University of Strathclyde

Department of Mechanical Engineering

DEVELOPMENT OF A MONTE CARLO MODEL FOR ASSESSING OFFSHORE WIND FARM CABLE RELIABILITY AND THE WORTH OF REDUNDANCY. A COMPARISON OF VARIOUS COLLECTOR CONFIGURATIONS

Thesis Submitted for the MSc Degree
"Energy Systems and the Environment"

GEORGIOS TAKOUDIS

Supervisor: Dr Graham Ault

Glasgow, 2004

Aknwoledgments

There are many people I should thank for helping me in their own way for the completion of this thesis.

First of all, I would like to thank my supervisor Dr Graham Ault for an excellent co-operation, a very good guidance and for his support through the entire project despite his extremely busy schedule.

I also owe thanks to all the professors and the teaching staff of the course for sharing their knowledge with me.

There are some people back in Greece that deserve a special reference here as well. My dear friend Kotsos, for encouraging me and helping me find my way through many different programming languages. His pointy remarks somehow balanced my lack of experience in the field. I should thank also Leandros, for his willingness to help and his comments on the code of my model.

My flatmates in Andrew Ure hall have been absolutely fantastic and created a really supportive atmosphere at home. They made me feel I would never have done it without them.

At last, but not least I would like to thank my parents for their great help –moral and material- for believing in me and for always being there for me.

Abstract

This study is dealing with the development of a model for evaluating the reliability of submarine cables in offshore wind farms and assessing its worth. In order to achieve that, the approach of Monte Carlo simulation has been chosen.

After presenting the basic aspects of offshore wind farms and giving a theoretical background in electrical systems reliability and Monte Carlo methods, certain algorithms for addressing the problem are being discussed. Those algorithms are configuration – dependent. Therefore, the basic collector configurations used in offshore wind farms are presented as well.

The model is created using Visual Basic, and certain experiments are conducted. These experiments are performed for three basic collector configurations (string collector, cluster collector and redundant string collector), varying certain key parameters such as the cable failure rate, the inaccessibility period due to bad weather conditions, the mean wind speed of the site and the rating of the turbines used in the collector.

The outcome of these experiments leads to the calculation of the energy loss for each arrangement in each case. Adding the capital cabling cost for each configurations, helps us conclude on which configuration is the preferred one as the key parameters of the experiments vary.

Key words: offshore wind farm, reliability, reliability worth, electrical systems, configuration, cables, Monte Carlo, energy loss

1 Offshore Wind Farms

1.1 Introduction

This study is investigating how the reliability of offshore wind farms is affected by introducing redundancy in its electrical system. In this first chapter we are going to see why offshore wind farms have been chosen (instead e.g. of onshore wind farms) by giving some background information regarding the offshore resource. Furthermore, the cabling options that have been chosen so far by the developers are going to be presented and grouped in order to provide a solid basis for our study. Finally, a word on the cost of cabling is given, in order to assist us defining the value of reliability later on in the project.

1.2 The resource

Wind energy has been established in the energy market as a mature, renewable source of energy. With onshore wind farms encountering problems regarding visual impact and noise pollution while the good sites are decreasing it seems that more and more people are turning into the development of offshore wind farms. The reasons for that are more than just the problems that have been encountered in onshore sites and extinguish in the offshore environment. Probably one of the biggest reasons is that Europe's offshore wind resource is extremely large. And regardless being evidently more expensive than onshore wind, the energy costs are cheaper than those of many other renewable technologies.

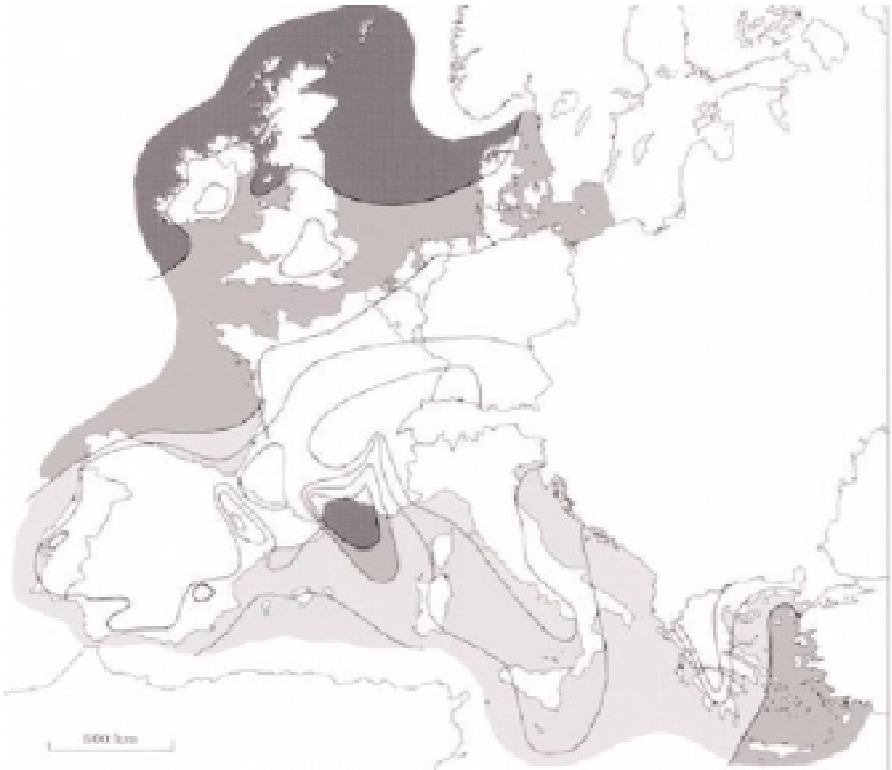
What stands out the most, is the huge resource of offshore winds. Numerous estimates have been done in Europe, both on a country by country basis and for the whole of Europe. Although there are many differences in those estimates depending on the criteria used or the uncertainties in the wind speed the conclusion is that the European resource is big. The table bellow reveals some numbers for EU according to the criteria used and taken from 2 different studies.

Criteria	EU
Water depths > 10m [1]	359 TWh
Water depths < 20m, < 20km from shore [2]	1623 TWh

Table 1. 1 Estimates of the EU offshore wind resource

To give an example regarding to how big the resource is we can say that offshore wind speeds in a distance of 10 km away from the shore may be 25% higher than at the shore. There are large areas in the Baltic and the North Sea with wind speeds above 8 m/s (at 50m) [3].

There are 2 published offshore wind maps for Europe. One -provided below- is an extension of the European Wind Atlas [4]. There is also a country by country study conducted in 1995 for the EU –then-. It was funded by the commission (Garrad Hassan, Germanischer Loyd, Windtest, 1995). Another European Offshore map is forthcoming from the POWER project.



	Wind resources for open sea (more than 10 km offshore) for 5 standard heights									
	10m		25m		50m		100m		200m	
	m/s	W/m^2	m/s	W/m^2	m/s	W/m^2	m/s	W/m^2	m/s	W/m^2
	>8.0	>600	>8.5	>700	>9.0	>800	>10.0	>1100	>11.0	>1500
	7.0-8.0	350-600	7.5-8.0	450-700	8.0-9.0	600-800	8.5-10.0	650-1100	9.5-11.0	900-1500
	6.0-7.0	250-300	6.5-7.5	300-450	7.0-8.0	400-600	7.5-8.5	450-650	8.0-9.5	600-900
	4.5-6.0	100-250	5.0-6.5	150-300	6.0-7.5	200-400	6.0-7.5	250-450	6.5-8.0	300-600
	<4.5	<100	<5.0	<150	<5.5	<200	<6.0	<250	<6.5	<300

Figure1. 1:European offshore wind atlas

The 100m height values are the most appropriate for offshore wind turbines. Most manufacturers of offshore wind turbines have the 70m height as a reference but they might offer constructions beyond this height that approach the 100 meters.

There are basically 2 ways for estimating offshore winds. The first and most obvious one is the use of existing offshore measurements. However, this method poses some problems since measurements for offshore winds are very expensive almost 50 times that of onshore measurements and many problems are associated with them such as effects of the towers or unsuitable data of vessels (because of low height). They are essential though, if a wind farm is to be built.

The other way is trying to estimate the winds using onshore data which should be straightforward, as the surface of the sea is more homogeneous than the land. In practice, though, the influence of land can extend to a considerable distance (around 50 km or more) out to sea [5].

Predicting the wind is very useful for calculating the expected energy to be delivered, but predicting that amount of energy is not only about predicting wind. The prediction of the energy delivered should be almost the same as in onshore wind farms with the exception of wake losses that are larger because of the less ambient turbulence of the wind. A validation of the wake modelling techniques offshore has been already carried out from Riso National Laboratory, Denmark, 2002.

However there is still uncertainty in the energy yield of offshore wind farms. There are various factors that lead to this conclusion such as the lack of onsite data and long-term records, the year to year variability in the offshore average speed, the lack of data for power curves measured offshore and the evaluation of the coastal effects, to name a few [4], [6].

The main conclusion though is that despite the problems and the uncertainty in calculating the exact value of offshore wind speed, the offshore resource is undoubtedly large and should be exploited.

1.3 Historical Review - Progress

The concept of offshore wind farms is not new at all. After the oil crisis in the 70's, many governmental programs supported research and development projects in wind energy. Researchers back then also recognised that there might be some restrictions in onshore projects while the offshore resource offered good winds and a very large energy potential without those restrictions.

Studies for offshore wind farms had been already conducted in the late 70s and the early 80s. Most studies were done assuming wind turbines in the range of 2 to 5 MW in clusters of up to a hundred machines, although commercial machines of that size did not exist. There were only some land based prototypes of similar rating [3].

Those studies were ahead of their time since they identified many of the key issues for offshore wind farms and in some points coincide with recent studies as well [3], [7].

Specifically for the UK there had been done a study in the '80s which was revised in 1991. It was dealing with the design of a very large wind farm (2000 MW) in the Wash [8]. Various turbine ratings up to 8.6 MW were assumed while generation voltages of 11kV and 400kV connection to the shore were considered.

Another UK study completed in 1993 considered some small wind farms [9]. It was basically a study of a prototype 400kW offshore wind turbine although there were electrical studies for wind farms of 10 and 54 machines (4MW and 21.6MW respectively). The generation voltage was considered to be 690kV, 0.69/11kV transformers were used on the turbines and the connection to the shore was a 33kV link.

Study [10] summarises some of those early studies. They can be seen in the table below

	Denmark	Sweden	UK
Date of study	1983	1979	1980
Turbine diameter/ rated power [MW]	80/3	90/5	80/3.73
Mean wind speed [m/s]	8.6	9.5	9.3
Number of turbines	595/630	70 per year	196
Wind Farm rated power [MW]	Circa 1800	350 per year	731
Yield from array [TWh]	4	0.95	1.6
Water depth	10	20	20
Foundation	Gravity or piled		Gravity or piled

Table 1. 2: Early studies for offshore wind farms

The first real offshore wind turbines were built at Helgoland, Germany in 1989, Blekinge Sweden, in 1990 and Vindeby Denmark in 1991 [3].

Coming to our times, at the end of 2001 we already had 6 pilot projects and three multi-megawatt projects in place (see Table 1.3). The experience with those projects was very positive. Therefore, a special topic conference on offshore wind energy, organized by EWEA in December 2001, attracted over 500 participants [11]. At that time, plans were presented for the construction of over 800 MW of wind farms by the end of 2003. Only half of them were, though, to be realised on time, but even this fact made the capacity of offshore wind energy to increase by a factor of four in two years [11].

Name and location	Turbine quantity and type	Project's rated capacity (MW)	Year on-line	Minimum distance to shore (km)	Water depth (metres)
Nogersund, Svante, Sweden (decommissioned)	1 Wind World 220 kW	0.22	1990	0.25	6.0
Vindeby, Denmark	11 Bonus 450 kW	5.00	1991	1.50	2-5.0
Lely, IJsselmeer, the Netherlands	4 NedWind 500 kW	2.00	1994	0.80	5-10.0
Tunø Knob, Denmark	10 Vestas 500 kW	5.00	1995	6.00	3-5.0
Irene Vorrink, IJsselmeer, Netherlands	28 Nordtank 600 kW	16.80	1996	0.02	5.0
Bockstigen, Sweden	5 Wind World 550 kW	2.75	1998	4.00	5.5-6.5
Blyth, UK	2 Vestas 2 MW	4.00	2000	1.00	8.5
Middelgrunden, Denmark	20 Bonus 2 MW	40.00	2000	2-3.00	3-6.0
Utgrunden, Sweden	7 Enron Wind 1.425 MW	10.00	2000	8.00	7-10.0
Yttre Stengrund, Sweden	5 NEG Micon 2 MW	10.00	2001	5.00	6-10.0
Horns Rev, Denmark	80 Vestas 2 MW	160.00	2002	14.00	6-12.0
Samsø, Denmark	10 Bonus 2.3 MW	23.00	2003	3.50	20.0
Frederikshavn I+II, Denmark	1 Vestas 3 MW, 1 Bonus 2.3 MW	5.30	2003	0-0.80	1.0
Nysted, Rødsand, Sweden	72 Bonus 2.2 MW	158.40	2003	6-9.50	9.0
North Hoyle, UK	30 Vestas, 2.0 MW	60	2003	7-8	12– 8 tide
Arklow Bank, Ireland	7 GEWE, 3.6 MW	25	2003	7-12	5

Table 1. 3: Current offshore projects

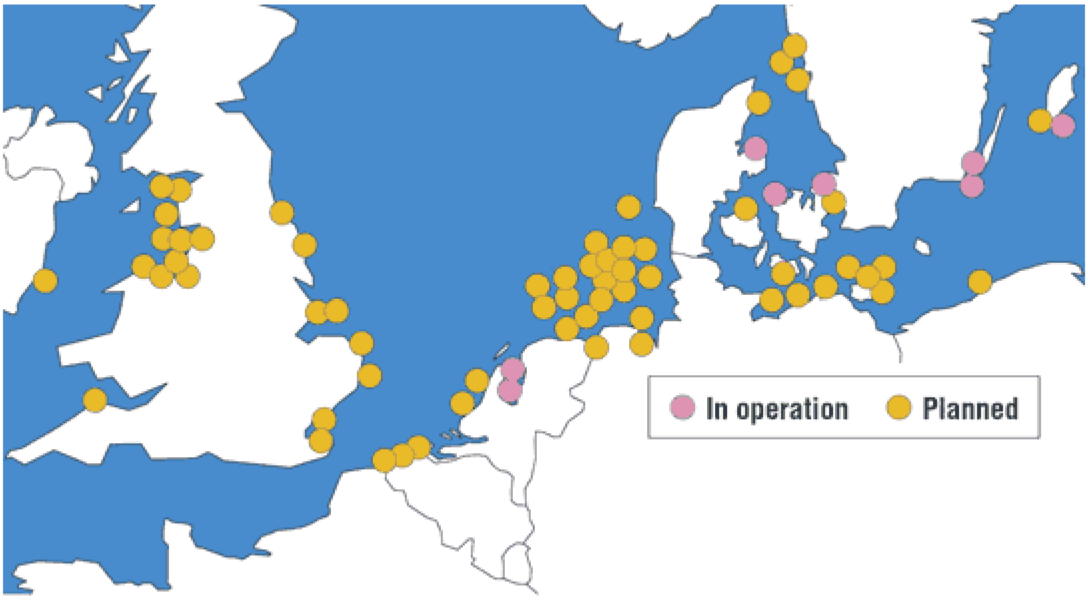


Figure1. 2: Existing and planned offshore wind projects, Northern Europe. Source: Elexyr Consultancy

Regarding future projects, it is said [12] that for the coming years offshore wind farms in the North and the Baltic Sea are planned to have rated powers of 100MW up to over 1500MW comprising of 10 to more than 200 wind turbines of 3-5 MW rated power. The declared projects are in the scale of 3.5 GW up to an horizon of 2007 [6].

1.4 Offshore Wind Turbines

Offshore wind turbines have slightly different characteristics than onshore ones, due to the special nature of the environment they are going to be placed in.

Generally, we can say that offshore machines are larger machines with higher ratings. They have large rotor diameters which is the general trend for the design of wind turbines for more energy capture. They also have a higher tip speed, since noise reduction is not a major issue offshore, and therefore we can benefit lower drive train costs.

Their height is approximately less or equal to their diameter but it must assure that the blades will remain clear of the waves in extreme weather conditions. High towers are not cost effective for offshore use since the costs of materials and erection are very high.

The most important of this feature which is relevant to our study is the magnitude of wind turbine rating because it plays a big role in energy losses. This is going to be discussed more detailed in a latter chapter. For the moment, a table with existing offshore turbines and their ratings is provided [4], [13], [14].

Wind Turbine Design	Power (MW)	Diameter (m)	Tip Speed (m/s)	Offshore to onshore ratio
BONUS 2.3 MW/82	2.30	82.4	71.6	1.26
De Wind D8/2 MW	2.00	80.0	86.7	1.14
ENERCON E66	1.80	70.0	80.7	1.11
ENERCON E112	4.50	114.0	78	1.07
GEWE 3.6s offshore	3.60	104.0	83.3	1.13
NEG Micon NM 92/2750	2.75	92.0	75.2	1.23
NEG Micon NM 110	4.20	110	-	-
Nordex N90	2.50	90.0	79.6	1.31
LAGERWEV LW 72/2000	2.00	71.2	69.5	1.31
Vestas V80	2.00	80.0	79.6	1.19

Table 1. 4: Offshore wind turbines

1.5 Cables

1.5.1 Generally – cable types

Early studies [8] and [9] considered the use of EPR cables (Ethylene Propylene Rubber). Nevertheless the most recent study [9] considered also the use of XLPE cables which are common in land uses and although an impermeable moisture barrier is required over the insulation there may be economies because of its widespread use. The particular care required to prevent ingress of moisture in XLPE cables is also emphasized in other sources [15]. Optic fibres for communication purposes can also be added in those cables.

More recent study [16] is comparing XLPE and paper insulated cables. XLPE cables are found to have lower capacitance and the reactive power generation can be easily accommodated from the system although the inductive generator self-excitation problem must be recognised. Study [17] is in accordance with that as it discusses the use of several configurations of both XLPE and paper insulating cables and finds the XLPE solution much better for long cable connections. It shows also that compensation shunts are not needed for distances up to 120km. However study [18] that considers cabling options for the Laeso Syd wind farm uses a 110 MVAr compensation shunt reactor for a 75km long cable. Other studies show that for similar lengths compensation is needed indeed [19].

XLPE cables are also preferred in study [20]. The idea of using oil-insulated cables was also carefully considered, but the tenders showed that the XLPE cable solution was by far the cheapest.

Furthermore, for the forthcoming offshore wind farms of large nominal powers discussed in [12] the cables planed to be used are three core XLPE submarine cables [21].

1.5.2 Within the collector

An important factor for sizing the cables is the electrical system configuration. There are different cable configurations. We will concentrate on two options and we will name them the “chain collector” configuration and the “cluster collector” configuration.

1.5.2.1 String (or “radial”, or “chain”) collector

It has been suggested that the best configuration is the “radial” arrangement for systems without redundancy [22]. A picture is shown bellow:

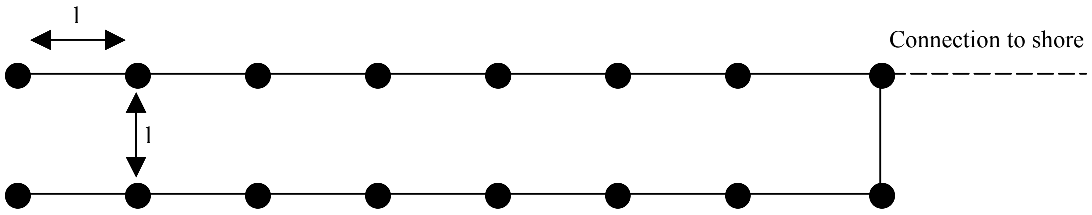


Figure1. 3: A simple string collector

The maximum number of wind turbines on each radial feeder is determined by the maximum rating of the cable but if the array dimensions allow, several shorter feeders with the same total length will result in reduced electrical losses and less lost production in the event of a cable failure.

In the case of an irregular array a "tree" structure may be justified at some points to reduce total cable length but there is a limitation concerning how many cables can be brought in to a simple turbine support structure. The radial feeders are brought to connection points on the side of the array closest to the cable landfall.

It is also possible to introduce redundancy in a certain array. This is shown here:

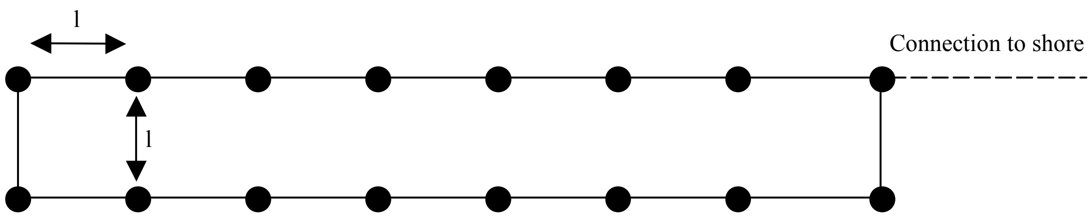


Figure1. 4: A redundant string collector

Arrays like the ones described here are going to be referred to from now on as "string collectors".

The aforementioned configuration without redundancy is currently used already in the Danish Horn Rev 150 MW offshore wind farm project. The one – phase equivalent circuit is shown in the picture below

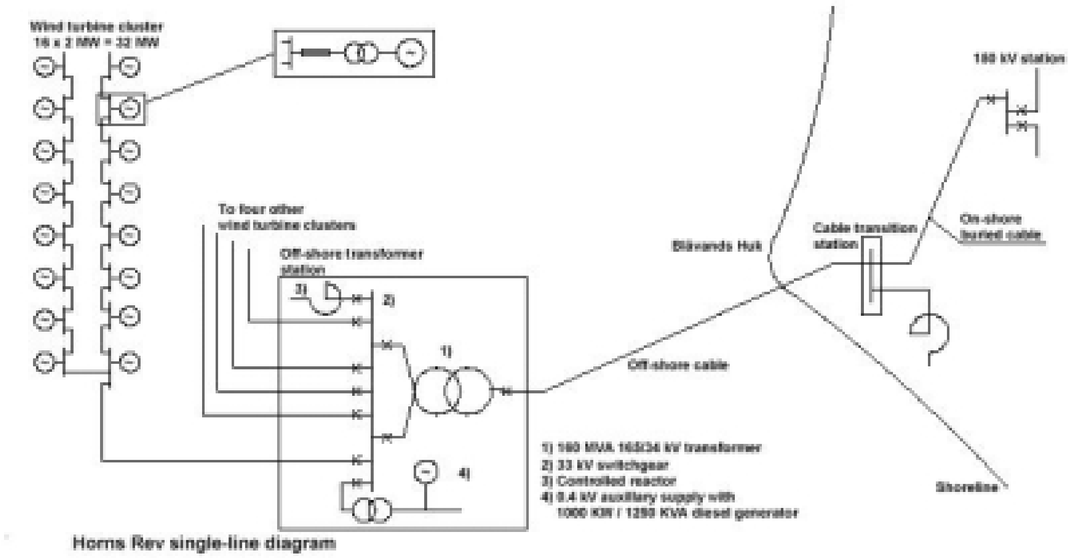


Figure1. 5:One-phase circuit diagram of the Horns Rev offshore wind farm [23]

The geometry of the wind farm is simple, 10 rows with 8 turbines each in an almost rectangular pattern [23].

1.5.2.2 Cluster collector

This is an alternative to the chain configuration and it is discussed in [16] and analysed (together with the chain collector) from the compensation and cable selection (type of cable) point of view. The cluster configuration is depicted bellow and is going to be called from now on the "cluster collector".

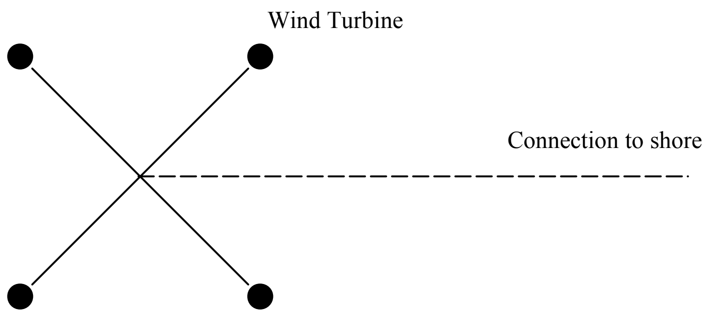


Figure1. 6: A cluster collector

Study [17] concludes that from the compensation point of view the configurations are similar, but obviously they do not have the same reliability and this fact should be studied.

The wind turbine distance inside the array of the wind farm - and hence the cable length in a string collector - might be from 500m up to 700m [12], or even close to 1 km [19]. In the Horns Rev project the distance between the machines is 560m [23] while study [22] gives a wider distance range from a few hundreds of meters up to 1 km. In order to minimise cable lengths, the number of accessories and laying processes study [21] proposes a string collector with chains of wind turbines created.

Regarding the type of the cables used, in the Horns Rev wind farm 400, 150 or 95 mm^2 XLPE-Cu cables are used (depending on load), operated at 34 kV nominal voltage. To be able to separate a faulty row, the first turbine in each of the 5 rows, where the cables to the transformer station are terminated, is equipped with motor operated disconnectors which can be operated from land. For the large planed projects (100MW - 1500MW described in [12]) three core XLPE submarine cables 10-30kV with cross sections up to 1000 mm^2 are likely to be used [21].

The grading of the cables depending on the load that is mentioned for the Horns Rev project tends to be a common practice in the design of electrical circuits of offshore wind farms, because it leads to cost – optimised solutions. In order to achieve the best choice of cabling cross section the capital investment together with the current losses have to be taken into account [21]. It is obvious that this is only applicable in a chain collector with no redundancy. Had we have used redundancy, cables should have been chosen in a way to allow full power flow in case of a fault. The grading of cables was also preferred for the Cape Wind project and it was also one of the main reasons for not using a looped chain collector (with redundancy) [24].

Conventional cable laying vessels are expensive and may have too large a draught to operate in relatively shallow waters. There is a need to develop new techniques for installing the relatively short cables within the wind farm (~ 1000 m lengths). Hauling the cables within the wind farm could be relatively straightforward and could be handled by winches temporarily mounted on the foundations, or on simple barges [20].

1.5.3 Connection to the shore

The connection to the shore has been dealt with in many studies mostly due to the numerous options we have. There are basically three options discussed:

a) Multi 33kV link to the shore
b) Single 132kV link to the shore
c) HVDC link

Nowadays, wind farms are usually connected to sub-transmission voltage levels (around up to 110kV or 132kV in Europe). Due to the size of planed offshore projects though, it will be necessary to connect them on transmission level (400kV). Taking into account the rated power and the distance of the wind farm from the shore, its connection should be optimised for each case separately [18].

The power transmission systems to the shore are normally comprised of a lot of submarine and land cables, AC switchgear, HVDC substation or AC compensation equipment, power transformers, OH lines and auxiliary equipment.

a) Multi 33kV link to the shore

This is the preferred option for distances up to 20 km and rated power up to 200MW [16], [25]. Outside these limits cable laying costs and electrical losses are limiting factors. It is also recognised that in case of a fault, if necessary, two collectors can be connected by one cable while the faulty cable is repaired in order not to lose energy production [16].

b) Single 132kV link to the shore

This option is preferred for projects further than 30km and larger than 200MW [16], [25]. It is understood that if the link fails, the whole wind farm is disconnected and large amounts of energy are lost [16].

c) HVDC link

This option is emerging for distances greater than 25 km and same power levels as option (b) [16], [25]. Again if the link fails the whole farm is lost.

Some of these solutions were discussed during the initial investigation period for the Horns Rev project. Specifically, the technical solutions proposed were 400 kV over 150 kV for multiple wind farms, HVDC (based on voltage source converters) and one 150 kV cable for the first wind farm alone. The solution finally chosen was one 150 kV cable but with space reserved on the offshore transformer station for an additional 150 kV circuit breaker intended for a cross connection to a possible future second section with its own 150 kV cable. The distance of the wind farm from the shore is 18km fact that appears to be interesting since in wind farms with less than 20 km distance from the shore multiple 33 kV links seem to be more attractive according to the aforementioned. However, the decision was made also for reasons of connection to the grid.

