Security of Supply of UK Electricity Generated by Wind Turbines

Prepared By

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Thursday, August 12, 2004

PROFESSOR JOHN H GITTUS.

John Gittus was elected Regents' Professor at the University of California in Los Angeles in 1990. He is Visiting Professor of Nuclear Engineering at the University of Plymouth, England. He was a Director of the United Kingdom Atomic Energy Authority (later AEA Technology) and is now a Consultant to Governments and private industry on nuclear matters world-wide. His recent clients include BNFL Plc, The UK Government's Department of Trade and Industry, Serco Plc, The Sumitomo Corporation, the French nuclear company COGEMA, Amersham Plc the radio pharmaceutical company, Cox Insurance Plc, the world's largest commercial insurer of nuclear risks, Chaucer Insurance Holdings and ESKOM, the South African utility.

Professor Gittus is a Fellow of the Royal Academy of Engineering (Britain's top 1,000 engineers) and has Doctor of Science degrees from the Universities of London and Stockholm. He has held over 30 patents and published over 100 papers in learned Journals describing his personal research. He invented Nimonic 115, the strongest of the early creep-resistant alloys used for the hottest turbine blades in jet engines and went on to develop a theory of creep that forms the basis of many of his papers to the Royal Society and the Philosophical Magazine. He used this theory to develop one of the world's first computer models of nuclear fuel elements, with which he forecast that some of the fuel element designs then extant would fail as their lives were extended in a quest for cheaper power. He was able to model the failure processes and deduced remedies that have been applied throughout the world. Fuel element failures are now rare, due in part to this early work.

He held a series of senior posts in the UKAEA, where he headed the late Lord Marshall's Task Force at Harwell and produced the UK's first nuclear-reactor Probabilistic Risk Assessment, for Sizewell B. He became Director of the R&D programme that underpinned the design details of Sizewell B, then Director of Safety and Director of Communications. He left the UKAEA to become the first Director General of the British Nuclear Industry Forum, where he helped with the restructuring of the UK nuclear industry, a process that is still going on. When his term of office there was complete he became a consultant, first to his successor and then, quickly, to other nuclear companies at home and overseas. On the death of Lord Marshall of Goring, Professor Gittus was appointed to succeed him at Cox Insurance Holdings Plc, advising on the insurance of the world's nuclear power stations and other nuclear installations. Since January 2003 Professor Gittus and Mr Michael Dawson have led Syndicate 1176, the biggest commercial nuclear insurer in the world and Lloyds of London's most profitable syndicate.

Amongst his published papers are two communicated to the Royal Society by P.A.M. Dirac and describing Professor Gittus's solution of a problem with the structure of matter which Dirac said he himself had been unable to solve.

Entry From Who's Who

Name
GITTUS, John Henry.

Awards
DSc. DTech; FREng 1989.

Positions
Consultant, Amersham Plc, since 1999. Consultant, Cox Power Holdings, since 1997; Consultant, Serco Plc (formerly AEA Technology) since 1993; Senior Partner, NUSYS Consultants, Paris.

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Born 25 July 1930; *son* of Henry Gittus and Amy Gittus; *married* 1953, Rosemary Ann Geeves; one *son* two *daughters*.

Education
BSc 1st Honours Mathematics London 1952; DSc Phys London 1976. DTech Metall Stockholm 1975. CEng, FIMechE, FIS, FIM.FREng

Work
British Cast Iron Res. Assoc., 1947-1955; Mond Nickel Co., R&D Labs, Birmingham, 1955-1960 (develt Nimonic series high temp. super alloys for aircraft gas turbine engines); United Kingdom Atomic Energy Authority, 1960-1989: Research Manager, Springfields; Head, Water Reactor fuel develt; Head, Atomic Energy Tech. Br., Harwell; Director: Water Reactor Safety Research; Safety and Reliability Directorate, Culcheth; Communication and Information; Dir Gen., British Nuclear Forum, 1990-1993. Consultant: Argonne Nat. Lab., USA, 1968; Oak Ridge Nat. Lab., 1969. Visiting Professor: Ecole Polytechnique Fédérale, Lausanne, 1976; Univ. de Nancy, 1984; Regents' Prof., UCLA, 1990-1991; Prof. of Risk Mgt, Plymouth Univ., 1997-. Editor-in-Chief, Res Mechanica, 1980-1991.

Publications
Uranium, 1962; Creep, Viscoelasticity and Creep-fracture in Solids, 1979; Irradiation Effects in Crystalline Solids, 1979; (with W. Crosbie) Medical Response to Effects of Ionizing Radiation, 1989; numerous articles in learned jls.

Recreations
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Summary

On shore wind farms already exist in the UK and there are plans for 21 wind farms to be built off the British coastline, Figure 1. A good example is the Carno Wind Farm. This project was submitted for planning permission in October 1993 following a full Environmental Impact Assessment and received unanimous approval in April 1994. It was completed in October 1996 and consists of 56 wind turbines each of 600 kilowatts (kW) maximum output. The combined maximum power of 33.6 megawatts (MW) makes Carno Wind Farm the largest in the UK and, at the time of its construction, the largest in Europe.

In this Report I give the forecasts that I have arrived at for the frequency and magnitude of the interruptions to wind power that will be produced by external hazards such as tornados, earthquakes and the collision of ships with offshore generators. Also given is the extent to which breakdown of the wind generator machinery will interrupt the output of electricity.

The present and presently-planned windfarms are shown in Figure 1 and the results of the forecasts in Figure 2 and Figure 3.

Introduction.

In this Report I give the forecasts that I have arrived at for the frequency and magnitude of the interruptions to wind power that will be produced by external hazards such as tornados, earthquakes and the collision of ships with offshore generators. Also given is the extent to which breakdown of the wind generator machinery will interrupt the output of electricity.

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A wind turbine obtains its power input by converting the force of the wind into a **torque** (turning force) acting on the rotor blades. The amount of energy which the wind transfers to the rotor depends on the density of the air, the rotor area, and the wind speed. One can imagine a cylindrical slice of air 1 metre thick moving through the 1,500 m^2 rotor of a typical 600 kilowatt wind turbine. With a 43-metre rotor diameter each cylinder actually weighs 1.9 tonnes, i.e. 1,500 times 1.25 kilogrammes. The kinetic energy of a moving body is proportional to its mass (or weight). The kinetic energy in the wind thus depends on the density of the air, i.e. its mass per unit of volume. In other words, the "heavier" the air, the more energy is received by the turbine. At normal atmospheric pressure and at 15° Celsius air weighs some 1.225 kilogrammes per cubic metre, but the density decreases slightly with increasing humidity. Also, the air is denser when it is cold than when it is warm. At high altitudes, (in mountains) the air pressure is lower, and the air is less dense. A typical 600 kW wind turbine has a rotor diameter of 43-44 metres, i.e. a rotor area of some 1,500 square metres. The rotor area determines how much energy a wind turbine is able to harvest from the wind. Since the rotor area increases with the **square** of the rotor diameter, a turbine which is twice as large will receive $2^2 = 2 \times 2 =$ **four** times as much energy.

