions. Based on contour maps of Sweden with median winds at 50 and 100 metres ASL a decision on the general areas of interest could be taken. These were:

- southwestern Sweden in the province of Skåne
- the island of Gotland in the Baltic
- the Baltic coast of northern province of Uppland.

A visual inspection of these areas, coupled with local know-how of wind conditions, and taking terrain, forested areas etc into account, narrowed the choice to 8 small areas of about 2 sq.km. each. As other priorities were given for Skåne and Uppland, we could plan our final wind assessment for only these areas. The methods used for this assessment were the following:

- free pilot ballons measured by theodolites
- stability checks with SODAR (Gotland only)
- high mast checkpoint (Gotland only).

In spite of a less windy autumn than usual - as you would expect when you really want some wind - and fairly cold weather beginning in November 1978, the wind assessment worked out quite well during September-December 1978. The measured data was treated by a special computer program to increase accuracy by statistical methods. The conclusions were:

- the isovent maps were generally correct.
- different sites on the southern coast of Skåne were very similar.
- the assessed sites on Gotland were rather different with some unexpectedly large roughness effects but a "best site" could easliy be found.

The Siting Committee recommeded to NE - and NE duly decided likewise - to site one prototype at Maglarp in the province of Skåne, south of the city of Malmö, and one prototype at Näsudden on the island of Gotland. These sites are shown on Figure 3.

Selection of prototypes

After receiving the prototype proposals, the selection process was started. Once again a committee was formed for the technical evaluation and selection process. This committee was almost the same as the one writing the specification, except - of course - that no prospective manufacturers were present. On the other hand, the work performed by the participating utilities was increased considerably, as they started to look deep into operation and maintenance aspects of the proposals.

We formulated a system of evaluation criteria - or perhaps rather evaluation aspects - breaking down the design concepts of the different proposals into successively finer details. The scope of this evaluation method was defined as to form a basis for:

- uniform evaluation of proposals
- objective judgement of technical problems
- distribution of work within the committee
- checking off the completeness of evaluation.

The evaluation aspects were devided into four groups, as listed below with the main contents of these groups.

System Design

Was evaluated for the prototype and for the design implications for future series deliveries. The following subsystems of the prototype were studied:

- wind turbine (rotor and hub)
- machinery and nacelle
- tower and foundations
- control and servo systems
- electrical installation
- safety and maintenance equipment
- system integration

The aerodynamics, system dynamics and load characteristics were studied.

Operational and maintenance feasibility was evaluated.

Performance

Was studied from purely technical and from operational viewpoints.

- wind/power conversion efficiency
- machinery losses
- operational availability
- failure-mode consequences
- system life estimates
- personnel safety

Cost-benefit analysis was also applied, partly for the prototype functions, but mainly for the series cost versus energy production situation.

Prototype delivery

The completeness and scope of the proposed delivery was compared with requirements.

The time and capacity planning for the realization of the prototype delivery was checked against independent project planning methods.

Contractual conditions as presented by the bidder were noted when differing from NE requirements. These questions are brought up in the final negotiations with the bidders.

The suitability for evaluation of the proposed design concept, was discussed in comparison between all five proposals, in order to arrive at a "mix" of design concepts in the final selection, that will give us a good technical coverage of what we consider to be the main development problems. More about that will follow later in this paper.

Contractor credibility

This part of the evaluation process was not considered critical, as all bidders are highly serious companies. Known differences, mainly in technical resources and know-how, between the five bidders were listed, to be used in the final comparisons.

When all these aspects were broken down into detailed technical "problem points", the committee worked its way straight through all proposals, judging the design solutions, calculations of loads and stresses, performance, planning etc with a very simple scoring system:

0 = not supplied, not dealt with or insufficient
1 = acceptable from all viewpoints
2 = more than required or special advantage.

We did not weigh the different aspects against each other, but merely summed up all the scores to arrive at a preliminary technical conclusion.

The method proved to give very conclusive results, we really never were in great doubt about our judgements.

After more detailed investigations concerning performance and stress calculations and cost-benefit aspects, we had to revise some of the given scores. From that point, the committee had to develop its own philosophy concerning the technological span of the two-prototype program, to arrive at a reasonably safe basis for the technical and economical recommendations on future wind power in Sweden, which are the target for the prototype testing program.