Since future trends show that offshore wind farms are likely to be large there seems to be a dilemma between options (b) and (c) especially for distances from 25-30 km.

Restrictions in building new overhead power lines onshore may require underground cables onshore, fact which narrows the gap between AC and HVDC [20]. It is very interesting to see the differences between the AC and HVDC connections.

1.5.3.1 AC versus HVDC

The main advantage of AC connection to the shore is the low cost of the station. However with growing distance the cable cost becomes significant and above a certain distance prohibitive. The charging current of the cables reduces the transmission capacity more and more. The capacitive power of the cable needs to be balanced by inductive reactive power in order not to cause overvoltage problems. Parameters for the optimisation of an AC system are the transmission voltage level and the number of system cables to be applied [19]. AC connection also means synchronous operation of the wind farm grid and the main grid. All faults of the grid affect the wind farm and vice versa. Thus, fast voltage control is required.

A case study of 2 wind farms in the Baltic Sea, one of 375 MW and one of 52 MW, shows that a combined connection of the farms to the shore proves to be more economic since it is used approximately the same cable length and compensation equipment as for the larger one alone [19].

This comparison is very interesting but it leads to a serial system, less reliable than the 2 different systems originally proposed. Failure of the main cable would lead to great losses of energy. As studies of similar projects progress things should be looked at in a more holistic way, adding reliability worth to the equation.

DC has the advantage of low cable cost and lower cable losses above a certain distance. This compensates for the high converter costs. It is clear that for very long distances DC becomes competitive for both investment and operational costs. DC transmission's main characteristic is that it generally decouples both grids, so that it allows asynchronous operation of the offshore wind farm AC grid and the main grid. This also facilitates a fast return to pre-fault power transmission in the case where a fault in the network should occur. Furthermore the use of Voltage Source Converters

(VSC) features the possibility of island operation and black start that are very important for the grid main support [19]. According also to study [26] a VSC based HVDC technology would allow the connection of large amounts of wind power even at weak grid points of a network and without having to improve the short circuit power ratio. HVDC light transmission system is developed by ABB [27] and is based on VSC technology.

HVDC systems have also been developed from ALSTOM and Siemens. Alstom makes use of conventional technology based on thyristor devices. Thyristor converters in conventional HVDC always require reactive power. Additional power components such as switched capacitor banks or Static VAr Compensators (SVC) must be used in order to supply the reactive power demand of the converter station [28].

The $HVDC^{PLUS}$ converter by Siemens is equipped with IGBTs, and the important characteristics are similar to HVDC-Light. The technology can deal nowadays with up to 200 MW through a single sea cable. Future developments, with Light Triggered Thyristors (LTT), will be able to manage up to 600 MW. Recently, SIEMENS has been awarded the contract for the HVDC converter stations of a 500 MW submarine cable link between Northern Ireland and Scotland. For the first time in a commercial HVDC system, direct-light-triggered thyristors with integrated overvoltage protection will be used for the AC/DC converter stations [29].

1.5.4 Damage

Submarine cables are vulnerable to damage by shipping, unless buried or otherwise protected. Burial is often the preferred method, although in some conditions other techniques are appropriate. Available information on actual likelihood of this sort of damage in the likely sites for offshore wind farms is sparse [30].

The major risk of damage is from ships' anchors and trawl equipment. The risk therefore varies greatly with location. It is also affected by seabed conditions. In areas with a hard bottom, anchors and trawl gear will not penetrate: therefore, the cable could be buried to a shallower depth than in areas with soft soils. Consequently, in a softer sea bottom, the cable would need deeper burial to have adequate protection, though the cost of burial would be lower [20].

Depending on the location the consequences can be severe: to obtain a suitable repair vessel and wait for suitable weather could take several months in winter. There are numerous cable failure data for many different types of cables in study [31] but it is difficult to extract a single conclusion out of this. A global figure of 0.32 failures/ year/ 100km is given but it is likely that this number is an overestimation since the data date back to (1950-1980) [22]. Study [32] is referring especially to Scotland where the failure rate is given to be $1.3 \cdot 10^{-2}$ failures per annum per km. This number is quite high but includes high damage territories such as Petland Firth and Sullon Voe Oil Terminal.

It is suggested that cables within the collector do not need to be buried under the seabed for extra protection since shipping and fishing which is the cause of 53% of submarine cable failures [22] is highly likely to be banned in those areas. However, it is common practice to burry those cables as well to ensure better protection.

1.5.5 Costs

Costs are a major issue, not only in offshore projects but for a project in general as well. Regarding the cabling costs, they are substantially higher in offshore wind farms than in onshore ones, since the cable has to be brought on the site in special vessels and then to be placed in the water and to be buried under the seabed. Cable costs are highly project sensitive. There is though an indication that for a three core 30 kV submarine cable with copper conductor of 800 mm^2 cross-section the price is in the region of £250 - £300 per meter installed at present prices [33]. Furthermore there are data associating the price of this cable with cables of different cross-sections for 30kV. This is illustrated in the diagram bellow [21].

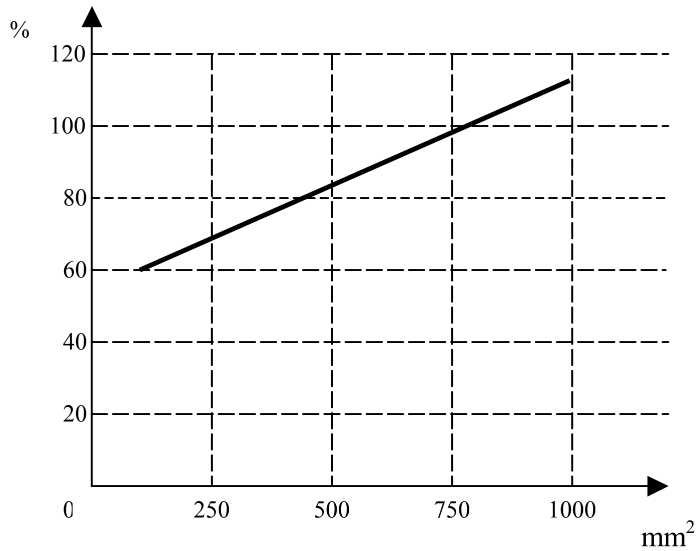


Figure1. 7: Relative costs of submarine cables versus their cross-section. Cost reference: cost of a three core 30 kV 800 mm2 copper submarine cable

Based on that diagram, we can generate a table of rough prices of some typical cross sections used by some studies [23],[21] and which will be very useful when calculating the capital costs of cabling for our different configurations in our results section.

Cable cross-section (mm^2)	Cost including burial (£/m)
200	150-180
300	175-210
350	188-225
400	200-240
500	210-255

Table 1. 5: Installation costs of some basic cross-sections for a 33kV XLPE 3 core copper conductor cable

However, there are some external costs linked to cable installation as well. When installing a cable, there has to be installed appropriate switchgear as well. Currently, the prices for a "Dead Tank" type 33kV circuit breaker - that utilise a vacuum interrupter usually in an SF_6 insulation and have current transformers in the bushing turrets – is in the region of £25,000 - £30,000 [34]. This has to be taken into account when calculating the cost of a new cable installation.

1.6 Summary

In this chapter, the offshore resource was presented and it was recognised that is extremely large for Europe although there are still problems for calculating it in detail. Then, a historical review of offshore wind farms followed by a list of current projects has been presented to show the progress and the special interest for the sector that is caused mainly by the magnitude of the resource. A list of the machines currently used has been presented and the cabling options used in the collector and for the connection to the shore in other projects and studies have been presented analytically. Those configurations will be used as a rough guide for generating the ones of the present study. The problem of the cable failures and the high cable cost has also been discussed. Some numbers from studies and companies are quoted, but the cable failure numbers are not in good agreement. Both of those numbers playa big role in assessing reliability and its worth, and this is what is going to be presented in the next chapter.

2 Electrical systems reliability - Definitions and the offshore context

2.1 Introduction

In this chapter the term electrical systems reliability is introduced. We are going to look at its classical definition and introduce some reliability indices. Redundancy for reliability is also going to be discussed and a special reference to the importance of reliability in an offshore context is going to be made.

2.2 Electrical Systems Reliability

The term reliability has a very wide range of meaning and cannot be associated with a single specific definition such as often used in the mission oriented sense. It is therefore necessary to recognise this fact and to use the term to indicate in a general sense the overall ability of the system to perform its function. Hence, power reliability can be divided into the 2 basic aspects of system adequacy and system security

Adequacy relates to the existence of sufficient facilities within the system to satisfy the system operational constraints. It is associated with static conditions which do not include system dynamic and transient disturbances. Security relates to the ability of the system to respond to dynamic or transient disturbances arising within the system. It is obvious that in the present study we are going to deal with adequacy.

When it comes to electrical systems, reliability studies are split in 3 categories [35]:

a) Generation system studies (HL1).

   Those studies examine the total system generation to determine its adequacy to meet the total system load requirement. The transmission system and its ability to move the generated energy to the consumer load points is totally ignored. This activity is usually termed "generating capacity reliability evaluation" and is referred to as Hierarchical Level 1 study (HL1).

b) Composite system studies (HL2).

Those are referred to as Hierarchical Level 2 studies. In HL2 studies bulk transmission is also included in the simple generation-load model of HL1 studies. They can be used to asses the adequacy of an existing or proposing system including the impact of various reinforcement alternatives in both the generation and the transmission levels. In order to asses that, 2 kinds of indices are introduced: individual bus indices that show the effect at individual busbars and provide input values for distribution system adequacy studies and overall system indices that provide an assessment of overall adequacy. Those indices are complementary and for a complete HL2 study both kinds should be taken into consideration.

c) Distribution system studies

The distribution system is usually handled separately in reliability studies because an HL3 study, containing all the parts of an electrical system, would be highly complex. It is therefore, common practice to regard the distribution system as a separate entity and to use HL2 indices as inputs in distribution system studies. In most systems, inadequacy of the individual customer points is caused mainly by the distribution system. However, HL1 and HL2 indices are very important because they affect large sections of the system and therefore can have widespread and perhaps catastrophic consequences for both the society and the environment.

2.3 The offshore wind farm case

In our case, we are going to be dealing either with an offshore wind farm in general or concentrating only on a part of it (i.e. a simple collector). Such a collector can be seen in the picture bellow

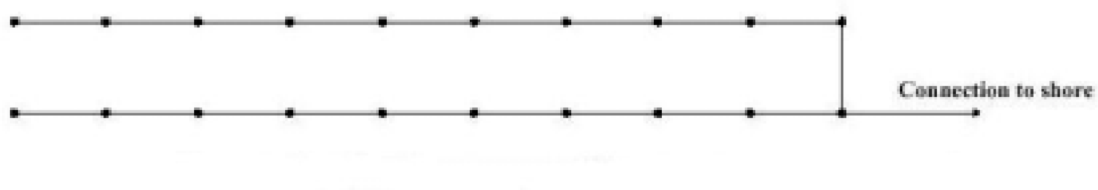


Figure 2. 1: String collector

The dots represent wind turbines and the lines the cabling. Evidently, this is more than a generating system since it is more complex than the generator – load model. Furthermore, it has nothing to do with energy distribution (although the connection might be in distribution voltage level).

Hence, in classic reliability terms, this study is a simplified case of an HL2 system study. Wind turbines are considered to be generating systems while the cables interconnecting them along with the cables that connect the farm to the shore and the main grid are considered to be part of the transmission system. Therefore indices of the HL2 studies are suitable to use in order to define the system adequacy. Note that the affect of the reliability of the wind turbines is ignored since we are focusing on the transmission components – the cables -, their reliability and their affect on the system as an entity.

The most suitable adequacy index to be used in our study is the EENS (Expected Energy Not Supplied) index, and it will be our goal to calculate it throughout the project.

2.4 Designing for improved reliability

If an improvement in system reliability is required it can be effected by using either better components or system design incorporating more redundancy.

Redundancy is a basic term in reliability studies. The simplest form of redundancy is the parallel configuration where a simple duplication of a component can result to a system of greater reliability.

A more complex form of redundancy is the r out of n configuration. In this case, we have n components between two nodes of a system, and as long as r out of n components are not faulty the system is in operation. This method is widely used in electronics applications. The simplest form of this kind of redundancy is the TMR system (triple modular redundancy) where 3 components and a voter are used. This kind of system works when 2 of its components are functioning correctly [36].

When it comes to electric power systems, we can have certain forms of redundancy in the generation, the transmission or even the distribution level. Usually when we are talking about redundancy in a generation system we mean having more generation capacity than the one needed to satisfy our loads. In the distribution level redundancy is used in the duplication of certain components in substations and in designing more sophisticated bus schemes.

The kind of redundancy that is going to be examined in the present study is redundancy in the transmission level. This means either ties between stations that are stronger than would be warranted by normal loads or links where more are required in the basic design; this extra transmission capacity may, however be needed to avoid overloading under unusual operating conditions.

Evidently, the concepts of reliability and reserves are so closely bound together and so are, obviously reliability and the costs of installing additional components and operating the system. Nevertheless, it should be observed that there are not one-to-one relationships between these quantities.

2.5 Worth of reliability

One of the major discussion points regarding reliability is whether it is worth it or not. It is evident that reliability and economics play a major integrated role in the decision-making process.

The first step in this process is to determine the relationship of reliability with the investment cost. Obviously an increased investment cost is required for a system with improved reliability. An indicative curve of investment cost versus reliability is given in the figure below [35].

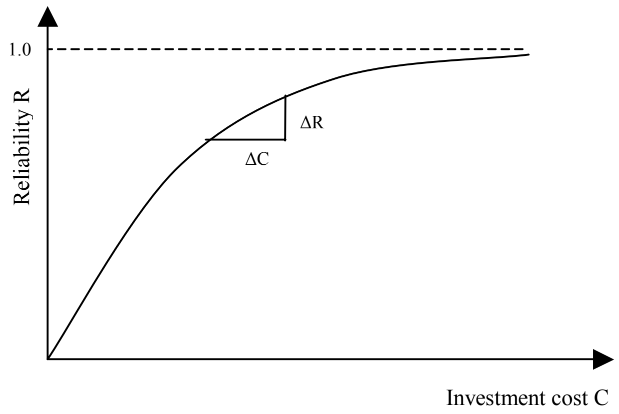


Figure 2. 2: Reliability Vs investment cost

This clearly shows that the incremental cost ΔC to achieve a given increase in reliability ΔR increases as the reliability level increases, or, alternatively, a given increase in investment produces a decreasing increment in reliability as the reliability is increased. In either case, high reliability is difficult to achieve.

The incremental cost of reliability ΔC/ΔR is one way of deciding whether an investment in the system is worth it. However, it does not adequately reflect the benefits seen by the utility, the customer or society. The two aspects of reliability and economics can be appraised more consistently by comparing reliability cost (the investment cost needed to achieve a certain level of reliability) and reliability worth (the benefit derived by the customer and the society).

This extension of quantitative reliability analysis to the evaluation of service worth is a deceptively simple process fraught with potential misapplication. The basic concept of reliability-cost/reliability-worth is relatively simple and illustrated in the picture below [35], [37].

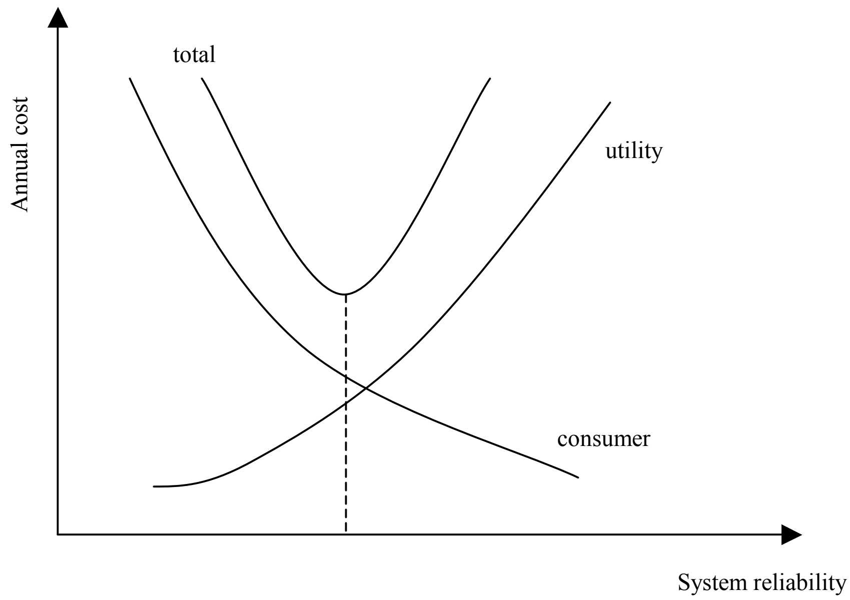


Figure 2. 3: System reliability Vs annual cost

These curves show that while the investment cost generally increases with higher reliability, the customer costs associated with failures decrease with higher reliability. Hence, the total cost which is the sum of the aforementioned costs, exhibits a minimum, which is obviously the "optimum" or target level o reliability to be achieved.

Although this is a quite valid concept, there are two main difficulties in its assessment. First, the calculated indices are usually derived from approximate models, and second, there are significant problems in assessing customer perceptions of system failure costs and a number of studies and surveys have been conducted for that reason.

In the present study, reliability cost is under discussion. The investment cost is going to be evaluated in terms of the increase in the reliability that it can give. Therefore, the evaluation resembles the incremental cost of reliability approach. It is recognised that in order to have a more holistic approach, customer failure costs should also be taken into consideration. However, we are purely investigating reliability cost and comparing it directly to the benefit of the amount of energy saved.

In detail, the capital cost of a redundant cable is compared to the cost of the energy savings this cable will result in. An assessment of customer failure costs is very complex and can be a subject of a different detailed study.

2.6 Reliability in an offshore context

When it comes to offshore wind farms, reliability tends to be a big issue. During harsh winter conditions, a complete wind farm may be inaccessible for a number of days due to sea wind and visibility conditions. Therefore, there have to be found ways of making the farm more reliable, needing less service and maintenance visits that are not only difficult but also costly.

From this point of view, it is evident why reliability has a greater value in offshore projects and thus, why people are willing to pay more for it in an offshore context.
How much more they are willing to pay though, is another issue. That is why numerous studies are being done about reliability in offshore wind farms.

It is observed that for the case of offshore wind farms a great deal of effort and research has been put in the first sector, which is improving the reliability of the components of the system. More reliable wind turbines are being constructed for use offshore and turbine reliability is still a big research field. It is indicative to say that various designs of wind turbines have been considered and a special tool for assessing their reliability has been developed and is going to be discussed in a latter chapter.

Redundancy has not been considered in the same extent for offshore wind farms. However some studies have been already conducted. Using probabilistic analysis, study [22] has found the energy savings due to prevented failure to be uneconomic (equivalent to only 0.026% of the ideal production in the most favourable case). However under different assumptions and configurations the answer could be different and this has to be looked into. It is believed that this kind of analysis will be common practice for designing offshore wind farms. A recent example is Cape Wind offshore wind farm which is the first proposed American offshore wind farm. A similar analysis took place and the simple radial configuration without redundancy was finally preferred over a looped arrangement as a more economical solution [24].

However, when it comes to the cables that connect the wind farm to the shore study [22] highlights the value of redundancy to the shore as well as the need for the minimisation of cable damage. Those cables must be buried always under the seabed for better protection. Below there is an example of system redundancy in an offshore wind farm without an offshore substation. A network design tool that determines the best location for redundancy links and that calculates the value has been developed.

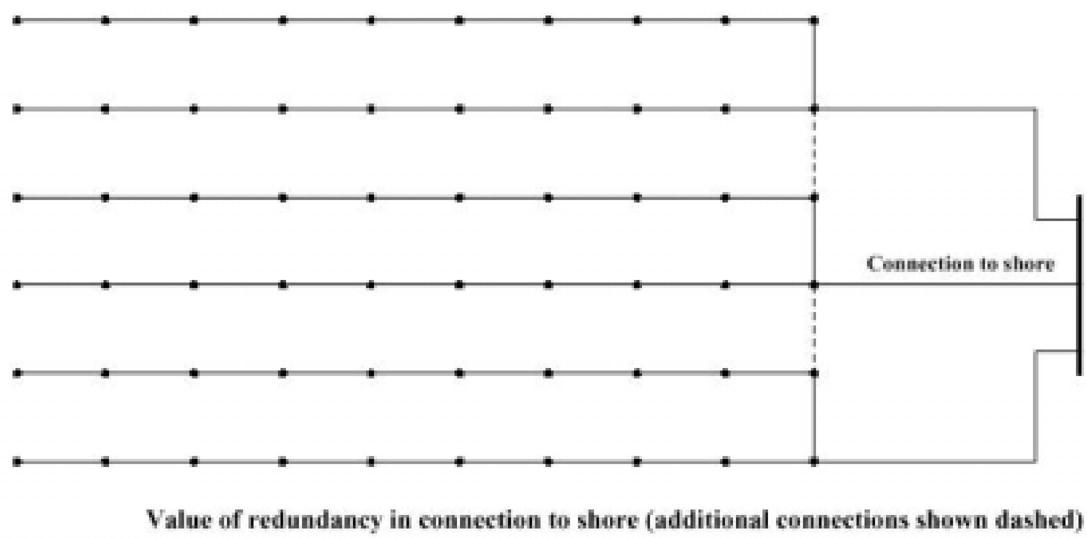


Figure 2. 4: An example of redundancy in shore links

In the event of failure of one on the links to shore the additional links allow the system to be reconfigured. The capacity of the links is no greater than the other cables in the system.

A special tool developed in [22] has shown significant savings for this system (£363,000 for mean annual wind speed 7m/s and £570,000 for 10m/s). When the constraint of 3 cables/ WT was introduced into the tool a different configuration was shown reducing the savings by 25%.

The Horns Rev system though, one of the largest offshore project to date and a reference for many studies on offshore wind farms, has no kind of redundancy [23].

2.7 Summary

In the present chapter some definitions and background regarding electrical power systems reliability have been given. Our case has been presented in bold lines and was identified as an HL II case. Ways of improving reliability have been discussed and reliability worth has been presented. Then, we had a look on how these ways of improving reliability have been applied in an offshore context and if there was estimated whether they were worth it. Our look was focused on cable redundancy, since this is the subject of the present study, and relevant studies about that were presented. The most relevant uses a tool that performs probabilistic analysis and finds redundancy within the collector to be uneconomic. One way of doing probabilistic analyses is the Monte Carlo method. This, together with our approach on the subject of redundancy is going to be presented in the following chapter.

3 Monte Carlo simulations, its applications in reliability assessment and in the present study

3.1 Introduction

In this chapter, the Monte Carlo method is going to be presented. Its use in reliability evaluation is then going to be discussed and some main approaches for reliability evaluation using Monte Carlo are going to be mentioned. The proposed method for this study is going to be analysed, and its algorithm is going to be presented analytically from the inputs to the results processing.

3.2 The definition and basic principles of Monte Carlo simulation

When we use the word simulation, we refer to any analytical method meant to imitate a real-life system, especially when other analyses are too mathematically complex or too difficult to reproduce.

Monte Carlo simulation is the general designation for stochastic simulation using random numbers. It was named after Monte Carlo, Monaco, where the primary attractions are casinos containing games of chance. Credit for inventing the Monte Carlo method often goes to Stanislaw Ulam, a Polish born mathematician who worked for John von Neumann on the United States' Manhattan Project during World War II. Ulam is primarily known for designing the hydrogen bomb with Edward Teller in 1951 [38]. He invented the Monte Carlo method in 1946 while pondering the probabilities of winning a card game of solitaire. The Monte Carlo method, as it is understood today, encompasses any technique of statistical sampling employed to approximate solutions to quantitative problems. Ulam did not invent statistical sampling. This had been employed to solve quantitative problems before, with physical processes such as dice tosses or card draws being used to generate samples. Ulam and Metropolis published the first paper on the Monte Carlo method in 1949 [39]. Because of the repetition of algorithms and the large number of calculations involved, Monte Carlo is a method suited to calculation using a computer, utilizing many techniques of computer simulation.

Monte Carlo is now used routinely in many diverse fields, from the simulation of complex physical phenomena such as radiation transport in the earth's atmosphere and the simulation of the esoteric sub-nuclear processes in high energy physics experiments, to the mundane, such as the simulation of a Bingo game. The analogy of Monte Carlo methods to games of chance is a good one, but the “game” is a physical system, and the outcome of the game is not a pot of money or stack of chips (unless simulated) but rather a solution to some problem.

Statistical simulation methods may be contrasted to conventional numerical discretization methods, which typically are applied to ordinary or partial differential equations that describe some underlying physical or mathematical system. In many applications of Monte Carlo, the physical process is simulated directly, and there is no need to even write down the differential equations that describe the behaviour of the system. The only requirement is that the physical (or mathematical) system be described by probability density functions (pdf's), which will be discussed in more detail later in this chapter. For now, we will assume that the behaviour of a system can be described by pdf's. Once the pdf's are known, the Monte Carlo simulation can proceed by random sampling from the pdf's. Many simulations are then performed (multiple “trials” or “histories”) and the desired result is taken as an average over the number of observations (which may be a single observation or perhaps millions of observations). In many practical applications, one can predict the statistical error (the “variance”) in this average result, and hence an estimate of the number of Monte Carlo trials that are needed to achieve a given error.

Assuming that the evolution of the physical system can be described by probability density functions (pdf's), then the Monte Carlo simulation can proceed by sampling from these pdf's, which necessitates a fast and effective way to generate random numbers uniformly distributed on the interval [0,1]. The outcomes of these random samplings, or trials, must be accumulated or tallied in an appropriate manner to produce the desired result, but the essential characteristic of Monte Carlo is the use of random sampling techniques (and perhaps other algebra to manipulate the outcomes) to arrive at a solution of the physical problem. In contrast, a conventional numerical solution approach would start with the mathematical model of the physical system, discretizing the differential equations and then solving a set of algebraic equations for the unknown state of the system [40].

The primary components of a Monte Carlo simulation method include the following:

- **Probability distribution functions** *(pdf's)* - the physical (or mathematical) system must be described by a set of pdf's.
- **Random number generator** - a source of random numbers uniformly distributed on the unit interval must be available.
- **Sampling rule** - a prescription for sampling from the specified pdf's, assuming the availability of random numbers on the unit interval, must be given.
- **Scoring (or tallying)** - the outcomes must be accumulated into overall tallies or scores for the quantities of interest.
- **Error estimation** - an estimate of the statistical error (variance) as a function of the number of trials and other quantities must be determined.
- **Variance reduction techniques** - methods for reducing the variance in the estimated solution to reduce the computational time for Monte Carlo simulation
- **Parallelization and vectorisation** - algorithms to allow Monte Carlo methods to be implemented efficiently on advanced computer architectures.

Regarding the error of the simulation in relation to the trials conducted, generally we have to increase the trials by a factor of 100 in order to decrease the error by a factor of 10 [40].

3.3 Monte Carlo in reliability assessment

There are three basic simulation approaches in reliability evaluation [37]:

- State sampling approach
- State duration sampling approach
- System state transition sampling approach

The state sampling approach has a relatively simple sampling requiring only the generation of uniformly distributed numbers between [0, 1] without the existence of a pdf. Furthermore the required basic reliability data are relatively few and many other parameters can be inserted besides components failure events. However this method cannot be used by itself to calculate the actual frequency index.

The state duration sampling approach can be easily used to calculate the actual frequency index. It can utilize any state duration distribution and the statistical probability distributions of the reliability indices can be calculated in addition to their expected values. On the other hand, compared to the state sampling approach it requires more computer time and storage because it is necessary to generate a random variant following a given distribution for each component and store information on chronological component state transition processes of all components in a long time span. It also requires parameters associated with all components state duration distributions.

The system state transition sampling approach can be used to calculate the exact frequency index without the need to sample the distribution function and store chronological information. It is also needed only one random number to obtain a system state of m components and not m random numbers as in the state duration sampling approach. However, it can be used solely for exponentially distributed component state durations.

It is obvious from the above that each approach is best suited for different types of applications. In our case the state duration sampling approach is the optimum solution. This is because we are in search of frequency indices, thus the state sampling approach does not fit our application. Furthermore, not all the system states can be described by exponential distribution function as we are going to see with more detail in a latter paragraph. It is essential, therefore, to describe the state duration sampling approach in more detail.