Figure 1: UK Wind Generators, Operating (now) and Planned (date), Onshore and Offshore. L=LOW, M = MEDIUM, H = HIGH, VH = VERY HIGH.

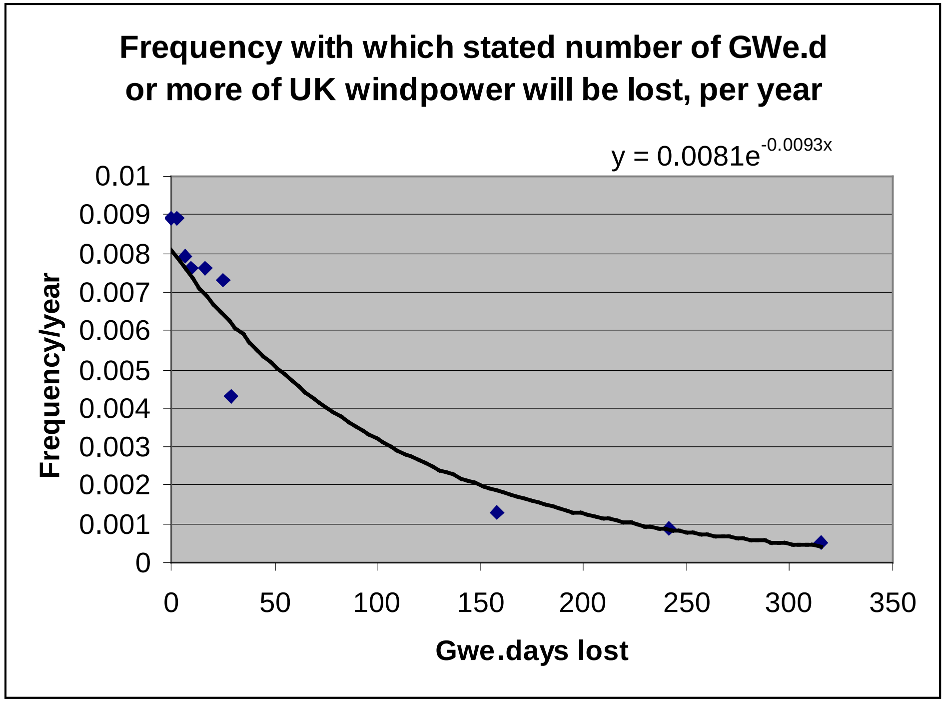
	now	now	now	now	now	now	now	now	now	now	now	now	now										2005		2004		2005		2000		
Area sq km		300ha	350ha	150ha				100ha															10sq km	10sq km		10				Total Onshore	Total Offshore
Mwe	17	8.4	21.6	4.8	6.5	2.3	20.4	5.6	10	33.6	9.9	9	9.6	180	90	90	270	90	60	180	90	60	90	108	76	100	72	90	4	162.7	1,646
	Onshore sites													Offshore sites																	
Source of Interruption.	Novar	Beinn Glas	Windy Standard	Kirkby Moor	Lambrigg	Tow Law	Llyn Alaw	Trysglwyn	Mynydd Gorddu	Carno	Bryn Titli	Taff Ely	Bears Down	Soway Firth	Teesside	Barrow	Shell Flat	Southport	North Hoyle	Rhyl Flats	Burbo	Scarweather Sands	Kentish Flats	Gunfleet Sands	Scroby Sands	Cromer	Lynn	Inner Dowsing			
Number of Generators	34	14	36	12				14		56	22	20	16	60	30	30	90	30	30	60	30	30	30	30	38	30	30	30	2		
Storm	H	H	H	H	H	H	H	H	H	H	H	H	H	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH		
Surge	NO.	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	YES	YES	YES	YES	YES	YES	YES	YES	NO	YES	YES	YES	YES	YES	YES	YES		
Tornado	L	L	L	M	M	M	M	M	M.	M	H	H	H	M	M	M	H	H	H	M	H	H	H	H	H	H	H	H	H		
Seismic	VII	VII	VI	VII	VII	VI	VI	VI	VI	VI	VII	VII	VI	VII	VII	VIII	VIII	VII	VII	VII	VII	VIII	VII	VII	VII	VII	VII	VII	VII		
Hail	L	L	L	L	L.	L	L.	L	M	M	M	M	M	L	L	L	L	L	L	L	L	M	M	M	M	M	M	M	M		
High Sea	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES		
Cable is cut at sea	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES		

Figure 2: Results of the Analysis Contained in this Report.

Year	2005	2010	***2015***	2020
GWe of wind	1.6	4	***7***	10

Source of Interruption.	Days: Duration of Consequent Interruption	Per Year: Likelihood	GBP Maximum Insurable Amount	Loss, Gwe.d	Loss, GWe	% of wind power lost	MGBP Cost of lost power	Cost of generating Loss MGBP/y	MGBP Cost of replacement	MGBP Cost of capital loss per year
Storm	180	0.0005	200,000,000	315	1.75	25	151	0.076	1750	0.8750
Surge on west coast	130	0.0004	200,000,000	241	1.86	26.54	116	0.046	1858	0.7431
Surge on east coast	130	0.0004	200,000,000	158	1.22	17.42	76	0.030	1219	0.4876
Tornado	60	0.003	100,000,000	29	0.49	7	14	0.042	490	1.4700
Seismic	70	0.00002	100,000,000	10	0.14	2	5	0.000	140	0.0028
Hail	30	1E-07	100,000,000	0.3	0.01	0.14	0	0.000	10	0.000001
High Sea	40	0.001	100,000,000	3	0.07	1	1	0.001	70	0.0700
Ship runs into windfarm	180	0.003	100,000,000	25	0.14	2	12	0.036	140	0.4200
Plane runs into windfarm	120	0.0003	100,000,000	17	0.14	2	8	0.002	140	0.0420
Cable is cut	50	0.0003	20,000,000	7	0.14	2	3	0.001	140	0.0420
								0.236		4.1525
Machinery Breakdown.	360	0.8	10,000,000	3	0.007	0.1	1			

Figure 3: Forecast Frequency with which stated Gwe.d or more is lost from UK windfarms in 2015.



An Example: The Carno Wind Farm

A good example is the Carno Wind Farm. This project was submitted for planning permission in October 1993 following a full Environmental Impact Assessment and received unanimous approval in April 1994. It was completed in October 1996 and consists of 56 wind turbines each of 600 kilowatts (kW) maximum output. The combined maximum power of 33.6 megawatts (MW) makes Carno Wind Farm the largest in the UK and, at the time of its construction, the largest in Europe. It is located on Trannon Moor, 4km west of Carno village in Mid Wales on private land that is used for grazing sheep. It was developed by and is owned and operated by National Wind Power Ltd.

