RECOMMENDED PRACTICES FOR WIND TURBINE TESTING

2. ESTIMATION OF COST OF ENERGY FROM WIND ENERGY CONVERSION SYSTEMS

2. EDITION 1994

Edited by
John Olav Tande
Risø National Laboratory
DK 4000 Roskilde, Denmark
&
Raymond Hunter
Renewable Energy Unit
NEL
East Kilbride
Glasgow G75 0QU
United Kingdom

Foreword

The evaluation of a Wind Turbine (WT) or Wind Energy Conversion System (WECS) encompasses many factors ranging from: energy production, quality of power, reliability, durability and safety, through to cost effectiveness or economics, noise characteristics, impact on the environment and electromagnetic interference. The development of internationally agreed evaluation procedures for each of these areas is needed to aid the development of the industry while strengthening confidence and preventing chaos in the market.

It is the purpose of the IEA expert groups to meet periodically to propose recommendations for wind turbine testing and evaluation. These address:

1. Power Performance
2. Cost of Energy
3. Fatigue Loads
4. Acoustics
5. Electromagnetic Interference
6. Structural Safety
7. Quality of Power
8. Glossary of Terms

This document deals with Cost of Energy, and it is an update of the first edition, published in 1983.

The expert committee will seek to gain approval of the procedures in each member country through the IEA agreements. The recommendations shall be regularly reviewed and areas in need of further investigation shall be identified.

Contents

Introduction

The cost of energy from wind turbines (and any other power generating system) may be estimated in a variety of ways. A macro economic approach will require methods which are different from those needed for a private financial analysis, and will possibly generate cost of energy figures not suitable for comparisons. Furthermore, even analyses intended for the same purpose may have different ways for estimating the cost of energy, and thus care should be taken whenever comparing energy cost figures to ensure that the analyses methods have been the same.

This document describes a standard method for estimating the cost of energy from wind energy conversion systems. The recommendations are for making *project specific* estimates for existing wind energy conversion systems or for wind energy feasibility studies.

This document is a complete update of the first edition.

Scope and field of application

This document describes the recommended procedure for estimating the cost of energy from a wind energy conversion system. The following should be noted:

1. The procedures and practices presented are generally applicable to wind turbines of all sizes and classifications, as well as to wind farms consisting of groups of wind turbines. Primarily, this document considers wind turbines connected to a public grid. However, the methods may also be applied to wind pumps and other wind turbine installations not connected to a public grid.
2. The recommended procedure may be applied to both existing and planned wind power projects.
3. The derived cost of energy figure is only as valid as the assumptions which are made, and will relate only to the specific wind turbine(s) at the specific location.
4. The method presented cannot replace an investment analysis, though it may be used to support it.

Estimation of cost of energy from WECS

1 Applications of the levelised cost concept

In this document a standard method for estimating the cost of energy from wind energy conversion systems is recommended. The cost of energy is expressed as the *levelised production cost* (*LPC*) which is the cost of production of one unit (kWh) levelised over the wind power station's entire lifetime.

The derived cost of energy figure is most suitable for making cost comparison between wind turbines and other sources of energy having similar functional and operational characteristics. Cost comparison with any other energy technologies may be appropriate for a market assessment and as an indication of the economic feasibility of installing the assessed wind turbine. The application of the *LPC* is further illustrated in examples 1 to 4.

Example 1:
A choice between two or more wind turbines for installation at a specific site is to be made. Basing the choice solely on cost efficiency, the wind turbine with the lowest *LPC* should be selected.

Example 2:
A choice is to be made between a wind energy, a solar and a wave power system. Basing the choice on cost efficiency, the system with the lowest *LPC* should be selected.

Example 3:
A specific wind turbine is to be installed at one of several possible sites. Basing the choice on cost efficiency, the site yielding the lowest *LPC* should be selected.

Example 4:
The economic feasibility of installing wind turbines in an electric power supply system is to be estimated. An initial indication is provided by comparing the *LPC* of the wind turbines with the short run marginal cost (*SRMC*, i.e. operation cost) of the existing system. A *LPC* of the wind turbines lower than the *SRMC* for the existing system indicates economic soundness for small wind energy penetration levels. Higher wind energy penetration levels may modify the power system operation, and in such cases the cost of wind energy calculation should be supported by total power system modelling for deriving all costs and benefits. It should also be noted that if expanding a power supply system with wind turbines, it can be shown statistically that the loss of load probability is reduced. The wind turbines will have a capacity value equivalent to the capacity of a conventional plant which would have to be installed to attain the same level of power supply reliability.

It is stressed that cost comparisons are meaningfull only if the cost of energy figures are estimated on the same basis and with the appropriate level of accuracy. Furthermore, cost calculations of energy technologies are not a substitute for full system analyses deriving the total system cost of energy for adopting different energy generating technologies.

2 Cost components and energy production

The cost components are assumed to be the investment cost (including possible interest during construction), operation and maintenance cost, repair cost, salvage value and social cost. Apart from the social costs, only the costs which relate to the wind turbine system up to the point of interconnection with the public transmission or distribution network are considered.

In some cases it may be necessary to reinforce the public transmission or distribution system (or to include special control devices, etc.) due to the introduction of wind power. In such cases, depending on the scope of the analysis, these extra costs (or a part thereof) may be included in the analysis.

The wind energy output considered could be a) the annual net energy (ANE_t) as *available* at the wind turbine terminals, or b) the annual energy as *utilized* in the connected power system i.e. the annual utilized energy (AUE_t). The relation between the annual utilized energy and the annual net energy can be described by:

$$AUE_t = ANE_t \cdot K_{los,t} \cdot K_{util,t}$$

Here, $K_{los,t}$ is a factor relating to the electric losses which occur between the wind turbine terminals and the electric grid where the energy is utilized, and $K_{util,t}$ is a factor which depends on how the transmitted wind energy is utilized in the power system, see figure 1.

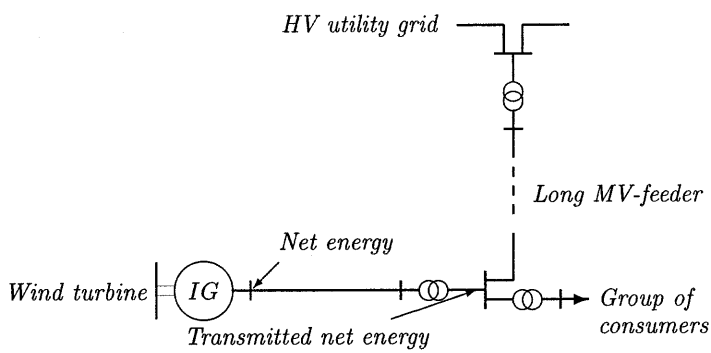


Figure 1: *Example of an electrical system where the energy losses in the long medium voltage feeder are reduced due to the wind power production so that the utilized wind energy becomes higher than the transmitted net energy and* $K_{util,t} > 1$.

Depending on the scope and field of application, both the annual net energy output and the annual utilized energy output are recognized as adequate energy measures, and the assessor must judge which to use in each case.