3.3.1 State duration sampling approach

The state duration sampling approach is based on sampling the probability distribution of the component state duration. In this approach, chronological component state transition processes for all components are first simulated by sampling. The chronological system state transition process is then created by combination of the chronological component state transition processes.

This approach uses the component state duration distribution functions. In a two state component representation, these are the operating and repair state distribution functions and are usually assumed to be exponential although other distributions can be easily used. This feature is going to be looked at in the presentation of the algorithm used in this study later on.

The state duration approach can be summed up in the following steps:

1. Specify the initial state of each component: generally this is the “up” state
2. Sample the duration of each component residing in its present state. For example, given an exponential distribution the sampling value of the state duration –in our case, duration of “up” state- is

   $$timetofailure = \frac{-\ln(U)}{lamda}$$

   Where U is a uniformly distributed random number between [0, 1] corresponding to each component.
3. Repeat step 2 in the given time span (yr) and record sampling values of each state duration for all components. Chronological component state transition processes in the given time span can then be obtained.
4. Chronological component state transition processes are obtained and combined to give the chronological system state transition processes.
5. The required system indices are extracted after the analysis needed.

These steps describe roughly the algorithm used for the model presented in this study. This is going to be discussed more thoroughly below.

3.4 The wind farm model

3.4.1 Monte Carlo in offshore applications

The idea of using Monte Carlo simulations in an offshore environment is not quite new. It has been used in several occasions in order to evaluate reliability availability and maintainability in offshore wind farms. This is done mainly because maintenance is costly and difficult in offshore environments. Reducing maintenance costs and needs is a great concern and a field of current research. In this field, Monte Carlo is a very useful and powerful tool.

TU Delft, have developed a simulation tool [41], [42], simulating 20 year periods of wind farm operation. This model includes stochastic failure occurrence in both the wind turbines and the weather conditions. The simulation is performed in an hourly basis and the response of the maintenance crew is simulated at the same time. This model however does not take into account the cabling of the farm and is completely focused on the wind turbines and their components.

3.4.2 Why model? The particularities of offshore wind farms

Before modelling, there has been an effort of finding and using existing "off the shelf" models either in the form of a program or as excel add-ins. However it was recognised that none of the existing programs fitted exactly our demands. Monte Carlo is a widespread method and there are a lot of models available but our case had some special requirements.

As described in the previous chapters, operation and maintenance of offshore wind farms is a subject to weather conditions. There are periods in which the wind farm is virtually inaccessible fact which leaves us with certain "service windows". This is how the periods in which the access to the wind farm is possible are known. Hence, the repair of a faulty cable follows this "interval" procedure.

Whenever the wind farm is accessible, the cables are supposed to be repaired the very next day. However if a fault occurs within the inaccessibility periods, the fault is supposed to be repaired on the first day that the wind farm is again accessible.

Furthermore, different analysis techniques are required in order to obtain frequency indices for each configuration.

3.4.3 Possible configurations of an offshore wind farm collector

First of all, it is clear that we have to define our collector in regards to the number of the turbines and the distance between them. A collector of 16 machines has been assumed for all of the following cases. This was found to be a good number, since it is the same number of machines that are used in the Horns Rev scheme. Collectors of more machines are not likely to be constructed, especially as the rating of the machines increases. We now have to look at the possible ways of connecting those machines in the collector and simulate all of them.

As it has been said earlier in this study there are two possibilities of connecting wind turbines within a collector; the string arrangement and the cluster arrangement. The circuit diagram of 16 wind turbines configured in a string collector can be seen in picture bellow.

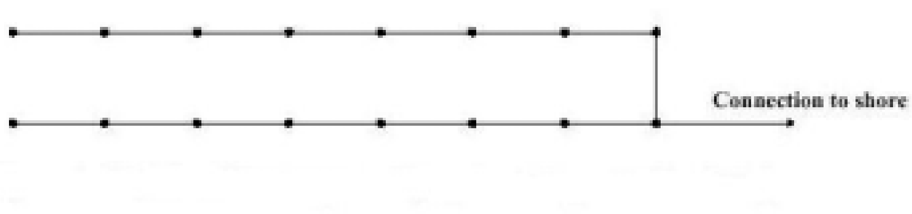


Figure 3. 1: A string collector of 16 wind turbines

As it is clearly shown, there are 15 cables within the collector and an extra cable that connects the wind farm to the shore. The wind turbines have a certain distance l between them, and as it can be seen in the figure as well the cables have all the same length “l”.

We can also have a cluster arrangement of those 16 wind turbines.

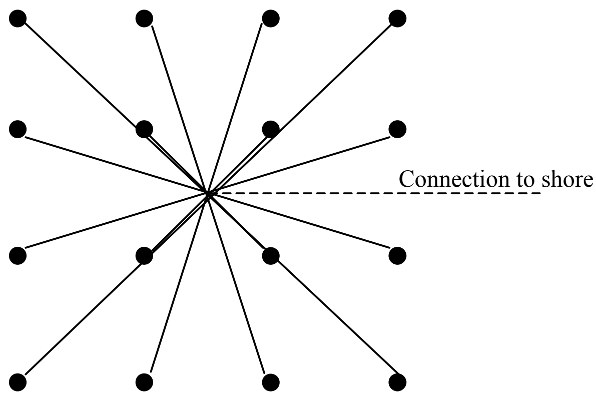


Figure 3. 2: Cluster collector with 16 wind turbines

This collector uses 16 cables for the wind turbines plus the extra cable that connects the collector to the shore. We should notice that the length of the cables is different than for the string collector. First of all, not all cables have identical lengths. We can say generally that we have 4 “short” cables, 4 “long” cables and 8 “medium” cables. Generally, the total cable length for such a configuration is bigger since not only are we using one more piece of cable, but we are also using longer cables. However, we should take into consideration that those cables connect only one wind turbine to the main point and are thus of a smaller cross-section.

All the aforementioned together with the reliability of each configuration have to be taken into account when calculating the costs associated with each configuration.

We can easily calculate the length of the cables of this configuration using again the distance l between the wind turbines as a reference. So, if l_s is the length of the “short” cables, l_m that of the “medium” ones and l_l that of the long ones, then:

$$l_s = \frac{l}{2}\sqrt{2}$$

$$l_m = \sqrt{\left(3l/2\right)^2 + \left(l/2\right)^2} = \sqrt{5l^2/2}$$

$$l_l = \frac{3l}{2}\sqrt{2}$$

3.4.4 The algorithm explained

The algorithm used for the model presented in this study could be split up in two parts. We are going two look at those parts separately, explaining in detail how the model works.

We are first going to go through some of the most fundamental variables and inputs used in our model.

Time units: the time unit used throughout the algorithm is a day. The simulated period is always a period of 7300 days, equivalent to 20 years. This is the expected life span of an offshore wind farm. The number of time units is declared within the program as a constant.

Number of components: the number of cables for the simulated scheme. This is dependant on the configuration of the collector of the wind farm. The collector simulated in the present study has always 16 wind turbines but the number of cables might be 15, 16 or again 16 depending if we are considering a simple string collector, a redundant string collector or a cluster collector. This was also illustrated above. The number of components is also declared as a constant in the program.

Number of experiments: (or trials). This is an input to our program, defining how many trials are going to be preformed in our Monte Carlo simulation.

First day, last day: (of inaccessibility period). Those are inputs to the program and they represent the first and the last day of the inaccessibility period of the offshore wind farm for a year. Evidently they can take any value between 1 and 365. By convention, though, we will consider the first day to be day number 150.

Failure Rate: input to the program. It is a number for submarine cables and it must be entered in failures/day/km

Distance: another input. It represents the distance between the wind turbines in km and in the string collector it coincides with the cable length. Therefore, when multiplied by **Failure Rate**, it will give us a **lamda** value for each component. In the cluster collector, the cable lengths have to be calculated in the program in order to get the desired **lamda** value.

Lamda: the failure rate of the component in failures/day and it is used for the generation of the time to failure of each component.

Time to failure: it is generated for each component using the inverse relationship

$$timetofailure = \frac{-\ln(U)}{lamda}$$

where U is a uniformly distributed random variable.

CompSurv(k,t): this is a table of chronological failure data for each component. In this table we can find stored information about each component state ("up" or "down", represented with "1" and "0" respectively) on any given day. It is evident that this table has dimensions **Number of components x time units.**

Days(k): this is an array which is used to count the down days of each of our components. It is, in a way, a counter of days. Nevertheless, it counts days under certain rules that are going to be discussed more analytically in the 2nd part of the algorithm description. Of course, there are as many counters as the **Number of Components**.

1st part – generating and storing chronological failure data

This is the most straightforward part of the model and it is common in all the "flavours" of it.

During that procedure, the inputs of the problem are read and the CompSurv table is generated with all its elements set to zero. Hence, the initial state for each component is assumed to be the "down" state. Then, a time to failure is generated for each component and assigned to it.

For each component separately, a time loop is initiated. There, the time to failure for that component is compared to the time index of the loop. If the time to failure is found to be greater than the time index, the corresponding number in the CompSurv table is changed to 1 ("up" state), the time index of the loop is incremented by one unit and the check is performed again.

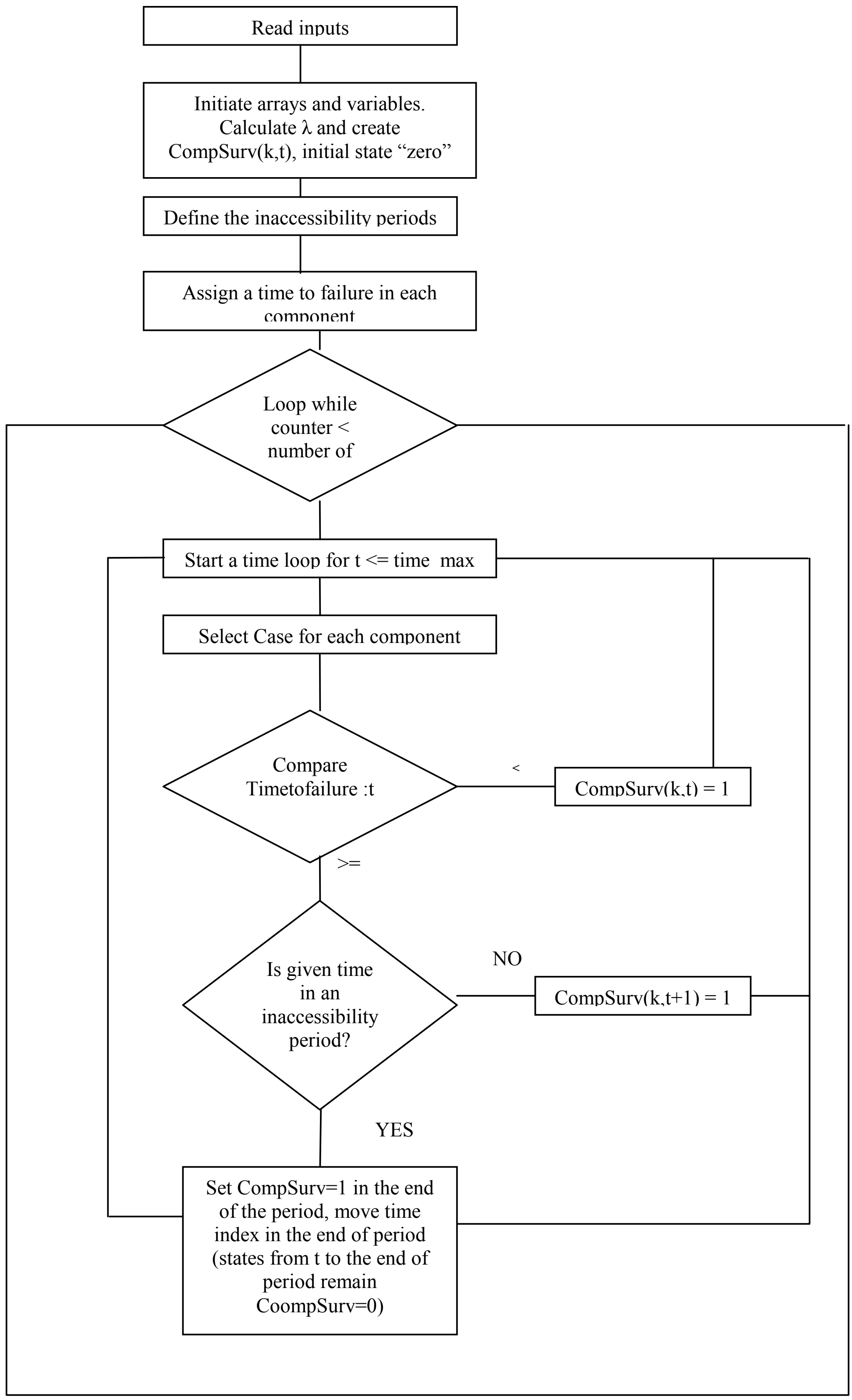
If the time to failure is found to be smaller than the time index of the loop, then it means that a failure has occurred. Thus, we must check whether this failure is within or outside the "service window".

If the failure occurred within the service window, then the fault is cleared the next day, and a new time to failure is assigned to that component so that it can be checked again in the next time loop.

If, however, the failure is in an "inaccessibility period" then the fault is supposed to be cleared on the first day of the next service window and the time index is moved to that very time. A new time to failure is generated again for the replaced cable and the loop goes on.

In both of these cases, the elements of the CompSurv table remain unchanged (state "0" or "down) for as long as the fault persists.

This procedure is –as said before- repeated for each component and gradually the CompSurv table is filled with 1s and 0s. Bellow, we can see the described procedure diagrammatically.



Read inputs
Initiate arrays and variables. Calculate λ and create CompSurv(k,t), initial state "zero"
Define the inaccessibility periods
Assign a time to failure in each component
Loop while counter < number of
Start a time loop for t <= time max
Select Case for each component
Compare Timetofailure :t
<
CompSurv(k,t) = 1
>=
Is given time in an inaccessibility period?
NO
CompSurv(k,t+1) = 1
YES
Set CompSurv=1 in the end of the period, move time index in the end of period (states from t to the end of period remain CoompSurv=0)

2nd part – calculating system down times and reliability indices

For this phase of the algorithm different "flavours" are designed. We are going to go through them all, one by one.

a) String collector

As we explained earlier on this is the most complex configuration of a wind farm array. The program is designed to give solid results under the assumption that a conventional numbering is used. This numbering is presented bellow for a string collector.

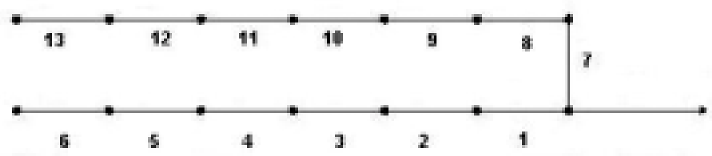


Figure 3. 3: Conventional numbering in the string collector

For this part of the algorithm, the cables are split up in two equal groups. The first group contains the first "row" of the cables (in our example, from 1 to 6) and the other one, the rest.

This is done because there is a certain interaction between the cables of each row. If a cable is faulty, but another cable on the same row and closer to the connection point (and thus a "smaller" number cable) is down as well, the failure of the first cable should be discarded when calculating the system frequency index. In order to fully understand why this is happening we have to look at the example bellow.

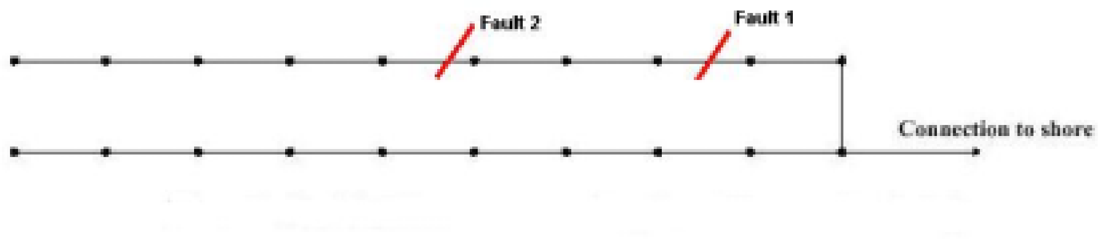


Figure 3. 4: Example of a double fault in the string collector

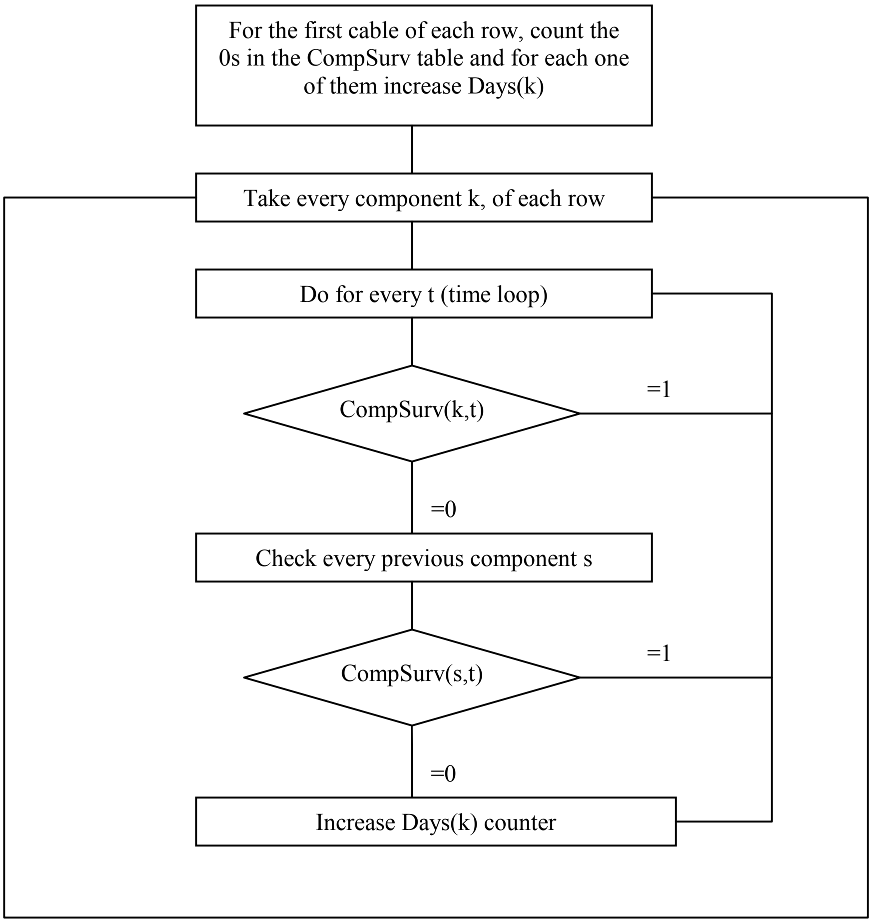
Fault 2 leaves 5 turbines out of the grid, while at the same time fault 1 leaves those 5 turbines plus 2 more out of the grid. When calculating the Expected Energy Not Supplied, if Faults 1 and 2 are simultaneous it is easily understood that Fault 2 should be discarded.

Let us see how we can incorporate this particularity of the design into our algorithm by describing it.

For the first cable of each row the situation is pretty straightforward. Whenever there is a zero in the CompSurv table, its Days(k) counter is increased by one.

For the rest cables of the group, a check has to be conducted. If the cable is faulty, then the state of each “previous” cable of the same row should be checked. If all the “previous” cables are in the “up” state, then the outage day for this cable is counted and its Days(k) counter is increased by one, else the outage day is discarded.

The whole procedure can be shown again diagrammatically in the following figure.



b) Introducing redundancy in the string collector

In case we want to introduce redundancy in the array, an extra cable has to be added. This cable will get the last number of our numbering. It is going to be assigned with time to failures a well, and it will also have a states row in the CompSurv table. The conventional numbering for this case is shown in the figure bellow.

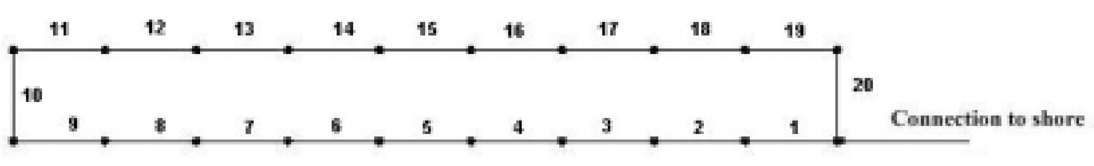


Figure 3. 5: Conventional numbering in the redundant string collector

However, in this case, our interest is concentrated only in double faults or faults of more than two cables. As it can be seen in the figure of the redundant string collector, should a single fault occur, there are ways of reconfiguring the collector by changing the direction of power flow in a way that we have no power losses. This is going to be explained analytically bellow.

In the figure, cable number 10 is the redundant cable. It is the only component which was not in the previous configuration.

Under normal circumstances the collector can operate without it. If a fault occurs though, in cable number 6 for example, then for the simple configuration we would have 4 turbines out of the grid. Cable number 10 allows the system to reconfigure, and the "lost" turbines of the lower row, are now delivering energy through cable 10 and the upper row. Obviously, with this configuration energy losses should be smaller since a fault of 2 or more components must take place in order to lose energy.

The conventional numbering was chosen in a way so that we can take the number of the turbines that are disconnected from the grid by subtracting the smaller numbered cable from the greater numbered cable. This way, if for example cables 3, 6 and 7 have a fault in a certain moment then we have 7-3 = 4 turbines disconnected in this very moment.

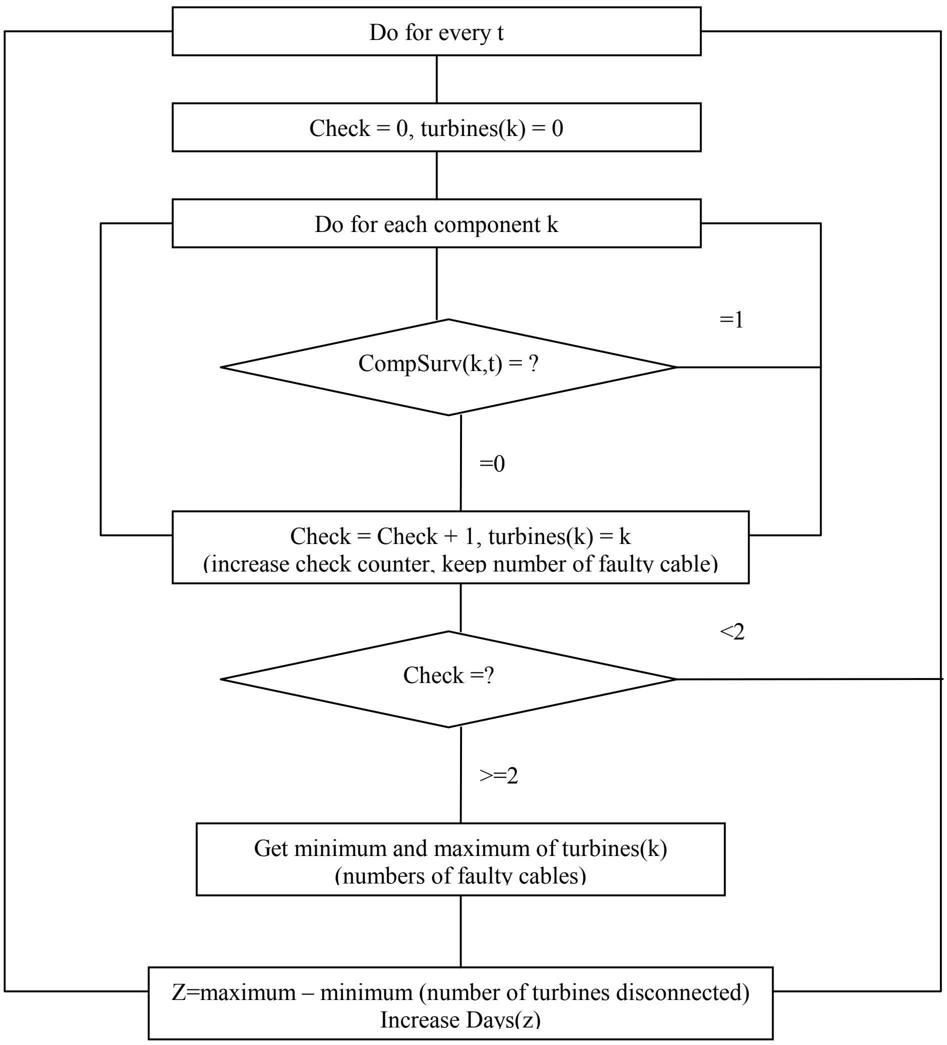
Let us now go through the algorithm. Firstly a time loop is initiated. For every day, we check the components one by one. If a component is faulty on that day, a check index ("Check") is increased by one. At the same time, the number of the faulty cable is kept in the array turbines(k).

If on that certain day more than two faults have occurred then the Check index should be greater than or equal to 2.

In that case, the greatest and the smallest number of the faulty cables are taken in order to find out how many turbines are out. After that, the Days(z) counter is increased.

In this very case, z does not stand for the number of a certain component, but for the number of turbines that are disconnected instead.

So, in the end of the program, we get a number of down days for numbers of turbines. Let us see how the algorithm works in the following flow chart.

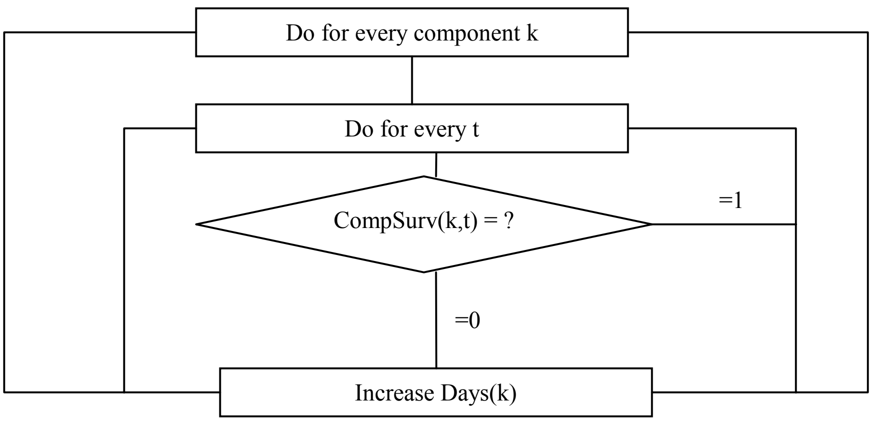


c) Cluster collector

This is the simplest configuration, since if a cable is faulty then only one wind turbine remains disconnected from the grid. Therefore, no special control has to be done. The only difference, between the cables is their length, which has an influence on their lamda (failure rate).

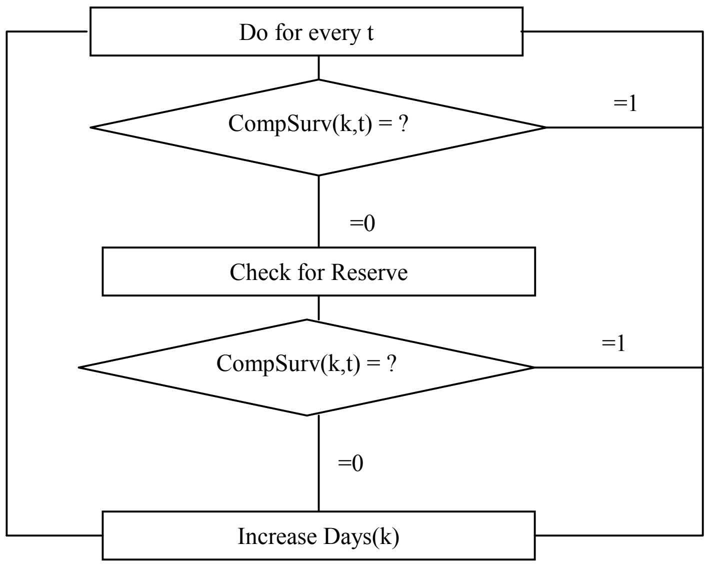
The algorithm for the cluster collector is designed so that the results for the 4 short cables come first, the results for the 8 “medium” cables follow, and the results for the 4 long cables come last. However, this does not matter, since every cable is connected to one turbine and this is all we need to know for our analysis.