The wind farm covers an area over 600 hectares (ha) of which only 6 ha (1%) are used by the turbines and access tracks. It is situated on a plateau that is 400 metres above sea level and includes areas of semi-natural grassland, changing to blanket bog and valley mire in the wetter areas. To the south west there is the extensive commercial coniferous forest of Dal Gau. The plateau is used by over 30 bird species including Red Kite, Hen Harrier, Buzzard, Red Grouse, Curlew and Golden Plover. There are archaeological features on the plateau including Bronze Age Cairns, standing stones and a possible Roman road crossing from east to west. Care was taken in planning the wind farm to avoid areas of ecological and archaeological interest and the construction routes have been reinstated as part of a detailed restoration programme.

The Local Community

This £26 million development represents a significant investment in the Welsh rural economy with around a third of the total cost of the project being placed with Welsh contractors or suppliers. Every year, £9,000 is contributed from the Carno Wind Farm revenue to finance a land management project. This project has been supporting studies of wildlife and archaeology, and will develop a programme to improve the natural habitats. Powys County Council administers the land management scheme with assistance and advice from Countryside Council for Wales (CCW). The wind farm also provides a community fund of over £20,000 per year, which is administered by local Councillors, to support worthwhile local projects in Trefeglwys, Carno and Llanbrynmair.

Figure 4: Technical Information Concerning the Carno Wind Farm.

Technical Information

Number of turbines	Turbine manufacturer & rating (kW)	Combined maximum power (MW)	Tower height to the hub	Number of blades	Rotor diameter (m)	Rotor speed (rpm)

		(MW)	hub (m)			
56	Bonus 600kWe	33.6 MWe	31.5m	3	44m	20 or 30 rpm

Amount of electricity produced annually	Efficiency, % of Rated Power actually Generated	Sufficient electricity to meet the annual needs of....	Amount of carbon dioxide prevented from entering the atmosphere (tonnes)	Amount of acid rain gases prevented from entering the atmosphere (tonnes)
90 million kWe.h	31%	About 25,000 homes This amount of electricity represents 15% of the total consumption of Powys County.	Around 80,000 tonnes	About 1,200 tonnes

Companies involved in the development, construction and operation

Responsibility	Company	Location
Developer, Owner and Operator	National Wind Power Ltd.	Bourne End
Turbine Supplier	Bonus Energy A/S	Denmark
Civil Engineering	David McLean Construction	Flint
Site Electrics	Celtic Contracting Services	Swansea
Grid Connection	MANWEB Ltd.	Oswestry
Access Road Works	Powys County Council DWO	Llandrindod Wells
Maintenance	Bonus Energy (UK) Ltd	Newtown

The Design of Offshore Wind Generators: Foundations.

The design of offshore wind generators largely determines their resistance to external events such as earthquakes..

Steel Gravity Foundations.

Most of the existing offshore wind parks use gravitation foundations. A new technology offers a similar method to that of the concrete gravity caisson. Instead of reinforced concrete it uses a cylindrical steel tube placed on a flat steel box on the sea bed.

Weight Considerations

A steel gravity foundation is considerably lighter than concrete foundations. Although the finished foundation has to have a weight of around 1,000 tonnes, the steel structure will only weigh some 80 to 100 tonnes for water depths between 4 and 10 m. (Another 10 tonnes have to be added for structures in the Baltic Sea, which require pack ice protection). The relatively low weight allows barges to transport and install many foundations rapidly, using the same fairly lightweight crane used for the erection of the turbines. The gravity foundations are filled with olivine, a very dense mineral, which gives the foundations sufficient weight to withstand waves and ice pressure.

Size Considerations

The base of a foundation of this type will be 14 by 14 m (or a diameter of 15 m for a circular base) for water depths from 4 to 10 m. (Calculation based on a wind turbine with a rotor diameter of 65 m).

Seabed Preparation

The advantage of the steel caisson solution is that the foundation can be made onshore, and may be used on all types of seabed although seabed preparations are required. Silt has to be removed and a smooth horizontal bed of shingles has to be prepared by divers before the foundation can be placed on the site.

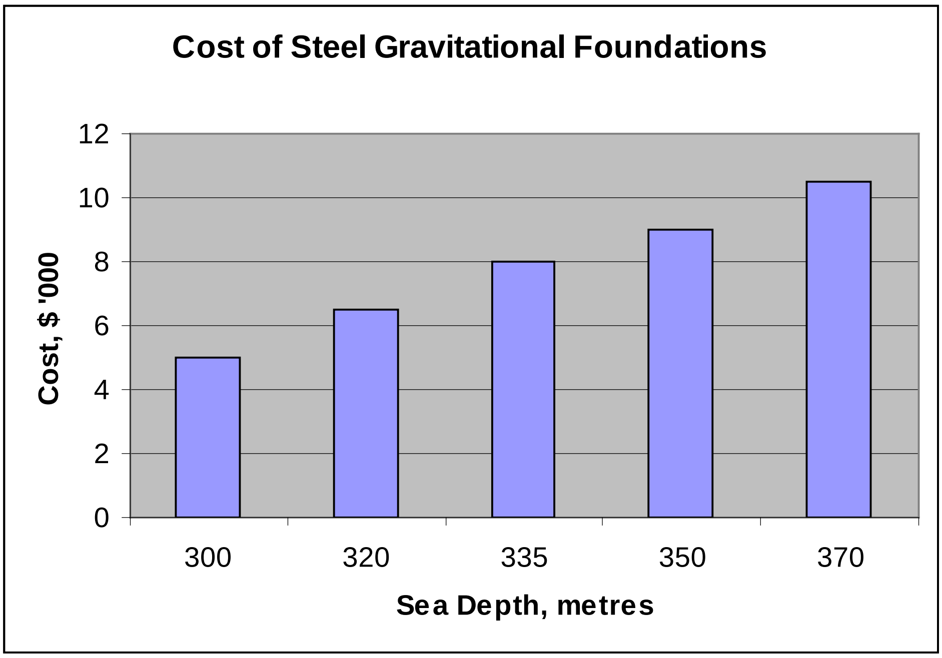
Erosion Protection

The seabed around the base of the foundation will normally have to be protected against erosion by placing boulders or rocks around the edges of the base. This is, of course, also the case for the concrete version of the gravitation foundation. This makes the foundation type relatively costlier in areas with significant erosion.

Costs by Water Depth for Steel Gravitational Foundations

The cost penalty of moving to larger water depths is minimal compared to traditional concrete foundations. The reason is, that the foundation base does not have to increase in size proportion to the water depth to lean against ice pressure or waves. The cost estimates for this type of foundation is for instance 2,343,000 DKK (= $335,000) for a 1.5 MW machine placed at 8 m water depth in the Baltic Sea (1997 figures). The costs include installation. The graph shows how the cost varies with water depth. Interestingly, the dimensioning factor (which decides the required strength and weight of the foundation) is not the turbine itself but ice and wave pressure forces.

