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Annex A – Cost-Benefit for Embedded Sensors in Large Wind Turbine Blades

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Risø National Laboratory, Roskilde, Denmark
May 2002

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Annex A - Cost-Benefit for Embedded Sensors in Large Wind Turbine Blades

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Abstract This report contains the results of a cost-benefit analysis for the use of embedded sensors for damage detection in large wind turbine blades - structural health monitoring - (in connection with remote surveillance) of large wind turbine placed off-shore. The total operating costs of a three-bladed 2MW turbine placed offshore either without sensors or with sensors are compared. The price of a structural health monitoring system of a price of 100 000 DKK (per turbine) results in a break-even time of about 3 years. For a price of 300 000 DKK the break-even time is about 8 years. However, the cost/benefit analysis has large uncertainties.

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Contents

Preface

This report is Annex A of the reports of the pre-project "Grundlag for fjernovervågning af vindmøllevingers tilstand (Fase I: Forprojekt)", supported by PSO-funding through Elkraft System, contract no. Bro-91.055, FU nr. 1102. The project was performed within 12 month 2001-2002 in collaboration between Risø National Laboratory (project leader), DELTA, Sensor Technology Center A/S, Force Technology, InnospeXion and LM Glasfiber. The project is reported in a summary-report and in some Annexes (A-F).

The title of the summary report is:

"Fundamentals for remote structural health monitoring of wind turbine blades - a pre-project", Bent F. Sørensen, Lars Lading, Peter Sendrup, Malcolm McGugan, Christian P. Debel, Ole J. D. Kristensen, Gunner Larsen, Anders M. Hansen, Jørgen Rheinländer, Jens Rusborg and Jørgen D. Vestergaard, Risø-R-1336(EN), May 2002.

The titles of the annexes are:

Annex A:
"Fundamentals for Remote Structural Health Monitoring of Wind Turbine Blades – a Preproject. Annex A - Cost benefit for embedded sensors in wind turbine blades", Lars Gottlieb Hansen and Lars Lading, Risø-R-1340(EN), Risø National Laboratory, Roskilde, Denmark, May 2002.

Annex B:
"Fundamentals for Remote Structural Health Monitoring of Wind Turbine Blades – a Preproject. Annex B - Sensors and non-destructive testing methods for damage detection in wind turbine blades", Lars Lading, Malcolm McGugan, Peter Sendrup, Jørgen Rheinländer and Jens Rusborg, Risø-R-1341(EN), Risø National Laboratory, Roskilde, Denmark, May 2002.

Annex C:
"Fundamentals for Remote Structural Health Monitoring of Wind Turbine Blades – a Preproject. Annex C - Fibre transducer for damage detection in adhesive layers of wind turbine blades", Peter Sendrup, Risø-R-1342(EN), Risø National Laboratory, Roskilde, Denmark, May 2002.

Annex D:
"Fundamentals for Remote Structural Health Monitoring of Wind Turbine Blades – a Preproject. Annex D - Laboratory tests using condition monitoring sensors", Malcolm McGugan, Risø-I-1878(EN), Risø National Laboratory, Roskilde, Denmark, May 2002.

Annex E:
"Fundamentals for Remote Structural Health Monitoring of Wind Turbine Blades – a Preproject. Annex E - Full-scale testing of wind turbine blade", Ole J. D. Kristensen, Malcolm McGugan, Peter Sendrup, Jørgen Rheinländer, Jens Rusborg, Bent F. Sørensen, Christian P. Debel and Anders M. Hansen, Risø-R1333(EN), Risø National Laboratory, Roskilde, Denmark, May 2002.

Annex F:
"Identification of damage to wind turbine blades by modal parameter estimation", Gunner Larsen, Anders M. Hansen and Ole J. D. Kristensen, Risø-R-1334(EN) Risø National Laboratory, Roskilde, Denmark, April 2002.

1.1 Introduction

Modern wind turbine blades are subject to rigorous quality control before the blades leave the production facility. However, various types of damage may still emerge during the use of wind turbines. This differential cost analysis aims to assess whether it is economically feasible to perform structural health monitoring on-line with the use of sensors embedded in the blades. Can the cost of a reliable sensor system be justified? The result of this investigation is that it will indeed be profitable to apply such a system.

1.2 Purpose

This differential cost analysis aims to present three scenarios – MOST LIKELY, WORST CASE, and BEST CASE – for the economic implications of operating either WITH SENSORS or WITHOUT SENSORS embedded in the blades of a large offshore wind turbine (see assumptions and details under *Methodology* below).

Key indicators are the accumulated differential operating cost, which has a positive value when using sensors is favourable compared to not using sensors, and the time-to-break-even, i.e. the point where accumulated costs are in balance turning from deficit to surplus.

Even though we assume an operator's view, we have chosen to include the cost irrespective of who legally may be declared liable.

The cost comparison will be over the entire projected life span of each turbine, which has been set to 20 years.

Assumptions are based on discussions with wind turbine industry experts, who wish to remain anonymous. Well-documented data from literature is scarce.

1.3 Methodology

The analysis is *differential* in that it compares costs for the two alternatives:

H0: Wind turbine WITHOUT SENSORS embedded in the blades versus

H1: Wind turbine WITH SENSORS embedded in the blades.

For simplicity and transparency, all cost pertaining to H0 are held constant in all scenarios.

The types of damage are classified in two categories. The first type is damage that can and will be repaired *without having to change a major component*, like e.g. a turbine blade. The cost associated with repairing this type of damage is called *Sys. fault rep. cost* and the lost electricity production income is called *Sys. fault idle cost*. The likelihood of s*ystematic faults* is typically high during the first few years of operation and will then decrease with time.

Over time there is a risk of disastrous events that will cause one or more blades to malfunction and be eligible for replacement. Such cost is termed *Disaster rep cost*. Costs pertaining to lost electricity production during repair of disastrous damage are termed *Disaster idle cost*.

From normal wear and tear, the need for occasional repair incurs a cost that we term *Repair cost*. The cost from lost energy production in normal damage situations is termed *Operation idle cost*. Cost of normal operation is termed *Operation cost* and includes cost pertaining from regular inspection, which will be needed even WITH SENSORS. *Repair cost* will typically remain constant over time.

Repair cost includes transportation over land and sea, occasional use of helicopters. Without sensors, one yearly inspection is assumed.

Please note that the cost of the sensor system (in H1s) is assigned as a start-up fixed cost added to the year-one Operation cost figure.

1.4 Analysis

A comparative cost analysis is performed for the two cases H1 and H2. The relevant quantities and the calculation methods are listed in Table 1. We have applied an operator's point-of-view and assumed one 2 MW three-bladed turbine. Please see Appendix 1 for a full-detail overview of the underlying figures and calculations.

Table 1. Definition of parameters and calculation methods.

COST	EXPLANATION	CALCULATION METHOD
Operation cost	Cost of ordinary operation. 1st year cost includes SENSOR SYSTEM COST	
Ope.idle cost	Cost of lost energy production, ordinary damage	Annual production value X idle-time factor X likelihood of ordinary fault
Rep.cost	Repair cost, ordinary damage	Average repair cost X likelihood of ordinary fault
Sys.fault idle cost	Cost of lost energy production, systematic damage	Annual production value X idle-time factor X likelihood of systematic fault
Sys.fault rep cost	Repair/replacement cost, systematic damage	Average systematic fault repair cost X likelihood of systematic fault
Disaster rep.cost	Repair cost, disastrous damage	Average disaster repair cost X likelihood of disaster
Disaster idle cost	Cost of lost energy production, disastrous damage	Annual production value X idle-time factor X likelihood of disaster

"Global" assumptions (used directly or indirectly to derive figures):

Cost of one 2MW unit: 12 million DKK
2MW offshore unit energy production per year: 5000MWh
(Source: Middelgrundens Vindmøllelaug,
http://www.middelgrunden.dk/projektinfo/produktion.htm)
In case of a disastrous event, e.g. major collapse of blade(s), an average cost of 2 million DKK is incurred.
Price/KWh: 0.43 DKK
(Source: Middelgrundens Vindmøllelaug,
http://www.middelgrunden.dk/projektinfo/produktion.htm)
H0: The average Sys fault cost (rep + idle) amounts to 20000 DKK/wind turbine/year. Disaster likelihood is 0.01 for the first 3 years, then 0.005.
H0 is the same for all three cases - only H1's are altered.

Scenario-specific assumptions:

H1: Wind turbines WITH embedded sensors – MOST LIKELY
This scenario attempts to establish a likely comparative cost profile based on realistic assumptions. For generality, the disaster likelihood is set to a tenth of that of H0 (irrespective of sensor system). It is, however, recognised, that different sensor systems will have different detection capabilities and thus the disaster likelihood will most likely depend on the system chosen.

The average Sys fault cost (rep + idle) over the 20-year lifetime is on average 5000 DKK per year (highest during the first three years)
Disaster likelihood=1/10 of H0 (this value has been selected arbitrarily; however the value has a relatively small impact on the final result)
1st year operation cost (with SENSOR COST)=121000 DKK

H1: Wind turbines WITH embedded sensors – WORST CASE
This scenario attempts to establish a cost profile based on pessimistic assumptions, i.e. Disaster cost will not be lowered at all, in spite of the embedded sensors, and considerable extra cost will result from unnecessary repair. The SENSOR COST is high, like in a situation with low production volume or when using an expensive technological solution.