3 Cost calculation methodology

3.1 General approach

The measure of the estimated cost of energy adopted in this document is *the levelised production cost.* The levelised cost method is thoroughly described and discussed in NEA 1983, [2]. The method will only be described briefly in the following text.

The levelised production cost (LPC) is the cost of one production unit (kWh) averaged over the wind power station's entire expected lifetime. The total utilized energy output and the total costs over the lifetime of the wind turbine are both discounted to the start of operation by means of the chosen discount rate, and the LPC is derived as the ratio of the discounted total cost and utilized energy output.

It is assumed that all costs are given in a fixed currency for a specified year. The currency and cost level year should be decided and clearly declared by the assessor when reporting the estimated cost of energy. In the calculations all costs are discounted to the present value, i.e. the first date of commercial operation of the wind turbine. The discounted present value of the total cost (TC) is given as:

$$\boxed{TC = I + \sum_{t=1}^{n}(OM_t + SC_t + RC_t) \cdot (1+r)^{-t} - SV \cdot (1+r)^{-n}}$$

The levelised production cost (LPC) is given as the ratio of the total discounted cost and the total discounted utilized energy, i.e.:

$$\boxed{LPC = TC / \sum_{t=1}^{n} AUE_t \cdot (1+r)^{-t}}$$

The annual utilized energy, AUE_t, should be specified for each year by adjusting the annual potential energy output, E_{pot}, with a number of correction factors:

$$\boxed{AUE_t = ANE_t \cdot K_{los,t} \cdot K_{util,t} = E_{pot} \cdot K_{per,t} \cdot K_{site,t} \cdot K_{ava,t} \cdot K_{los,t} \cdot K_{util,t}}$$

The parameters required for estimating the LPC are further specified and discussed in section 4, whereas section 5 suggests a method for estimating the uncertainty in the cost of energy.

3.2 Simplified approach

In many cases it may be appropriate to assume the annual utilized energy to be constant from year to year (i.e. $AUE_t = AUE$ for $t = 1$ to n). In such cases, the LPC can be calculated as:

$$LPC = I/(a \cdot AUE) + TOM/AUE$$

a is the annuity factor as defined in the table below. I/a is the capital to be paid annually during the assumed period in order to cover both the depreciation and the assumed interest.

TOM is the total levelised annual "downline costs", i.e. all costs other than the initial investment. TOM may for simplicity be estimated as a certain percentage of the investment. The exact definition of TOM is given in table 1 below.

Table 1: *Summary specification of symbols used in this document for calculating the levelised production cost.*

Symbol	Unit	Definition
TC	currency	Discounted present value of total cost of energy production.
I	currency	Investment including possible interest during construction.
OM_t	currency	Operation and maintenance cost during year t.
SC_t	currency	Social cost during year t.
RC_t	currency	Retrofit cost during year t.
SV	currency	Salvage value after n years.
LPC	currency/kWh	Levelised production cost.
ANE_t	kWh	Net energy output during year t.
AUE_t	kWh	Utilized energy during year t.
$K_{per,t}$		Performance factor (rain, dirt, etc.).
$K_{site,t}$		Site factor (obstacles).
$K_{ava,t}$		Technical availability factor (failure, service).
$K_{los,t}$		Electric transmission losses factor.
$K_{util,t}$		Utilization factor.
E_{pot}	kWh	Annual potential energy output.
r		Discount rate.
n	year	Economic lifetime.
t		Year index.
a		Annuity factor, $a = 1/\sum_{t=1}^{n}(1+r)^{-t} = (1-(1+r)^{-n})/r$
TOM	currency	Total levelised annual "downline cost", $TOM = a^{-1} \cdot \sum_{t=1}^{n}(OM_t + SC_t + RC_t)(1+r)^{-t} - SV(1+r)^{-n}$

4 Estimation and specification of input parameters

In this section the input parameters are specified further and guidance is given for their estimation. In many cases one or more of the input parameters will be known explicitly, and of course, the known figures should be used whenever possible.

4.1 Economic parameters

This document considers the cost of energy from wind turbines excluding all possible taxes and subsidies.

4.1.1 Investment

The investment should include all the costs of constructing the WECS. Although only the total investment is included in the formula for calculating the levelised production cost, the analysis report should include a break-down of the investment as indicated in table 2.

In some cases, e.g. for very large wind farms, the construction time may be of substantial length, and the interest on the investment, during the time from when the payment is made until the start of commercial operation, should be calculated and included in the total investment:

$$I = \sum_{i=1}^{j} I_i \cdot (1 + r)^{t_i}$$

Here, j is the number of investment payments, r is the discount rate, and I_i is the investment part paid t_i years before the start of commercial operation of the wind power installation.

It is important to notice that bank interest for financing the investment is not considered, since in this document the *project* is being assessed, not how it will be financed.

4.1.2 Operation & maintenance

The O&M costs will depend on the number of wind turbines, the wind turbine type, the site conditions and the connected system. Accordingly, this document recommends project specific estimates of the O&M costs to be specified for each year of the scheme's lifetime. Although only the total annual O&M cost for each year is included in the formula for calculating the levelised production cost, the analysis report should include a break-down as indicated in table 3.

Table 2: *List and specification of investment cost components for grid connected wind turbines. The cost components may be further divided into parts and labour costs. The table is partly based on Nielsen (1990) ref. [5].*

- Wind turbine ex factory cost.
- Special certification or other external test procedure costs if procured.
- Transportation costs, i.e. loading and unloading and other costs associated with transporting the wind turbine from the manufacturer to the site.
- Site preparation costs, i.e. civil works for preparing access road(s), leveling the site, and other actions depending on the specific landscape and ground conditions.
- Foundation costs, i.e. civil works for preparing the wind turbine foundation.
- Erection costs, i.e. costs for erecting the wind turbine at the foundation.
- Internal electrical connections, i.e. costs associated with the low voltage (< 1000 V) electrical works.
- Grid connection costs, i.e. costs associated with the high voltage (> 1000 V) electrical works.
- External monitoring and control system costs. Such external systems are typically associated with large wind farms monitored and operated from a remote utility central.
- Consultancy services and other costs for design and supervision of the installation works.
- General site costs, i.e. costs associated with possible temporary installations such as sanitary installations, work-shops, etc. at the site while installing the wind turbine.
- Land costs, i.e. the cost of buying or renting land for the wind power installation. The use of land near a wind turbine may be restricted by regulations concerning safety and noise aspects as well as restrictions for avoiding construction of buildings or other obstacles which would reduce the wind turbine output. The costs should be discounted to the first date of commercial operation using the discount rate as specified in section 4.1.7. In cases where the land is also used for farming or other activities, the land investment cost should be reduced by the discounted income of these activities.