Figure 5: Cost of Steel Gravitational Foundations, North Sea or Baltic.



Offshore Foundations: Mono Pile

The mono pile foundation is a simple construction. The foundation consists of a steel pile with a diameter of between 3.5 and 4.5 metres. The pile is driven some 10 to 20 metres into the seabed depending on the type of underground. The mono pile foundation is effectively extending the turbine tower under water and into the seabed. An important advantage of this foundation is that no preparations of the seabed are necessary. On the other hand, it requires heavy duty piling equipment, and the foundation type is not suitable for locations with many large boulders in the seabed. If a large boulder is encountered during piling, it is possible to drill down to the boulder and blast it with explosives.

Costs by Water Depth for Mono Pile Foundations.

The dimensioning factor of the foundation varies from the North Sea to the Baltic Sea. In the North Sea it is the wave size that determines the dimension of the mono pile. In the Baltic Sea the pack ice pressure decides the size of the foundation. This is the reason why the mono pile foundation cost increases more rapidly in the Baltic Sea than in the North Sea. The costs include installation (1997 prices).

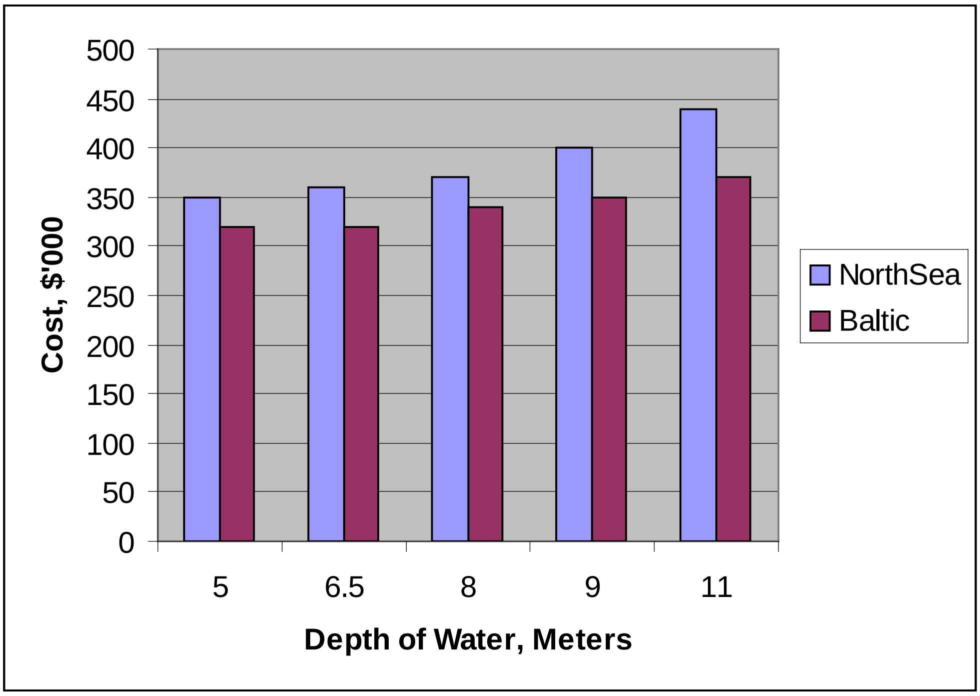
Erosion Considerations.

Erosion will normally not be a problem with this type of foundation.

Swedish Offshore Mono Pile Project.

A 2.5 MW pilot project with five Danish wind turbines using mono pile technology has been installed in the Baltic sea south of the Swedish island of Gotland. Using the mono pile foundation technique at Gotland involved drilling a hole of 8 to 10 metres depth for each of the turbines (Wind World 500 kW). Each steel pile is slotted into the solid rock. When the foundations are in place the turbines can be bolted on top of the mono piles. The whole operation takes about 35 days under average Baltic weather conditions.

Figure 6: Costs of Monopile Foundations.



Interruption to Electricity Supplies from Wind Generators.

Aircraft Crash.

If an aircraft were accidentally to crash into a wind farm then supplies of electricity from many of the turbine generators would be lost for up to a year.

Wind turbines have grown considerably in size over the past 20 years. In 1980 the average size wind turbine had a rotor diameter of 10.5 metres - today there are many wind turbines with rotor diameters of more than 80 metres, roughly 25% larger than the wingspan of a Boeing 747. Consequently, an increasing number of wind turbines exceed the 100 metres limit of height for when obstruction marking may be required by the aviation authorities. The first time in Denmark was in 1999, when six 2 MW turbines were erected at Hagesholm on Zealand. According to Danish aviation regulations on obstruction marking, constructions of less than 100 metres tall are not marked, whereas constructions taller than 150 metres are always marked. For constructions which are between 100 and 150 metres tall the Danish Civil Aviation Administration passes judgement on a case-by-case basis whether, and if so, how a construction must be marked.

Danish authorities, wind turbine manufacturers and project developers began to seriously address the question of how to mark wind turbines with a total height of above 100 metres in 2000 during the planning phase for the two first large scale Danish offshore wind farms. The two 160 MW wind parks were erected in 2002 and 2003 respectively, at Horns Rev in the North Sea and off the Nysted coast of the island Lolland. A Danish software company, was given the task to develop computer models of the wind farm with alternative lighting arrangements, designed to identify the generators to aircraft after dark. The final visualisation software comprises a number of modules: wind turbine module, light emission module, and wind farm module. In addition, the software can handle a landscape database, e.g. sea, coastline or a location on land. The project used Nysted Offshore Wind Farm south of Lolland as a case for its model. The offshore farm will be connected to the grid in 2003. Nysted Offshore Wind Farm will consist of 72 wind turbines, each having a rated power of 2,2 MW. The hub height is 68.8 m (226 ft), the rotor diameter is 82.4 m (270 ft). Maximum tip height is therefore 110 m (361 ft). The offshore farm will be laid out as 8 rows of 9 turbines - the closest some 10 kilometres off shore.

Ship Impact[1].

Offshore windfarms are typically 10 km out to sea, in water that is deep enough for large ships to float in it without grounding. Ships run aground not infrequently and from the statistics for such groundings round the coasts of the UK where windfarms are to be located, shown in Figure 10, I have calculated the frequency with which a collision will occur for each windfarm and the proportion of the windgenerators that will on average be put out of action by the collision. Analysis of 10 years casualty data (1989-1998 inclusive for UK Waters) identified a total of 341 reported incidents (i.e. an average of 34.1 incidents per annum).

. Figure 8 shows typical frequencies of shipping incidents in UK waters. Figure 9 shows, for shipping accidents in UK coastal waters, that 33% involve grounding.

Figure 7: Shipping Incidents in UK waters, per year: About 11 involve grounding.

Model	Frequency of Incidents Predicted Per Annum
Ship to Ship Collisions	7.0
Foundering	7.3
Fire and Explosion	9.5
Drifting Grounding	1.5
Powered Grounding	9.8
TOTAL	35.1

[1] DETR MEHRA ST 8639 M1-1-REV 01 2002.