The Sys fault cost (rep + idle) over the 20-year lifetime is on average 20000 DKK per year
Disaster likelihood=same as in H0
1st year operation cost (with SENSOR COST)=451000 DKK

H1: Wind turbines WITH embedded sensors – BEST CASE
This scenario attempts to establish a cost profile based on optimistic assumptions, i.e. Disaster cost will be minimal and only necessary repair is undertaken. The SENSOR COST will be negligible, like in an "ideal" situation with very high production volume.

The Sys fault cost (rep + idle) over the 20-year lifetime is on average 2000 DKK per year
Disaster likelihood=negligible
1st year operation cost (with SENSOR COST)=11000 DKK

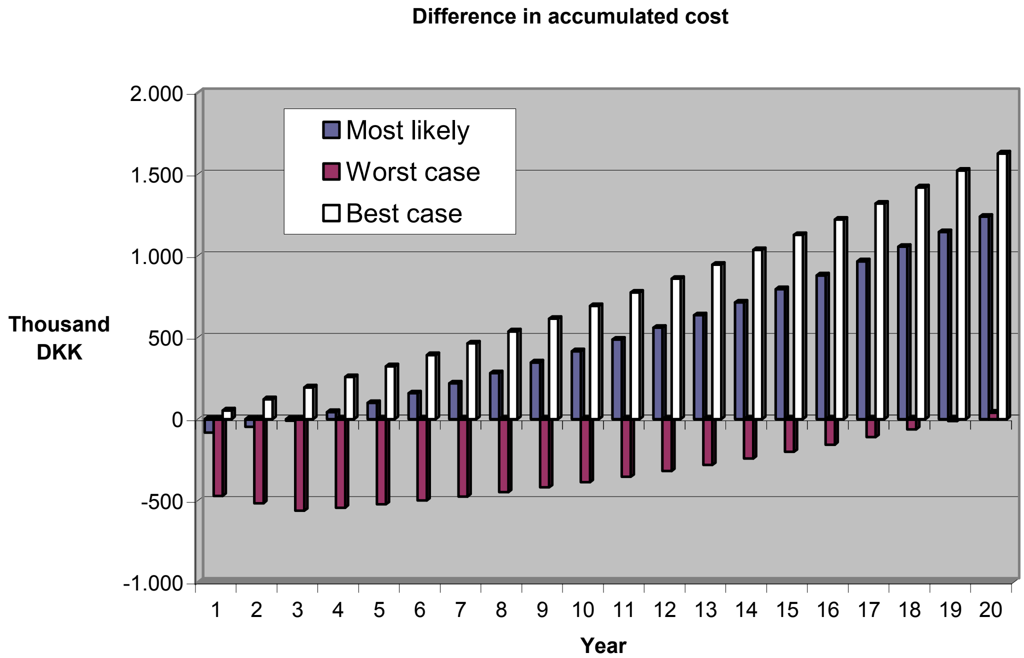

Figure 1. Difference in accumulated cost.

1.5 Results

The analysis leads to the following conclusions for the three scenarios, which can be seen in Figure 1:

In the **MOST LIKELY** case:
Break-even is reached in slightly more than 3 years.
In the **WORST CASE**:
Break-even is reached in slightly more than 19 years.
In the **BEST CASE:**
Cost savings will occur almost immediately after setting up the wind turbine.

In the MOST LIKELY case, systematic damage is more likely to be discovered early on with sensors than without sensors. In addition to this, using sensors implies an initial higher cost. After the initial three years, costs from repair of systematic damage become insignificant, subsequently allowing for a mounting surplus.

In the WORST CASE, the sensor system is very expensive, but in spite of this the risk of disaster is not even reduced and lots of unnecessary repair is being undertaken, all in all leading to a time-to-break-even close to 20 years.

In the BEST CASE, it is assumed that initial sensor cost will be negligible, resulting in a time-to-break-even of a few months. This scenario is intended to define the "theoretical" lower boundary for what is possible.

1.6 About the sensor price

The MOST LIKELY case is based on the estimated price of a sensor system of 120 000 DKK. This price lies within the range of the estimated prices for sensor systems (see Annex B).

1.7 Sensitivity analysis

To get an impression of the sensitivity of time-to-break-even to different sensor system costs, see Figure 2 below:

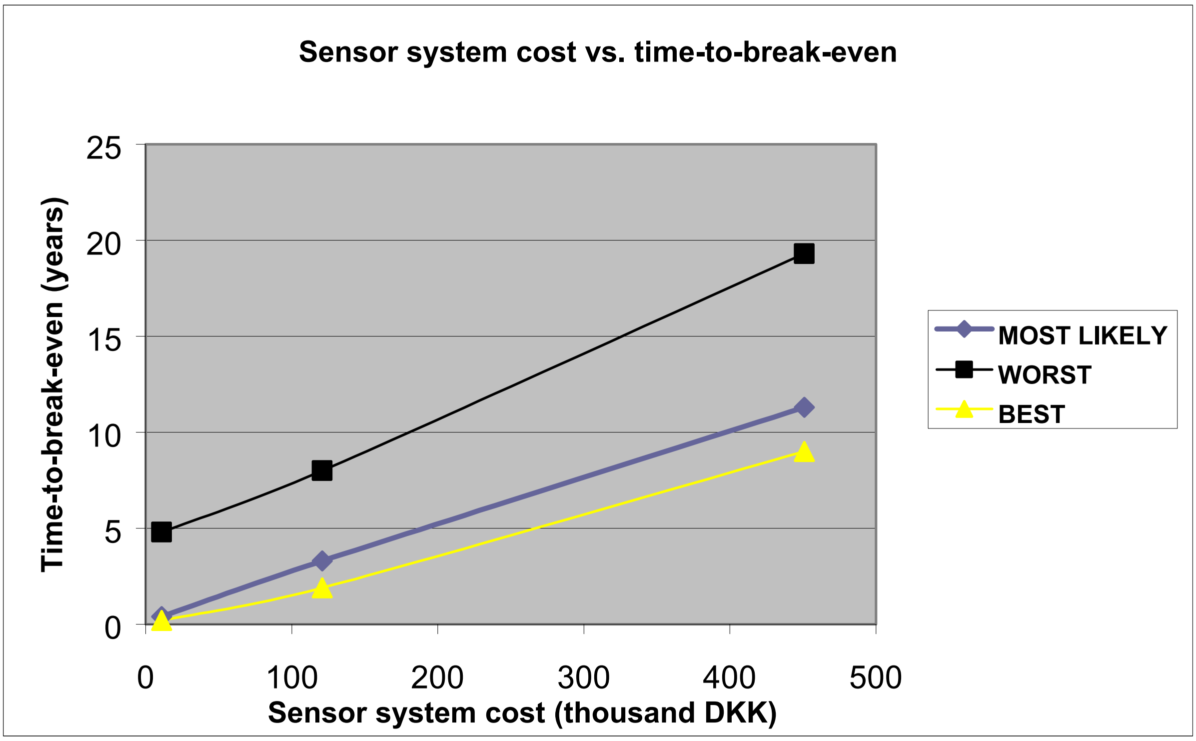

Figure 2. Sensor system cost vs. time-to-break-even.

In the MOST LIKELY case, it is observed that time-to-break-even is closely linked to the cost of the sensor system. Furthermore, it is observed that there is quite a gap between MOST LIKELY and WORST CASE, which illustrates a considerable downside risk, e.g. will total production volume of the required sensor system be sufficiently high to bring prices down? Time-to-break-even could be almost as long as the economic lifetime under the most pessimistic assumptions.