Table 3: *List of operation and maintenance cost components for grid connected wind turbines. The cost components may be further divided into parts and labour costs.*

- Normal liability and property insurance costs covering sudden wind turbine damage and operational losses due to such damage.
- Special insurance for an annual energy output guarantee.
- Service costs may include the man-power costs of the scheduled services. Service costs during the first years are sometimes included in the wind turbine price.
- Consumable spare parts for wear and tear as well as lubrication grease and oil.
- Repair costs, i.e. minor repairs outside the scheduled service and not covered by any insurance or guarantee surveillance.
- Management costs, i.e. costs connected to the construction and operation management of the wind turbine(s). Management costs may be substantial for large wind farms.

4.1.3 Social costs

The social (or external) costs of energy production are those which are borne by third parties and are not reflected in the market price of energy. Social costs may be associated with environmental damage, nuisance to people, etc.

Consensus on specific methods for estimation of social costs has yet to be established. However, it is accepted that social costs exist and that they should be included when calculating the cost of energy production. It is also widely accepted that social costs of wind energy production are small or negligible, especially when compared to those associated with energy generation from non-renewable sources.

4.1.4 Retrofit cost

The need and costs for replacements or major repairs during the adopted lifetime (see section 4.1.6) should be evaluated. These are dependent on numerous factors, and it is recommended that project specific estimates are made of the timing and cost of possible major repairs.

4.1.5 Salvage value

The salvage value is defined as the difference between the scrap value and the decommissioning cost of the entire scheme at the end of the lifetime adopted for the economic analysis.

If the adopted economic lifetime, n, is less than the assumed technical lifetime of the wind turbine, the salvage value should be a positive value reflecting the capital value of the total wind power installation after n year of operation.

Note that even if the adopted economic lifetime (see section 4.1.6) is set equal to the assumed technical lifetime of the wind turbine, the salvage value of the total investment may not be zero as land, electrical cables, etc. may have a significant capital value.

4.1.6 Economic lifetime

The actual technical lifetime of a wind power installation depends on numerous factors, and it may in fact be very difficult to predict.

Modern electricity producing wind turbines are commonly designed to have a life of 20 years, and normally a 20 year economic life can also be assumed.

The economic life should not be set to a value which exceeds the technical life of the wind turbine.

It should be noted that the economic life as described in this document is a parameter that can be set by the analyst. It should not be confused with other parameters such as the possible loan payback period.

4.1.7 Discount rate

The discount rate, r, given in real terms may be defined as the rate at which the nominal rate, i, exceeds the inflation rate, v, i.e.:

$$1 + r = \frac{1 + i}{1 + v}$$

The choice of the numerical value for the discount rate must be decided by the relevant country, utility, developer etc. and may reflect the cost of financing the project, the possible earned return of an alternative investment or the opportunity cost of capital, the project risks, or any policy objective or constraint.

The following points should be noted:

- The levelised production cost of energy will be higher for a higher discount rate and lower for a lower discount rate.
- If the energy is sold at the calculated levelised production cost, the project costs and income will balance each other and the internal rate of return will be equal to the assumed discount rate.
- An increased discount rate will reduce the economic attractiveness of projects with high investments and low running costs compared to less capital intensive projects.

International studies of electricity generation costs often adopt 5 to 7 % as the annual discount rate in real terms, whereas private investors investigating commercial projects may adopt higher values. In general, it is recommended that an analysis is carried out to determine the the cost of energy sensitivity to the discount rate.

4.2 Wind energy output

The following discussion on estimating the annual utilized energy highlights the most important factors to be considered and reported. It is not meant to give strict directions and thus the appropriate calculation methods may vary considerably from system to system. This document recommends that the assessor uses the best available information for estimation of the annual utilized wind energy output.

Measured values give actual achieved operational statistics and production costs per kWh. Single "spot" measurements (e.g. one year of production figures) should however be used with care for calculation of the levelised production cost, as they can be significantly biased compared to the levelised lifetime figures.

The subsequent sections 4.2.1 – 4.2.8 consider single wind turbines only. The utilized energy output of a wind power plant consisting of more wind turbines can be estimated either by treating the plant as a single large wind turbine, or it can be found by summing the individual utilized energy output estimates of all the wind turbines in the wind power plant.

4.2.1 Potential energy output

The annual potential energy output, E_{pot}, of a wind turbine experiencing specific meteorological conditions is given as:

$$E_{pot} = 8766 \cdot \int_0^{\infty} p(u) \cdot f(u) du$$

Here, 8766 is the average number of hours in a year, $p(u)$ is the power curve of the wind turbine, and $f(u)$ is the normalised wind speed probability distribution at the hub height of the wind turbine. Often, the wind speed probability distribution is expressed by a Weibull or Rayleigh distribution.

The wind speed distribution should ideally be based on many years of on-site wind speed measurements, but in practice it will often be necessary to extrapolate long term wind data from nearby high quality measurement stations, using for instance the wind atlas method as embodied in the European Wind Atlas, ref. [1], or by applying the statistical "measure-correlate-predict" approach, see for instance Derrick (1992) [7].

The power curve normally gives (as recommended in ref. [3]) the net power output for standard air density conditions (i.e. 15°C and 1013.3 mbar) and for carefully selected weather conditions (e.g. absence of precipitation). When calculating $E_{pot,i}$, corrections must be made for actual atmospheric conditions at the specific site.

For a stall regulated wind turbine, the power curve can be approximately adapted to the actual site by applying the formula:

$$p(u) = p(u)_{std} \cdot \frac{\rho}{1.225}$$

Here $p(u)_{std}$ is the power curve for standard conditions and ρ is the actual annual average air density in kg/m^3. The standard air density is 1.225kg/m^3.

4.2.2 Wind turbine performance factor

The performance of a wind turbine may be reduced dramatically due to dirt, rain or ice on the blades. If the site conditions are likely to give such problems, then either cleaning of the blades must be included in the O&M costs or a reduction in the annual energy output relative to the potential output must be assumed. This reduction in the annual energy output, $\Delta E_{per,t}$, can be expressed by the performance factor, $K_{per,t}$, defined as the ratio of the reduced annual energy output and the annual potential output:

$$K_{per,t} = 1 - \frac{\Delta E_{per,t}}{E_{pot}}$$

The performance factor may change over time due to turbine wear, and changing seasonal climatic conditions.

4.2.3 Site factor

The wind speed distribution assumed for calculating the potential energy output should be the wind speed distribution at the hub height of the wind turbine. In some cases however, the site surroundings may change with time due to erection of new wind turbines, tree planting, construction of new houses, etc. thus influencing the wind speed distribution and the energy output from the wind turbine. In such cases, it may be adequate to take the assumed annual potential energy output, E_{pot}, and then apply a site factor to take account of the reduction in annual energy output, $\Delta E_{site,t}$, due to the changed surroundings. The annual reduction may be expressed by means of the site factor, $K_{site,t}$:

$$K_{site,t} = 1 - \frac{\Delta E_{site,t}}{E_{pot} \cdot K_{per,t}}$$

4.2.4 Technical availability factor

The technical availability, $C_{ava,t}$, of a wind turbine is defined as the fraction of the year the wind turbine is ready for operation:

$$C_{ava,t} = \frac{8766 - T_{out,t}}{8766}$$

Here, 8766 is the number of hours in an average year, $T_{out,t}$ is the total annual scheduled and forced outage time of the wind turbine.