Figure 8: Typical Frequencies of Shipping Incidents in UK Waters.

Location	Incident Category	Frequency
In vicinity of Humber estuary (Non- coastal cell)	Ship to ship collision	0.053
	Fire & explosion	0.03
	Powered grounding	Not applicable
	Drifting grounding	Not applicable
	Foundering	0.02
	Total	0.105
Dover Strait (Non- coastal cell)	Ship to ship collision	0.15
	Fire & explosion	0.06
	Powered grounding	Not applicable
	Drifting grounding	Not applicable
	Foundering	0.04
	Total	0. 25
West Coast of Lewis (Coastal cell)	Ship to ship collision	Not applicable
	Fire & explosion	Not applicable
	Powered grounding	0.0075
	Drifting grounding	0.0106
	Foundering	Not applicable
	Total	0.018

Figure 9: Powered and Drifting Grounding form 3% of UK Shipping Accidents.

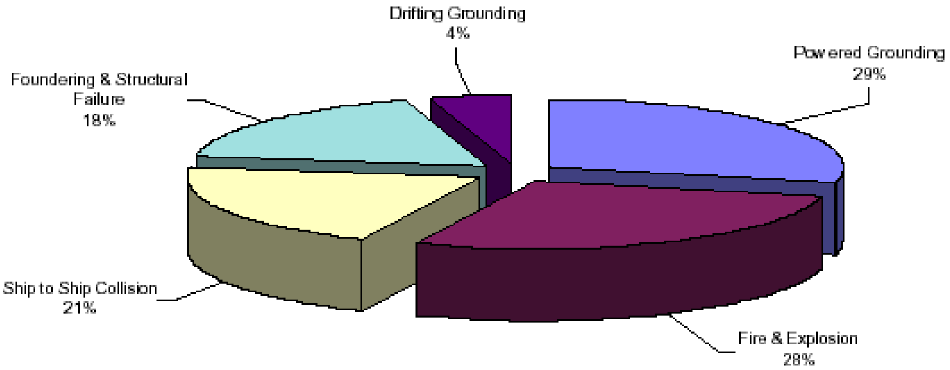


Figure 10: Incidents, one third of which involve grounding, for Ships in UK Coastal Waters.

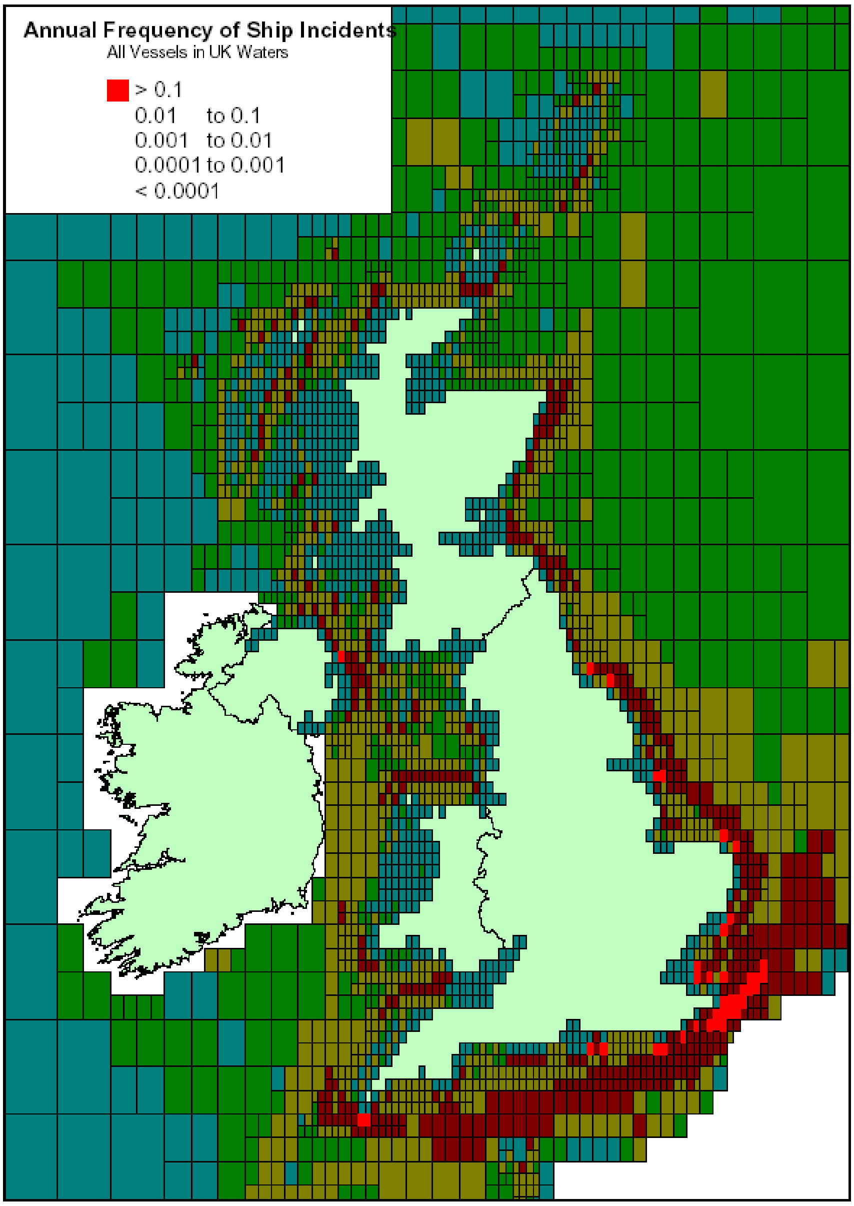


Figure 11: Ships colliding with other ships.