In terms of describing the algorithm, there is no special difficulty. For each component, the 0s in the CompSurv table are counted, and Days(k) are increased each time a zero occurs. In terms of a diagram, the algorithm is as follows.



d) Shore links

No special task has to be done here. There is usually a small number of cables and each one of them is examined separately. If a cable is down, then its “reserve” –if any- is checked. The process is shown in the following diagram.



3.4.5 Programming Language Considerations

There is a lot of work done in Monte Carlo Simulations and various algorithms to choose from. We already mentioned the approaches in the reliability context and selected the most appropriate for us, justifying our selection.

Once we have chosen our approach, which is actually a rough guide to the specific algorithm, this approach has to be translated into programming language. There are many programming languages available, but not all suit every occasion. In order to decide on a special language, one has to review what has been done before.

The first consideration was to program in basic since Kontoleontos [36] has developed a similar algorithm in that language and it appeared to be common in simple Monte Carlo approaches. The model was, therefore, firstly written in basic only to discover that the memory limitations of that language were prohibitive for the development of our problem in our environment.

There has also been a brief effort to use Pascal [43], but the same memory problems emerged once again. The huge array containing all the chronological information for the components states was once again too large for the memory to handle. The aiding use of heap memory was not enough to overcome this problem.

Therefore, a language with less memory limitations had to be used. Visual languages are ideal for this kind of use, hence Visual Basic was considered for the development of the model [44].

The first attempt was partly successful, since the model would run for several trials but as the number of trials increased, more memory was required from the system, causing the model to block. This was found to be happening because of a "busy loop" inside the program, which was of course, the loop that was running for each trial. The only way to overcome this problem was to "slow down" the procedures happening in that loop. The best proposed way of achieving that in visual basic is by using the Timer function [45]. This allows us to set a pace for each loop by adjusting the Timer interval. The process of transforming a Do loop into a Timer controlled loop is quite simple.

- A Sub statement replaces Do, whole End Sub replaces Loop
- To exit the loop the Timer.Enabled = false statement has to be used
- The time period is set by the interval property
- The variables must be declared static because the loop will be left on every iteration

It has to be highlighted though that variables which are cumulative, have to be declared as global variables since their value changes after each loop. The "Days(k)" array is a proper example in our model. This array counts the down times for each component for every iteration and at the end of the simulation it provides us with an average number of down time for each component. Since some days are added in each timer loop, this array should be declared as a global array. The complete code in Visual Basic is provided in the appendix.

3.4.6 Outputs of the model

As said before, the model provides us with the components down times in days for each configuration. If we use the conventional numbering, then we can estimate exactly how many turbines were not connected and for how many days. This can lead us to the EENS index (expected energy not supplied) as explained here.

Multiplying the down times with the correspondent number of turbines and summing all of them together we will take a total number of "turbine · days". This is the equivalent outage time (in days) of a single wind turbine in order to produce the same result, which is to loose the exact same amount of energy.

Using this outcome, we can then process it with RETScreen -a tool that is going to be presented next- in order to get the EENS index.

3.4.7 Calculating EENS – The RETScreen Software

The RETScreen software is a quite simple but very useful tool for conducting studies involving renewable energy sources. It is developed by Natural Resources Canada and can be downloaded freely from their website, http://www.retscreen.net. Amongst its features are the following:

- Estimating energy production
- Assessing emission savings
- Calculating life cycle costs of installation

In order to do that, it has a complete product database, contains meteorological information and even some indicative costs. However all of these parameters can be varied or defined by the user. It is possible, for example, to insert a new wind turbine in its product database. The user is asked to enter the rotor diameter of the wind turbine, the swept area and its rating. Furthermore, the power curve of the wind turbine can be processed manually. A model name for the newly inputted wind turbine can also be given. The sheet were this information can be managed is shown bellow

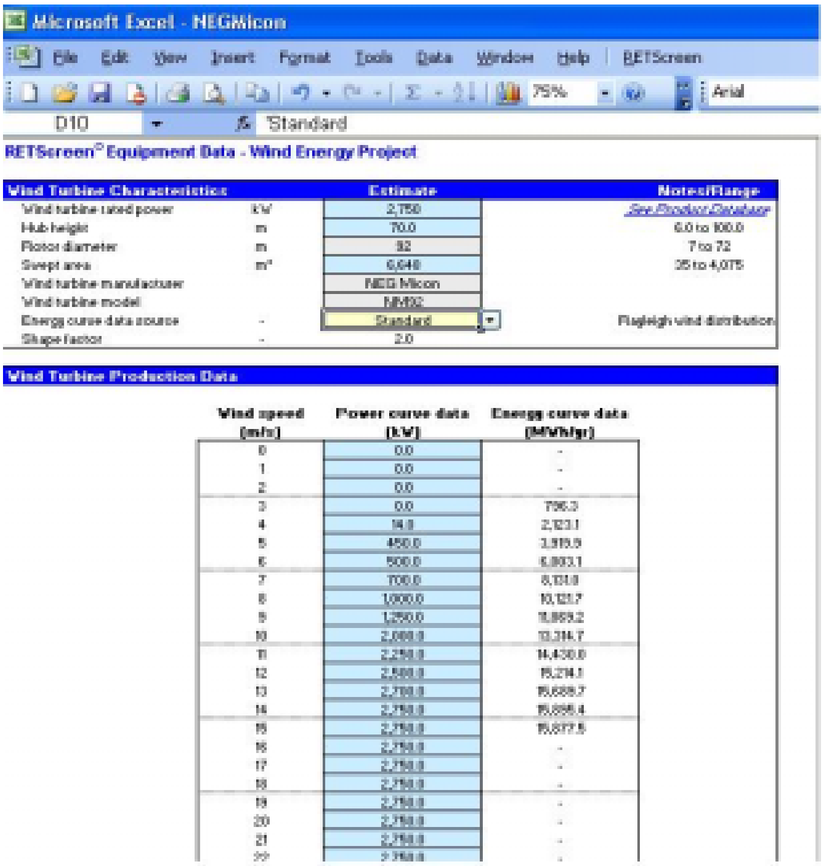
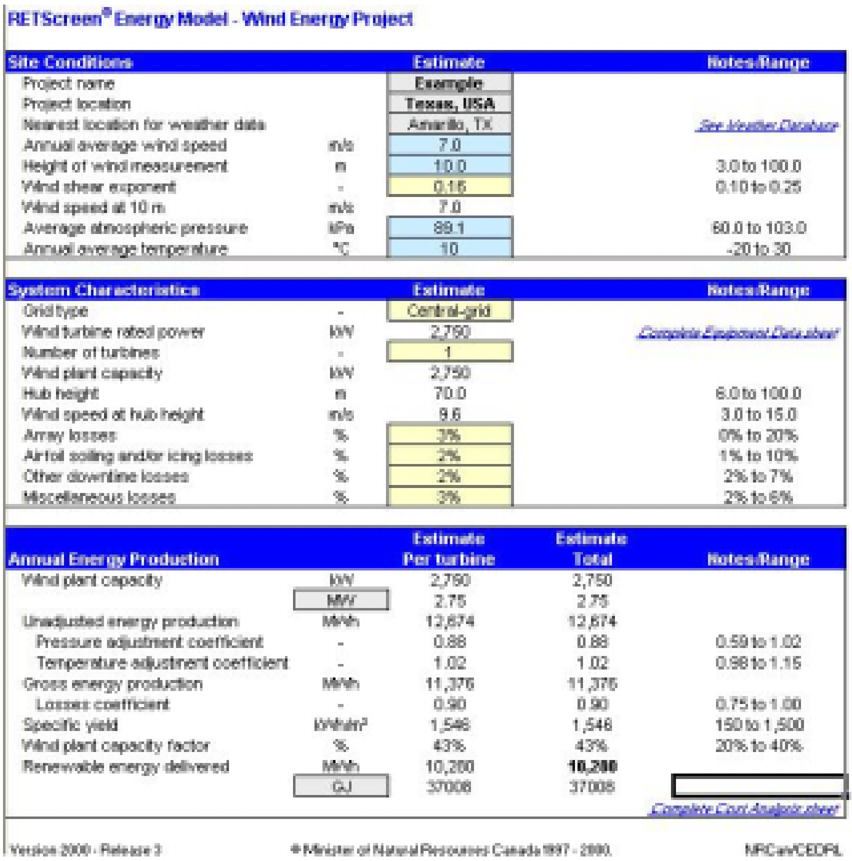


Figure 3. 6: Screenshot of the power curve input page of RETScreen

Regarding the calculation of the energy delivered by a wind turbine, the user can – again- interfere in many ways in RETScreen. The mean ambient temperature and the average wind speed measured in any height are subjective to alterations. Nevertheless there is a weather databank available as well. The sheet where those inputs are processed has the form shown in the screenshot bellow.


RETScreen® Energy Model - Wind Energy Project

Site Conditions		Estimate	Notes/Range
Project name		Example	
Project location		Texas, USA	
Nearest location for weather data		Amarillo, TX	See Weather Database
Annual average wind speed	m/s	7.0	
Height of wind measurement	m	10.0	3.0 to 100.0
Wind shear exponent	-	0.15	0.10 to 0.25
Wind speed at 10 m	m/s	7.0	
Average atmospheric pressure	kPa	89.1	60.0 to 103.0
Annual average temperature	°C	10	-20 to 30

System Characteristics		Estimate	Notes/Range
Grid type	-	Central-grid	
Wind turbine rated power	kW	2,750	Complete Equipment Data sheet
Number of turbines	-	1	
Wind plant capacity	kW	2,750	
Hub height	m	70.0	6.0 to 100.0
Wind speed at hub height	m/s	9.6	3.0 to 15.0
Array losses	%	3%	0% to 20%
Airfoil soiling and/or icing losses	%	2%	1% to 10%
Other downtime losses	%	2%	2% to 7%
Miscellaneous losses	%	3%	2% to 6%

Annual Energy Production		Estimate Per turbine	Estimate Total	Notes/Range
Wind plant capacity	kW	2,750	2,750	
	MW	2.75	2.75	
Unadjusted energy production	MWh	12,674	12,674	
Pressure adjustment coefficient	-	0.88	0.88	0.59 to 1.02
Temperature adjustment coefficient	-	1.02	1.02	0.98 to 1.15
Gross energy production	MWh	11,376	11,376	
Losses coefficient	-	0.90	0.90	0.75 to 1.00
Specific yield	kWh/m²	1,546	1,546	150 to 1,500
Wind plant capacity factor	%	43%	43%	20% to 40%
Renewable energy delivered	MWh	10,280	**10,280**	
	GJ	37008	37008	
				Complete Cost Analysis sheet

Version 2000 - Release 3 © Minister of Natural Resources Canada 1997 - 2000. NRCan/CEDRL

Figure 3. 7: Screenshot of the energy output calculation of RETScreen

As we can see, this tool has a very simple spreadsheet form and is therefore easy to use. However it is quite powerful and helpful in many situations

3.5 Summary

In this chapter the basic principles of Monte Carlo simulation have been presented. Then, some basic parameters for our Monte Carlo model have been defined, in order to go through our algorithms more easily. Then each configuration was presented and the corresponding algorithm was described in detail and by means of a diagram as well. A model for a cluster arrangement a string arrangement and a redundant string arrangement have been developed. A model for shore links is also presented and discussed. The form of the outputs of the model is shown as well, and the way they are going to be processed through RETScreen is finally discussed. With our model in place, we are ready to start our simulations in the next Chapter.

4 Results and discussion

4.1 Introduction

In this chapter, the results of some simulations with the model presented on chapter 3 are going to be presented, analysed and discussed. Before getting into the results, we will have a look at all the factors that may affect them, and we will chose some values for each one of them. Afterwards the number and kind of the simulations conducted are going to be presented and then the discussion will take part.

4.2 Factors affecting reliability and its worth

Some factors that are very likely to affect the outcome for different configurations are:

- Service windows
- Average wind speed of the site
- The price of electricity
- Trends of cable prices
- Wind turbine ratings
- Failure rates

Usually there is a strong connection of the two first factors, since greater winds might mean harsher weather conditions and hence, a smaller service window. This is not always the case, but it is an interesting observation, since not only a failure might mean more outage days, but also even more lost production because of the higher wind speeds.

The price of electricity is generally affected by the governmental incentives on renewable technologies. Policies play a great role in that. Furthermore, an increase in the oil prices (which seems to be the case for the following years) will have an analogous effect on the electricity prices. This factor will also play an important role concerning the value of redundancy.

Lastly, the installed cable prices seem to be very high at the moment. This is very reasonable, since special vessels have to be used and the cables need to be buried under the seabed. There is however, a significant effort, to try and reduce these costs. This matter is also in the research priorities of CA – OWEE [20]. A change in cost will certainly have an immediate effect on the value of redundant cables.

It has been said that offshore turbines are generally larger than onshore turbines. The rating of a turbine clearly affects the amount of energy that would be lost in case of a cable failure. Larger turbines mean even bigger losses and, hence, redundancy might make more economic sense and might prove to be beneficial. Since the trend is for the development of larger turbines, this parameter has to be studied carefully.

As mentioned in an earlier chapter there are no recent and reliable data for cable failures. Several numbers are quoted in certain studies, and of course they indicate an average life time for cables. Since failure rates are quoted in failures/year/km (or per 100 km) it is evident that the distance between the wind turbines is also a factor that affects their reliability. Distances of wind turbines in offshore wind farms vary between 500m and 1 km. Since the design trend is for larger machines with bigger blades and taking into account that wake losses are larger for offshore wind farms than onshore ones, it is safe to estimate that distances are going to be increased in the future. A current number is 560m for the 2 MW turbines of horns rev.

4.3 Parameters for the simulations

Service Windows: The inaccessibility periods for the wind farm are defined as the periods for which the farm is inaccessible by a vessel. Cable laying is being done by special vessels and no other means of approaching the wind farm is suitable for a similar operation. It is reported that in sites of very bad conditions the accessibility by vessel can approach numbers such as 60% [20]. This means that the farm is inaccessible for 40% of the year, a respectable 146 days. In order to study the effect of inaccessibility periods in down times we have to assume some numbers for them. A 50-days step would be ideal. Hence, 50, 100 and 150 days will be studied.

Failure Rates: This parameter is going to be varied through the variation of the length of the cables and the failure rate for submarine cables. The latter is usually been given in failures per annum per km or sometimes even per 100 km. In order to convert it to a suitable input for our program, we have to divide it with 356 in order to get failures per day per km. The numbers available from our bibliography are those of $8.8 \cdot 10^{-6}$ up to $3.56 \cdot 10^{-5}$ for very hazardous sites, including values from sites in Scotland (Petland Firth, Sunoil Voe). Some intermediate and rounded values are therefore taken into account. Those are 10^{-6}, $2 \cdot 10^{-6}$, and $3 \cdot 10^{-6}$.

The distance between the turbines – thus, the cable length - can be varied as well. A mean value of 0.75 km is chosen for our set of simulations. This was found to be a good number especially for large wind turbines which are now developed from most manufacturers although slightly larger than the ones used in current.
The other set of parameters do not have an influence down times of the farm, but they do have an influence in the energy delivered by the farm. Thus, no more simulations are needed for those. Their effect is to be studied in the results analysis. Let us examine now the range of values that these parameters can take.

Wind Speed: Some variations for the wind speed are going to be taken into account after consulting as well with the European offshore wind atlas; 7, 8, and 9m/sec at 10m height. Those are numbers for most proposed "good" sites.

Cable prices: A range is already been given. Hypotheses for future scenarios with lower prices could also take place.

Turbine Ratings: A wide variety of offshore wind turbines exists already, from 2 MW up to 3.6 MW. Future trends show that the size of the turbines will increase, with Enercon producing already a 4 MW offshore wind turbine and NEG Micon coming back with its N110, 4.2 MW offshore wind turbine. The target for the manufacturers appears to be at 5 MW. A turbine of this rating might well be investigated. The turbines chosen for the initial investigation though are three. Those are the Vestas V80 2 MW offshore wind turbine, the NEG Micon NM 92, 2.75 MW offshore wind turbine and the General Electric 3.6s, 3.6 MW offshore wind turbine.

Price of electricity: Currently 8.44 p/ kWh (January 2004) in the UK according to the DTI [46].

4.4 Simulations Conducted

As said above, the parameters that affect the number of simulation are the number of inaccessibility days and the failure rates of the cables. Since we are varying both of these parameters for three discrete values it is evident that we must conduct 9 different simulations per arrangement.

Since those simulations will be done for 3 different arrangements, we have a total number of 27 simulations. Those simulations are going to be performed for 300,000 trials each, a number which is considered to be adequate for good results and not too large computer time-wise. For that number of trials the standard deviance of the results was found to be in the worst case 4%.

The results obtained from these simulations are further processed in order to take into account the parameters that do not affect the simulations but play a major role in the definition of reliability worth. The results of all simulations are attached in the appendix. In the following paragraphs we are going to have a look at some of these results processed and grouped, and we will try to drawn some conclusions out of them.

4.5 Results

4.5.1 String collector without redundancy

The first simulation results discussed concern the string collector without redundancy, which seems to be the most used configuration in offshore wind farms so far. Our string collector has 16 wind turbines as illustrated bellow.

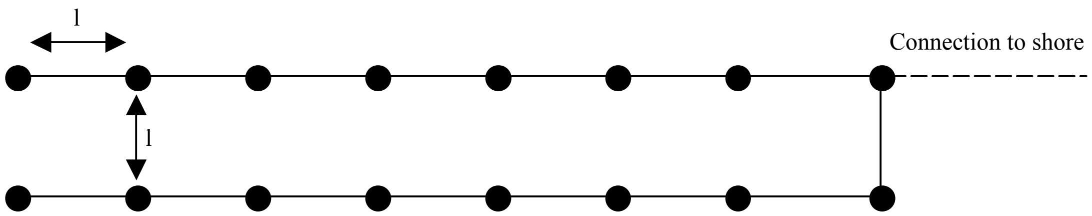


Figure 4. 1: The simulated string collector

First of all we will have to determine the capital cost for those 15 cables within the collector. This is essential and will be done for every configuration in order to estimate reliability worth and compare all of the configurations on a total cost basis.
As depicted, the distance between the wind turbines is “l” hence, the total cable length used for the collector is 15·l. In our case we selected a distance of 750m between the wind turbines. Therefore:

$$l = 750m$$
$$l_{cables} = 15 \cdot 750 = 11{,}250m = 11.25km$$

Regarding the cross-section of the cables we have basically two different choices. Either we use a constant cross-section for all the cables within the collector or we use a “graded” cross-section in order to minimise the total cost of the cables. This is done because, apparently, we do not have the same current flowing through every cable. The cables that are nearer to the connection to the shore will have to cope with greater currents since they are connected to more turbines.

Assuming a constant cross-section for our cables for our cables a 500 mm^2 3-core XLPE cable operated at 33kV seems a reasonable option according also to [20] and [22]. Looking at the cable costs presented in our first chapter we could say that the price range for this kind of cables is at around £210 - £255 per meter including cable burial, or at £85 - £130 per meter if burial is not required. Hence:

$$\text{Capital Cost}_{burial} = 11{,}250 \cdot C = £2{,}362{,}500 - £2{,}868{,}750$$
$$\text{Capital Cost}_{no\ burial} = 11{,}250 \cdot C = £956{,}250 - £1{,}462{,}500$$

Cable grading is a common practice in offshore wind farms as we have also mentioned in our first chapter [24], [23], [21]. Study [21] presents an optimised cable grading that takes into account the minimisation of life cycle costs (capital cost and current losses) and not just the minimisation of the capital costs of the cables used. Cross-sections that lead to this kind of minimisation are going to be used throughout our study as well and numbers from [21] are going to be used as a reference for us since they investigate a series of 7 wind turbines of 3MW which is exactly what we are dealing with in our own string collector. Let us take a look to a single string of the collector and discuss the cables selected:

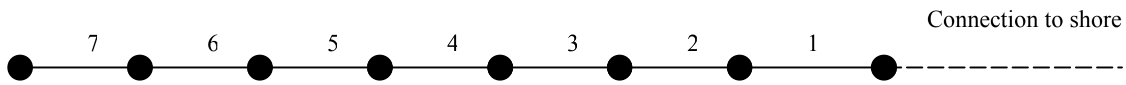


Figure 4. 2: Cable grading on a single string of the string collector

Cables 7 and 6 use a 200mm^2 cross-section 3-core copper XLPE cable, cables 5 and 4 are supposed to have a 300mm^2 cross-section, while cable 3 has a 350mm^2 cross-section, cable 2 a 400mm^2 cross-section and, finally cable 1 a 500mm^2 cross-section. The cable interconnecting the 2 strings is supposed to have a 500mm^2 as well. The price range for those cables in £ is shown in our cost reference cable as presented on chapter 1 and is presented again below.

Cable cross-section (mm^2)	Cost including burial (£/m)
200	150-180
300	175-210
350	188-225
400	200-240
500	210-255

Working out the capital costs using the formula:

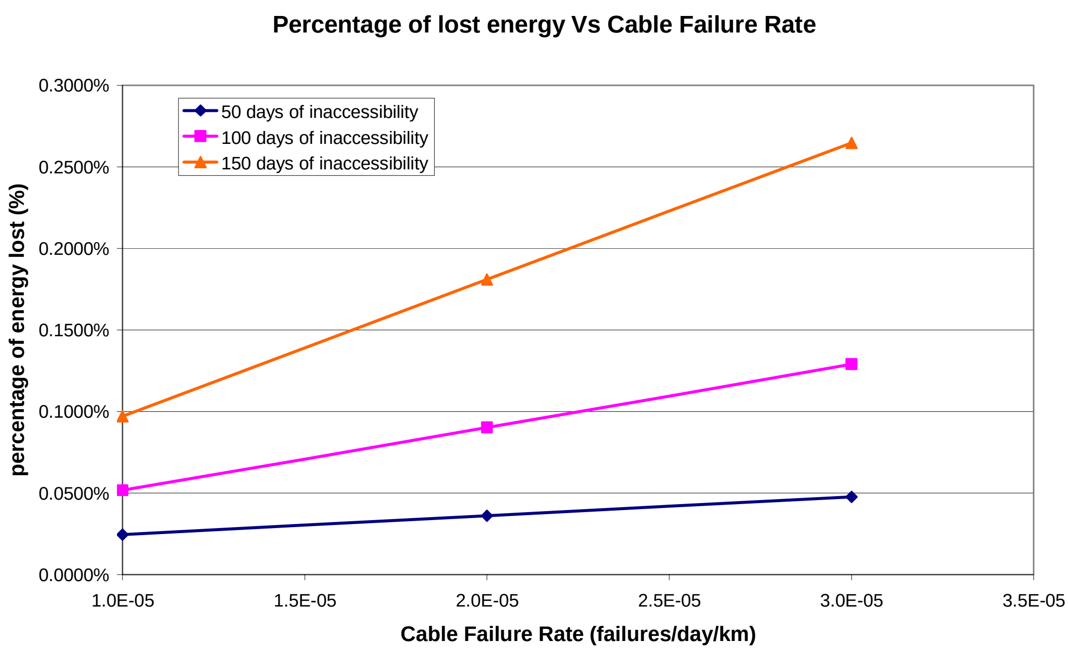
$$CapitalCost = 3000m \cdot \left(C_{200mm^2} + C_{300mm^2}\right) + 1500m \cdot \left(C_{350mm^2} + C_{400mm^2}\right) + 1750m \cdot C_{500mm^2}$$

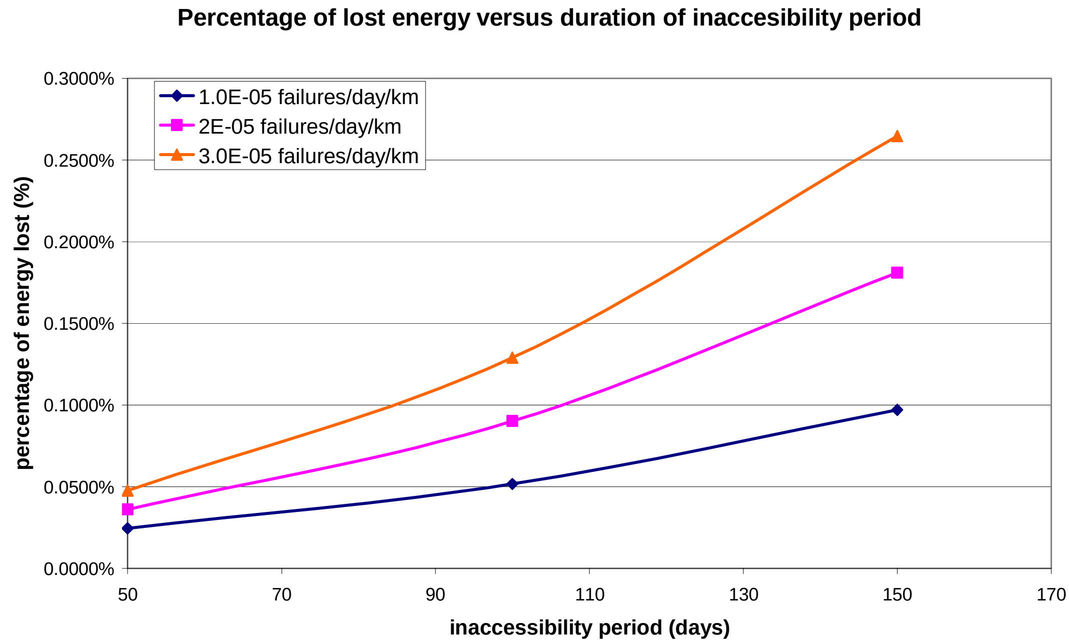
We will finally get

Capital Cost = £2,029,500 - £2,441,250

Where C_{xmm^2} is the specific cost (£/m) for a cable of a x mm^2 cross-section as stated in the relevant table.

In the graphs bellow, we can see how the percentage of the lost energy of the collector (or the whole wind farm) is varied when the days of inaccessibility or the failure rates of the cables are varied.





As we can see from the first graph the relationship between the failure rates and the percentage of energy lost is almost a linear one. As the service window becomes smaller and the inaccessibility period is decreasing, the slope of the line becomes steeper, indicating that a smaller change in the failure rate could cause a greater energy loss in areas of low accessibility. The maximum energy loss, as we can see is a little bit above 0.25% which is substantially higher than that of study [22] but it has also been calculated for much harsher conditions and almost a tripled cable failure rate.

Looking at the second graph, we can say with certainty that the increase of inaccessibility plays a greater role in offshore wind farms than the increase of failure rate. This time, the relationship that links the two variables is not a quasi-linear but rather a quasi-exponential or polynomial relationship. The slope of the curves is increasing indicating that an increase of inaccessibility days will play a greater role on a site with already many days of inaccessibility (harsh conditions) rather than on a site with few days of inaccessibility.

And while looking at the percentages might be interesting, looking at the absolute costs is even more interesting. In order to look at the cost of the losses of course we need the absolute amount of energy lost. This is subject to other parameters as well.