The resulting technical availability, $C_{ava,t}$, may in general depend both on the wind power installation and on the connected system, e.g. a grid connected wind turbine will shut down in the event of an external grid failure. In such cases, it is often adequate to specify the technical availability of the wind turbine and the connected system separately, and to estimate the resulting technical availability, $C_{ava,t}$, as the product of these two availability factors. It should be noted that for large modern power systems, the grid availability may be very close to 1, whereas for smaller rural grids, the availability will typically be lower.

The *technical availability factor*, $K_{ava,t}$, assumed by this document is defined by the energy loss, $\Delta E_{ava,t}$, due to the wind turbine availability:

$$K_{ava,t} = 1 - \frac{\Delta E_{ava,t}}{E_{pot} \cdot K_{per,t} \cdot K_{site,t}}$$

$K_{ava,t}$ may be different from $C_{ava,t}$, e.g. if the wind turbine servicing is scheduled during calm periods, $K_{ava,t}$ will probably be higher than $C_{ava,t}$.

4.2.5 Net energy output

The annual net energy output (ANE_t) is the annual energy output at the wind turbine terminals:

$$ANE_t = E_{pot} \cdot K_{per,t} \cdot K_{site,t} \cdot K_{ava,t}$$

4.2.6 Electric transmission losses factor

The annual electrical transmission loss, $\Delta E_{los,t}$, is the difference between the wind turbine net energy output and the transmitted net energy fed into the point of public utilization.

The annual electrical transmission losses may be expressed as a factor, $K_{los,t}$:

$$K_{los,t} = 1 - \frac{\Delta E_{los,t}}{ANE_t}$$

An estimate of the annual electric transmission losses may be based on the annual net wind power distribution and specifications of the site transmission system. It is important to know the actual net wind power distribution as the transmission losses will be a function of the square of the net wind turbine output power.

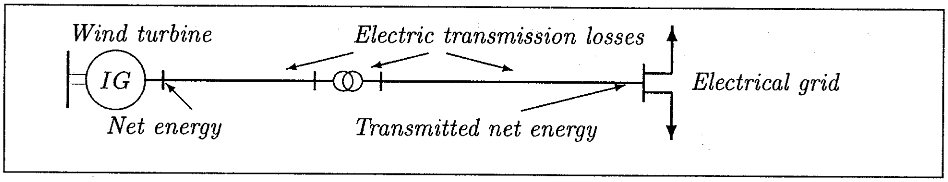


Figure 2: *Example of the electrical grid connection of a wind turbine. The wind energy electric transmission losses occur between the wind turbine and the grid where the wind energy is utilized.*

4.2.7 Utilization factor

In most cases, the transmitted wind energy ($ANE_t \cdot K_{los,t}$) will be very close both geographically and numerically to the wind energy utilized in the connected system (AUE_t), see also figure 2. However, in certain cases (see example 5 and 6) there may be a substantial difference, and the utilization factor is defined to take account for such cases:

$$K_{util,t} = 1 - \frac{\Delta E_{util,t}}{ANE_t \cdot K_{los,t}}$$

Example 5:
In an electrical system with high wind energy penetration, the power production may be higher than the load during high wind and low load periods. Thus, the excess energy has to be dissipated during these periods, and the utilized wind energy will be lower than the transmitted net wind energy output.
Example 6:
In an electrical system where the wind turbines are connected to the grid at a point close to a large group of consumers and far from any other power plant, the grid losses (in the grid between the power plant and the consumers in question) may be reduced, and the utilized wind energy will be higher than the transmitted net wind energy output. See figure 1 for illustration.

4.2.8 Utilized energy

The annual utilized energy, AUE_t is the wind energy output utilized in the connected system. The AUE_t may be estimated for each year of the wind turbine's lifetime by assuming the potential output, E_{pot}, and the year specific factors $K_{per,t}$, $K_{site,t}$, $K_{ava,t}$, $K_{los,t}$ and $K_{util,t}$.

$$AUE_t = E_{pot} \cdot K_{per,t} \cdot K_{site,t} \cdot K_{ava,t} \cdot K_{los,t} \cdot K_{util,t}$$

5 Uncertainties

5.1 Nomenclature and general considerations

It is recommended that the LPC estimate is accompanied by an uncertainty analysis, which follows the "Guide to Expression of Uncertainty in Measurements", ref. [8]. This document provides an outline explanation to the guide, but is stressed that the simplifications proposed may not be valid in specific cases and should be carefully evaluated be the user.

Clearly, a forecast of the *LPC* is to some extent uncertain, and this uncertainty should be specified. A simple methodology for estimating the uncertainty is outlined in the following text.

When quoting an uncertainty, it is vital to state the associated confidence interval and confidence level. The confidence level defines the probability that the (actual) value lies within a given range, i.e. the confidence interval.

Table 4: *Nomenclature and basic mathematical rules for stochastical variables used in this document for calculation of the levelised production cost uncertainty.*

Nomenclature		
X		stochastical variable
$f(x)$		probability distribution of X
$E(X) = \int X \cdot f(x)dx = \mu$		expectation value of X
$V(X) = \int (X - E(X))^2 \cdot f(x)dx = \sigma^2$		variance of X
$STD(X) = \sqrt{V(X)} = \sigma$		standard deviation of X
Basic rules		
$E(X_1 + X_2) = \mu_1 + \mu_2$		$E(X + c) = E(X) + c$
$E(X \cdot c) = E(X) \cdot c$		$V(X + c) = V(X)$
$V(X \cdot c) = V(X) \cdot c^2$		c is a constant
If X_1 and X_2 are independent	$\Longrightarrow$	$V(X_1 + X_2) = \sigma_1^2 + \sigma_2^2$

5.2 Uncertainties on input parameters

Any input parameter may have two types of attached uncertainty:

- category A: uncertainty which is estimated on the basis of measurements; it is typically due to random error in observation of the parameter considered, and
- category B: uncertainty estimated on basis of the knowledge other than from measurements.

Category A uncertainty can be derived from the probability distribution of the observations, i.e. the classical method of probability. Furthermore, the (true) value of a parameter with only category A uncertainty will be equal to the mean value of N observations when $N \to \infty$, thus category A uncertainty may be reduced to any small value simply by making more observations.

Category B uncertainties are determined by means other than measurements. It could be an uncertainty related to instrument calibration or the way the instrument is used, and the magnitude of the uncertainty is evaluated by employing the experience of the analyst, i.e. statements regarding category B uncertainties will include judgment and/or belief. Category B uncertainties, unlike these from category A, cannot be reduced to a small value by making more observations. Qualified estimates of category B uncertainties may however still be obtained by utilizing historical data for the project in question and experience from other similar projects.

Category B uncertainties are likely to dominate the input parameters considered in this document, and thus, for simplicity, category A uncertainties are assumed negligible.

In this document all uncertainties, category A or B, are considered independent.