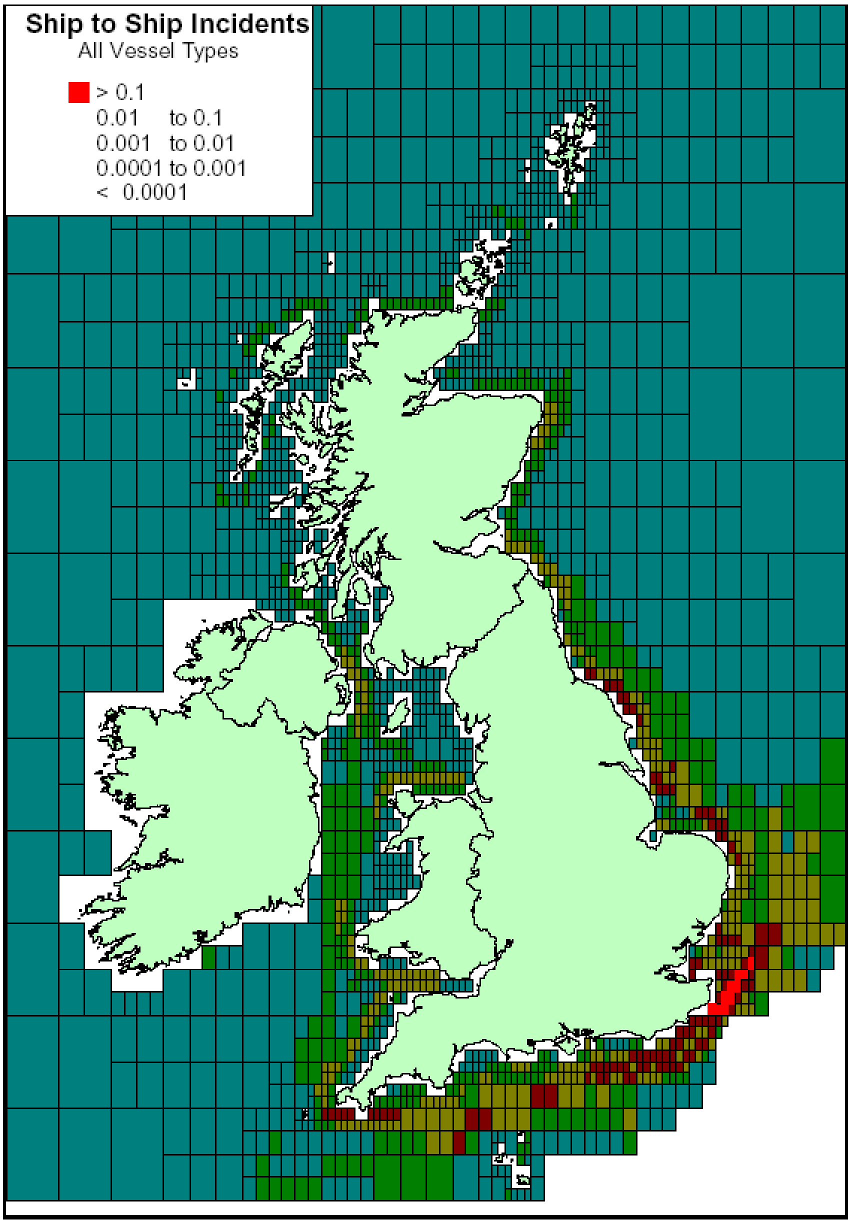


Figure 12: Powered Grounding Incidents.

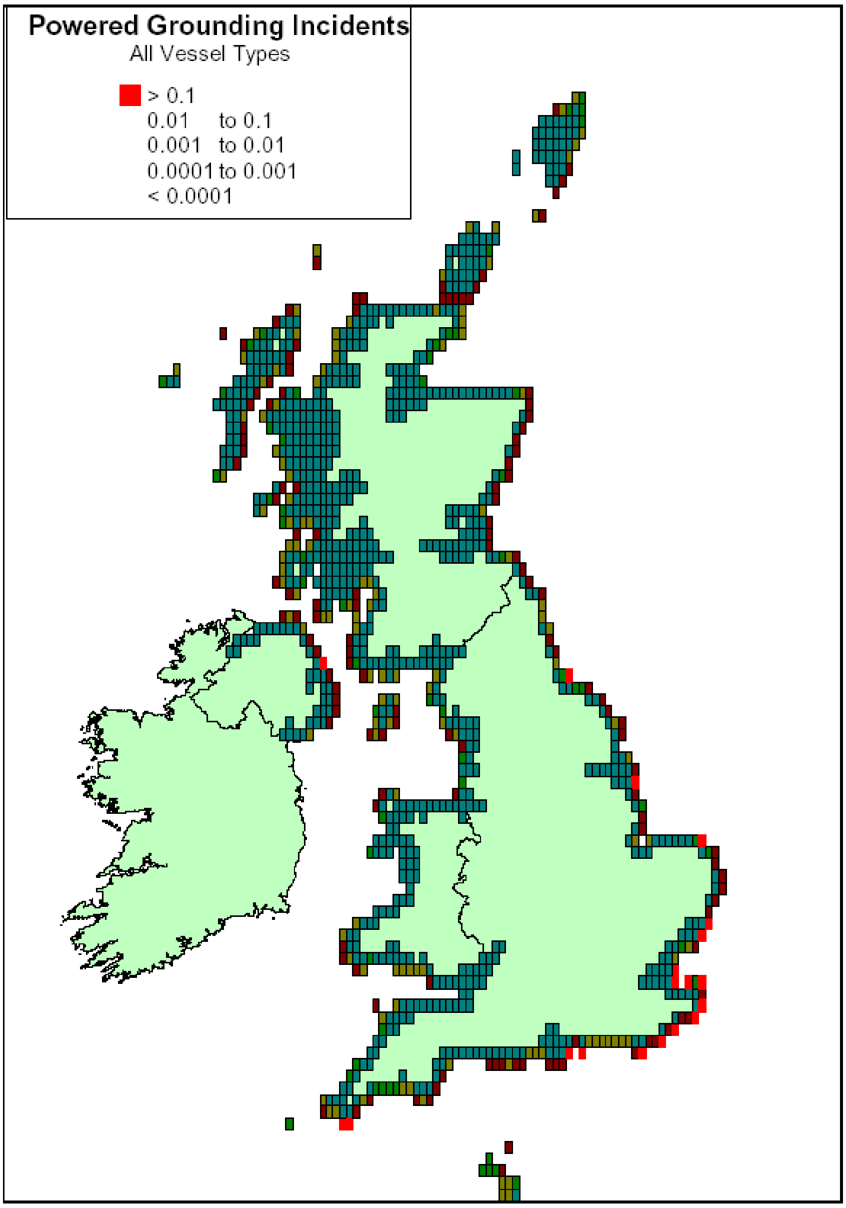


Figure 13: Drifting Grounding Incidents.