References

Middelgrundens Vindmøllelaug, http://www.middelgrunden.dk/projektinfo/produktion.htm

Appendix 1: Comparative cost analysis for the two cases: (H1) Wind turbine WITH and (H0) WITHOUT embedded sensors

H1: Wind turbines WITH embedded sensors - MOST LIKELY

Thousand DKK — **Disaster likelihood=1/10 of H0** — **Operation cost (incl. SENSOR COST)=121000 DKK**

Year	Ope.idle cost	Operation cost	Rep.cost	Disaster idle c	Disaster rep.cost	Sys.fault idle c	Sys.fault rep cost	Sum	Int.rate	Interest	Annual cost	Accumulated	Difference
1	5	121	1	2,0	2,0	4,5	20,0	155	0,05	0	155	155	-82
2	5	1	1	2,0	2,0	4,5	20,0	35	0,05	10	45	200	-47
3	5	1	1	2,0	2,0	4,5	20,0	35	0,05	11	47	247	-10
4	5	1	1	1,0	1,0	1,0	1,0	11	0,05	12	23	270	43
5	5	1	1	1,0	1,0	1,0	1,0	11	0,05	12	23	294	99
6	5	1	1	1,0	1,0	1,0	1,0	11	0,05	13	24	318	157
7	5	1	1	1,0	1,0	1,0	1,0	11	0,05	14	25	342	218
8	5	1	1	1,0	1,0	1,0	1,0	11	0,05	14	25	367	281
9	5	1	1	1,0	1,0	1,0	1,0	11	0,05	15	26	393	347
10	5	1	1	1,0	1,0	1,0	1,0	11	0,05	15	26	419	416
11	5	1	1	1,0	1,0	1,0	1,0	11	0,05	16	27	446	487
12	5	1	1	1,0	1,0	1,0	1,0	11	0,05	16	27	473	560
13	5	1	1	1,0	1,0	1,0	1,0	11	0,05	17	28	501	637
14	5	1	1	1,0	1,0	1,0	1,0	11	0,05	17	28	529	715
15	5	1	1	1,0	1,0	1,0	1,0	11	0,05	18	29	558	796
16	5	1	1	1,0	1,0	1,0	1,0	11	0,05	18	29	587	880
17	5	1	1	1,0	1,0	1,0	1,0	11	0,05	19	30	618	967
18	5	1	1	1,0	1,0	1,0	1,0	11	0,05	20	31	648	1.055
19	5	1	1	1,0	1,0	1,0	1,0	11	0,05	20	31	679	1.147
20	5	1	1	1,0	1,0	1,0	1,0	11	0,05	21	32	711	1.241

H0: Wind turbines WITHOUT embedded sensors

Thousand DKK

Year	Ope.idle cost	Operation cost	Rep.cost	Disaster idle c	Disaster rep.cost	Sys.fault idle c	Sys.fault rep cost	Sum	Int.rate	Interest	Annual cost	Accumulated
1	5	25	1	2,0	20,0	10,0	10,0	73	0,05	0	73	73
2	5	25	1	2,0	20,0	10,0	10,0	73	0,05	7	80	153
3	5	25	1	2,0	20,0	10,0	10,0	73	0,05	11	84	237
4	5	25	1	1,0	10,0	10,0	10,0	62	0,05	14	76	313
5	5	25	1	1,0	10,0	10,0	10,0	62	0,05	17	79	392
6	5	25	1	1,0	10,0	10,0	10,0	62	0,05	20	82	475
7	5	25	1	1,0	10,0	10,0	10,0	62	0,05	23	85	560
8	5	25	1	1,0	10,0	10,0	10,0	62	0,05	26	88	649
9	5	25	1	1,0	10,0	10,0	10,0	62	0,05	30	92	740
10	5	25	1	1,0	10,0	10,0	10,0	62	0,05	33	95	835
11	5	25	1	1,0	10,0	10,0	10,0	62	0,05	36	98	932
12	5	25	1	1,0	10,0	10,0	10,0	62	0,05	39	101	1.033
13	5	25	1	1,0	10,0	10,0	10,0	62	0,05	42	104	1.137
14	5	25	1	1,0	10,0	10,0	10,0	62	0,05	45	107	1.244
15	5	25	1	1,0	10,0	10,0	10,0	62	0,05	48	110	1.354
16	5	25	1	1,0	10,0	10,0	10,0	62	0,05	51	113	1.468
17	5	25	1	1,0	10,0	10,0	10,0	62	0,05	54	116	1.584
18	5	25	1	1,0	10,0	10,0	10,0	62	0,05	57	119	1.704
19	5	25	1	1,0	10,0	10,0	10,0	62	0,05	61	123	1.826
20	5	25	1	1,0	10,0	10,0	10,0	62	0,05	64	126	1.952

H1: Wind turbines WITH embedded sensors - WORST CASE

Thousand DKK | **Disaster likelihood=same as H0** | **Operation cost (Incl. SENSOR COST)= 451000 DKK**

Year	Ope.idle cost	Operation cost	Rep.cost	Disaster idle c	Disaster rep.cost	Sys.fault idle c	Sys.fault rep cost	Sum	Int.rate	Acc.int.	Annual cost	Accumulated	Difference
1	5	451	1	2,0	20,0	4,5	60,0	543	0,05	0	543	543	-470
2	5	1	1	2,0	20,0	4,5	60,0	93	0,05	32	125	669	-515
3	5	1	1	2,0	20,0	4,5	60,0	93	0,05	37	130	799	-562
4	5	1	1	1,0	10,0	1,0	1,0	20	0,05	38	58	856	-543
5	5	1	1	1,0	10,0	1,0	1,0	20	0,05	39	59	915	-522
6	5	1	1	1,0	10,0	1,0	1,0	20	0,05	40	60	974	-500
7	5	1	1	1,0	10,0	1,0	1,0	20	0,05	41	61	1.035	-475
8	5	1	1	1,0	10,0	1,0	1,0	20	0,05	42	62	1.096	-448
9	5	1	1	1,0	10,0	1,0	1,0	20	0,05	43	63	1.159	-419
10	5	1	1	1,0	10,0	1,0	1,0	20	0,05	44	64	1.222	-388
11	5	1	1	1,0	10,0	1,0	1,0	20	0,05	45	65	1.287	-354
12	5	1	1	1,0	10,0	1,0	1,0	20	0,05	46	66	1.352	-319
13	5	1	1	1,0	10,0	1,0	1,0	20	0,05	47	67	1.419	-282
14	5	1	1	1,0	10,0	1,0	1,0	20	0,05	48	68	1.487	-242
15	5	1	1	1,0	10,0	1,0	1,0	20	0,05	49	69	1.555	-201
16	5	1	1	1,0	10,0	1,0	1,0	20	0,05	50	70	1.625	-157
17	5	1	1	1,0	10,0	1,0	1,0	20	0,05	51	71	1.695	-111
18	5	1	1	1,0	10,0	1,0	1,0	20	0,05	52	72	1.767	-63
19	5	1	1	1,0	10,0	1,0	1,0	20	0,05	53	73	1.839	-13
20	5	1	1	1,0	10,0	1,0	1,0	20	0,05	54	74	1.913	39

H0: Wind turbines WITHOUT embedded sensors

Thousand DKK

Year	Ope.idle cost	Operation cost	Rep.cost	Disaster idle c	Disaster rep.cost	Sys.fault idle c	Sys.fault rep cost	Sum	Int.rate	Interest	Annual cost	Accumulated
1	5	25	1	2,0	20,0	10,0	10,0	73	0,05	0	73	73
2	5	25	1	2,0	20,0	10,0	10,0	73	0,05	7	80	153
3	5	25	1	2,0	20,0	10,0	10,0	73	0,05	11	84	237
4	5	25	1	1,0	10,0	10,0	10,0	62	0,05	14	76	313
5	5	25	1	1,0	10,0	10,0	10,0	62	0,05	17	79	392
6	5	25	1	1,0	10,0	10,0	10,0	62	0,05	20	82	475
7	5	25	1	1,0	10,0	10,0	10,0	62	0,05	23	85	560
8	5	25	1	1,0	10,0	10,0	10,0	62	0,05	26	88	649
9	5	25	1	1,0	10,0	10,0	10,0	62	0,05	30	92	740
10	5	25	1	1,0	10,0	10,0	10,0	62	0,05	33	95	835
11	5	25	1	1,0	10,0	10,0	10,0	62	0,05	36	98	932
12	5	25	1	1,0	10,0	10,0	10,0	62	0,05	39	101	1.033
13	5	25	1	1,0	10,0	10,0	10,0	62	0,05	42	104	1.137
14	5	25	1	1,0	10,0	10,0	10,0	62	0,05	45	107	1.244
15	5	25	1	1,0	10,0	10,0	10,0	62	0,05	48	110	1.354
16	5	25	1	1,0	10,0	10,0	10,0	62	0,05	51	113	1.468
17	5	25	1	1,0	10,0	10,0	10,0	62	0,05	54	116	1.584
18	5	25	1	1,0	10,0	10,0	10,0	62	0,05	57	119	1.704
19	5	25	1	1,0	10,0	10,0	10,0	62	0,05	61	123	1.826
20	5	25	1	1,0	10,0	10,0	10,0	62	0,05	64	126	1.952

H1: Wind turbines WITH embedded sensors - BEST CASE

Thousand DKK **Disaster likeli-hood=negligible** **Operation cost (Incl. SENSOR COST)=11000 DKK**