Those are the turbine ratings and the wind speeds. In terms of cable failures and inaccessibility periods, three cases are going to be investigated:

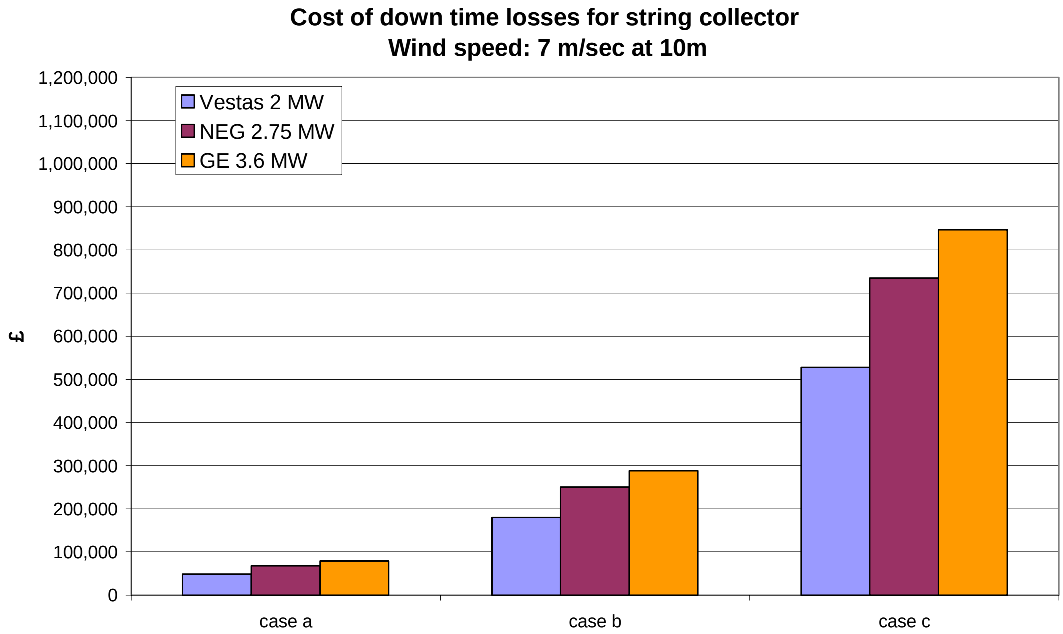
- Case a: this is the "best" or most optimistic case, comprising the smallest failure rate (0.00001 failures/ day/ km) investigated, and the smallest inaccessibility period (50 days)
- Case b: this is our "middle" case. It features the intermediate failure rate number (0.00002 failures/ day/ km) and the intermediate interval of inaccessibility days which is 100.
- Case c: the worst case scenario. An inaccessible wind farm (150 days of inaccessibility) with cables highly susceptible to damage (0.00003 failures/ day/ km failure rate)

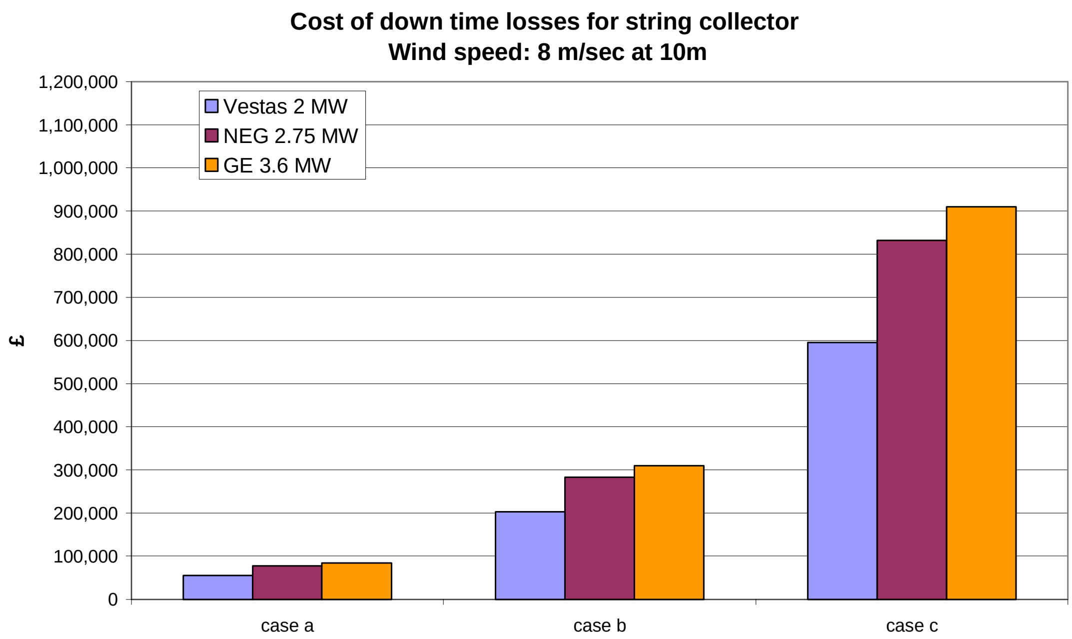
The results are going to be presented in the following charts. The price of electricity considered in order to get these results is 8.44 p/ kWh. This was the average price of electricity for small consumers for January of 2004, including taxes according to the DTI and it is the most recent figure for electricity prices [46].

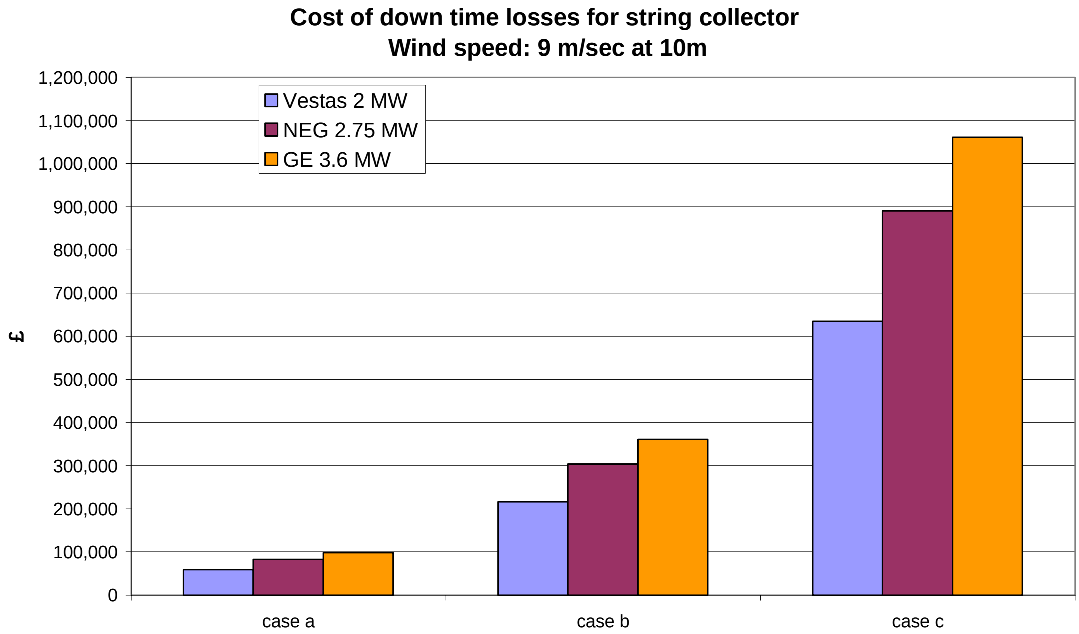
In order to get the results as we described in our 3rd Chapter, we have to get the total "turbine · days" number from our model and multiply it to the annual energy production of a single wind turbine. The annual yields of the wind turbines used in our study can be seen in the table below.

	ouputs (MWh/year)		
	wind speed = 7m/s	wind speed = 8m/s	wind speed = 9m/s
Vestas V80 2 MW offshore	7376	8323	8878
NEG Micon NM 92, 2.75 MW offshore	10280	11634	12451
General Electric 3.6s, 3.6 MW offshore	11842	12723	14844

Table 4. 1: Energy outputs of the examined Wind Turbines


Cost of down time losses for string collector
Wind speed: 7 m/sec at 10m
1,200,000
1,100,000
1,000,000
900,000
800,000
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0
£
Vestas 2 MW
NEG 2.75 MW
GE 3.6 MW
case a
case b
case c

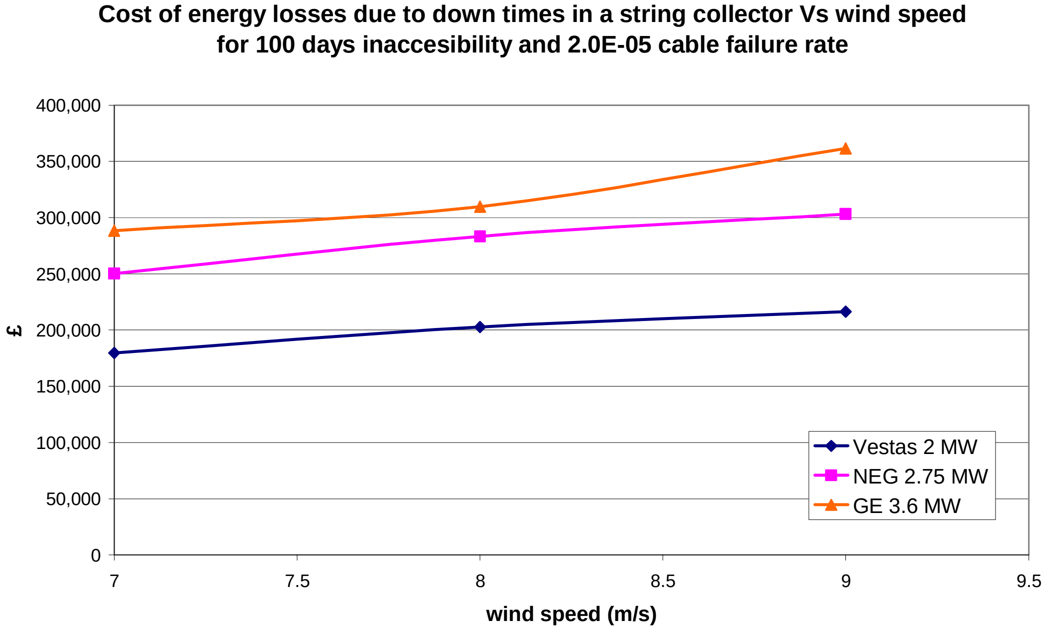

Cost of down time losses for string collector
Wind speed: 8 m/sec at 10m
1,200,000
1,100,000
1,000,000
900,000
800,000
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0
£
Vestas 2 MW
NEG 2.75 MW
GE 3.6 MW
case a
case b
case c



We can see that the difference between the costs of losses for different types of turbine used is increasing as we move towards the worst case. Furthermore, for the same case and different wind speeds, the cost differences among different wind turbines increase as well. It seems that the largest the turbine, the bigger the loss rate as we go up either in wind speed or as we move on to a worst case scenario.

Another observation concerns the absolute number of the cost of the losses. We see that in the worst case scenario this cost becomes for the largest turbine around £ 1 million. This is a significant amount of money and it will be even higher for a turbine of larger rating. Taking into account that the distance of our turbines in a string collector was supposed to be 750m and that the installation of a submarine cable with burial costs about £210-£255 we can say that a redundant cable would cost from around £157,500 to £192,000.

A rough conclusion is that its cost is compensated by the saved energy production assuming that the whole energy would be saved. It is also important to mention that the cost of extra switchgear has not been taken into consideration as well, so we should not start jumping into conclusions. This is only an indication and will be looked at in greater detail later in the chapter.
We move on to the variation of the cost of losses with the increase of wind speed.



We can see for the Vestas and the NEG Micon turbines that as the wind speed increases the margin between them is slightly increasing, while the GE turbine has a different behaviour with the gap closing and then increasing again. This variation though is very dependent on the turbine characteristics and especially its energy curve. So, this area goes more into wind turbine differences and design rather than weather parameters.

4.5.2 Cluster collector

We are now moving no to the cluster configuration with a cluster of 16 wind turbines arranged as shown in the figure below

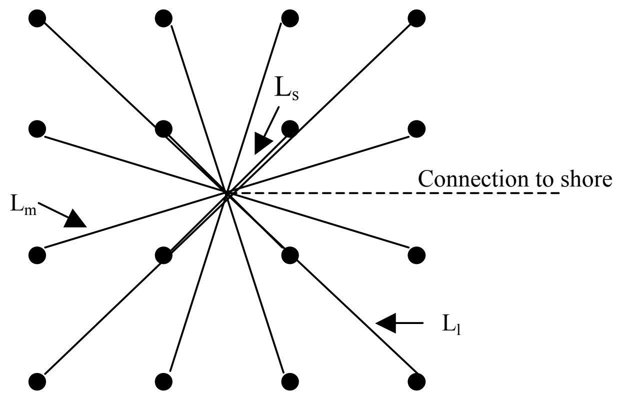


Figure 4. 3: The simulated cluster collector

The cable lengths have been calculated in Chapter 3. Here is a reminder of our calculations:

$$l_s = \frac{l}{2}\sqrt{2}$$

$$l_m = \sqrt{\left(\frac{3l}{2}\right)^2 + \left(\frac{l}{2}\right)^2} = \sqrt{\frac{5l^2}{2}}$$

$$l_l = \frac{3l}{2}\sqrt{2}$$

Where "l" represents again the distance between the wind turbines and is 750m.

The cables connect only one wind turbine to the main connection point and therefore are of a 200mm^2 cross section each. The number of the cables is –this time- 16 and the total capital cost can be calculated from the formula:

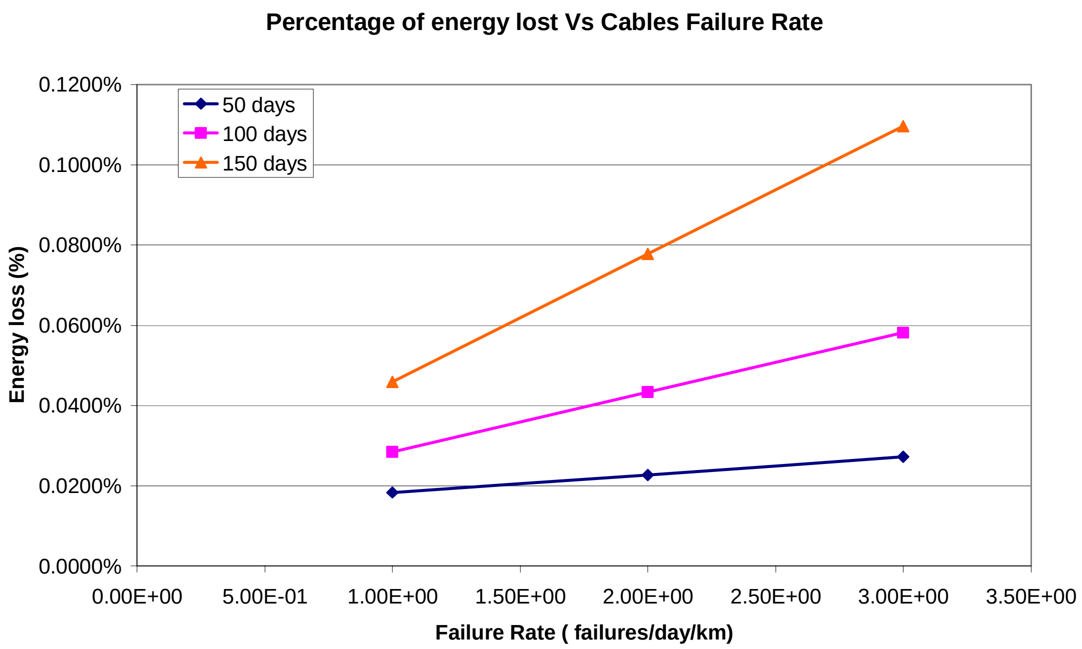
$$CapitalCost = C_{200mm^2} \cdot \left(4 \cdot l_s + 8 \cdot l_m + 4 \cdot l_l\right) \approx 17975 \cdot C_{200mm^2}$$

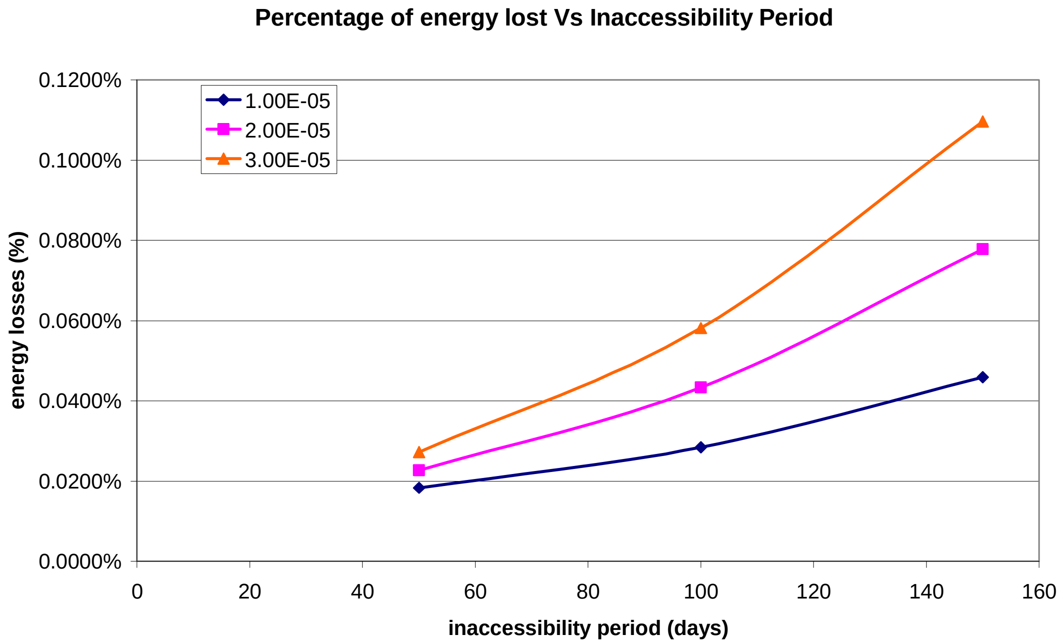
Hence:

Capital Cost = £2,696,250 - £3,235,500

As we can see the capital cost required is substantially higher than the string configuration because of the existence of the increased total cable length caused by the extra cable and the particularities of the configuration. The reduced costs for the smaller cross-section cables cannot compensate the cost for the increased cable length.

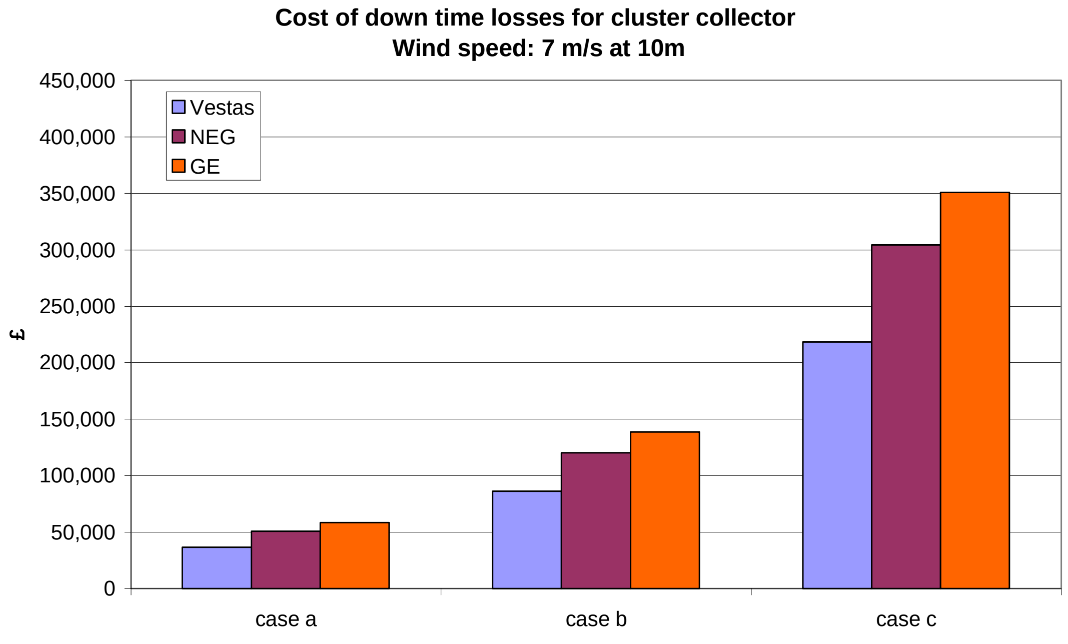
Moving on to our graphs to calculate the energy loss in the wind farm life span we can see that the shape of the graphs is similar to that of the string collector.

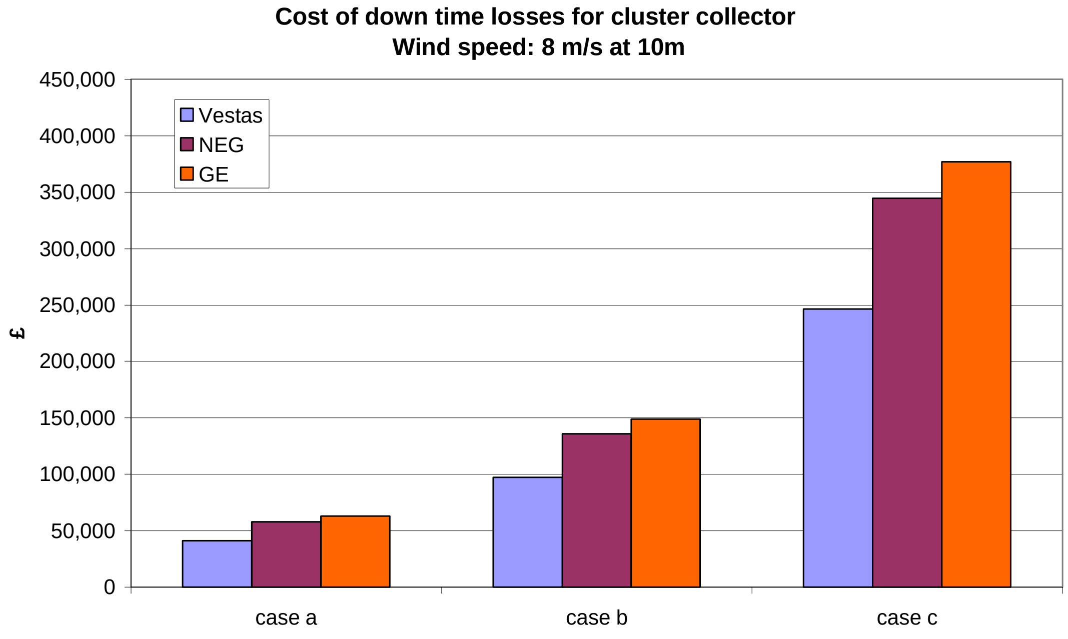


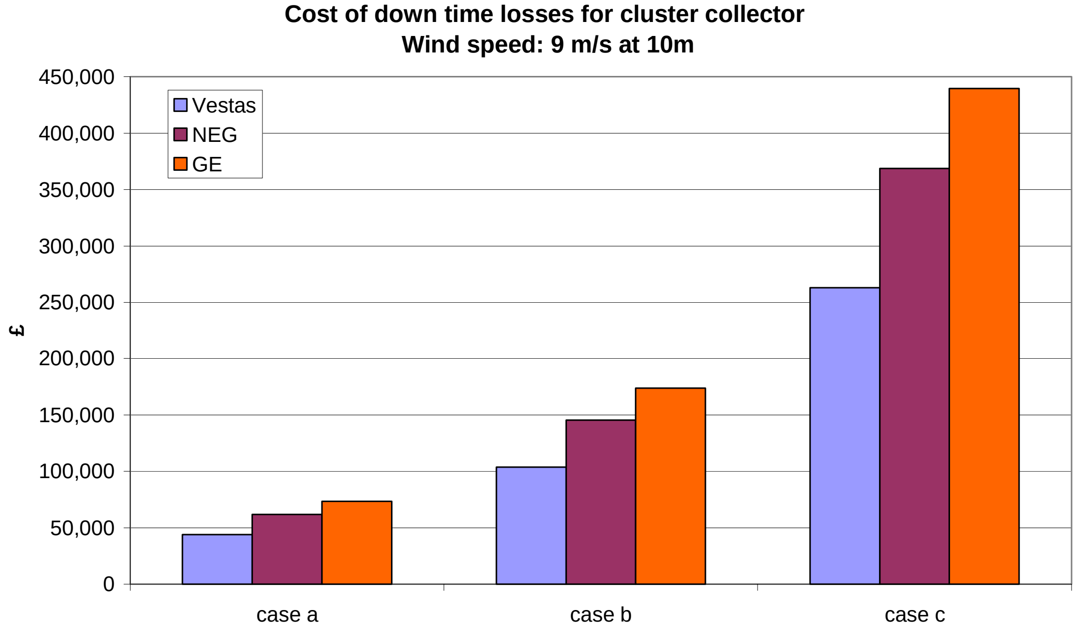


However, we can clearly see that this arrangement seems to be more reliable, since the percentage of the energy lost is substantially lower. The difference can be even more than 50%. A related graph is going to be presented in our comparative results section later on.

Similarly we can get the diagrams for the 3 different cases as described above, "case a", "case b" and "case c".


Cost of down time losses for cluster collector
Wind speed: 7 m/s at 10m
450,000
400,000
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
£
Vestas
NEG
GE
case a
case b
case c


Cost of down time losses for cluster collector
Wind speed: 8 m/s at 10m
450,000
400,000
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
£
Vestas
NEG
GE
case a
case b
case c



We can see that the losses are significantly lower, up to almost 60% lower than the string configuration. However, there is no way of improving the reliability of the scheme since no sort of redundancy can be added on the cluster collector.

4.5.3 String collector with redundancy

This collector has pretty much the same configuration as the simple string collector with the only exception of an extra cable. The configuration for our 16 wind turbines is illustrated bellow.

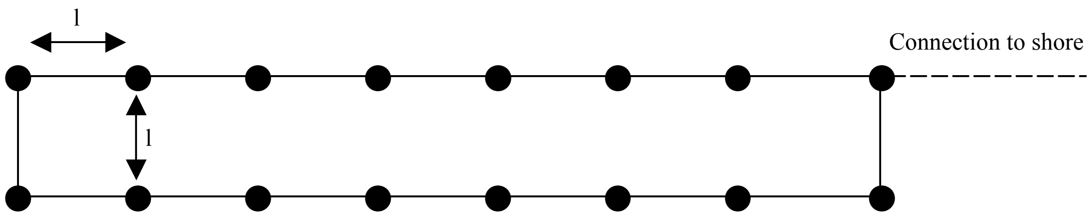


Figure 4. 4: The simulated redundant string collector

The distance between the wind turbines equals the cable length similarly to the simple string collector. However the total cabling length now is:

$$l_{cables} = 16 \cdot 750m = 12{,}000m$$

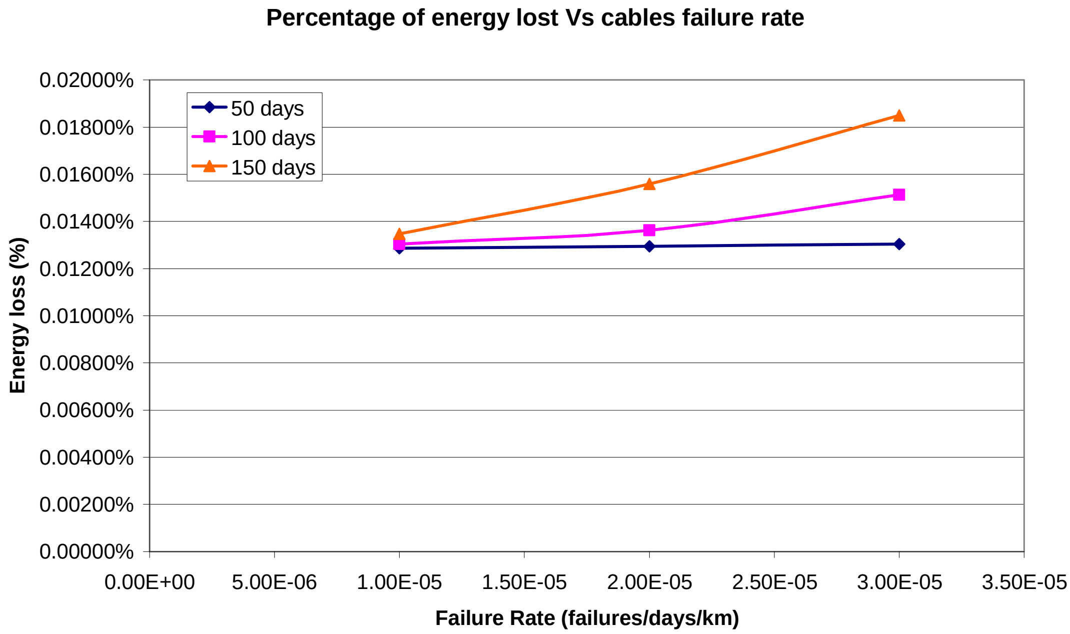
In this configuration cable grading is not considered at all. Cables must be designed to carry more power than they would under normal conditions because if a fault occurs they have to curry much more current than in operating conditions.