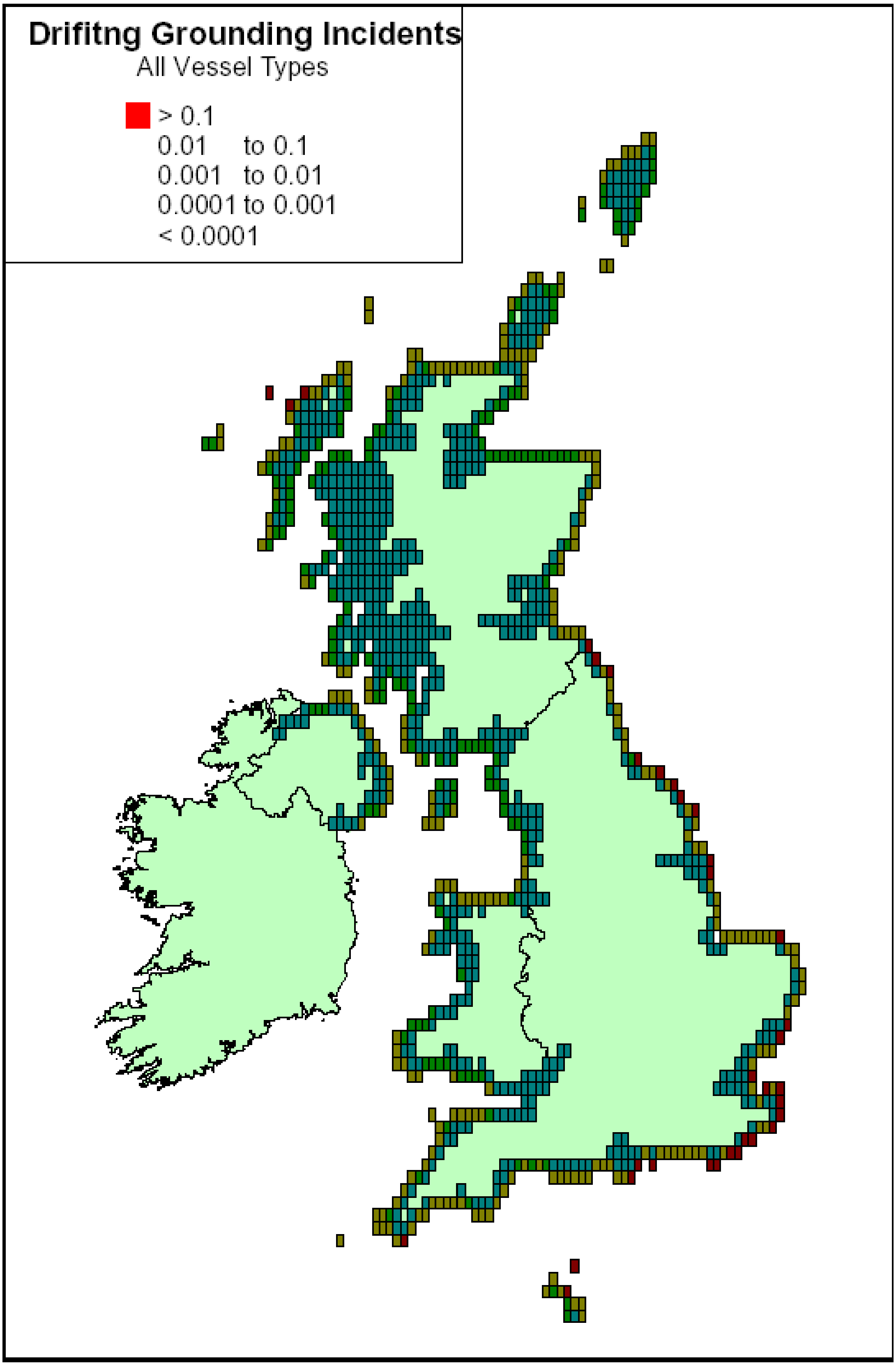


Figure 14 Model Predictions and Historical data for Powered Grounding in UK waters.

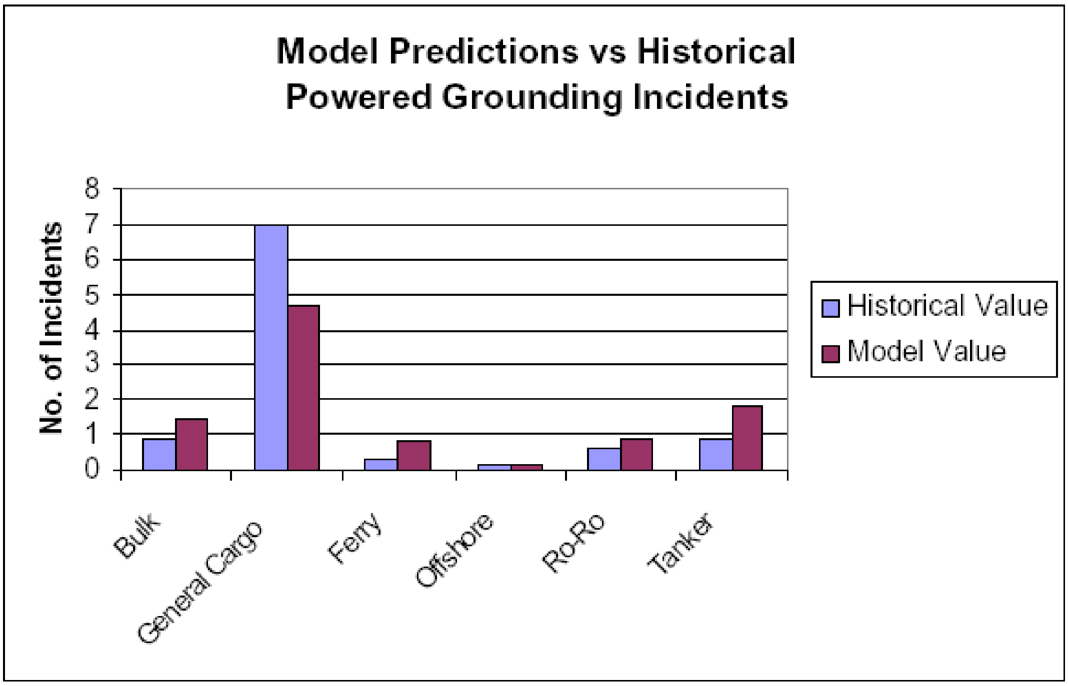


Figure 15: Forecasts and Data for Ship to Ship Collisions in UK waters.