Year	Ope.idle cost	Operation cost	Rep.cost	Disaster idle c	Disaster rep.cost	Sys.fault idle c	Sys.fault rep cost	Sum	Int.rate	Interest	Annual cost	Accumulated	Difference
1	5	11	1	0,0	1,0	1,0	1,0	20	0,05	0	20	20	53
2	5	1	1	0,0	1,0	1,0	1,0	10	0,05	2	12	32	122
3	5	1	1	0,0	1,0	1,0	1,0	10	0,05	2	12	44	194
4	5	1	1	0,0	1,0	1,0	1,0	10	0,05	3	13	56	257
5	5	1	1	0,0	1,0	1,0	1,0	10	0,05	3	13	69	323
6	5	1	1	0,0	1,0	1,0	1,0	10	0,05	4	14	83	392
7	5	1	1	0,0	1,0	1,0	1,0	10	0,05	4	14	97	464
8	5	1	1	0,0	1,0	1,0	1,0	10	0,05	5	15	111	538
9	5	1	1	0,0	1,0	1,0	1,0	10	0,05	5	15	126	614
10	5	1	1	0,0	1,0	1,0	1,0	10	0,05	6	16	142	693
11	5	1	1	0,0	1,0	1,0	1,0	10	0,05	6	16	158	775
12	5	1	1	0,0	1,0	1,0	1,0	10	0,05	7	17	174	859
13	5	1	1	0,0	1,0	1,0	1,0	10	0,05	7	17	191	946
14	5	1	1	0,0	1,0	1,0	1,0	10	0,05	8	18	209	1.036
15	5	1	1	0,0	1,0	1,0	1,0	10	0,05	8	18	227	1.128
16	5	1	1	0,0	1,0	1,0	1,0	10	0,05	9	19	245	1.223
17	5	1	1	0,0	1,0	1,0	1,0	10	0,05	9	19	264	1.320
18	5	1	1	0,0	1,0	1,0	1,0	10	0,05	10	20	284	1.420
19	5	1	1	0,0	1,0	1,0	1,0	10	0,05	10	20	304	1.523
20	5	1	1	0,0	1,0	1,0	1,0	10	0,05	11	21	324	1.628

H0: Wind turbines WITHOUT embedded sensors

Thousand DKK

Year	Ope.idle cost	Operation cost	Rep.cost	Disaster idle c	Disaster rep.cost	Sys.fault idle c	Sys.fault rep cost	Sum	Int.rate	Interest	Annual cost	Accumulated
1	5	25	1	2,0	20,0	10,0	10,0	73	0,05	0	73	73
2	5	25	1	2,0	20,0	10,0	10,0	73	0,05	7	80	153
3	5	25	1	2,0	20,0	10,0	10,0	73	0,05	11	84	237
4	5	25	1	1,0	10,0	10,0	10,0	62	0,05	14	76	313
5	5	25	1	1,0	10,0	10,0	10,0	62	0,05	17	79	392
6	5	25	1	1,0	10,0	10,0	10,0	62	0,05	20	82	475
7	5	25	1	1,0	10,0	10,0	10,0	62	0,05	23	85	560
8	5	25	1	1,0	10,0	10,0	10,0	62	0,05	26	88	649
9	5	25	1	1,0	10,0	10,0	10,0	62	0,05	30	92	740
10	5	25	1	1,0	10,0	10,0	10,0	62	0,05	33	95	835
11	5	25	1	1,0	10,0	10,0	10,0	62	0,05	36	98	932
12	5	25	1	1,0	10,0	10,0	10,0	62	0,05	39	101	1.033
13	5	25	1	1,0	10,0	10,0	10,0	62	0,05	42	104	1.137
14	5	25	1	1,0	10,0	10,0	10,0	62	0,05	45	107	1.244
15	5	25	1	1,0	10,0	10,0	10,0	62	0,05	48	110	1.354
16	5	25	1	1,0	10,0	10,0	10,0	62	0,05	51	113	1.468
17	5	25	1	1,0	10,0	10,0	10,0	62	0,05	54	116	1.584
18	5	25	1	1,0	10,0	10,0	10,0	62	0,05	57	119	1.704
19	5	25	1	1,0	10,0	10,0	10,0	62	0,05	61	123	1.826
20	5	25	1	1,0	10,0	10,0	10,0	62	0,05	64	126	1.952

SENSITIVITY ANALYSIS: SENSOR SYSTEM COST vs. TIME-TO-BREAK-EVEN
MOST LIKELY case assumptions used

H1: Wind turbines WITH embedded sensors

Thousand DKK — Disaster likelihood=1/10 of H0 — **Operation cost (Incl. SENSOR COST)=11000 DKK**

Year	Ope.idle cost	Operation cost	Rep.cost	Disaster idle c	Disaster rep.cost	Sys.fault idle c	Sys.fault rep cost	Sum	Int.rate	Interest	Annual cost	Accumulated	Difference
1	5	11	1	2,0	2,0	4,5	20,0	45	0,05	0	45	45	28
2	5	1	1	2,0	2,0	4,5	20,0	35	0,05	4	40	85	68
3	5	1	1	2,0	2,0	4,5	20,0	35	0,05	6	41	126	111
4	5	1	1	1,0	1,0	1,0	1,0	11	0,05	6	17	144	170
5	5	1	1	1,0	1,0	1,0	1,0	11	0,05	7	18	162	231
6	5	1	1	1,0	1,0	1,0	1,0	11	0,05	7	18	180	295
7	5	1	1	1,0	1,0	1,0	1,0	11	0,05	8	19	199	361
8	5	1	1	1,0	1,0	1,0	1,0	11	0,05	9	20	219	430
9	5	1	1	1,0	1,0	1,0	1,0	11	0,05	9	20	239	501
10	5	1	1	1,0	1,0	1,0	1,0	11	0,05	10	21	259	575
11	5	1	1	1,0	1,0	1,0	1,0	11	0,05	10	21	281	652
12	5	1	1	1,0	1,0	1,0	1,0	11	0,05	11	22	302	731
13	5	1	1	1,0	1,0	1,0	1,0	11	0,05	11	22	325	813
14	5	1	1	1,0	1,0	1,0	1,0	11	0,05	12	23	348	897
15	5	1	1	1,0	1,0	1,0	1,0	11	0,05	12	23	371	983
16	5	1	1	1,0	1,0	1,0	1,0	11	0,05	13	24	395	1.073
17	5	1	1	1,0	1,0	1,0	1,0	11	0,05	14	25	420	1.165
18	5	1	1	1,0	1,0	1,0	1,0	11	0,05	14	25	445	1.259
19	5	1	1	1,0	1,0	1,0	1,0	11	0,05	15	26	470	1.356
20	5	1	1	1,0	1,0	1,0	1,0	11	0,05	15	26	496	1.455

H0: Wind turbines WITHOUT embedded sensors

Thousand DKK

Year	Ope.idle cost	Operation cost	Rep.cost	Disaster idle c	Disaster rep.cost	Sys.fault idle c	Sys.fault rep cost	Sum	Int.rate	Interest	Annual cost	Accumulated
1	5	25	1	2,0	20,0	10,0	10,0	73	0,05	0	73	73
2	5	25	1	2,0	20,0	10,0	10,0	73	0,05	7	80	153
3	5	25	1	2,0	20,0	10,0	10,0	73	0,05	11	84	237
4	5	25	1	1,0	10,0	10,0	10,0	62	0,05	14	76	313
5	5	25	1	1,0	10,0	10,0	10,0	62	0,05	17	79	392
6	5	25	1	1,0	10,0	10,0	10,0	62	0,05	20	82	475
7	5	25	1	1,0	10,0	10,0	10,0	62	0,05	23	85	560
8	5	25	1	1,0	10,0	10,0	10,0	62	0,05	26	88	649
9	5	25	1	1,0	10,0	10,0	10,0	62	0,05	30	92	740
10	5	25	1	1,0	10,0	10,0	10,0	62	0,05	33	95	835
11	5	25	1	1,0	10,0	10,0	10,0	62	0,05	36	98	932
12	5	25	1	1,0	10,0	10,0	10,0	62	0,05	39	101	1.033
13	5	25	1	1,0	10,0	10,0	10,0	62	0,05	42	104	1.137
14	5	25	1	1,0	10,0	10,0	10,0	62	0,05	45	107	1.244
15	5	25	1	1,0	10,0	10,0	10,0	62	0,05	48	110	1.354
16	5	25	1	1,0	10,0	10,0	10,0	62	0,05	51	113	1.468
17	5	25	1	1,0	10,0	10,0	10,0	62	0,05	54	116	1.584
18	5	25	1	1,0	10,0	10,0	10,0	62	0,05	57	119	1.704
19	5	25	1	1,0	10,0	10,0	10,0	62	0,05	61	123	1.826
20	5	25	1	1,0	10,0	10,0	10,0	62	0,05	64	126	1.952

H1: Wind turbines WITH embedded sensors

Thousand DKK | Disaster likelihood=1/10 of H0 | **Operation cost (Incl. SENSOR COST)=121000 DKK**

Year	Ope.idle cost	Operation cost	Rep.cost	Disaster idle c	Disaster rep.cost	Sys.fault idle c	Sys.fault rep cost	Sum	Int.rate	Interest	Annual cost	Accumulated	Difference
1	5	121	1	2,0	2,0	4,5	20,0	155	0,05	0	155	155	-82
2	5	1	1	2,0	2,0	4,5	20,0	35	0,05	10	45	200	-47
3	5	1	1	2,0	2,0	4,5	20,0	35	0,05	11	47	247	-10
4	5	1	1	1,0	1,0	1,0	1,0	11	0,05	12	23	270	43
5	5	1	1	1,0	1,0	1,0	1,0	11	0,05	12	23	294	99
6	5	1	1	1,0	1,0	1,0	1,0	11	0,05	13	24	318	157
7	5	1	1	1,0	1,0	1,0	1,0	11	0,05	14	25	342	218
8	5	1	1	1,0	1,0	1,0	1,0	11	0,05	14	25	367	281
9	5	1	1	1,0	1,0	1,0	1,0	11	0,05	15	26	393	347
10	5	1	1	1,0	1,0	1,0	1,0	11	0,05	15	26	419	416
11	5	1	1	1,0	1,0	1,0	1,0	11	0,05	16	27	446	487
12	5	1	1	1,0	1,0	1,0	1,0	11	0,05	16	27	473	560
13	5	1	1	1,0	1,0	1,0	1,0	11	0,05	17	28	501	637
14	5	1	1	1,0	1,0	1,0	1,0	11	0,05	17	28	529	715
15	5	1	1	1,0	1,0	1,0	1,0	11	0,05	18	29	558	796
16	5	1	1	1,0	1,0	1,0	1,0	11	0,05	18	29	587	880
17	5	1	1	1,0	1,0	1,0	1,0	11	0,05	19	30	618	967
18	5	1	1	1,0	1,0	1,0	1,0	11	0,05	20	31	648	1.055
19	5	1	1	1,0	1,0	1,0	1,0	11	0,05	20	31	679	1.147
20	5	1	1	1,0	1,0	1,0	1,0	11	0,05	21	32	711	1.241