The basic reason for choosing a prototype program with more than one unit - we had originally planned for three units - was that our systems analysis projects had pointed at the necessity to evaluate and test more than one design concept. We were convinced, that we would otherwise not be able to predict with any certainty the future pro's and con's of wind power.

Within the general limits of fairly large, horizontal axis machines, there are still many options, such as:

- upwind or downwind turbine
- number of rotor blades
- rotor blade material
- type of hub
- synchronous or induction generator
- controlled or free in yaw
- rigid or soft turbine-tower dynamics
- tower material

We will give emphasis to selecting and testing the following conceptual differences:

- steel or concrete towers
- metal or composite rotor blades
- two different hub types
- soft or rigid towers
- synchronous or induction generators

These priorities concerning the "technological span" to be tested were used as "weighting factors" for the scores given under the various evaluation aspects. An assessment of know-how in the form of systems analysis background and methods for the different bidders was also used as such a factor.

This has led us up to a very definite conclusion as to which proposals we would like to buy from the technical viewpoint. Present negotiations with the bidders concerning prices, schedules and other more commercial conditions will show if the technical conclusions will be upheld also in the cold light of available money.

Our general time schedule for the continued prototype program calls for:

- Contracts signed	June 1979
- Meteorological mast installed	October 1979
- Design phase ended	March 1980
- Manufacturing ended	June 1981
- Tower erected at site	March 1981
- Installations ended, unit operational	Late 1981
- Delivery tests completed	Early 1982

At the "4th Biennial Conference and Workshop on WECS" in Washington D.C. in October this year, we hope to be able to present the selected prototypes in more detail, presumably by the happy Contractors.

Discussion

Q. Are all of your potential contractors Swedish organizations?

A. The main contractors are Swedish, and they have foreign partners. One of them is Hamilton Standard and two are German contractors.

Table I . Load Cases for Prototypes

Case 1: Normal operation in steady winds.
10 minute mean winds between cut-in and cut-out speeds.

Case 2: Superimposed periodic and stochastic loads.
Periodic fatigue loads (wind profile, tower shadow, gravity forces). Stochastic turbulence loads.

Case 3: Sharp gradient wind shear.
At V_R and normal RPM a vertical wind shear of 0.2 m/s/m.

Case 4: Blade angle faults in normal operation.
Possible control malfunctions and their consequences to be analyzed.
- A: Wind is at cut-out speed. RPM is nominal. Blade pitch (β) instantaneously set at $\beta=\beta(V_R)$.
- B: Wind is at rated speed. RPM is nominal. β instantaneously set at β (max).

Case 5: Wind turbine over-speed.
Wind is at cut-out speed. $\beta=\beta(V_{CO})$. Torque reaction suddenly lost. Overspeed set by control system at RPM$\leq$1.25 x nominal RPM.

Case 6: Loads on wind turbine in emergency braking.
$V=V_{CO}$. RPM$\leq$1.25 x nominal RPM. Turbine being stopped by emergency braking system, as designed.

Case 7: Loads due to electrical faults.
Sudden cut-off (zero torque). Short circuit (dynamic oscillating torque).

Case 8: Loads on parked prototype.
Define parking geometry. Define yaw response.
- A: Symmetrical extreme gale wind.
  V=51 m/s. $C_L=C_L$ (max) over entire blade.
- B: Unsymmetrical extreme gale wind. (Applies only in case of vertical parking).
  V=51 m/s. $C_L=C_L$ (max) over entire upper blade, $C_L=0$ on entire lower blade.
- C: Parked with critical fault.
  Locked in yaw. Blade feathered vertically. Wind transversal to nacelle at V=43 m/s. $C_D=1.8$ over entire blade.

Case 9: Ice loads.
- A: On parked prototype.
  Blades feathered in parked position. V=43 m/s. 50 mm ice on both sides of the entire blade, at $\rho=0.9$. In horizontal parking $C_L=-0.8$.
- B: On prototype in operation.
  $V=V_{CO}$. Normal RPM and pitch angle. Leading edge ice buildup. Sudden loss of ice on one blade. Unbalance.