In general, the uncertainty of an input parameter may be represented by any probability distribution judged appropriate for the specific parameter and type of analysis. In this document however, only Gaussian probability functions are assumed. A consequence of this suggestion is, that it is adequate simply to specify the expectation value and variance for each input parameter in question.

Annex B identifies the input parameters to be considered, and gives sample suggestions for their 95% confidence interval. The economic lifetime and the discount rate is not included in the table as they are regarded as decision parameters not connected with uncertainty. It should be stressed however, that both the lifetime and the discount rate have significant impact on the derived LPC, and that their impact should be determined in a sensitivity analysis by calculating the LPC for a number of chosen values, e.g. assuming a lifetime of 15, 20 and 25 years and a discount rate of 5, 10 and 15%.

5.3 Calculation of resulting uncertainty

The best estimate (expectation value) of the LPC may be calculated by combining, according to section 3, the best estimates of the input parameters.

The sensitivity, α_l, is defined as the partial derivative of the LPC with respect to the specific parameter, X_l:

$$\alpha_l = \delta LPC / \delta X_l$$

By varying one parameter at a time, graphs can be drawn, as shown in figure 3, in which the slopes define the sensitivities.

For small perturbations, the formula for calculating the LPC may be approximated by a linear function:

$$LPC = E(LPC) + \sum_{l=1}^{k} \alpha_l \cdot \Delta X_l$$

Here, $E(LPC)$ is the expectation value of the LPC and ΔX_l the perturbations about the expectation values of the input parameters.

Following the definitions of section 5.1, and assuming the input parameters to be independent of each other, the standard uncertainty of the LPC may be expressed as:

$$V(LPC) = \sum_{l=1}^{k} \alpha_l^2 \cdot V(X_l)$$

and the overall uncertainty U specifying the confidence interval, $(LPC - U, LPC + U)$, of the LPC may be given as:

$$U = c \cdot \sqrt{V(LPC)} = c \cdot STD(LPC)$$

Here, c is a factor which can be chosen to give the expanded confidence interval corresponding to a desired confidence level. If the LPC has a Gaussian distribution, $c = 2$ gives a confidence level of 95%.

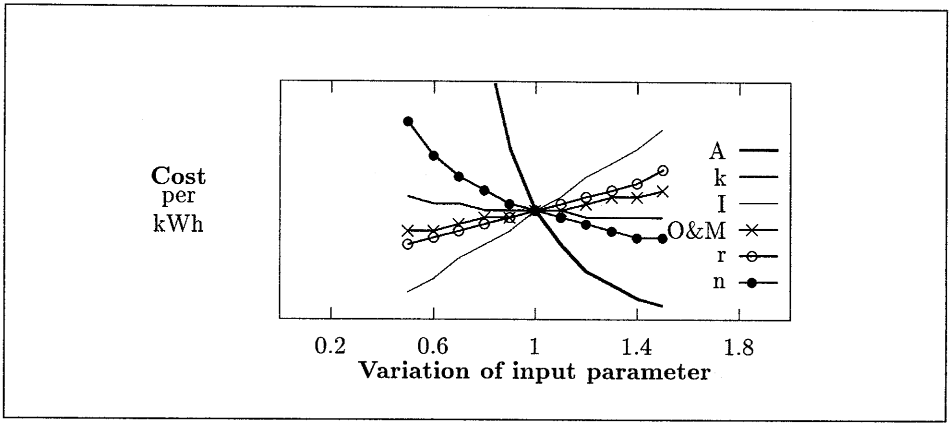


Figure 3: *Energy cost as a function of selected input parameters. The input parameters considered are the investment, I, the levelised annual operation and maintenance cost, OM, the wind speed distribution (expressed by a Weibull distribution with scale parameter A and shape parameter k), the discount rate, r, and the economic lifetime, n. The figure is for illustration purposes only.*

6 Information to be reported

A report stating an estimate for the cost of energy for a specific wind energy project shall include, but not be limited to, the items listed below:

1. Bibliographic data
2. WECS specification
3. Energy system specification
4. Site specification
5. Economic data
6. Energy calculation
7. Specification of uncertainties
8. Sensitivity analysis

A sample reporting format for selected parts of a full report is included in appendix C.

7 Acknowledgements

The present edition of this document has been developed through a series meetings involving participants from different signatory countries to the IEA R&D - agreement.

The following have made valuable contributions:

G. Elliot (UK)
S. Frandsen (Denmark)
J.C. Hansen (Denmark)
P.H. Jensen (Denmark)
P.E. Morthorst (Denmark)
P. Nielsen (Denmark)
B. Maribo Pedersen (Denmark)
W. Stam (The Netherlands)
R.W. Sherwin (USA)
S.E. Thor (Sweden)

References

[1] Troen I. and E.L. Petersen (1989). *European Wind Atlas.* ISBN 87-550-1482-8. 656 p.

[2] Nuclear Energy Agency (1983). *The cost of generating electricity in nuclear and coal fired power stations.*

[3] IEA (1990). *1. Power performance testing.* Expert group study on recommended practices for wind turbine testing and evaluation. Editors: Frandsen S. and B.M. Pedersen.

[4] Frandsen S., C.J. Christensen (1990). *Uncertainties in energy production forecasting.* Proc. of EWEC'90.

[5] Nielsen P. (1990). *Study on the next generation of large wind turbines. Part 3. Site and installation costs. Operation and maintenance costs.* Proc. of EWEC'90.

[6] Morthorst P.E. et. al. (1991), *The economics of privately owned wind turbines.* Ministry of Energy, Danish Energy Agency. (Report in Danish from Energistyrelsen, original title: Privatejede vindmøllers økonomi).

[7] Derrick A. (1992), *Development of the measure-correlate-predict strategy for site assessment.* Proc. of BWEA'92.

[8] *Guide to the Expression of Uncertainty in Measurements.* First edition 1993. ISBN 92-67-10188-9.