H0: Wind turbines WITHOUT embedded sensors

Thousand DKK

Year	Ope.idle cost	Operation cost	Rep.cost	Disaster idle c	Disaster rep.cost	Sys.fault idle c	Sys.fault rep cost	Sum	Int.rate	Interest	Annual cost	Accumulated
1	5	25	1	2,0	20,0	10,0	10,0	73	0,05	0	73	73
2	5	25	1	2,0	20,0	10,0	10,0	73	0,05	7	80	153
3	5	25	1	2,0	20,0	10,0	10,0	73	0,05	11	84	237
4	5	25	1	1,0	10,0	10,0	10,0	62	0,05	14	76	313
5	5	25	1	1,0	10,0	10,0	10,0	62	0,05	17	79	392
6	5	25	1	1,0	10,0	10,0	10,0	62	0,05	20	82	475
7	5	25	1	1,0	10,0	10,0	10,0	62	0,05	23	85	560
8	5	25	1	1,0	10,0	10,0	10,0	62	0,05	26	88	649
9	5	25	1	1,0	10,0	10,0	10,0	62	0,05	30	92	740
10	5	25	1	1,0	10,0	10,0	10,0	62	0,05	33	95	835
11	5	25	1	1,0	10,0	10,0	10,0	62	0,05	36	98	932
12	5	25	1	1,0	10,0	10,0	10,0	62	0,05	39	101	1.033
13	5	25	1	1,0	10,0	10,0	10,0	62	0,05	42	104	1.137
14	5	25	1	1,0	10,0	10,0	10,0	62	0,05	45	107	1.244
15	5	25	1	1,0	10,0	10,0	10,0	62	0,05	48	110	1.354
16	5	25	1	1,0	10,0	10,0	10,0	62	0,05	51	113	1.468
17	5	25	1	1,0	10,0	10,0	10,0	62	0,05	54	116	1.584
18	5	25	1	1,0	10,0	10,0	10,0	62	0,05	57	119	1.704
19	5	25	1	1,0	10,0	10,0	10,0	62	0,05	61	123	1.826
20	5	25	1	1,0	10,0	10,0	10,0	62	0,05	64	126	1.952

H1: Wind turbines WITH embedded sensors

Thousand DKK | Disaster likelihood=1/10 of H0 | **Operation cost (Incl. SENSOR COST)=451000 DKK**

Year	Ope.idle cost	Operation cost	Rep.cost	Disaster idle c	Disaster rep.cost	Sys.fault idle c	Sys.fault rep cost	Sum	Int.rate	Interest	Annual cost	Accumulated	Difference
1	5	451	1	2,0	2,0	4,5	20,0	485	0,05	0	485	485	-412
2	5	1	1	2,0	2,0	4,5	20,0	35	0,05	26	62	547	-394
3	5	1	1	2,0	2,0	4,5	20,0	35	0,05	28	63	610	-373
4	5	1	1	1,0	1,0	1,0	1,0	11	0,05	28	39	650	-336
5	5	1	1	1,0	1,0	1,0	1,0	11	0,05	29	40	690	-297
6	5	1	1	1,0	1,0	1,0	1,0	11	0,05	29	40	730	-255
7	5	1	1	1,0	1,0	1,0	1,0	11	0,05	30	41	771	-211
8	5	1	1	1,0	1,0	1,0	1,0	11	0,05	31	42	813	-164
9	5	1	1	1,0	1,0	1,0	1,0	11	0,05	31	42	855	-115
10	5	1	1	1,0	1,0	1,0	1,0	11	0,05	32	43	897	-63
11	5	1	1	1,0	1,0	1,0	1,0	11	0,05	32	43	941	-8
12	5	1	1	1,0	1,0	1,0	1,0	11	0,05	33	44	984	49
13	5	1	1	1,0	1,0	1,0	1,0	11	0,05	33	44	1.029	109
14	5	1	1	1,0	1,0	1,0	1,0	11	0,05	34	45	1.074	171
15	5	1	1	1,0	1,0	1,0	1,0	11	0,05	34	45	1.119	235
16	5	1	1	1,0	1,0	1,0	1,0	11	0,05	35	46	1.165	303
17	5	1	1	1,0	1,0	1,0	1,0	11	0,05	36	47	1.212	373
18	5	1	1	1,0	1,0	1,0	1,0	11	0,05	36	47	1.259	445
19	5	1	1	1,0	1,0	1,0	1,0	11	0,05	37	48	1.306	520
20	5	1	1	1,0	1,0	1,0	1,0	11	0,05	37	48	1.354	597

H0: Wind turbines WITHOUT embedded sensors

Thousand DKK

Year	Ope.idle cost	Operation cost	Rep.cost	Disaster idle c	Disaster rep.cost	Sys.fault idle c	Sys.fault rep cost	Sum	Int.rate	Interest	Annual cost	Accumulated
1	5	25	1	2,0	20,0	10,0	10,0	73	0,05	0	73	73
2	5	25	1	2,0	20,0	10,0	10,0	73	0,05	7	80	153
3	5	25	1	2,0	20,0	10,0	10,0	73	0,05	11	84	237
4	5	25	1	1,0	10,0	10,0	10,0	62	0,05	14	76	313
5	5	25	1	1,0	10,0	10,0	10,0	62	0,05	17	79	392
6	5	25	1	1,0	10,0	10,0	10,0	62	0,05	20	82	475
7	5	25	1	1,0	10,0	10,0	10,0	62	0,05	23	85	560
8	5	25	1	1,0	10,0	10,0	10,0	62	0,05	26	88	649
9	5	25	1	1,0	10,0	10,0	10,0	62	0,05	30	92	740
10	5	25	1	1,0	10,0	10,0	10,0	62	0,05	33	95	835
11	5	25	1	1,0	10,0	10,0	10,0	62	0,05	36	98	932
12	5	25	1	1,0	10,0	10,0	10,0	62	0,05	39	101	1.033
13	5	25	1	1,0	10,0	10,0	10,0	62	0,05	42	104	1.137
14	5	25	1	1,0	10,0	10,0	10,0	62	0,05	45	107	1.244
15	5	25	1	1,0	10,0	10,0	10,0	62	0,05	48	110	1.354
16	5	25	1	1,0	10,0	10,0	10,0	62	0,05	51	113	1.468
17	5	25	1	1,0	10,0	10,0	10,0	62	0,05	54	116	1.584
18	5	25	1	1,0	10,0	10,0	10,0	62	0,05	57	119	1.704
19	5	25	1	1,0	10,0	10,0	10,0	62	0,05	61	123	1.826
20	5	25	1	1,0	10,0	10,0	10,0	62	0,05	64	126	1.952

SUMMARY: Values for the graph, MOST LIKELY case

1st year Ope.cost (+SENSOR C): 11000	0,4
1st year Ope.cost (+SENSOR C): 121000	3,3
1st year Ope.cost (+SENSOR C): 451000	11,3

SENSITIVITY ANALYSIS: SENSOR SYSTEM COST vs. TIME-TO-BREAK-EVEN
WORST CASE assumptions used

H1: Wind turbines WITH embedded sensors

Thousand DKK — Disaster likelihood=same as H0 — **Operation cost (Incl. SENSOR COST)=11000 DKK**