Case 10: Bird collision with blade.
$V=1.5 \times V_R$; $V_{BIRD} = V + 15$ m/s. Bird weight 4 kgs. Bird impact at (0.7-1.0) x R at or near leading edge. May not cause damage to the load carrying structure or cause sizeable parts to be thrown off.

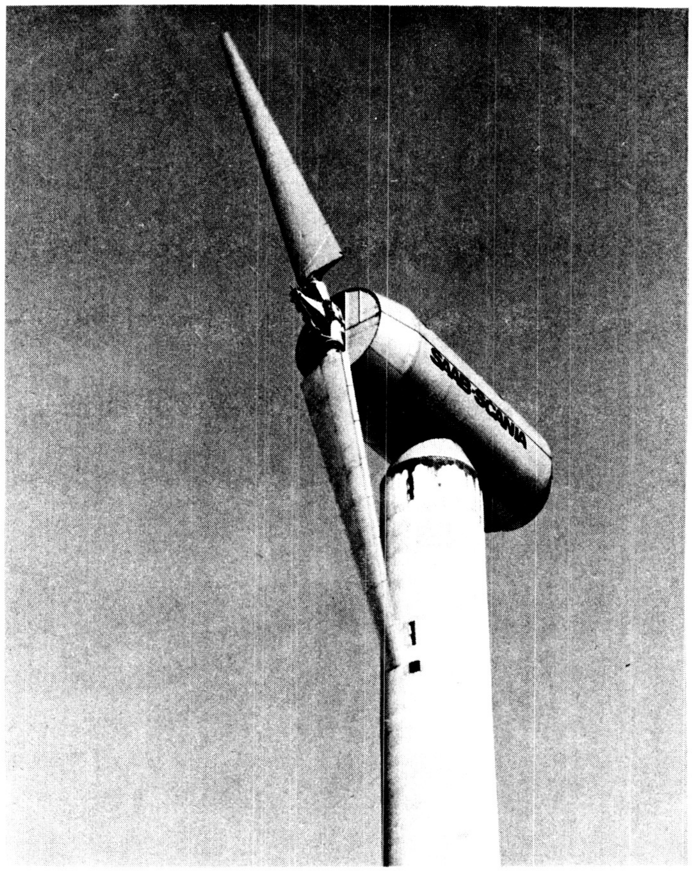

Figure 1. Research unit with flapping hub.

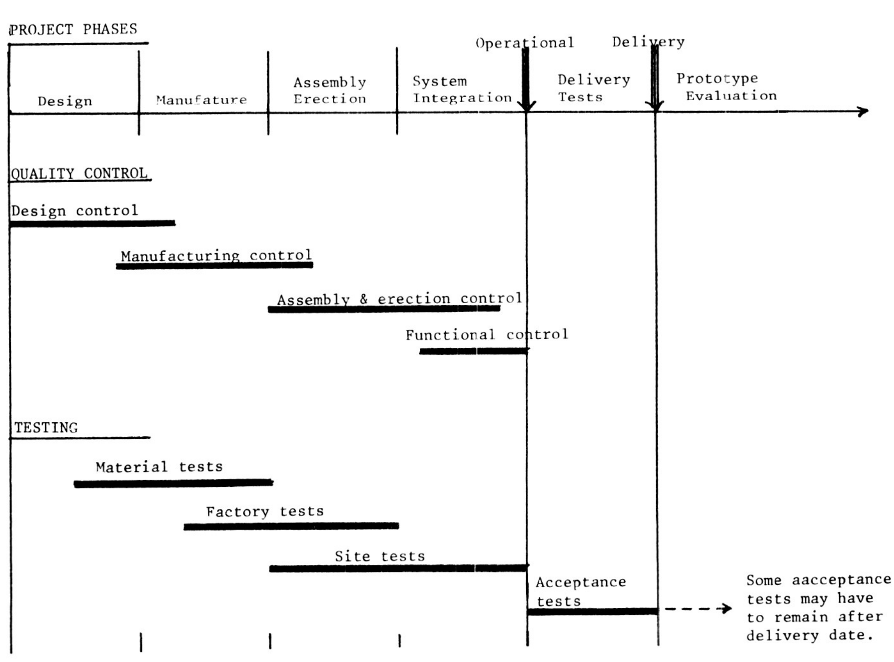

Figure 2. General schedule for the inspection and testing process.