A Summary of input parameters

Input parameter	Range & Comment
Total initial capital investment, I	Wind turbine and system specific.
O&M cost, OM_t	Wind turbine and system specific; average annual O&M costs of $\sim$ 2% of ex factory wind turbine investment can be assumed.
Social cost, SC_t	Wind turbine and system specific; commonly accepted as being negligible for wind turbines.
Retrofit cost, RC_t	Wind turbine and system specific; a retrofit after 10 years costing approx. 10-15% of the ex factory wind turbine investment is often assumed for proven grid connected wind turbines.
Salvage value, SV	Wind turbine and system specific; depends also on the adopted economic lifetime.
Economic lifetime, n	Decision parameter; should be equal to or shorter than the technical lifetime, 20 year is commonly assumed for proven grid connected wind turbines.
Discount rate, r	Decision parameter, 5-7% is commonly assumed in international studies of electricity generation costs.
Power curve, $p(u)$	Wind turbine specific, should be corrected to air density at site.
Air density, ρ	Site specific, 1.225 kg/m^3 at 15^{o}C, 1013.3mbar.
Wind speed distribution, $f(u)$	Site specific; commonly expressed by a Weibull or Rayleigh distribution.
Annual potential production, E_{pot}	$E_{pot} = 8766 \int_0^\infty p(u) \cdot f(u)du$
Performance factor, $K_{per,t}$	Wind turbine and site specific; the factor may range from 0.7 to $\sim$ 1.0 depending on dirt, rain and ice conditions and on wind turbine maintenance, $\sim$ 1.0 is typical.
Site factor, $K_{site,t}$	Site specific; factors from 0.6 to $\sim$ 1.0 are experienced for wind turbines in wind farms, 0.95 is typical.
Technical availability factor, $K_{ava,t}$	Wind turbine and system specific; 0.9 to $\sim$ 1.0 is a typical range for proven grid connected WECS.
Annual net energy, ANE_t	$ANE_t = E_{pot} \cdot K_{per,t} \cdot K_{site,t} \cdot K_{ava,t}$
Electric transmission losses factor, $K_{los,t}$	Dependent on site transmission system and power production distribution; 0.9 to $\sim$ 1.0 is a typical range for proven grid connected wind turbines.
Utilization factor, $K_{util,t}$	Dependent on system configuration, load and power production distribution; $\sim$ 1.0 is typical for electrical power systems with low penetration of wind power; values much below 1.0 may be experienced if the installed wind power capacity is higher than the minimum consumer load.
Annual utilized energy, AUE_t	$AUE_t = E_{pot} \cdot K_{per,t} \cdot K_{site,t} \cdot K_{ava,t} \cdot K_{los,t} \cdot K_{util,t}$

B Summary of uncertainty parameters

Sample parameter	confidence interval*	Comments
Total investment, I	5	Assuming short term (less than 2 years) forecast for specified proven technology at specific site.
O&M cost, OM_t	5-10	Assuming the forecast is for specified proven technology at a specific site; uncertainty depends on forecast length.
Social cost, SC_t	??	The uncertainty may be neglected as the social cost of wind power is commonly assumed to be very low.
Retrofit cost, RC_t	??	Uncertainty may be neglected as having very little impact on the LPC.
Salvage value, SV	??	Uncertainty may be neglected as having very little impact on the LPC.
Power curve, $p(u)$	10-15	Dependent on average wind speed; thoroughly discussed in ref. [3].
Wind speed distribution, $f(u)$	10-15	Dependent on quality and amount of historical wind speed data, complexity of terrain and on wind speed data analysis method; see ref. [4].
Air density, ρ	1	Uncertainty due to instrument bias error; see ref. [3].
Performance factor, $K_{per,t}$	5	Estimated uncertainty on forecasted performance factor assuming no extreme operation conditions; see ref. [4].
Site factor, $K_{site,t}$	4-6	Estimated as 1/3 of observed total variability range of wake factor; see ref. [4].
Technical availability, $K_{ava,t}$	1-2	Assuming proven technology; uncertainty depends on forecast length; see ref. [4].
Electric transmission losses, $K_{los,t}$	3	Estimated as 1/3 of typical range of transmission efficiency, actual uncertainty depends strongly on method used for estimating the parameter.
Utilization factor, $K_{util,t}$	6	Estimated as 1/3 of typical range of utilization factor, actual uncertainty depends strongly on method used for estimating the parameter.

* The confidence interval, $\frac{\Delta}{E(X_l)}$, is in % of the expectation value of the input parameter, X_l. The numbers are samples for the 95 % confidence level, and the given numbers should not be regarded as a substitute for the recommended project specific analysis.

C Calculation and reporting format example

This example has been prepared by using a spreadsheet which uses the formulae specified in this document for calculating the levelised cost of energy figure and uncertainty.

The example also includes calculation of the profit and internal rate of return. The profit is the difference between revenue and cost for the given lifetime and discount rate, whereas the internal rate of return is the discount rate which would give zero profit. The revenue could be specified by for instance the kWh sales price.

The input cost figures in the example are partly from ref. [6].

ESTIMATION OF COST OF ENERGY FROM WIND TURBINES
SUMMARY INPUT DATA AND RESULTS

Spreadsheet printout. Date and time: 26-Sep-93 05:54 PM
Sample calculation. Costs in DKK of 1993.

Wind speed distribution Weibull para.		A (m/s)	k	Avg (m/s)
Height (m)	10.00	8.00	3.00	7.14
Hub height	30.00	9.27	3.00	8.28

Rotor area (m^2)	962	Roughness length (m)	0.01
WT capacity (kW)	400	Temperature (C)	15.00
WT capacity scale	1		
Pot. efficiency (%)	35.0	Pressure (mbar)	1013.00
Pot cap. factor (%)	41.1	Density (kg/m^3)	1.22

Levelised correction factors						
	Kper	Ksite	Kava	Klos	Kutil	Total
	1.00	0.95	0.95	0.95	1.00	0.86

Levelised Annual Utilized Energy, AUE (MWh/year)	1236

Discount rate (%)	6		
Lifetime (year)	20	Annuity factor	11.47

	Scale	NPV (DKK)	Annual (DKK)	(DKK/kW)	(DKK/kWh)	Distribution (%)
Investment	1	3327000	290063	8318	0.23	76.13
O&M	1	847949	73928	2120	0.06	19.40
Social	1	0	0	0	0.00	0.00
Retrofit	1	211632	18451	529	0.01	4.84
Salvage	1	-16214	-1414	-41	-0.00	-0.37
Total		4370367	381029	10926	0.31	100.00

					IRR (%)
Saved Cost	7088771	618031	17722	0.50	
Profit	2718404	237003	6796	0.19	15.91

+/- Input Parameters Uncertainty (%)

A	k	Density	P(u)	Investment	O&M
10.0	10.0	1.0	5.0	5.0	5.0

Kper	Ksite	Kava	Klos	Kutil
5.0	5.0	2.0	3.0	5.0

Levelised Production Cost, LPC (DKK/kWh)		0.31
Total Uncertainty, U (DKK/kWh)	+/-	0.08

ESTIMATION OF COST OF ENERGY FROM WIND TURBINES - INPUT DATA

Spreadsheet printout. Date and time: 26-Sep-93 05:54 PM
Sample calculation. Costs in DKK of 1993.

Wind speed distribution Weibull parameters

Height (m)	Scale (m/s)	Shape	Avg. wind speed (m/s)
10.0	8.0	3.0	7.1
30.0	9.3	3.0	8.3

Roughness length (m)	0.01	Pressure (mBar)	1013
Temperature (deg. C)	15	Air density (kg/m^3)	1.22

Wind Turbine Data

Rated power (kW)	400
Hub height (m)	30
Rotor diameter (m)	35

Wind speed	Standard conditions		Site conditions
u (m/s)	P (kW)	Cp	P (kW)
4.0	0.0	0.00	0.0
5.0	3.0	0.04	3.0
6.0	40.0	0.31	40.0
7.0	80.0	0.40	80.0
8.0	130.0	0.43	130.0
9.0	190.0	0.44	189.9
10.0	250.0	0.42	249.9
11.0	320.0	0.41	319.9
12.0	370.0	0.36	369.9
13.0	390.0	0.30	389.9
14.0	400.0	0.25	399.9
15.0	400.0	0.20	399.9
16.0	400.0	0.17	399.9
17.0	400.0	0.14	399.9
18.0	400.0	0.12	399.9
19.0	400.0	0.10	399.9
20.0	400.0	0.08	399.9
21.0	400.0	0.07	399.9
22.0	400.0	0.06	399.9
23.0	400.0	0.06	399.9
24.0	400.0	0.05	399.9
25.0	400.0	0.04	399.9
26.0	0.0	0.00	0.0

ESTIMATION OF COST OF ENERGY FROM WIND TURBINES - INPUT DATA

Spreadsheet printout. Date and time: 26-Sep-93 05:54 PM
Sample calculation. Costs in DKK of 1993.