Year	Ope.idle cost	Operation cost	Rep.cost	Disaster idle c	Disaster rep.cost	Sys.fault idle c	Sys.fault rep cost	Sum	Int.rate	Acc.int.	Annual cost	Accumulated	Difference
1	5	11	1	2,0	20,0	4,5	60,0	103	0,05	0	103	103	-30
2	5	1	1	2,0	20,0	4,5	60,0	93	0,05	10	103	207	-53
3	5	1	1	2,0	20,0	4,5	60,0	93	0,05	15	108	315	-78
4	5	1	1	1,0	10,0	1,0	1,0	20	0,05	16	36	350	-37
5	5	1	1	1,0	10,0	1,0	1,0	20	0,05	17	37	387	6
6	5	1	1	1,0	10,0	1,0	1,0	20	0,05	18	38	424	50
7	5	1	1	1,0	10,0	1,0	1,0	20	0,05	19	39	463	97
8	5	1	1	1,0	10,0	1,0	1,0	20	0,05	20	40	502	146
9	5	1	1	1,0	10,0	1,0	1,0	20	0,05	21	41	543	197
10	5	1	1	1,0	10,0	1,0	1,0	20	0,05	22	42	584	250
11	5	1	1	1,0	10,0	1,0	1,0	20	0,05	23	43	627	306
12	5	1	1	1,0	10,0	1,0	1,0	20	0,05	24	44	670	363
13	5	1	1	1,0	10,0	1,0	1,0	20	0,05	25	45	715	422
14	5	1	1	1,0	10,0	1,0	1,0	20	0,05	26	46	761	484
15	5	1	1	1,0	10,0	1,0	1,0	20	0,05	27	47	807	547
16	5	1	1	1,0	10,0	1,0	1,0	20	0,05	28	48	855	613
17	5	1	1	1,0	10,0	1,0	1,0	20	0,05	29	49	903	681
18	5	1	1	1,0	10,0	1,0	1,0	20	0,05	30	50	953	751
19	5	1	1	1,0	10,0	1,0	1,0	20	0,05	31	51	1.003	823
20	5	1	1	1,0	10,0	1,0	1,0	20	0,05	32	52	1.055	897

H0: Wind turbines WITHOUT embedded sensors

Thousand DKK

Year	Ope.idle cost	Operation cost	Rep.cost	Disaster idle c	Disaster rep.cost	Sys.fault idle c	Sys.fault rep cost	Sum	Int.rate	Interest	Annual cost	Accumulated
1	5	25	1	2,0	20,0	10,0	10,0	73	0,05	0	73	73
2	5	25	1	2,0	20,0	10,0	10,0	73	0,05	7	80	153
3	5	25	1	2,0	20,0	10,0	10,0	73	0,05	11	84	237
4	5	25	1	1,0	10,0	10,0	10,0	62	0,05	14	76	313
5	5	25	1	1,0	10,0	10,0	10,0	62	0,05	17	79	392
6	5	25	1	1,0	10,0	10,0	10,0	62	0,05	20	82	475
7	5	25	1	1,0	10,0	10,0	10,0	62	0,05	23	85	560
8	5	25	1	1,0	10,0	10,0	10,0	62	0,05	26	88	649
9	5	25	1	1,0	10,0	10,0	10,0	62	0,05	30	92	740
10	5	25	1	1,0	10,0	10,0	10,0	62	0,05	33	95	835
11	5	25	1	1,0	10,0	10,0	10,0	62	0,05	36	98	932
12	5	25	1	1,0	10,0	10,0	10,0	62	0,05	39	101	1.033
13	5	25	1	1,0	10,0	10,0	10,0	62	0,05	42	104	1.137
14	5	25	1	1,0	10,0	10,0	10,0	62	0,05	45	107	1.244
15	5	25	1	1,0	10,0	10,0	10,0	62	0,05	48	110	1.354
16	5	25	1	1,0	10,0	10,0	10,0	62	0,05	51	113	1.468
17	5	25	1	1,0	10,0	10,0	10,0	62	0,05	54	116	1.584
18	5	25	1	1,0	10,0	10,0	10,0	62	0,05	57	119	1.704
19	5	25	1	1,0	10,0	10,0	10,0	62	0,05	61	123	1.826
20	5	25	1	1,0	10,0	10,0	10,0	62	0,05	64	126	1.952

H1: Wind turbines WITH embedded sensors

Thousand DKK — Disaster likelihood=same as H0 — **Operation cost (Incl. SENSOR COST)= 121000 DKK**

Year	Ope.idle cost	Operation cost	Rep.cost	Disaster idle c	Disaster rep.cost	Sys.fault idle c	Sys.fault rep cost	Sum	Int.rate	Acc.int.	Annual cost	Accumulated	Difference
1	5	121	1	2,0	20,0	4,5	60,0	213	0,05	0	213	213	-140
2	5	1	1	2,0	20,0	4,5	60,0	93	0,05	15	109	322	-169
3	5	1	1	2,0	20,0	4,5	60,0	93	0,05	20	113	436	-199
4	5	1	1	1,0	10,0	1,0	1,0	20	0,05	21	41	477	-163
5	5	1	1	1,0	10,0	1,0	1,0	20	0,05	22	42	519	-126
6	5	1	1	1,0	10,0	1,0	1,0	20	0,05	23	43	562	-87
7	5	1	1	1,0	10,0	1,0	1,0	20	0,05	24	44	606	-46
8	5	1	1	1,0	10,0	1,0	1,0	20	0,05	25	45	651	-2
9	5	1	1	1,0	10,0	1,0	1,0	20	0,05	26	46	697	43
10	5	1	1	1,0	10,0	1,0	1,0	20	0,05	27	47	744	91
11	5	1	1	1,0	10,0	1,0	1,0	20	0,05	28	48	792	141
12	5	1	1	1,0	10,0	1,0	1,0	20	0,05	29	49	841	192
13	5	1	1	1,0	10,0	1,0	1,0	20	0,05	30	50	891	246
14	5	1	1	1,0	10,0	1,0	1,0	20	0,05	31	51	942	302
15	5	1	1	1,0	10,0	1,0	1,0	20	0,05	32	52	994	360
16	5	1	1	1,0	10,0	1,0	1,0	20	0,05	33	53	1.047	421
17	5	1	1	1,0	10,0	1,0	1,0	20	0,05	34	54	1.101	483
18	5	1	1	1,0	10,0	1,0	1,0	20	0,05	35	55	1.156	547
19	5	1	1	1,0	10,0	1,0	1,0	20	0,05	36	56	1.212	614
20	5	1	1	1,0	10,0	1,0	1,0	20	0,05	37	57	1.269	683

H0: Wind turbines WITHOUT embedded sensors

Thousand DKK

Year	Ope.idle cost	Operation cost	Rep.cost	Disaster idle c	Disaster rep.cost	Sys.fault idle c	Sys.fault rep cost	Sum	Int.rate	Interest	Annual cost	Accumulated
1	5	25	1	2,0	20,0	10,0	10,0	73	0,05	0	73	73
2	5	25	1	2,0	20,0	10,0	10,0	73	0,05	7	80	153
3	5	25	1	2,0	20,0	10,0	10,0	73	0,05	11	84	237
4	5	25	1	1,0	10,0	10,0	10,0	62	0,05	14	76	313
5	5	25	1	1,0	10,0	10,0	10,0	62	0,05	17	79	392
6	5	25	1	1,0	10,0	10,0	10,0	62	0,05	20	82	475
7	5	25	1	1,0	10,0	10,0	10,0	62	0,05	23	85	560
8	5	25	1	1,0	10,0	10,0	10,0	62	0,05	26	88	649
9	5	25	1	1,0	10,0	10,0	10,0	62	0,05	30	92	740
10	5	25	1	1,0	10,0	10,0	10,0	62	0,05	33	95	835
11	5	25	1	1,0	10,0	10,0	10,0	62	0,05	36	98	932
12	5	25	1	1,0	10,0	10,0	10,0	62	0,05	39	101	1.033
13	5	25	1	1,0	10,0	10,0	10,0	62	0,05	42	104	1.137
14	5	25	1	1,0	10,0	10,0	10,0	62	0,05	45	107	1.244
15	5	25	1	1,0	10,0	10,0	10,0	62	0,05	48	110	1.354
16	5	25	1	1,0	10,0	10,0	10,0	62	0,05	51	113	1.468
17	5	25	1	1,0	10,0	10,0	10,0	62	0,05	54	116	1.584
18	5	25	1	1,0	10,0	10,0	10,0	62	0,05	57	119	1.704
19	5	25	1	1,0	10,0	10,0	10,0	62	0,05	61	123	1.826
20	5	25	1	1,0	10,0	10,0	10,0	62	0,05	64	126	1.952

H1: Wind turbines WITH embedded sensors

Thousand DKK — Disaster likelihood=same as H0 — **Operation cost (Incl. SENSOR COST)= 451000 DKK**