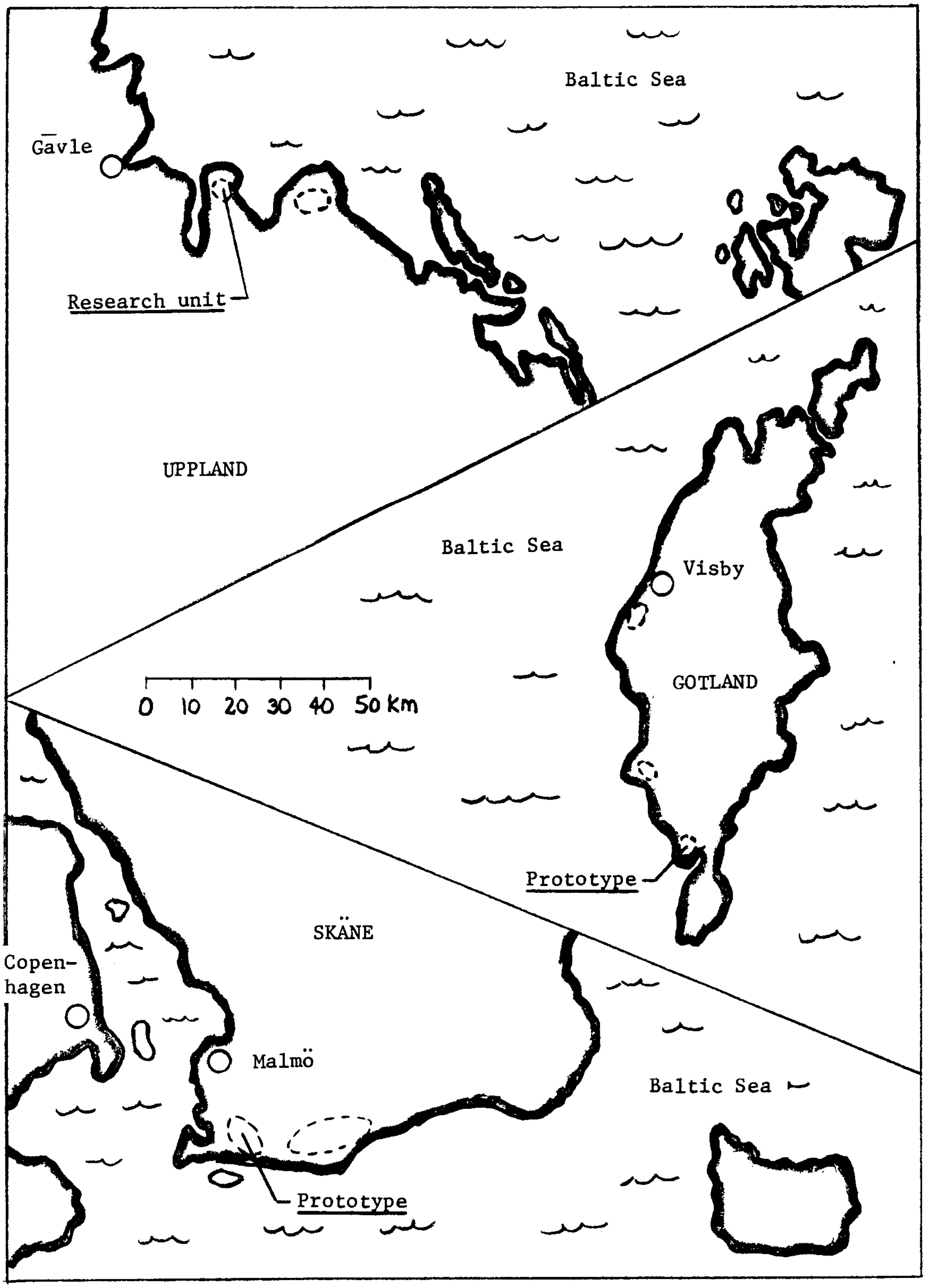

Figure 3. - Prototype sites.