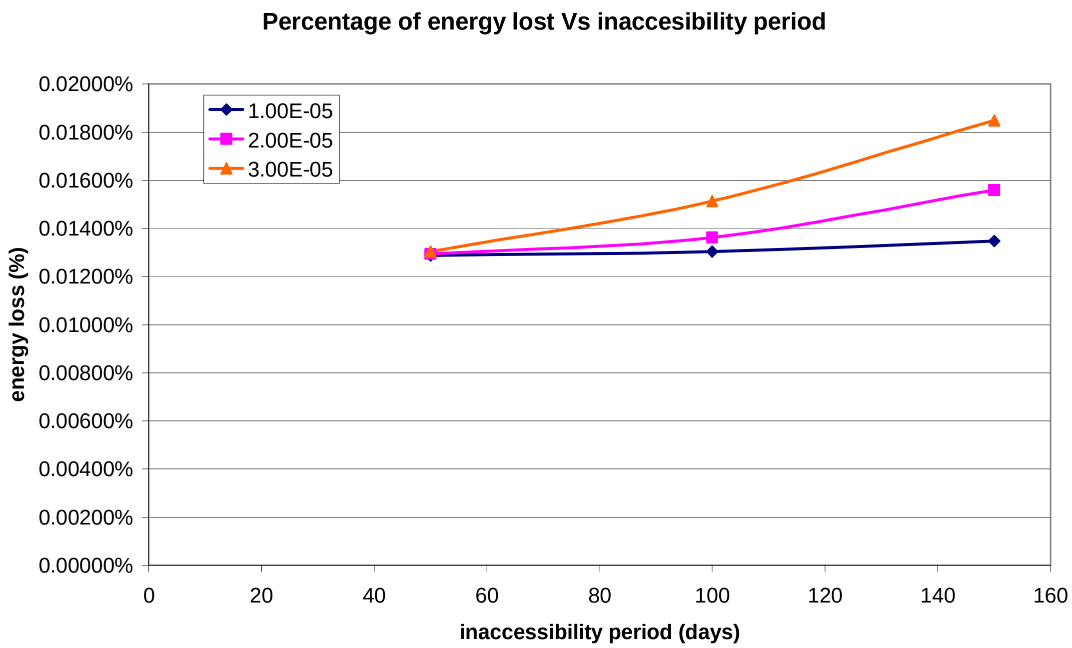
A cross-section of $500mm^2$ for all cables of the collector is considered to be appropriate for any faulty case [20]. The cost of additional switchgear has to be added as well. This is estimated to be at around $C_{switchgear}$ = £50,000.

This leads as to a capital cost of:

$$\text{Capital Cost} = 12{,}000 \cdot C + C_{switchgear} = £2{,}570{,}000 - £3{,}110{,}000$$

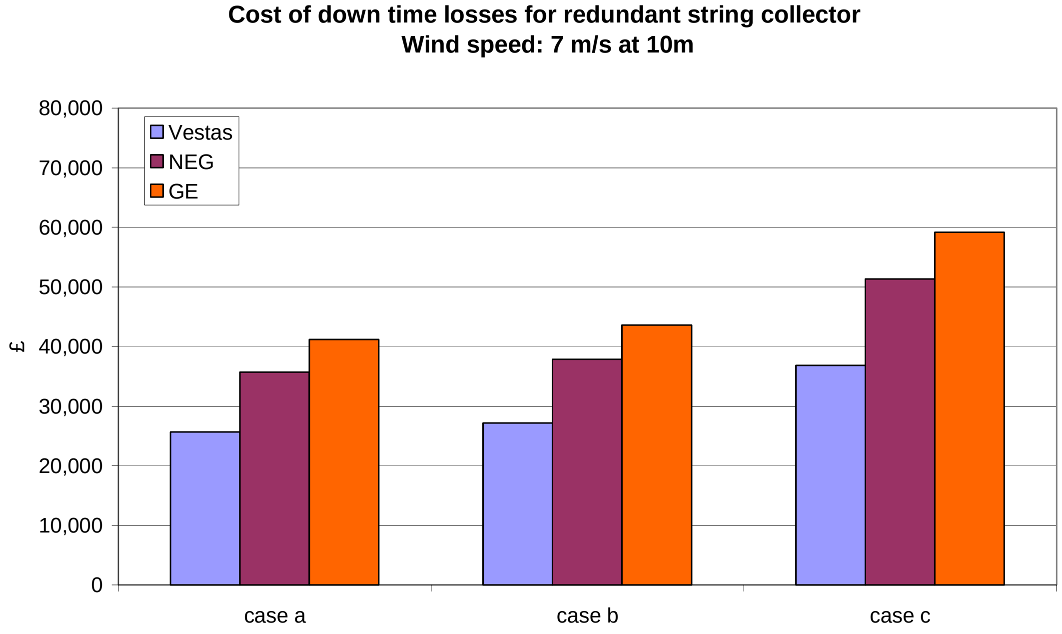
In theory this configuration should have the least losses of all for reasons explained in previous chapters. Our simulation results are confirming that, as can be seen in the graphs bellow.

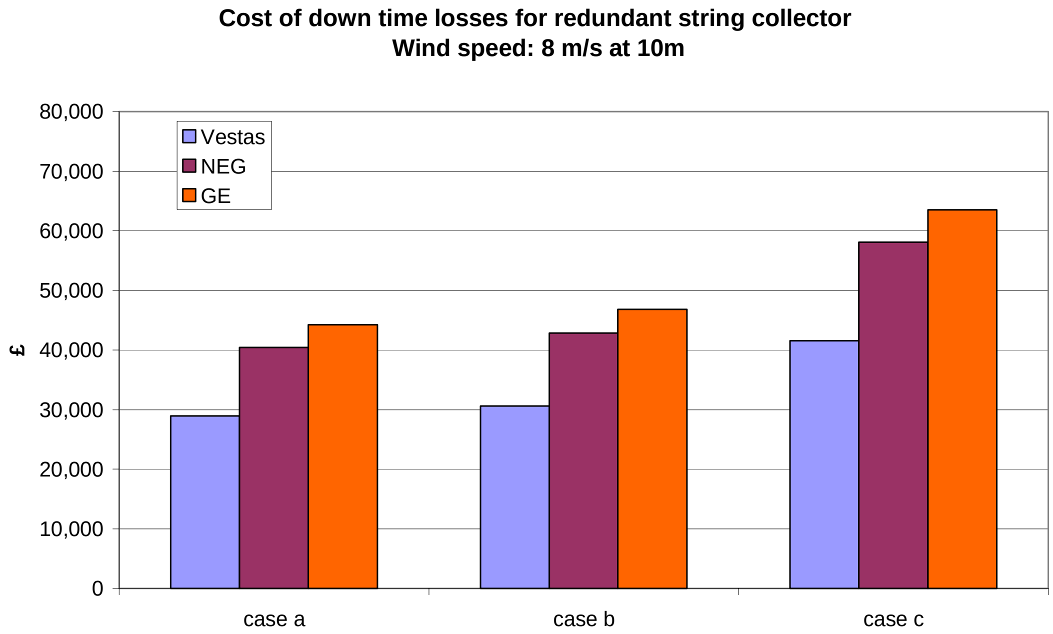


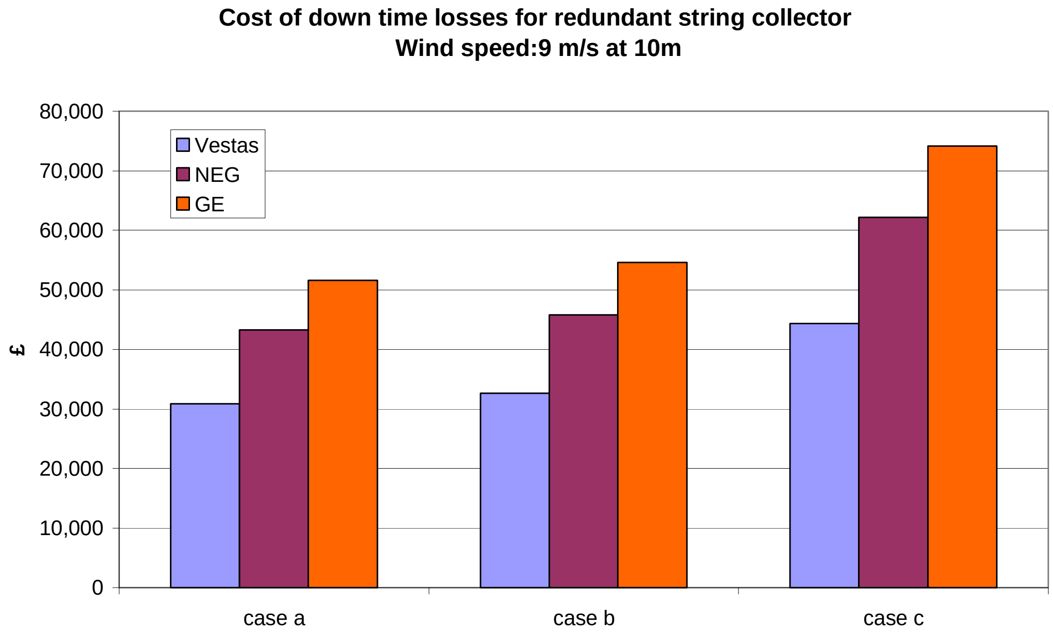


We can see that in our worst case the losses are under 0.02% of the total production, which is more than 10 times less than the simple string configuration. The variation of the values appears to be very small for this configuration especially for the 50 days of inaccessibility period. The difference in the energy lost for a cable failure rate of 0.00003 failures/ day/ km and for a cable failure rate of 0.00001 failures/ day/ km is only 0.00017%.

Now, if we move on to the cost of down times for our 3 cases we will see that they are much lower as well.







We can see that in the very worst of our cases the energy losses are less than £75,000. This is more than 10 times less compared to the losses of the string collector and more than 8 times less compared to the losses of the cluster collector for the same case. It is obvious and expected that the greatest differences would arise in the worst conditions, because this is when reliability really matters. It would be better, though to have a comparative look to all of our arrangements at the same time to understand better their differences in any kind of situation. This is going to be done in the next paragraph, the comparative result analysis.

4.5.4 Comparative result analysis

The first interesting observation in our comparative analysis is relevant to the capital costs of each configuration. If we take an average capital cost for each configuration, including cable burial, we will have the following:

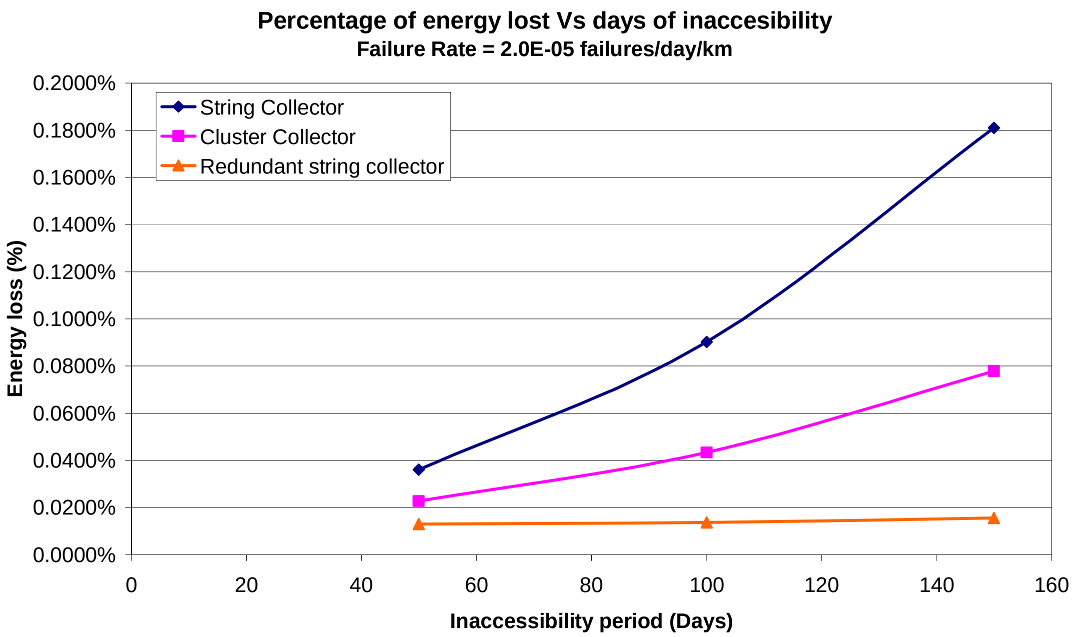
$$C_{string} = £2,235,000$$

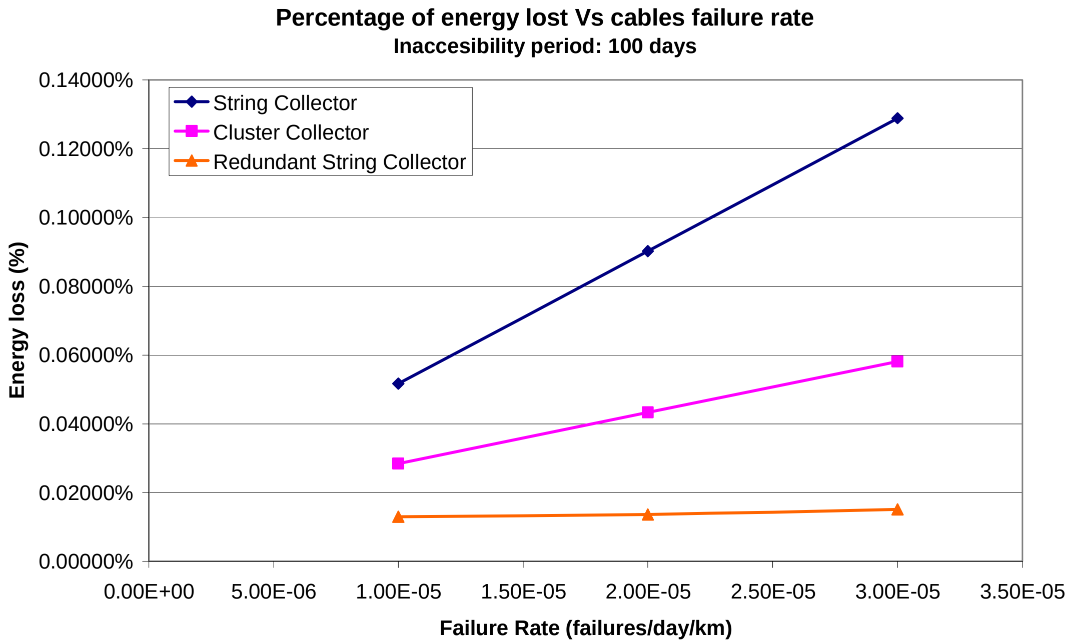
$$C_{cluster} = £2,950,000$$

$$C_{redundant\ string} = £2,840,000$$

It seems that the cluster configuration is the most expensive. This is due to the high total cable length and it cannot be compensated by the more economic, smaller cross-section cables. It also explains why the string configuration seems to be the preferred one in an offshore context.

Let us compare now the percentage of lost energy for each configuration in the same conditions.





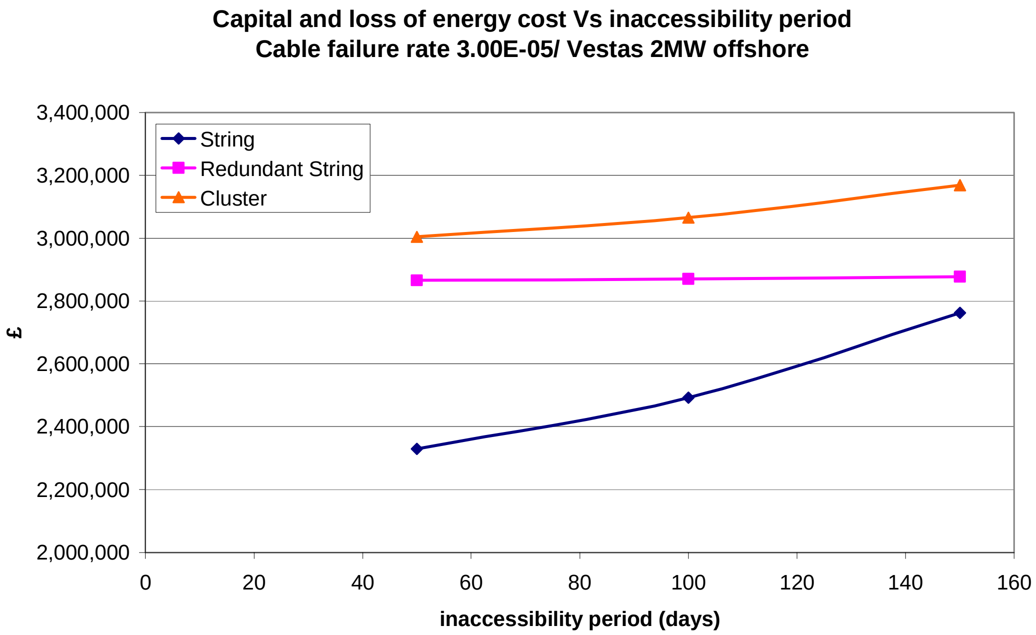
We can see that the cluster collector has less energy losses than the string collector, but more than the redundant string collector, in any case. This means –given also the higher capital cost of the cluster collector- that the cluster collector is not cost effective in any case.

We should note also that the difference of energy losses increases as we move on to a "worst case" (either more inaccessibility days or a greater cable failure rate). Observing that increasing trend, we come to think if there is a certain threshold after which the greater capital cost of the redundant string collector will be compensated by the energy losses of the string collector, and if there is, which are the factors that affect it.

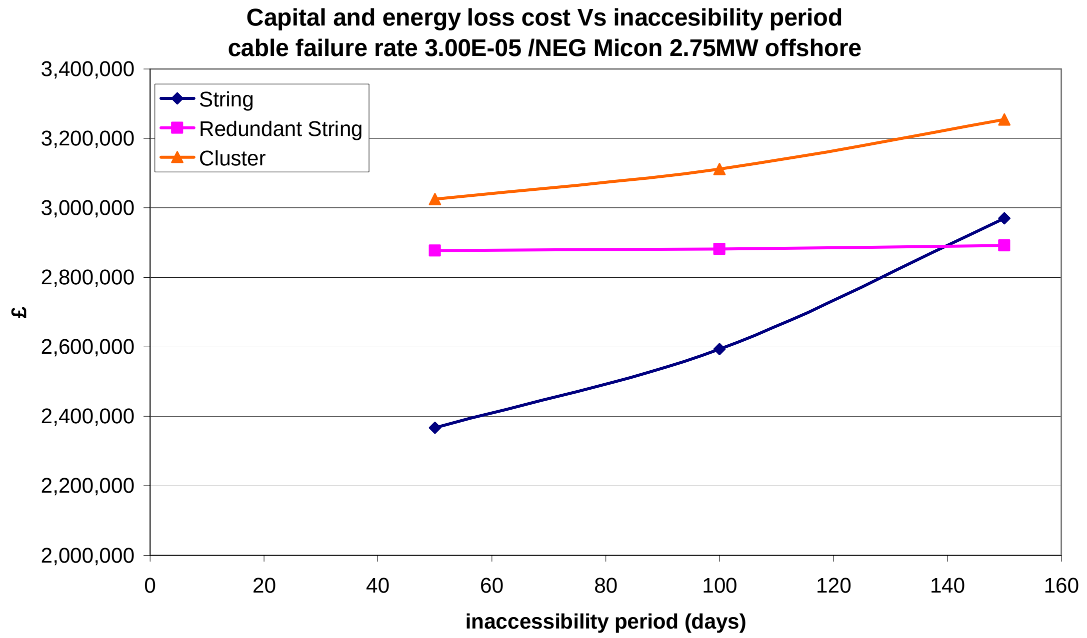
In order to investigate that we are going to compare the total costs of the configurations, that is both the capital cost and the lost energy cost. This investigation is going to be done differently for each of our wind speeds. The difference between the examined wind turbines is also going to be taken into account.

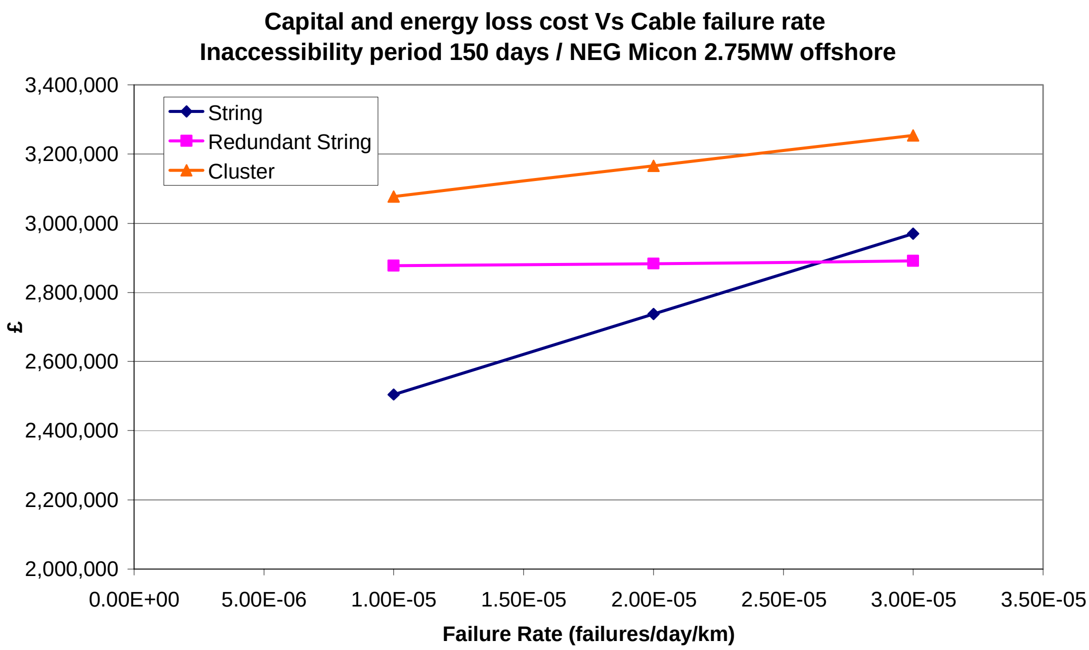
a) Wind speed: 7 m/s at 10m

This is considered to be a relatively good wind speed (although the lowest examined in the present study). Offshore wind farms could be developed in sites like these. Examining the Vestas V80 2 MW for the "worst cases" we can see that the simple string configuration is always the most economic one.



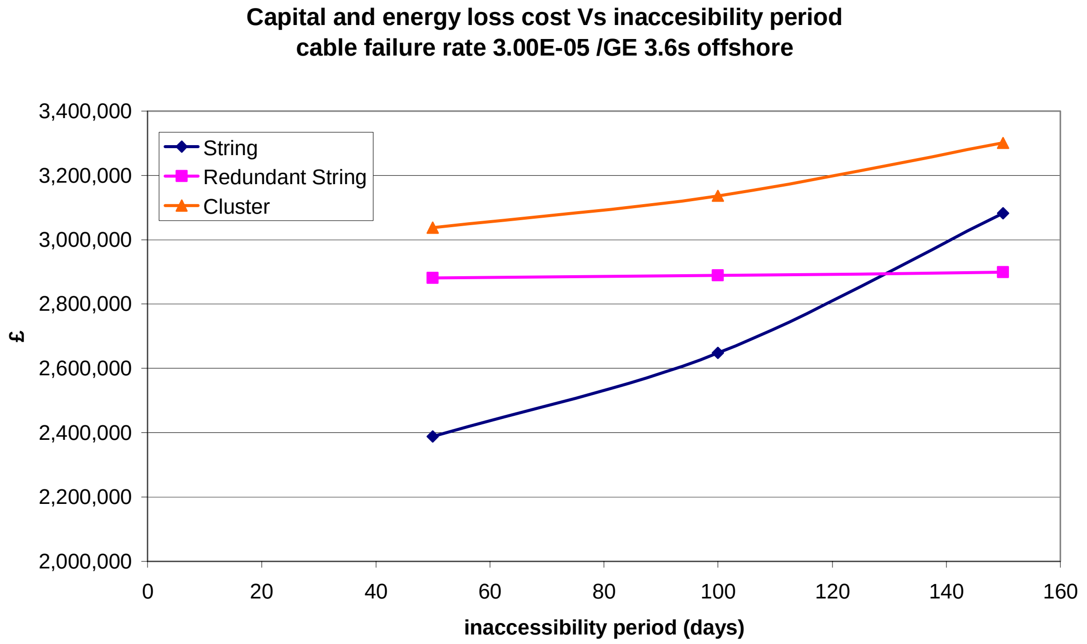
Our second choice of wind turbines is the NEG Micon NM 92, 2.75 MW offshore wind turbine. It has a rated power of 2.75MW and thus, in some cases, introducing redundancy into the string collector is more economic when looking at the total capital and energy losses cost.

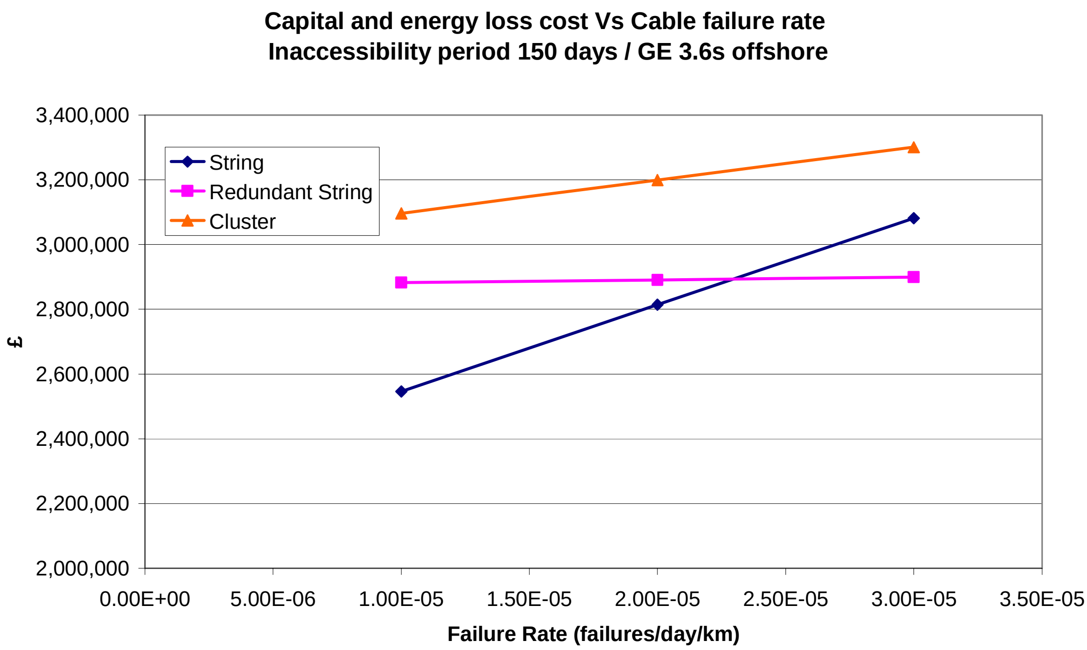




Holding one out of two parameters in their highest value, we can define a threshold for the other one, after which the redundant string is more profitable than the simple string arrangement. We can see at the graphs for example that for a 150 days inaccessibility period, if the cable failure rate exceeds the value of $2.62 \cdot 10^{-5}$ failures/ day/ km, the costs associated to the redundant configuration are less. The same happens after a 138 day inaccessibility period for a constant failure rate of $3 \cdot 10^{-5}$ failures/ day/ km.