Year	Ope.idle cost	Operation cost	Rep.cost	Disaster idle c	Disaster rep.cost	Sys.fault idle c	Sys.fault rep cost	Sum	Int.rate	Acc.int.	Annual cost	Accumulated	Difference
1	5	451	1	2,0	20,0	4,5	60,0	543	0,05	0	543	543	-470
2	5	1	1	2,0	20,0	4,5	60,0	93	0,05	32	125	669	-515
3	5	1	1	2,0	20,0	4,5	60,0	93	0,05	37	130	799	-562
4	5	1	1	1,0	10,0	1,0	1,0	20	0,05	38	58	856	-543
5	5	1	1	1,0	10,0	1,0	1,0	20	0,05	39	59	915	-522
6	5	1	1	1,0	10,0	1,0	1,0	20	0,05	40	60	974	-500
7	5	1	1	1,0	10,0	1,0	1,0	20	0,05	41	61	1.035	-475
8	5	1	1	1,0	10,0	1,0	1,0	20	0,05	42	62	1.096	-448
9	5	1	1	1,0	10,0	1,0	1,0	20	0,05	43	63	1.159	-419
10	5	1	1	1,0	10,0	1,0	1,0	20	0,05	44	64	1.222	-388
11	5	1	1	1,0	10,0	1,0	1,0	20	0,05	45	65	1.287	-354
12	5	1	1	1,0	10,0	1,0	1,0	20	0,05	46	66	1.352	-319
13	5	1	1	1,0	10,0	1,0	1,0	20	0,05	47	67	1.419	-282
14	5	1	1	1,0	10,0	1,0	1,0	20	0,05	48	68	1.487	-242
15	5	1	1	1,0	10,0	1,0	1,0	20	0,05	49	69	1.555	-201
16	5	1	1	1,0	10,0	1,0	1,0	20	0,05	50	70	1.625	-157
17	5	1	1	1,0	10,0	1,0	1,0	20	0,05	51	71	1.695	-111
18	5	1	1	1,0	10,0	1,0	1,0	20	0,05	52	72	1.767	-63
19	5	1	1	1,0	10,0	1,0	1,0	20	0,05	53	73	1.839	-13
20	5	1	1	1,0	10,0	1,0	1,0	20	0,05	54	74	1.913	39

H0: Wind turbines WITHOUT embedded sensors

Thousand DKK

Year	Ope.idle cost	Operation cost	Rep.cost	Disaster idle c	Disaster rep.cost	Sys.fault idle c	Sys.fault rep cost	Sum	Int.rate	Interest	Annual cost	Accumulated
1	5	25	1	2,0	20,0	10,0	10,0	73	0,05	0	73	73
2	5	25	1	2,0	20,0	10,0	10,0	73	0,05	7	80	153
3	5	25	1	2,0	20,0	10,0	10,0	73	0,05	11	84	237
4	5	25	1	1,0	10,0	10,0	10,0	62	0,05	14	76	313
5	5	25	1	1,0	10,0	10,0	10,0	62	0,05	17	79	392
6	5	25	1	1,0	10,0	10,0	10,0	62	0,05	20	82	475
7	5	25	1	1,0	10,0	10,0	10,0	62	0,05	23	85	560
8	5	25	1	1,0	10,0	10,0	10,0	62	0,05	26	88	649
9	5	25	1	1,0	10,0	10,0	10,0	62	0,05	30	92	740
10	5	25	1	1,0	10,0	10,0	10,0	62	0,05	33	95	835
11	5	25	1	1,0	10,0	10,0	10,0	62	0,05	36	98	932
12	5	25	1	1,0	10,0	10,0	10,0	62	0,05	39	101	1.033
13	5	25	1	1,0	10,0	10,0	10,0	62	0,05	42	104	1.137
14	5	25	1	1,0	10,0	10,0	10,0	62	0,05	45	107	1.244
15	5	25	1	1,0	10,0	10,0	10,0	62	0,05	48	110	1.354
16	5	25	1	1,0	10,0	10,0	10,0	62	0,05	51	113	1.468
17	5	25	1	1,0	10,0	10,0	10,0	62	0,05	54	116	1.584
18	5	25	1	1,0	10,0	10,0	10,0	62	0,05	57	119	1.704
19	5	25	1	1,0	10,0	10,0	10,0	62	0,05	61	123	1.826
20	5	25	1	1,0	10,0	10,0	10,0	62	0,05	64	126	1.952

SUMMARY: Values for the graph, WORST CASE

1st year Ope.cost (+SENSOR C): 11000	4,8
1st year Ope.cost (+SENSOR C): 121000	8,0
1st year Ope.cost (+SENSOR C): 451000	19,3

SENSITIVITY ANALYSIS: SENSOR SYSTEM COST vs. TIME-TO-BREAK-EVEN
BEST CASE assumptions used

H1: Wind turbines WITH embedded sensors

Thousand DKK — Disaster likeli-hood=negligible — **Operation cost (Incl. SENSOR COST)= 11000 DKK**

Year	Ope.idle cost	Operation cost	Rep.cost	Disaster idle c	Disaster rep.cost	Sys.fault idle c	Sys.fault rep cost	Sum	Int.rate	Acc.int.	Annual cost	Accumulated	Difference
1	5	11	1	0,0	1,0	1,0	1,0	20	0,05	0	20	20	53
2	5	1	1	0,0	1,0	1,0	1,0	10	0,05	2	12	32	122
3	5	1	1	0,0	1,0	1,0	1,0	10	0,05	2	12	44	194
4	5	1	1	0,0	1,0	1,0	1,0	10	0,05	3	13	56	257
5	5	1	1	0,0	1,0	1,0	1,0	10	0,05	3	13	69	323
6	5	1	1	0,0	1,0	1,0	1,0	10	0,05	4	14	83	392
7	5	1	1	0,0	1,0	1,0	1,0	10	0,05	4	14	97	464
8	5	1	1	0,0	1,0	1,0	1,0	10	0,05	5	15	111	538
9	5	1	1	0,0	1,0	1,0	1,0	10	0,05	5	15	126	614
10	5	1	1	0,0	1,0	1,0	1,0	10	0,05	6	16	142	693
11	5	1	1	0,0	1,0	1,0	1,0	10	0,05	6	16	158	775
12	5	1	1	0,0	1,0	1,0	1,0	10	0,05	7	17	174	859
13	5	1	1	0,0	1,0	1,0	1,0	10	0,05	7	17	191	946
14	5	1	1	0,0	1,0	1,0	1,0	10	0,05	8	18	209	1.036
15	5	1	1	0,0	1,0	1,0	1,0	10	0,05	8	18	227	1.128
16	5	1	1	0,0	1,0	1,0	1,0	10	0,05	9	19	245	1.223
17	5	1	1	0,0	1,0	1,0	1,0	10	0,05	9	19	264	1.320
18	5	1	1	0,0	1,0	1,0	1,0	10	0,05	10	20	284	1.420
19	5	1	1	0,0	1,0	1,0	1,0	10	0,05	10	20	304	1.523
20	5	1	1	0,0	1,0	1,0	1,0	10	0,05	11	21	324	1.628

H0: Wind turbines WITHOUT embedded sensors

Thousand DKK

Year	Ope.idle cost	Operation cost	Rep.cost	Disaster idle c	Disaster rep.cost	Sys.fault idle c	Sys.fault rep cost	Sum	Int.rate	Interest	Annual cost	Accumulated
1	5	25	1	2,0	20,0	10,0	10,0	73	0,05	0	73	73
2	5	25	1	2,0	20,0	10,0	10,0	73	0,05	7	80	153
3	5	25	1	2,0	20,0	10,0	10,0	73	0,05	11	84	237
4	5	25	1	1,0	10,0	10,0	10,0	62	0,05	14	76	313
5	5	25	1	1,0	10,0	10,0	10,0	62	0,05	17	79	392
6	5	25	1	1,0	10,0	10,0	10,0	62	0,05	20	82	475
7	5	25	1	1,0	10,0	10,0	10,0	62	0,05	23	85	560
8	5	25	1	1,0	10,0	10,0	10,0	62	0,05	26	88	649
9	5	25	1	1,0	10,0	10,0	10,0	62	0,05	30	92	740
10	5	25	1	1,0	10,0	10,0	10,0	62	0,05	33	95	835
11	5	25	1	1,0	10,0	10,0	10,0	62	0,05	36	98	932
12	5	25	1	1,0	10,0	10,0	10,0	62	0,05	39	101	1.033
13	5	25	1	1,0	10,0	10,0	10,0	62	0,05	42	104	1.137
14	5	25	1	1,0	10,0	10,0	10,0	62	0,05	45	107	1.244
15	5	25	1	1,0	10,0	10,0	10,0	62	0,05	48	110	1.354
16	5	25	1	1,0	10,0	10,0	10,0	62	0,05	51	113	1.468
17	5	25	1	1,0	10,0	10,0	10,0	62	0,05	54	116	1.584
18	5	25	1	1,0	10,0	10,0	10,0	62	0,05	57	119	1.704
19	5	25	1	1,0	10,0	10,0	10,0	62	0,05	61	123	1.826
20	5	25	1	1,0	10,0	10,0	10,0	62	0,05	64	126	1.952

H1: Wind turbines WITH embedded sensors

Thousand DKK — Disaster likelihood= negligible — **Operation cost (Incl. SENSOR COST)= 121000 DKK**