Correction Factors

Year	Kper	Ksite	Kava	Klos	Kutil
0					
1	1.00	0.95	0.95	0.95	1.00
2	1.00	0.95	0.95	0.95	1.00
3	1.00	0.95	0.95	0.95	1.00
4	1.00	0.95	0.95	0.95	1.00
5	1.00	0.95	0.95	0.95	1.00
6	1.00	0.95	0.95	0.95	1.00
7	1.00	0.95	0.95	0.95	1.00
8	1.00	0.95	0.95	0.95	1.00
9	1.00	0.95	0.95	0.95	1.00
10	1.00	0.95	0.95	0.95	1.00
11	1.00	0.95	0.95	0.95	1.00
12	1.00	0.95	0.95	0.95	1.00
13	1.00	0.95	0.95	0.95	1.00
14	1.00	0.95	0.95	0.95	1.00
15	1.00	0.95	0.95	0.95	1.00
16	1.00	0.95	0.95	0.95	1.00
17	1.00	0.95	0.95	0.95	1.00
18	1.00	0.95	0.95	0.95	1.00
19	1.00	0.95	0.95	0.95	1.00
20	1.00	0.95	0.95	0.95	1.00

ESTIMATION OF COST OF ENERGY FROM WIND TURBINES - INPUT DATA

Spreadsheet printout. Date and time: 26-Sep-93 05:54 PM

Sample calculation. Costs in DKK of 1993.

Investment	Payment (DKK)	Year	Interest (DKK)	Distribut. (%)
WT cost	2600000	0	0	78.1
Certification	0	0	0	0.0
Transport	0	0	0	0.0
Site preparation	0	0	0	0.0
Erection	0	0	0	0.0
Foundation	200000	0	0	6.0
Low voltage instal.	110000	0	0	3.3
Grid connection	280000	0	0	8.4
Monitoring system	20000	0	0	0.6
Consultancy services	50000	0	0	1.5
General site costs	0	0	0	0.0
Land	52000	0	0	1.6
Roads	15000	0	0	0.5
Other	0	0	0	0.0
SUM:	3327000		0	100

Total investment including interest (DKK)	3327000
Cost per installed kW (DKK/kW)	8317.5

ESTIMATION OF COST OF ENERGY FROM WIND TURBINES - INPUT DATA

Spreadsheet printout. Date and time: 26-Sep-93 05:54 PM
Sample calculation. Costs in DKK of 1993.

Input Operation and Maintenance Costs

Year	Insur. (DKK)	Service (DKK)	Wear pa. (DKK)	Repair (DKK)	Managem. (DKK)	Total (DKK)
1	24000	0	6000	0	8000	38000
2	24000	0	6000	0	8000	38000
3	24000	17000	6000	16000	8000	71000
4	24000	17000	6000	16000	8000	71000
5	24000	17000	6000	16000	8000	71000
6	21000	17000	6000	28000	8000	80000
7	21000	17000	6000	28000	8000	80000
8	21000	17000	6000	28000	8000	80000
9	21000	17000	6000	28000	8000	80000
10	21000	17000	6000	28000	8000	80000
11	18000	17000	6000	38000	8000	87000
12	18000	17000	6000	38000	8000	87000
13	18000	17000	6000	38000	8000	87000
14	18000	17000	6000	38000	8000	87000
15	18000	17000	6000	38000	8000	87000
16	18000	17000	6000	38000	8000	87000
17	18000	17000	6000	38000	8000	87000
18	18000	17000	6000	38000	8000	87000
19	18000	17000	6000	38000	8000	87000
20	18000	17000	6000	38000	8000	87000

ESTIMATION OF COST OF ENERGY FROM WIND TURBINES - INPUT DATA

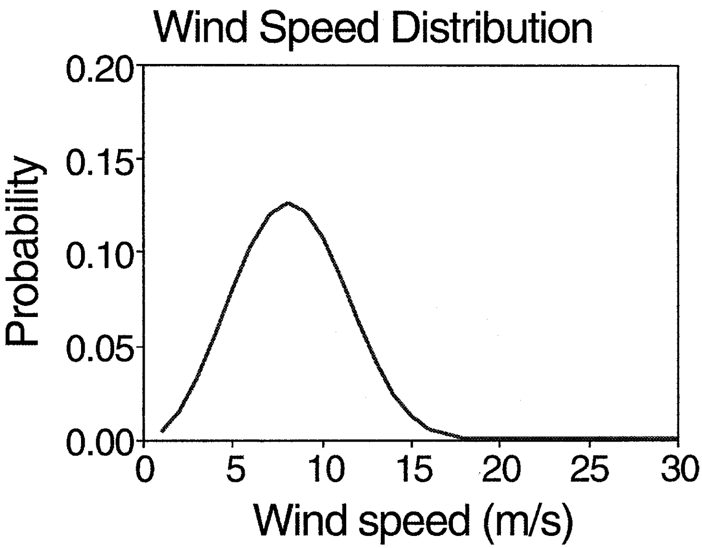
Spreadsheet printout. Date and time: 26-Sep-93 05:54 PM

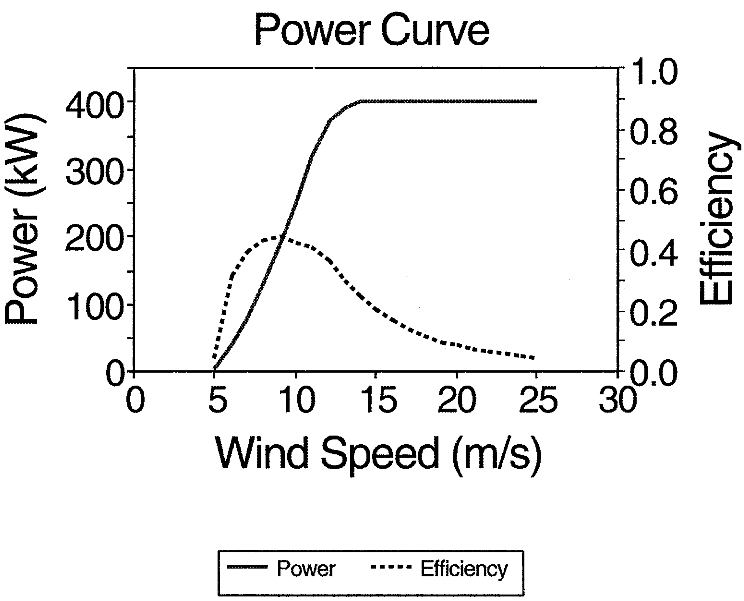
Sample calculation. Costs in DKK of 1993.