As expected, for the GE 3.6s offshore wind turbine, those threshold values are a bit smaller. The relevant graphs are given bellow

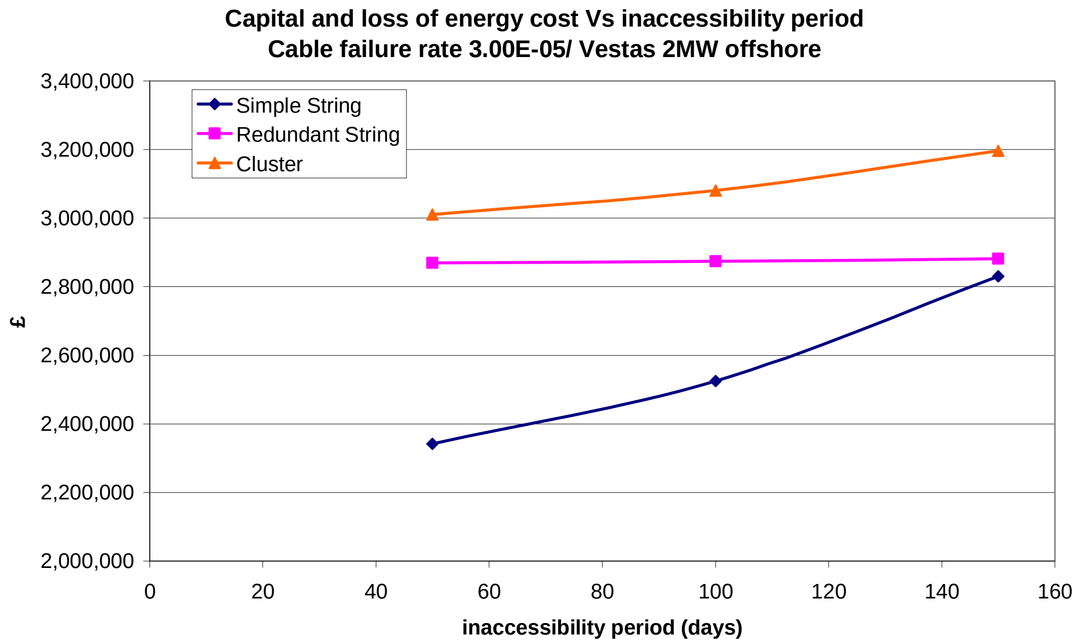




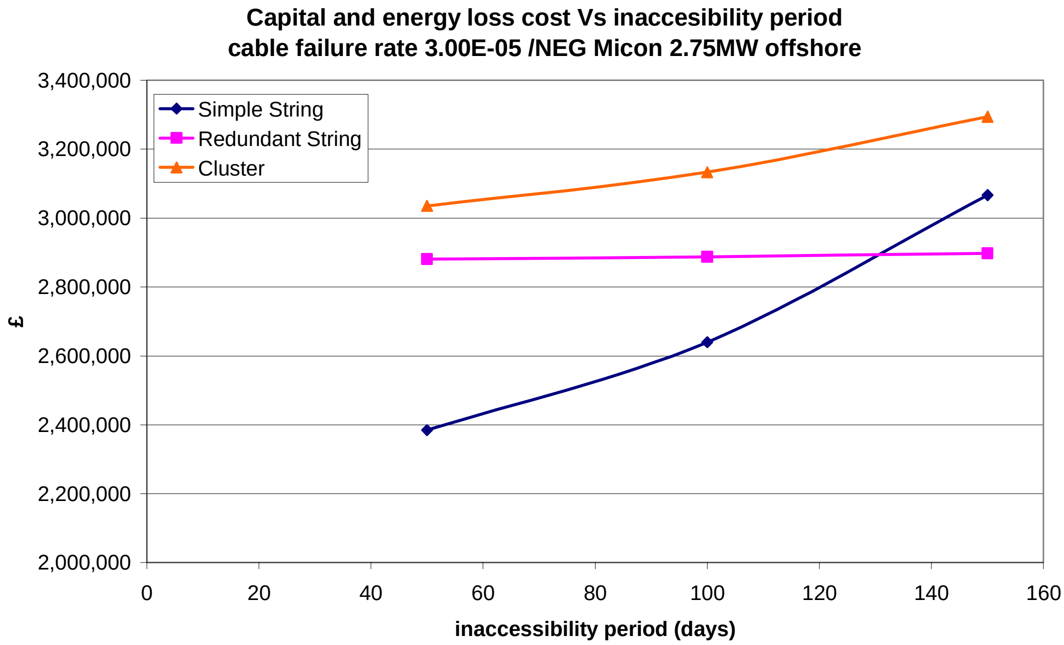
b) Wind speed: 8 m/s at 10m

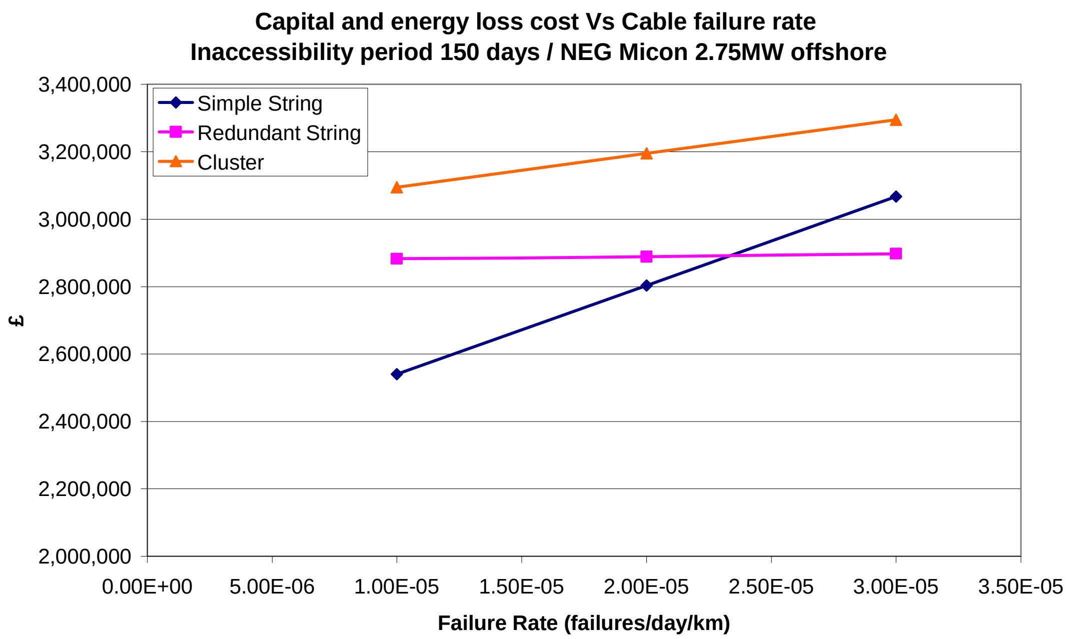
This is probably the most common wind speed for offshore wind farms. If we have a look at the European offshore wind atlas (1st Chapter) we will see that the 7-8 m/s area covers a huge surface in the waters of Europe and offers a very good resource. Of course there are some places in Northern Sea with wind speeds greater than 8 m/s at 10m, and many wind farms operate or are planned for those sites, but still there are projects planed in the 7-8 m/s area as well.

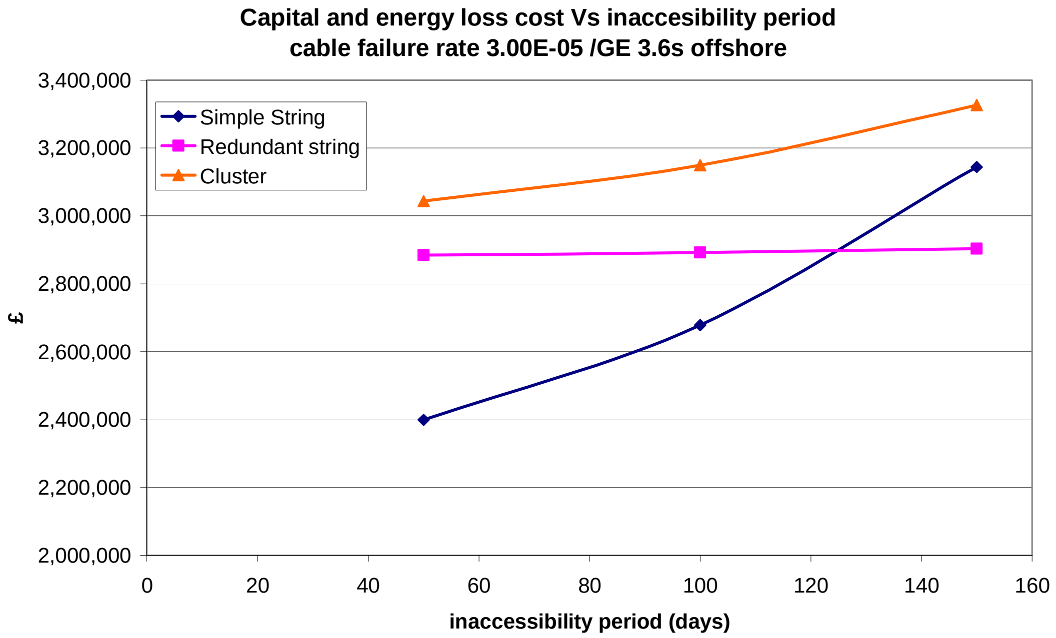
Our first observation regards the string of the Vestas V80 2MW machines. It seems once again that the conditions are not harsh enough to justify a redundant cable as can be seen in the graph bellow.

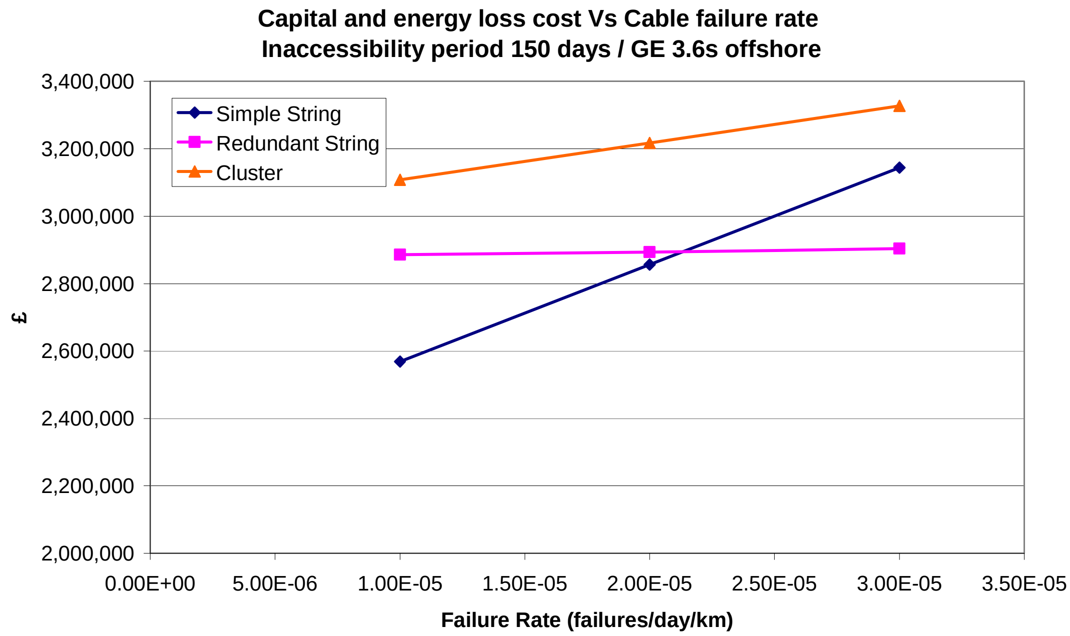


For our other two wind turbines, the cost curves are about the same as in the 7 m/s wind speed, only the thresholds come a little bit earlier. This means that there is a larger area of application for the redundant string collector in those conditions. The graphs for the other turbines can be seen bellow


Capital and energy loss cost Vs inaccesibility period
cable failure rate 3.00E-05 /NEG Micon 2.75MW offshore
Simple String
Redundant String
Cluster
£
3,400,000
3,200,000
3,000,000
2,800,000
2,600,000
2,400,000
2,200,000
2,000,000
0
20
40
60
80
100
120
140
160
inaccessibility period (days)


Capital and energy loss cost Vs Cable failure rate
Inaccessibility period 150 days / NEG Micon 2.75MW offshore
Simple String
Redundant String
Cluster
£
3,400,000
3,200,000
3,000,000
2,800,000
2,600,000
2,400,000
2,200,000
2,000,000
0.00E+00
5.00E-06
1.00E-05
1.50E-05
2.00E-05
2.50E-05
3.00E-05
3.50E-05
Failure Rate (failures/day/km)



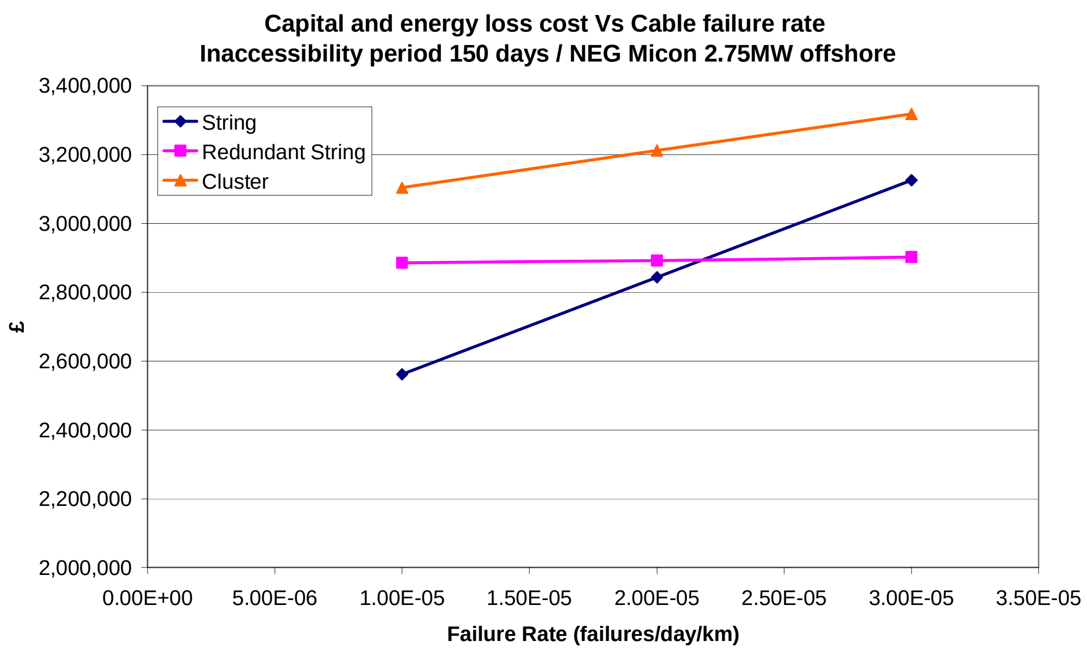


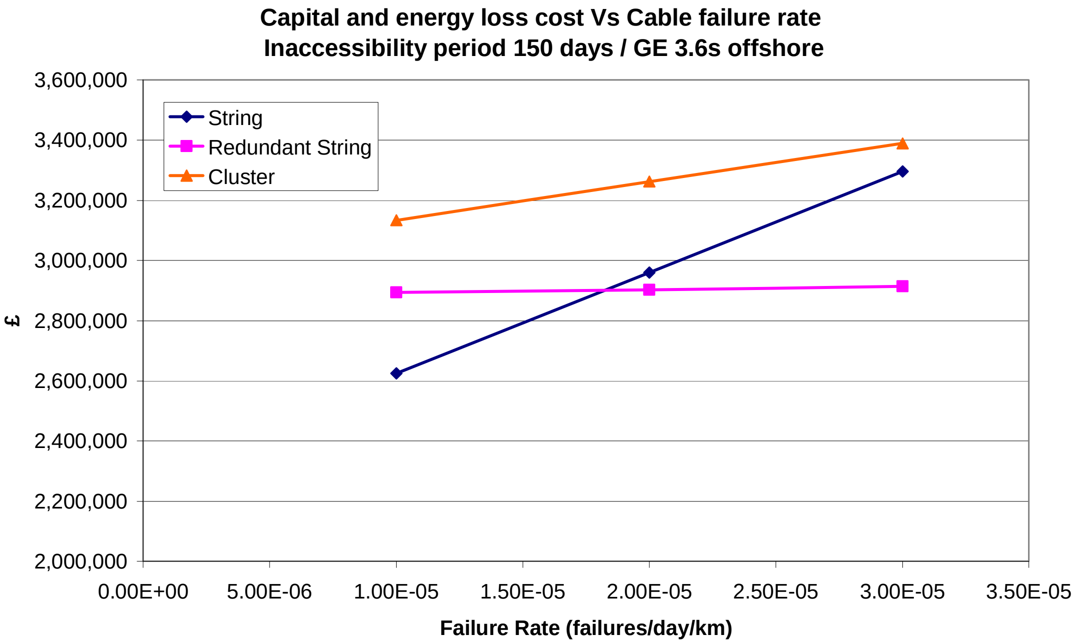
c) Wind speed: 9 m/s at 10m

This is an excellent wind speed and it characterizes the best sites available. Having a look at the offshore wind atlas, we can see that the majority of those sites belong to Scotland, Ireland, Northern England and Denmark. Because of the high wind conditions, those sites are more likely to be inaccessible to vessels for a larger period. Furthermore, many of those sites present large cable failure rate numbers [32]. So, our extreme values here make more sense than in any other case. We will look once again at the turbines separately.

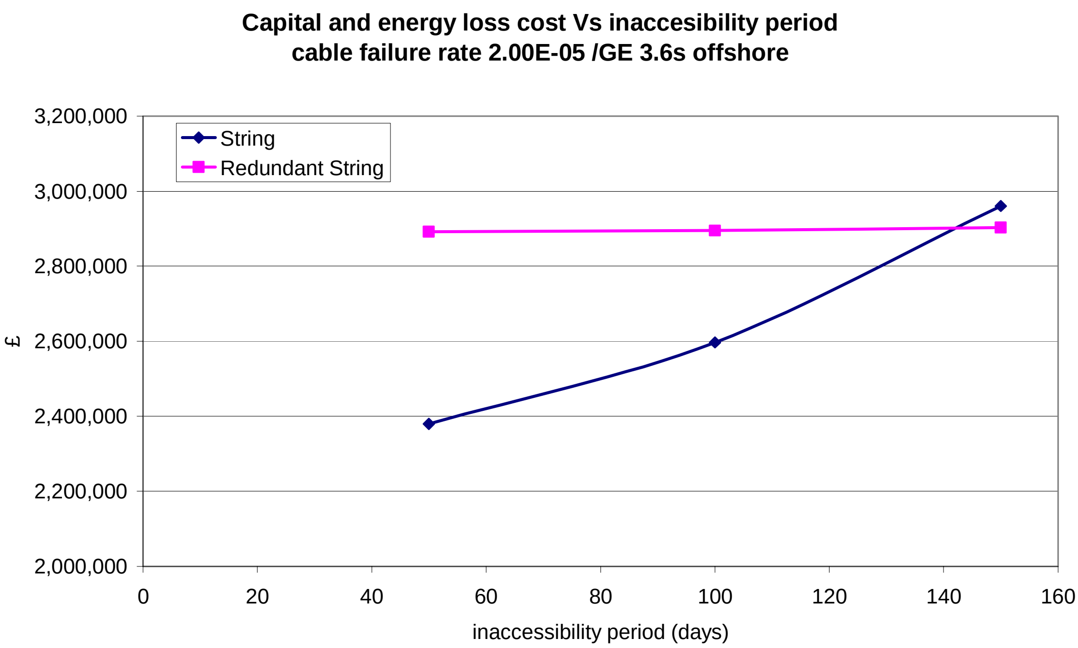
The Vestas V80 2MW offshore wind turbine has again the exact same behaviour. Only this time the costs associated with the simple string arrangement are just marginally higher for our worst conditions. The difference is a mere £14,473, which means that for any condition slightly harsher than that (either a larger inaccessibility period or a fractionally higher cable rate failure like the one quoted in [32]) the redundant string configuration should be the preferred one.

For the other 2 wind turbines, the graphs are identical once again, only the threshold values are smaller. We are going to show as an example the graphs for a 150 days inaccessibility period for both of them



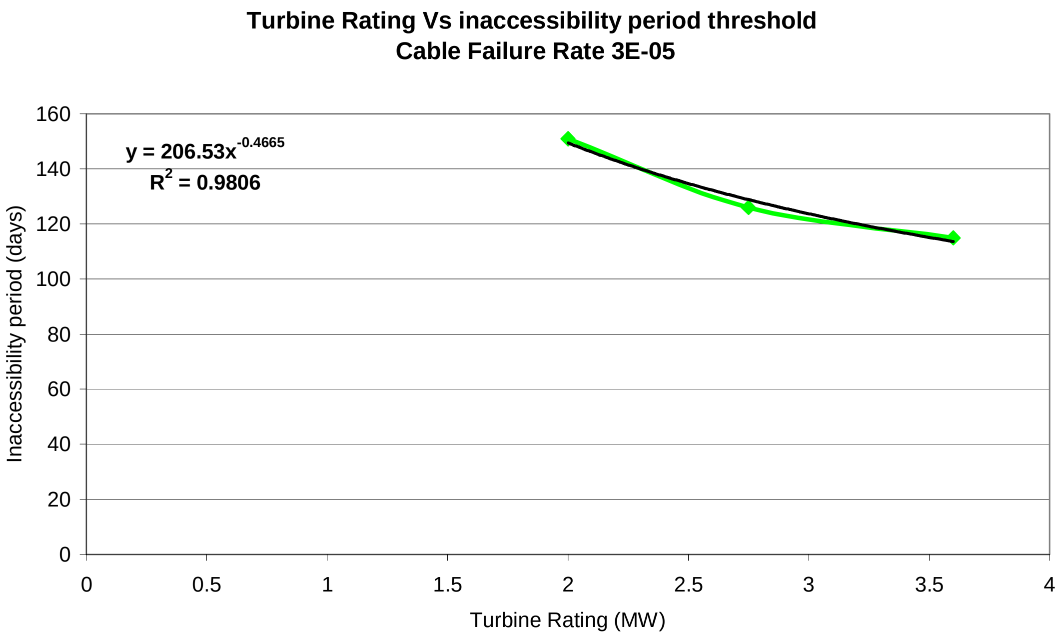


What presents a special interest in these wind conditions is the fact that the redundant string collector is the most economic choice for a middle value as well. For a $2{\cdot}10^{-5}$ failures/ day/ km failure rate, the redundant configuration seems to be the preferred one, if the inaccessibility period exceeds the value of 140 days as it can be seen in the graph bellow



However, we should note again, that under these wind conditions our extreme values are more likely to apply.

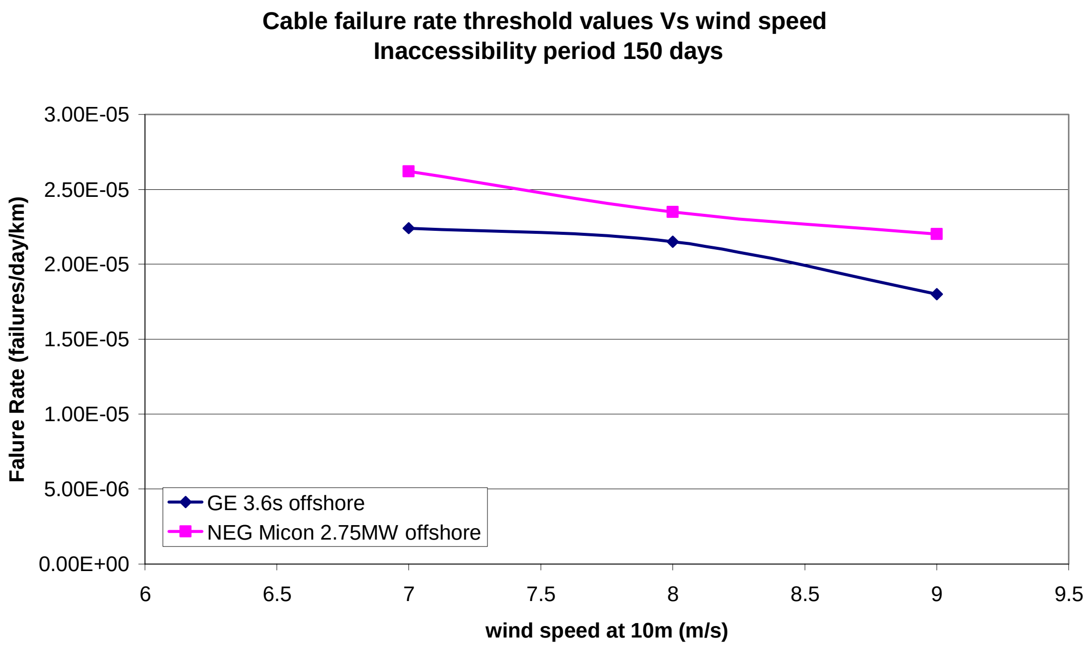
There is another interesting observation that can be made here as well. Assuming that if we increase the inaccessibility period for just a day for the Vestas composed string, the redundant string will be more economic than the simple one (since the cost difference was very small) we can say that we have threshold values for a configuration of all our three turbines. That is, we have values above which the redundant configuration is the preferred one. Since we have three values (one for each wind turbine) we can plot a diagram of threshold of inaccessibility period for a failure rate of $3 \cdot 10^{-5}$ failures/ day/ km versus the rating of the turbines used in the cluster. This is illustrated bellow.

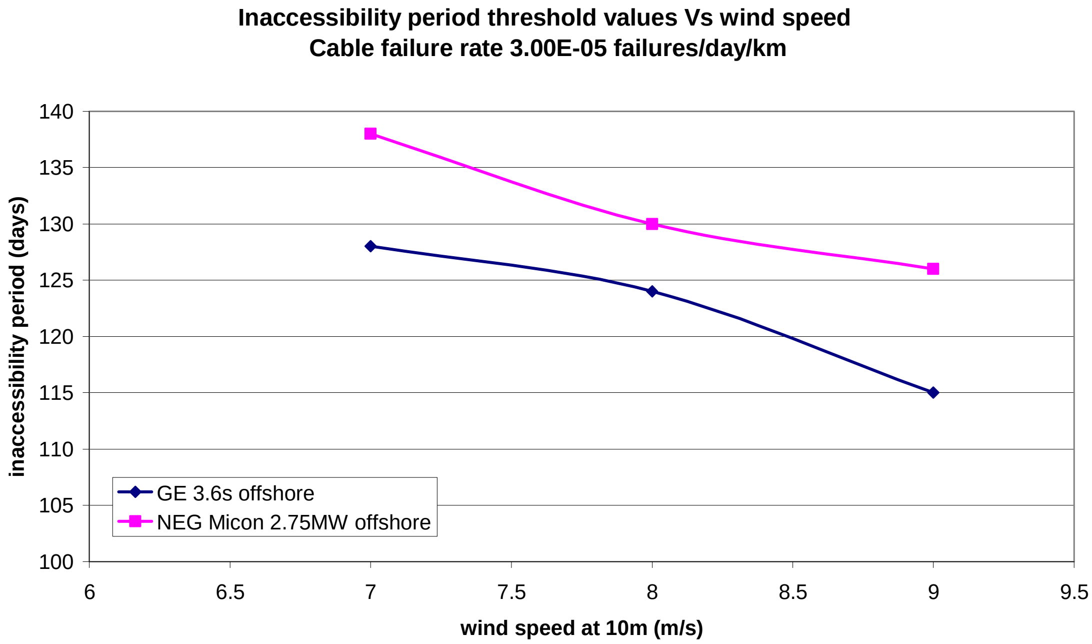


A trend line has been added as well. This trend line can help us drawn some conclusions for machines of a larger rating. For example, a collector comprised of 5 MW machines (the current target for turbine manufacturers in offshore technology) in areas with such a high failure rate, redundancy is economic if we have an inaccessibility period which is more than 95-100 days.

4.5.5 Monitoring the threshold values

As discussed above, we can get some threshold values regarding either inaccessibility days or cable failure rates for collectors comprised either from NEG Micon or GE machines in any wind speed. We are going to examine now how exactly these values vary with the wind speed.





We can see that the curves have a different shape after the 8 m/s point. Threshold values for the GE 3.6s tend to drop faster after 8 m/s as the slope of the curve increases. This does not happen for the NEG Micon though, where after the 8 m/s point the slope of the curve is decreasing.

This feature has more to do with the energy curve and the features of each machine. What we could say though, is that for a larger rated machine, the curve is moving downwards, therefore threshold values are lowering. Since the trend is to use larger machines offshore, it is clear that in this context, redundancy within the collector will be surely taken into account more into the future and it will become even more attractive than it is now.

Regarding the absolute values of the thresholds, the lowest inaccessibility period for a failure rate of $3{\cdot}10^{-5}$ failures/ day/ km was found to be 115 days, which is less than 4 months and not unlikely to be encountered.