Year	Ope.idle cost	Operation cost	Rep.cost	Disaster idle c	Disaster rep.cost	Sys.fault idle c	Sys.fault rep cost	Sum	Int.rate	Acc.int.	Annual cost	Accumulated	Difference
1	5	121	1	0,0	1,0	1,0	1,0	130	0,05	0	130	130	-57
2	5	1	1	0,0	1,0	1,0	1,0	10	0,05	7	17	147	6
3	5	1	1	0,0	1,0	1,0	1,0	10	0,05	8	18	165	73
4	5	1	1	0,0	1,0	1,0	1,0	10	0,05	8	18	183	131
5	5	1	1	0,0	1,0	1,0	1,0	10	0,05	9	19	201	191
6	5	1	1	0,0	1,0	1,0	1,0	10	0,05	9	19	220	255
7	5	1	1	0,0	1,0	1,0	1,0	10	0,05	10	20	240	321
8	5	1	1	0,0	1,0	1,0	1,0	10	0,05	10	20	260	389
9	5	1	1	0,0	1,0	1,0	1,0	10	0,05	11	21	280	460
10	5	1	1	0,0	1,0	1,0	1,0	10	0,05	11	21	301	534
11	5	1	1	0,0	1,0	1,0	1,0	10	0,05	12	22	323	610
12	5	1	1	0,0	1,0	1,0	1,0	10	0,05	12	22	345	689
13	5	1	1	0,0	1,0	1,0	1,0	10	0,05	13	23	367	770
14	5	1	1	0,0	1,0	1,0	1,0	10	0,05	13	23	390	854
15	5	1	1	0,0	1,0	1,0	1,0	10	0,05	14	24	414	941
16	5	1	1	0,0	1,0	1,0	1,0	10	0,05	14	24	438	1.030
17	5	1	1	0,0	1,0	1,0	1,0	10	0,05	15	25	462	1.122
18	5	1	1	0,0	1,0	1,0	1,0	10	0,05	15	25	487	1.217
19	5	1	1	0,0	1,0	1,0	1,0	10	0,05	16	26	513	1.314
20	5	1	1	0,0	1,0	1,0	1,0	10	0,05	16	26	539	1.413

H0: Wind turbines WITHOUT embedded sensors

Thousand DKK

Year	Ope.idle cost	Operation cost	Rep.cost	Disaster idle c	Disaster rep.cost	Sys.fault idle c	Sys.fault rep cost	Sum	Int.rate	Interest	Annual cost	Accumulated
1	5	25	1	2,0	20,0	10,0	10,0	73	0,05	0	73	73
2	5	25	1	2,0	20,0	10,0	10,0	73	0,05	7	80	153
3	5	25	1	2,0	20,0	10,0	10,0	73	0,05	11	84	237
4	5	25	1	1,0	10,0	10,0	10,0	62	0,05	14	76	313
5	5	25	1	1,0	10,0	10,0	10,0	62	0,05	17	79	392
6	5	25	1	1,0	10,0	10,0	10,0	62	0,05	20	82	475
7	5	25	1	1,0	10,0	10,0	10,0	62	0,05	23	85	560
8	5	25	1	1,0	10,0	10,0	10,0	62	0,05	26	88	649
9	5	25	1	1,0	10,0	10,0	10,0	62	0,05	30	92	740
10	5	25	1	1,0	10,0	10,0	10,0	62	0,05	33	95	835
11	5	25	1	1,0	10,0	10,0	10,0	62	0,05	36	98	932
12	5	25	1	1,0	10,0	10,0	10,0	62	0,05	39	101	1.033
13	5	25	1	1,0	10,0	10,0	10,0	62	0,05	42	104	1.137
14	5	25	1	1,0	10,0	10,0	10,0	62	0,05	45	107	1.244
15	5	25	1	1,0	10,0	10,0	10,0	62	0,05	48	110	1.354
16	5	25	1	1,0	10,0	10,0	10,0	62	0,05	51	113	1.468
17	5	25	1	1,0	10,0	10,0	10,0	62	0,05	54	116	1.584
18	5	25	1	1,0	10,0	10,0	10,0	62	0,05	57	119	1.704
19	5	25	1	1,0	10,0	10,0	10,0	62	0,05	61	123	1.826
20	5	25	1	1,0	10,0	10,0	10,0	62	0,05	64	126	1.952

H1: Wind turbines WITH embedded sensors

Thousand DKK | Disaster likelihood= negligible | **Operation cost (Incl. SENSOR COST)= 451000 DKK**

Year	Ope.idle cost	Operation cost	Rep.cost	Disaster idle c	Disaster rep.cost	Sys.fault idle c	Sys.fault rep cost	Sum	Int.rate	Acc.int.	Annual cost	Accumulated	Difference
1	5	451	1	0,0	1,0	1,0	1,0	460	0,05	0	460	460	-387
2	5	1	1	0,0	1,0	1,0	1,0	10	0,05	24	34	494	-340
3	5	1	1	0,0	1,0	1,0	1,0	10	0,05	24	34	528	-290
4	5	1	1	0,0	1,0	1,0	1,0	10	0,05	25	35	562	-249
5	5	1	1	0,0	1,0	1,0	1,0	10	0,05	25	35	597	-205
6	5	1	1	0,0	1,0	1,0	1,0	10	0,05	26	36	633	-158
7	5	1	1	0,0	1,0	1,0	1,0	10	0,05	26	36	669	-108
8	5	1	1	0,0	1,0	1,0	1,0	10	0,05	27	37	705	-56
9	5	1	1	0,0	1,0	1,0	1,0	10	0,05	27	37	742	-2
10	5	1	1	0,0	1,0	1,0	1,0	10	0,05	28	38	780	55
11	5	1	1	0,0	1,0	1,0	1,0	10	0,05	28	38	818	115
12	5	1	1	0,0	1,0	1,0	1,0	10	0,05	29	39	856	177
13	5	1	1	0,0	1,0	1,0	1,0	10	0,05	29	39	895	242
14	5	1	1	0,0	1,0	1,0	1,0	10	0,05	30	40	935	310
15	5	1	1	0,0	1,0	1,0	1,0	10	0,05	30	40	975	380
16	5	1	1	0,0	1,0	1,0	1,0	10	0,05	31	41	1.015	453
17	5	1	1	0,0	1,0	1,0	1,0	10	0,05	31	41	1.056	528
18	5	1	1	0,0	1,0	1,0	1,0	10	0,05	32	42	1.098	606
19	5	1	1	0,0	1,0	1,0	1,0	10	0,05	32	42	1.140	687
20	5	1	1	0,0	1,0	1,0	1,0	10	0,05	33	43	1.182	770

H0: Wind turbines WITHOUT embedded sensors

Thousand DKK

Year	Ope.idle cost	Operation cost	Rep.cost	Disaster idle c	Disaster rep.cost	Sys.fault idle c	Sys.fault rep cost	Sum	Int.rate	Interest	Annual cost	Accumulated
1	5	25	1	2,0	20,0	10,0	10,0	73	0,05	0	73	73
2	5	25	1	2,0	20,0	10,0	10,0	73	0,05	7	80	153
3	5	25	1	2,0	20,0	10,0	10,0	73	0,05	11	84	237
4	5	25	1	1,0	10,0	10,0	10,0	62	0,05	14	76	313
5	5	25	1	1,0	10,0	10,0	10,0	62	0,05	17	79	392
6	5	25	1	1,0	10,0	10,0	10,0	62	0,05	20	82	475
7	5	25	1	1,0	10,0	10,0	10,0	62	0,05	23	85	560
8	5	25	1	1,0	10,0	10,0	10,0	62	0,05	26	88	649
9	5	25	1	1,0	10,0	10,0	10,0	62	0,05	30	92	740
10	5	25	1	1,0	10,0	10,0	10,0	62	0,05	33	95	835
11	5	25	1	1,0	10,0	10,0	10,0	62	0,05	36	98	932
12	5	25	1	1,0	10,0	10,0	10,0	62	0,05	39	101	1.033
13	5	25	1	1,0	10,0	10,0	10,0	62	0,05	42	104	1.137
14	5	25	1	1,0	10,0	10,0	10,0	62	0,05	45	107	1.244
15	5	25	1	1,0	10,0	10,0	10,0	62	0,05	48	110	1.354
16	5	25	1	1,0	10,0	10,0	10,0	62	0,05	51	113	1.468
17	5	25	1	1,0	10,0	10,0	10,0	62	0,05	54	116	1.584
18	5	25	1	1,0	10,0	10,0	10,0	62	0,05	57	119	1.704
19	5	25	1	1,0	10,0	10,0	10,0	62	0,05	61	123	1.826
20	5	25	1	1,0	10,0	10,0	10,0	62	0,05	64	126	1.952

SUMMARY: Values for the graph, BEST CASE

1st year Ope.cost (+SENSOR C): 11000	0,2
1st year Ope.cost (+SENSOR C): 121000	1,9
1st year Ope.cost (+SENSOR C): 451000	9,0

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Fundamentals for Remote Structural Health Monitoring of Wind Turbine Blades - a Preproject

Annex A - Cost-Benefit for Embedded Sensors in Large Wind Turbine Blades

Lars Gottlieb Hansen and Lars Lading

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Abstract (max. 2000 characters)

This report contains the results of a cost-benefit analysis for the use of embedded sensors for damage detection in large wind turbine blades - structural health monitoring - (in connection with remote surveillance) of large wind turbine placed off-shore. The total operating costs of a three-bladed 2MW turbine placed offshore either without sensors or with sensors are compared. The price of a structural health monitoring system of a price of 100 000 DKK (per turbine) results in a break-even time of about 3 years. For a price of 300 000 DKK the break-even time is about 8 years. However, the cost/benefit analysis has large uncertainties.

Descriptors INIS/EDB

COST BENEFIT ANALYSIS, DAMAGE; OPERATING COST; REMOTE SENSING; TURBINE BLADES; WIND TURBINES

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