Input Social, Retrofit and Avoided Costs (= revenue)

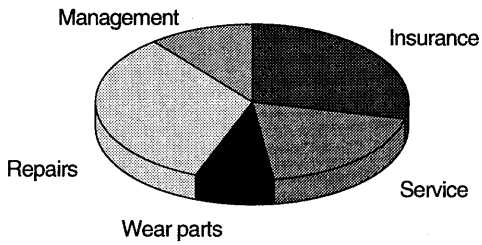
Year	O&M (DKK)	Social (DKK)	Retrofit (DKK)	Avoided (DKK/kWh)
1	38000	0	0	0.50
2	38000	0	0	0.50
3	71000	0	0	0.50
4	71000	0	0	0.50
5	71000	0	0	0.50
6	80000	0	0	0.50
7	80000	0	0	0.50
8	80000	0	0	0.50
9	80000	0	0	0.50
10	80000	0	379000	0.50
11	87000	0	0	0.50
12	87000	0	0	0.50
13	87000	0	0	0.50
14	87000	0	0	0.50
15	87000	0	0	0.50
16	87000	0	0	0.50
17	87000	0	0	0.50
18	87000	0	0	0.50
19	87000	0	0	0.50
20	87000	0	0	0.50

Salvage value (DKK) 52000

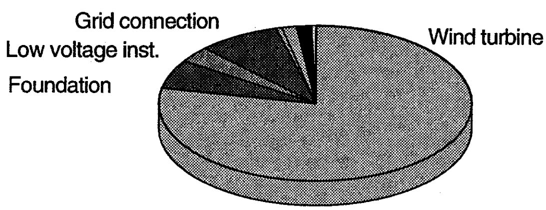

Wind Speed Distribution
0.20
0.15
0.10
0.05
0.00
Probability
0
5
10
15
20
25
30
Wind speed (m/s)


Power Curve
400
300
200
100
0
Power (kW)
1.0
0.8
0.6
0.4
0.2
0.0
Efficiency
0
5
10
15
20
25
30
Wind Speed (m/s)
Power
Efficiency

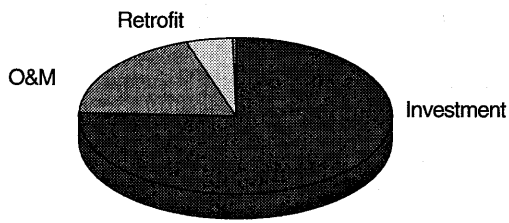
O&M distribution



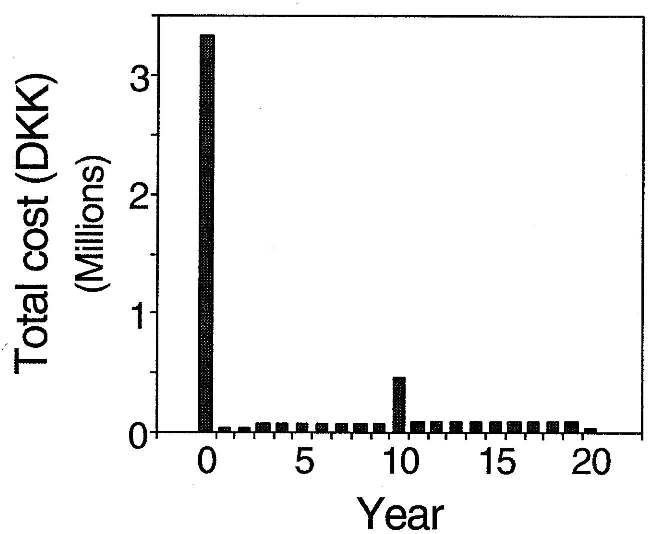
Investment distribution

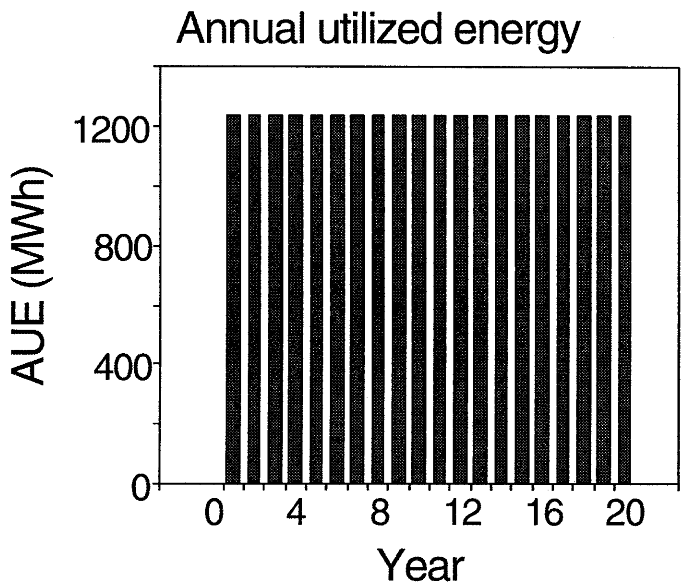


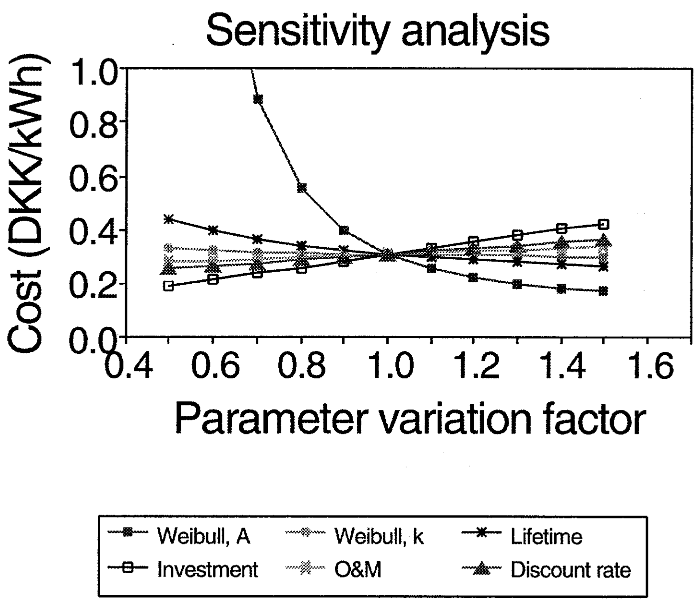
Cost distribution



Cash flow




Annual utilized energy
AUE (MWh)
1200
800
400
0
0
4
8
12
16
20
Year


Sensitivity analysis
Cost (DKK/kWh)
1.0
0.8
0.6
0.4
0.2
0.0
0.4
0.6
0.8
1.0
1.2
1.4
1.6
Parameter variation factor
Weibull, A
Weibull, k
Lifetime
Investment
O&M
Discount rate