Similarly, for inaccessibility period of 150 days, or 5 months (which has been reported for some sites) the threshold value of $1.80{\cdot}10^{-5}$ failures/ day/ km is not an unlike value especially if we take into account that almost double failure rates have been reported in extreme sites and a site inaccessible for 5 months is definitely an extreme site.

4.6 Summary

Summarising, in this chapter we firstly referred to the factors that are likely to affect reliability and its worth. We assumed some values for all of them and we proceeded to our simulations and analysis results. Each configuration was examined separately, the capital cost of the installation of the cables was calculated and the energy loss from the cable down times were estimated both as a percentage of the total production in the wind farm life span and as an absolute value in pounds for some selected cases. After that, the comparative result analysis part of our chapter looked at all the configurations together extracting some valuable remarks. The cluster configuration not only presents the highest capital cost but also –mostly because of that- is not the preferred arrangement in any case. When adding both capital costs and energy losses costs in order to define the best configuration each time, wind turbine ratings and wind speeds emerged as very important variables together with the cable failure rate and the duration of the inaccessibility period. A string comprised of larger machines favours the redundant configuration in more cases as it was expected. Sites with high wind speeds that are potentially linked to harsher conditions favour the redundant configuration as well. All these remarks are going to be grouped and presented better along with other comments in our following chapter.

5 Conclusions – Further work recommendation

Several interesting conclusions can be drawn from the present study, but its field is quite wide so there are still a lot of suggestions for future work. Regarding the conclusions of our study, it could be said that:

- From our literature review, we can say that there have to be done more assessments about submarine cable failures since existing data are out of date and sometimes a bit controversial (although cable failures can be very much site specific)
- From the literature review as well we can say that there are not many studies dealing with cable redundancy
- Monte Carlo is a powerful tool for approaching this kind of problems and 300,000 trials is an adequate number since the standard deviation in the worst case was 4%.
- The simple string arrangement has the greatest energy losses because of cable failures with second the cluster and third the redundant string arrangement
- The cluster arrangement has the highest cable capital cost of all three configurations with the redundant string coming second and the simple string third.
- From the previous two conclusions we can say that the cluster configuration is uneconomic in any case since not only does it have always higher capital cost than the redundant string configuration, but also it has greater energy losses.
- The simple string configuration is generally more economic than the redundant string. Results have shown that in most cases the total cost (installation plus energy losses) is smaller in the simple string arrangement. However, there are cases where this is not true, and those are the cases that present the greatest interest (especially when trying to determine threshold values).
- In high wind speed sites redundancy is more economic. Furthermore, the rating of the turbines used in the array plays a very important role in assessing the worth of redundancy. As the size of the wind turbines increases and wind farms are planned in high wind and low accessibility sites cable redundancy

tends to be more economical and should be taken into consideration during planning. Generally, if the wind turbines used are going to be larger than 2MW, the wind speed on site is over 8 m/s at 10m, and the site is fairly remote our analysis has shown that there is a pretty good chance that a redundant cable is worth it. However a specific analysis is recommended for any recommended site.

- Our analysis has shown a great influence of the wind turbine rating in reliability worth. It is therefore safe to conclude that larger wind turbines that are going to be built soon will highlight the need to investigate the worth of cable redundancy so that these kinds of analyses will be common practice.
- The link between high wind speeds and harsh weather conditions tends to favour the redundant configuration on windy sites since redundancy tends to be more economic both when the wind speed, and the inaccessibility period of the site are increasing.
- Threshold values above which the redundant configuration is more economic have been determined for some standard situations. The windier the site, the lower the values. For $3 \cdot 10^{-5}$ failures/ day/ km the threshold value of inaccessibility period can be 115 days and for a 150 day inaccessibility period the threshold value for cables failure rate can be as low as $1.80 \cdot 10^{-5}$ failures/ day/ km.

As we said there are many things that can be done to progress this study since the subject of the study has not been investigated greatly yet. Those consist of the following:

- Optimisation of the algorithm, so that it can generate weather conditions using Monte Carlo methods as well and comparison with the simple "interval" model presented here
- Incorporation of the algorithms to a large reliability assessment tool similar to that described in [41] that estimates as well the components reliability and simulates the response of service crews
- Differentiating the algorithm so that it can also indicate when do faults usually occur and in which moment of the project life span. This could help us do a

more detailed economic analysis since we will be able to add interest rates in the equation.

- Comparing savings of arrangements with improved reliability with savings of arrangements that offer less compensation costs but are less reliable. In our first Chapter we point at a certain case where connecting 2 wind farms with a single cable can result to much less compensation equipment but leads to a less reliable system. Case studies analyses have to be done on that
- Investigate the value of a redundant link to the shore. An algorithm has been proposed in this study and other studies clearly indicate that it is worth it. However, cost information on 132kV and HVDC cables could not be gathered. There might be also cases that having a multiple system with more than one spares might be worth as well.
- Investigate the need of burying the collector cables. Burial is a significant proportion of the cable installation cost. A buried cable though, is less susceptible to damage. Finding out how much more the failure rate for the loose cables should be so that burial should take place using Monte Carlo techniques, should be interesting.

6 References

[1] Selzer, H, 1986, "Potential of Wind Energy in the European Community"

[2] Matthies H. G. et al, "Offshore wind energy potential in the EC. European Commission, Brussels

[3] BWEA, "Prospects for offshore wind energy"

[4] EWEA, Wind Energy – The facts, Volume 1, Technology

[5] Lange B, Hojstrup J, "Estimation of offshore wind resources - the influence of sea fetch"

[6] www.offshorewindenergy.org, updated 20 July 2004

[7] Wind Developments (1999). Offshore wind: the technical challenge. In: Wind Directions, September

[8] Burton, A. L. (ed) offshore wind energy assessment phase IIB study ETSU-WN-5009 Vol. I, Vol. II, Vol. III, 1985, revised 1991

[9] Renewable Energy Systems Ltd, feasibility study for a prototype offshore wind turbine, ETSU W/35/00251/REP/C Vol. I, Vol. II, Vol. III, 1993

[10] Dixon JC and Swift R. H., Offshore wind power systems: a review of developments and comparison of national studies. Wind Engineering 10, 2, 64-77

[11] Zaaijer M, Henderson A., Offshore update - A global look at offshore wind energy, Renewable Energy World, July-August 2003

[12] Alstom Power Conversion, "Netzabindung eines Windparks in der Nordsee", El. Wirtsch. (2001) pp 32-34

[13] www.enercon.de, accessed September 2004

[14] http://www.neg-micon.com, accessed September 2004

[15] Moore G F (ed), 1998, "Electric cables handbook", 3rd edition, Blackwell science

[16] Graigner W, Jenkins N, Offshore wind farm electrical connection options

[17] Pavlovsky M, Bauer P, Cable selection and shunt compensation for offshore windpark

[18] Sobrink K et al., AC cable versus DC cable transmission for offshore wind farms

[19] Eriksson K, Halvarsson P, Wensky D, Hausler M, "System approach of designing an offshore windpower grid connection"

[20] CA – OWEE Offshore wind energy - Ready to power a sustainable Europe

[21] Brakelmann H, "Aspects of cabling in great offshore windfarms"

[22] Gardner P, Craig I M, Smith G J, Electrical power systems for offshore wind farms, 1998

[23] P Christiansen et al, "Grid Connection and Remote Control for the Horns Rev 150 MW Offshore Wind Farm in Denmark"

[24] Bryan C et al, "Engineering design and integration experience from Cape Wind 420 MW offshore wind farm"

[25] Rogers N, Border Wind Ltd, Offshore Wind Energy, MSc course, Loughborough University

[26] Soebrink K et al, "Large-scale offshore wind power integration and HVDC using Voltage Source Converters", Cigre fourth South Africa regional conference, Cape Town, South Africa, October 2001

[27] ABB, http://www.abb.com

[28] Alstom, http://www.tde.alstom.com/systems/en/pes/products/hvdc.htm

[29] Siemens, http://ww.ev.siemens.de/en/pages/lighttri.htm

[30] Lyall G, Minimum Standards for Subsea Cable Route Surveys, UnderWater Magazine,Nov/Dec2000,http://www.diveweb.com/telecom/features/novdec2000.01.htm

[31] CIGRE Study Committee 21. Methods to prevent mechanical damage to submarine cables (1985)

[32] Wallace, A.R.S. & Whittington H.R., 1981, "Routing of submarine cables for wave power transmission" Third International Conference on Future Energy Concepts, IEE Conference Publications No192, p 123-126

[33] Cns Ltd, private correspondence, June 2004

[34] VATECH Transmission & Distribution Ltd, private correspondence, September 2004

[35] Roy Billinton, Ronald N. Allan, Reliability Evaluation of Power Systems, New York 1996

[36] I.M. Kontoleontos, Reliability and tolerance of sysstem failures, Thessaloniki 2000

[37] Roy Billinton, Wenyuan Li, Reliability Assessment of Electric Power Systems Using Monte Carlo Methods, New York 1994

[38] http://csep1.phy.ornl.gov/mc/node1.html, accessed September 2004

[39] Metropolis, Nicholas and Stanislaw Ulam (1949). The Monte Carlo method, *Journal of the American Statistical Association*, 44 (247), 335-341

[40] Eckhardt, Roger (1987). Stan Ulam, John von Neumann, and the Monte Carlo method, *Los Alamos Science*, Special Issue (15), 131-137

[41] G.J.W. van Bussel, Chr. Schontag, "Operation and Maintenance Aspects of Large Offshore Wind farms", Proceedings of the 1997 EWEA conference, Dublin, Ireland, October 1997, pp. 272-279

[42] Chr. Schontag, G.J.W. van Bussel, "Optimisation of Operation and Maintenance, Opti-OWECS Final Report Vol. 2"; Methods Assisting the design of Offshore Wind Energy Conversion Systems, Part B, Institute for Wind Energy, TU Delft, The Netherands

[43] Avery Catlin, Pascal for Engineers and Scintists with Turbo Pascal, New Jersey 1990

[44] Michael Halvorson, Visual Basic .NET step by step, Microsoft Press, Whashington 2003

[45] Bruce McKinney, Hardcore Visual Basic, Microsoft Press, Washington 1995

[46] www.dti.gov.uk, accessed September 2004

7 Appendix

7.1 Visual basic algorithm for assessing down times in a simple string configuration

```
Const ComponentsNo = 15, max_time = 7300
Dim R(1 To ComponentsNo), Days(1 To ComponentsNo) As Variant
Dim correction1, correction2, experiments As Integer




Private Sub Command1_Click()
  kounter = 0
  counter = 0
  For k = 1 To ComponentsNo
    Days(k) = 0
  Next k
Timer1.Interval = 100
Timer1_Timer

End Sub




Private Sub Command2_Click()

experiments = Text1.Text
Timer1.Enabled = False
 For k = 1 To ComponentsNo
 R(k) = Days(k) * experiments / (correction1 + (correction2 / 100))
 List1.AddItem (R(k) / 100)
 Label12.Caption = correction1
 Label13.Caption = correction2
```

```
 Next k

End Sub

Private Sub Timer1_Timer()

Static distance, timeoffailure, W As Variant
Static NumberOfExp, FirstDay, LastDay, counter, x, k, s, j, i, t, z As Integer
Static p(1 To 40), criterion, kounter, indicator As Integer
Static Check, turbines(1 To ComponentsNo) As Integer
Static lamda(1 To ComponentsNo), Tf(1 To ComponentsNo), FailureRate, Days(1 To ComponentsNo) As Variant
Static CompSurv(1 To ComponentsNo, 1 To max_time) As Integer

NumberOfExp = Text1.Text
FirstDay = Text2.Text
LastDay = Text3.Text
distance = Text4.Text
FailureRate = Text5.Text

criterion = NumberOfExp
Randomize
For i = 1 To ComponentsNo
  lamda(i) = distance * FailureRate
Next i



  p(1) = FirstDay
  p(2) = LastDay
  For i = 2 To 20
    p(2 * i - 1) = p(1) + 365 * i
    p(2 * i) = p(2) + 365 * i
  Next i
```

```
For k = 1 To ComponentsNo
  Tf(k) = -Log(Rnd()) / lamda(k)
Next k


For k = 1 To ComponentsNo
  For t = 1 To max_time
   CompSurv(k, t) = 0
  Next t
Next k


 For k = 1 To ComponentsNo
   timeoffailure = Tf(k)
   W = 1
   x = 1
   Do

     If timeoffailure >= W Then
       CompSurv(k, W) = 1
       W = W + 1

     Else

       Select Case W
         Case p(1) To p(2)

           CompSurv(k, p(2)) = 1
           W = p(2) + 1
           timeoffailure = -Log(Rnd()) / lamda(k) + W

         Case p(3) To p(4)

           CompSurv(k, p(4)) = 1
```

```
  W = p(4) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W

Case p(5) To p(6)

  CompSurv(k, p(6)) = 1
  W = p(6) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W

Case p(7) To p(8)

  CompSurv(k, p(8)) = 1
  W = p(8) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W

Case p(9) To p(10)

  CompSurv(k, p(10)) = 1
  W = p(10) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W

Case p(11) To p(12)

  CompSurv(k, p(12)) = 1
  W = p(12) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W

Case p(13) To p(14)

  CompSurv(k, p(14)) = 1
  W = p(14) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W

Case p(15) To p(16)
```

```
  CompSurv(k, p(16)) = 1
  W = p(16) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W

Case p(17) To p(18)

  CompSurv(k, p(18)) = 1
  W = p(18) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W

Case p(19) To p(20)

  CompSurv(k, p(20)) = 1
  W = p(20) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W

Case p(21) To p(22)

  CompSurv(k, p(22)) = 1
  W = p(22) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W

Case p(23) To p(24)

  CompSurv(k, p(24)) = 1
  W = p(24) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W

Case p(25) To p(26)

  CompSurv(k, p(26)) = 1
  W = p(26) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W
```

```
Case p(27) To p(28)

  CompSurv(k, p(28)) = 1
  W = p(28) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W

Case p(29) To p(30)

  CompSurv(k, p(30)) = 1
  W = p(30) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W

Case p(31) To p(32)

  CompSurv(k, p(32)) = 1
  W = p(32) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W

Case p(33) To p(34)

  CompSurv(k, p(34)) = 1
  W = p(34) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W

Case p(35) To p(36)

  CompSurv(k, p(36)) = 1
  W = p(36) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W

Case p(37) To p(38)

  CompSurv(k, p(38)) = 1
```

```
          W = p(38) + 1
          timeoffailure = -Log(Rnd()) / lamda(k) + W

         Case Else

          CompSurv(k, W + 1) = 1
          W = W + 1
          timeoffailure = -Log(Rnd()) / lamda(k) + W

        End Select
      End If
    Loop While W < max_time
  Next k


' calculating the down times of the turbines

  For t = 1 To max_time
    If CompSurv(1, t) = 0 Then
      Days(1) = Days(1) + (1 / criterion)
    End If
  Next t


    For k = 2 To ComponentsNo \ 2

      For t = 1 To max_time
       If CompSurv(k, t) = 0 Then
       Check = 0
        For s = 1 To k - 1
         If CompSurv(s, t) = 0 Then
           Check = 1
         End If
        Next s
```

```
            If Check = 0 Then
              Days(k) = Days(k) + (1 / criterion)
            End If
          End If
        Next t

      Next k

'to idio akribws kai gia thn deyterh seira e3arthmatwna, apo 8 ws 15

    For t = 1 To max_time
      If CompSurv(ComponentsNo \ 2 + 1, t) = 0 Then
        Days(ComponentsNo \ 2 + 1) = Days(ComponentsNo \ 2 + 1) + (1 / criterion)
      End If
    Next t

      For k = ComponentsNo \ 2 + 2 To ComponentsNo

        For t = 1 To max_time
          If CompSurv(k, t) = 0 Then
          Check = 0
           For s = ComponentsNo \ 2 + 1 To k - 1
            If CompSurv(s, t) = 0 Then
              Check = 1
            End If
           Next s
            If Check = 0 Then
              Days(k) = Days(k) + (1 / criterion)
            End If
          End If
        Next t

      Next k
```

```
  If kounter = 100 Then
    counter = counter + 1
    indicator = counter
    Label9.Caption = counter
    kounter = 0
  End If
  kounter = kounter + 1

If indicator = criterion Then
Timer1.Enabled = False
 For k = 1 To ComponentsNo
   List1.AddItem (Days(k) / 100)
 Next k
End If
correction1 = counter
correction2 = kounter



End Sub
```

7.2 Visual basic algorithm for assessing down times in a redundant string configuration

```
Const ComponentsNo = 15, max_time = 7300
Dim R(1 To ComponentsNo), Days(1 To ComponentsNo) As Variant
Dim correction1, correction2, experiments As Integer
```

```
Private Sub Command1_Click()
  kounter = 0
  counter = 0
  For k = 1 To ComponentsNo
    Days(k) = 0
  Next k
Timer1.Interval = 100
Timer1_Timer

End Sub




Private Sub Command2_Click()

experiments = Text1.Text
Timer1.Enabled = False
 For k = 1 To ComponentsNo
 R(k) = Days(k) * experiments / (correction1 + (correction2 / 100))
 List1.AddItem (R(k) / 100)
 Label12.Caption = correction1
 Label13.Caption = correction2
 Next k

End Sub

Private Sub Timer1_Timer()

Static distance, timeoffailure, W As Variant
Static NumberOfExp, FirstDay, LastDay, counter, x, k, s, j, i, t, z As Integer
Static p(1 To 40), criterion, kounter, indicator As Integer
Static Check, turbines(1 To ComponentsNo) As Integer
Static lamda(1 To ComponentsNo), Tf(1 To ComponentsNo), FailureRate, Days(1 To
ComponentsNo) As Variant
```

```
Static CompSurv(1 To ComponentsNo, 1 To max_time) As Integer

NumberOfExp = Text1.Text
FirstDay = Text2.Text
LastDay = Text3.Text
distance = Text4.Text
FailureRate = Text5.Text

criterion = NumberOfExp
Randomize
For i = 1 To ComponentsNo
  lamda(i) = distance * FailureRate
Next i



  p(1) = FirstDay
  p(2) = LastDay
  For i = 2 To 20
    p(2 * i - 1) = p(1) + 365 * i
    p(2 * i) = p(2) + 365 * i
  Next i

  For k = 1 To ComponentsNo
    Tf(k) = -Log(Rnd()) / lamda(k)
  Next k



  For k = 1 To ComponentsNo
    For t = 1 To max_time
     CompSurv(k, t) = 0
    Next t
  Next k
```

```
For k = 1 To ComponentsNo
 timeoffailure = Tf(k)
 W = 1
 x = 1
 Do

  If timeoffailure >= W Then
   CompSurv(k, W) = 1
   W = W + 1

  Else

   Select Case W
    Case p(1) To p(2)

     CompSurv(k, p(2)) = 1
     W = p(2) + 1
     timeoffailure = -Log(Rnd()) / lamda(k) + W

    Case p(3) To p(4)

     CompSurv(k, p(4)) = 1
     W = p(4) + 1
     timeoffailure = -Log(Rnd()) / lamda(k) + W

    Case p(5) To p(6)

     CompSurv(k, p(6)) = 1
     W = p(6) + 1
     timeoffailure = -Log(Rnd()) / lamda(k) + W

    Case p(7) To p(8)

     CompSurv(k, p(8)) = 1
```

```
  W = p(8) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W

Case p(9) To p(10)

  CompSurv(k, p(10)) = 1
  W = p(10) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W

Case p(11) To p(12)

  CompSurv(k, p(12)) = 1
  W = p(12) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W

Case p(13) To p(14)

  CompSurv(k, p(14)) = 1
  W = p(14) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W

Case p(15) To p(16)

  CompSurv(k, p(16)) = 1
  W = p(16) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W

Case p(17) To p(18)

  CompSurv(k, p(18)) = 1
  W = p(18) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W

Case p(19) To p(20)
```

```
  CompSurv(k, p(20)) = 1
  W = p(20) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W

Case p(21) To p(22)

  CompSurv(k, p(22)) = 1
  W = p(22) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W

Case p(23) To p(24)

  CompSurv(k, p(24)) = 1
  W = p(24) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W

Case p(25) To p(26)

  CompSurv(k, p(26)) = 1
  W = p(26) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W

Case p(27) To p(28)

  CompSurv(k, p(28)) = 1
  W = p(28) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W

Case p(29) To p(30)

  CompSurv(k, p(30)) = 1
  W = p(30) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W
```

```
      Case p(31) To p(32)

        CompSurv(k, p(32)) = 1
        W = p(32) + 1
        timeoffailure = -Log(Rnd()) / lamda(k) + W

      Case p(33) To p(34)

        CompSurv(k, p(34)) = 1
        W = p(34) + 1
        timeoffailure = -Log(Rnd()) / lamda(k) + W

      Case p(35) To p(36)

        CompSurv(k, p(36)) = 1
        W = p(36) + 1
        timeoffailure = -Log(Rnd()) / lamda(k) + W

      Case p(37) To p(38)

        CompSurv(k, p(38)) = 1
        W = p(38) + 1
        timeoffailure = -Log(Rnd()) / lamda(k) + W

      Case Else

        CompSurv(k, W + 1) = 1
        W = W + 1
        timeoffailure = -Log(Rnd()) / lamda(k) + W

    End Select
  End If
Loop While W < max_time
```

```
   Next k


' calculating the down times of the turbines

   For t = 1 To max_time
   Check = 0
     For k = 1 To ComponentsNo
        turbines(k) = 0
        If CompSurv(k, t) = 0 Then
           turbines(k) = k
           Check = Check + 1
        End If
      Next k
        If Check > 1 Then
           maxim = 0
           For k = 1 To ComponentsNo
               If turbines(k) > maxim Then
               maxim = turbines(k)
               End If
           Next k
           minim = ComponentsNo
             For k = 1 To ComponentsNo
                If turbines(k) < minim And turbines(k) > 0 Then
                minim = turbines(k)
                End If
             Next k
           z = maxim - minim
           Days(z) = Days(z) + (1 / criterion)
        End If
   Next t
```

```
  If kounter = 100 Then
     counter = counter + 1
     indicator = counter
     Label9.Caption = counter
     kounter = 0
  End If
  kounter = kounter + 1

If indicator = criterion Then
Timer1.Enabled = False
 total = 0
 For k = 1 To ComponentsNo
   List1.AddItem (Days(k) / 100)
   total = total + ((Days(k) / 100) * k)
 Next k
 Text6.Text = total
End If

correction1 = counter
correction2 = kounter

End Sub
```

7.3 Visual basic algorithm for assessing down times in a cluster configuration

```
Const ComponentsNo = 15, max_time = 7300
Dim R(1 To ComponentsNo), Days(1 To ComponentsNo) As Variant
Dim correction1, correction2, experiments As Integer
```

```
Private Sub Command1_Click()
  kounter = 0
  counter = 0
  For k = 1 To ComponentsNo
    Days(k) = 0
  Next k
Timer1.Interval = 100
Timer1_Timer

End Sub



Private Sub Command2_Click()

experiments = Text1.Text
Timer1.Enabled = False
 For k = 1 To ComponentsNo
 R(k) = Days(k) * experiments / (correction1 + (correction2 / 100))
 List1.AddItem (R(k) / 100)
 Label12.Caption = correction1
 Label13.Caption = correction2
 Next k

End Sub

Private Sub Timer1_Timer()

Static distance, timeoffailure, W As Variant
Static NumberOfExp, FirstDay, LastDay, counter, x, k, s, j, i, t, z As Integer
Static p(1 To 40), criterion, kounter, indicator As Integer
Static Check, turbines(1 To ComponentsNo) As Integer
```

```
Static lamda(1 To ComponentsNo), Tf(1 To ComponentsNo), FailureRate, Days(1 To
ComponentsNo) As Variant
Static CompSurv(1 To ComponentsNo, 1 To max_time) As Integer

NumberOfExp = Text1.Text
FirstDay = Text2.Text
LastDay = Text3.Text
distance = Text4.Text
FailureRate = Text5.Text

criterion = NumberOfExp
Randomize
For i = 1 To ComponentsNo
  lamda(i) = distance * FailureRate
Next i


  p(1) = FirstDay
  p(2) = LastDay
  For i = 2 To 20
    p(2 * i - 1) = p(1) + 365 * i
    p(2 * i) = p(2) + 365 * i
  Next i

  For k = 1 To ComponentsNo
    Tf(k) = -Log(Rnd()) / lamda(k)
  Next k


  For k = 1 To ComponentsNo
    For t = 1 To max_time
     CompSurv(k, t) = 0
    Next t
  Next k
```

```
For k = 1 To ComponentsNo
 timeoffailure = Tf(k)
 W = 1
 x = 1
 Do

  If timeoffailure >= W Then
   CompSurv(k, W) = 1
   W = W + 1

  Else

   Select Case W
    Case p(1) To p(2)

     CompSurv(k, p(2)) = 1
     W = p(2) + 1
     timeoffailure = -Log(Rnd()) / lamda(k) + W

    Case p(3) To p(4)

     CompSurv(k, p(4)) = 1
     W = p(4) + 1
     timeoffailure = -Log(Rnd()) / lamda(k) + W

    Case p(5) To p(6)

     CompSurv(k, p(6)) = 1
     W = p(6) + 1
     timeoffailure = -Log(Rnd()) / lamda(k) + W

    Case p(7) To p(8)
```

```
  CompSurv(k, p(8)) = 1
  W = p(8) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W

Case p(9) To p(10)

  CompSurv(k, p(10)) = 1
  W = p(10) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W

Case p(11) To p(12)

  CompSurv(k, p(12)) = 1
  W = p(12) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W

Case p(13) To p(14)

  CompSurv(k, p(14)) = 1
  W = p(14) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W

Case p(15) To p(16)

  CompSurv(k, p(16)) = 1
  W = p(16) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W

Case p(17) To p(18)

  CompSurv(k, p(18)) = 1
  W = p(18) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W
```

```
Case p(19) To p(20)

  CompSurv(k, p(20)) = 1
  W = p(20) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W

Case p(21) To p(22)

  CompSurv(k, p(22)) = 1
  W = p(22) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W

Case p(23) To p(24)

  CompSurv(k, p(24)) = 1
  W = p(24) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W

Case p(25) To p(26)

  CompSurv(k, p(26)) = 1
  W = p(26) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W

Case p(27) To p(28)

  CompSurv(k, p(28)) = 1
  W = p(28) + 1
  timeoffailure = -Log(Rnd()) / lamda(k) + W

Case p(29) To p(30)

  CompSurv(k, p(30)) = 1
```

```
    W = p(30) + 1
    timeoffailure = -Log(Rnd()) / lamda(k) + W

  Case p(31) To p(32)

    CompSurv(k, p(32)) = 1
    W = p(32) + 1
    timeoffailure = -Log(Rnd()) / lamda(k) + W

  Case p(33) To p(34)

    CompSurv(k, p(34)) = 1
    W = p(34) + 1
    timeoffailure = -Log(Rnd()) / lamda(k) + W

  Case p(35) To p(36)

    CompSurv(k, p(36)) = 1
    W = p(36) + 1
    timeoffailure = -Log(Rnd()) / lamda(k) + W

  Case p(37) To p(38)

    CompSurv(k, p(38)) = 1
    W = p(38) + 1
    timeoffailure = -Log(Rnd()) / lamda(k) + W

  Case Else

    CompSurv(k, W + 1) = 1
    W = W + 1
    timeoffailure = -Log(Rnd()) / lamda(k) + W

End Select
```

```
      End If
    Loop While W < max_time
  Next k

' calculating the down times of the turbines

  For t = 1 To max_time
    For k = 1 To ComponentsNo
    If CompSurv(k, t) = 0 Then
      Days(k) = Days(k) + (1 / criterion)
    End If
    Next k
  Next t



 If kounter = 100 Then
    counter = counter + 1
    indicator = counter
    Label9.Caption = indicator
    kounter = 0
 End If

kounter = kounter + 1



If indicator = criterion Then
Timer1.Enabled = False
total = 0
 For k = 1 To ComponentsNo
  List1.AddItem (Days(k) / 100)
  total = total + (Days(k) / 100)
 Next k
Text6.Text = total
End If
```

End Sub

7.4 Screenshots of the programs

The form of the variations of the program are identical, hence only one form is illustrated bellow as an example