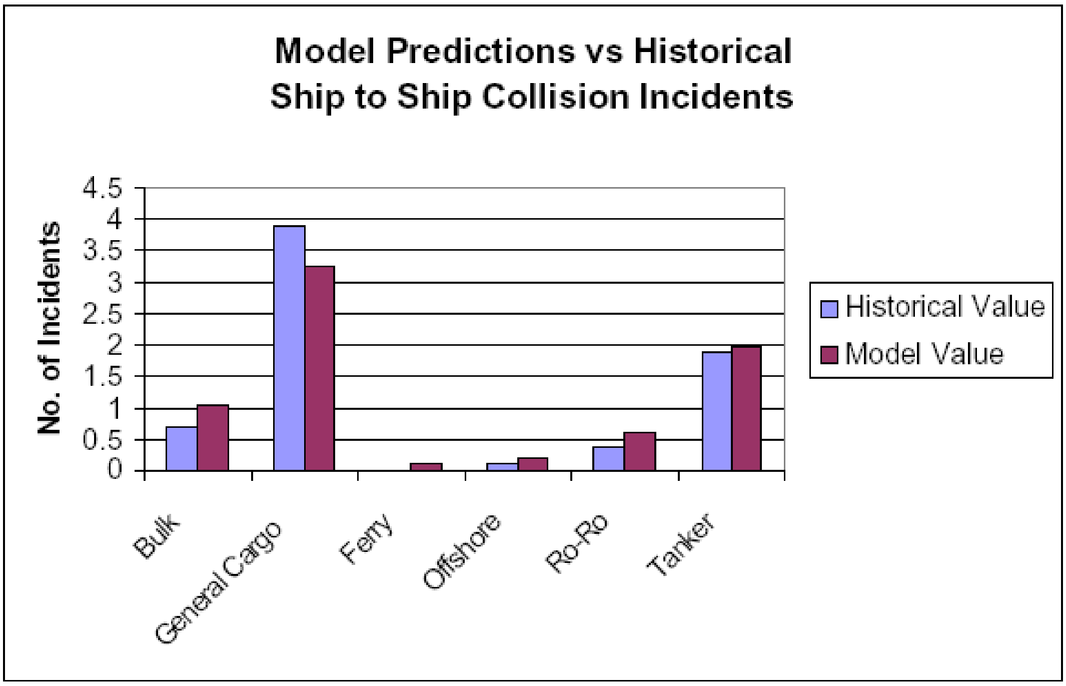
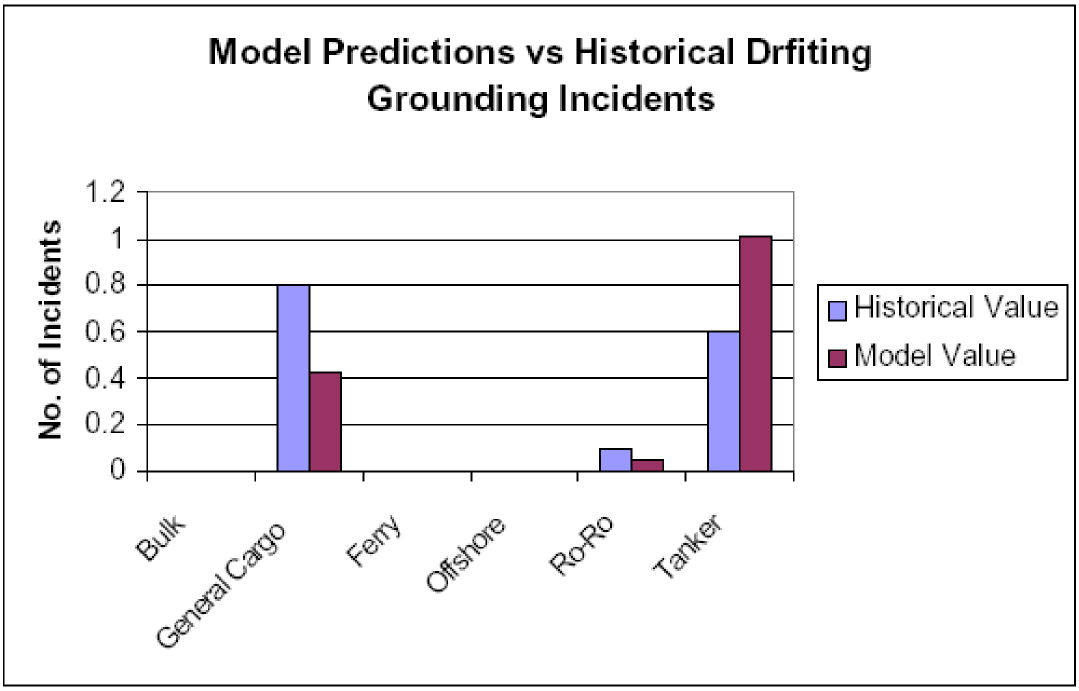


Figure 16: Forecasts and Historical Data for Drifting Grounding of Ships in UK Waters.



From this analysis the following conclusions derive:

- The frequency of powered grounding incidents where there are offshore windfarms is 0.0001 to 0.001 per year.
- The frequency of drifting grounding incidents where there are offshore windfarms is 0.0001 to 0.001 per year.
- The frequency of ship to ship collisions where there are offshore windfarms is zero.

The likelihood that the track of a ship, as it grounds and is therefore not steerable, will intersect a windfarm in a given rectangle is equal to the fraction of the rectangle occupied by a windfarm, which is of order 1/100 of the area of a rectangle.

A more detailed analysis leads to the conclusion that, in 2015, the frequency with which ships will collide with windfarms is 0.003 per year.

Severed Cable.

In the case of the offshore windfarms, which will be the dominant source of wind power in the UK, there is a finite possibility that the cable linking the generators with the grid, will be severed, for example by the anchor of a ship that is grounding. The chance of this happening in cases where the ship does not collide with the windfarm itself is low, only one tenth of the chance that the ship will collide with the windfarm.

Numerical Weather Prediction and Risk Assessment.

In this section we consider the effects of various extremes of weather on the availability of wind generation in the UK. Although Numerical Weather Prediction (NWP) is not new, its commercial application in the catastrophe modeling arena is. The idea of NWP was first proposed by Norwegian physicist Vilhelm Bjerknes in 1904. He theorized that future weather conditions could be predicted by taking an initial snapshot of current conditions and then solving the set of physical equations that govern fluid flow or, in this case, the atmosphere. Since those early days, advances in computing power, a deeper understanding of the laws of physics, and access to global environmental data have made the commercial application of NWP models possible. NWP has been the focus of decades of intense research conducted by the global scientific community. Billions of dollars have been invested in its development, and the rate of investment continues to increase. Today, NWP is the core operational forecasting technology used by meteorologists who analyze the weather and climate at all major meteorological agencies around the world, including NOAA, the UK Met Office, Meteo-France and the European Center for Medium-Range Weather Forecasts.

The traditional parameterized models perform quite well for many hazards. They do a reasonable job, for example, of capturing the relatively simple, symmetric structures that characterize hurricanes. They are unable, however, to realistically capture the highly complex meteorological structures of mid-latitude windstorms. These are the windstorms that occur in the UK. These so-called extratropical systems or, more generically, winter storms, are typically comprised of multiple areas of relatively low and high pressure, the locations of which can change quickly and frequently. While such storms typically do not achieve the intensity, in terms of wind speeds, that hurricanes achieve, they can affect, at a single time, an area of tens of thousands of square miles and can subject individual locations to high winds for up to several days. They can also produce large losses. As one example, the series of storms that swept across Europe in the winter of 1999 caused insured losses in excess of $17 billion.

Given the highly non-linear, or “chaotic”, nature of the atmosphere, small differences in the initial conditions that spawn such storms can result in large differences in storm evolution. In the case of winter storm models, then, the stochastic catalog of simulated events can be generated by taking data sets comprising the initial pressure fields of historical storms, perturbing them both spatially and temporally, and moving them forward in time through the application of a set of partial differential equations governing fluid flow. The result is a stochastic storm set that is much more realistic than could be produced by any statistical, or parameterized, model.

Storm.

Using a deterministic approach to estimating potential catastrophe losses, one might ask, for example: what would losses be today from a repeat of Daria, the winter storm that caused significant losses in the United Kingdom and continental Europe in 1990? It is interesting to speculate on these questions and catastrophe models are, in fact, well equipped to provide reliable loss estimates in response. As intriguing as such questions are, however, we also know that an exact repeat of these or other historical events has near zero probability of occurrence.

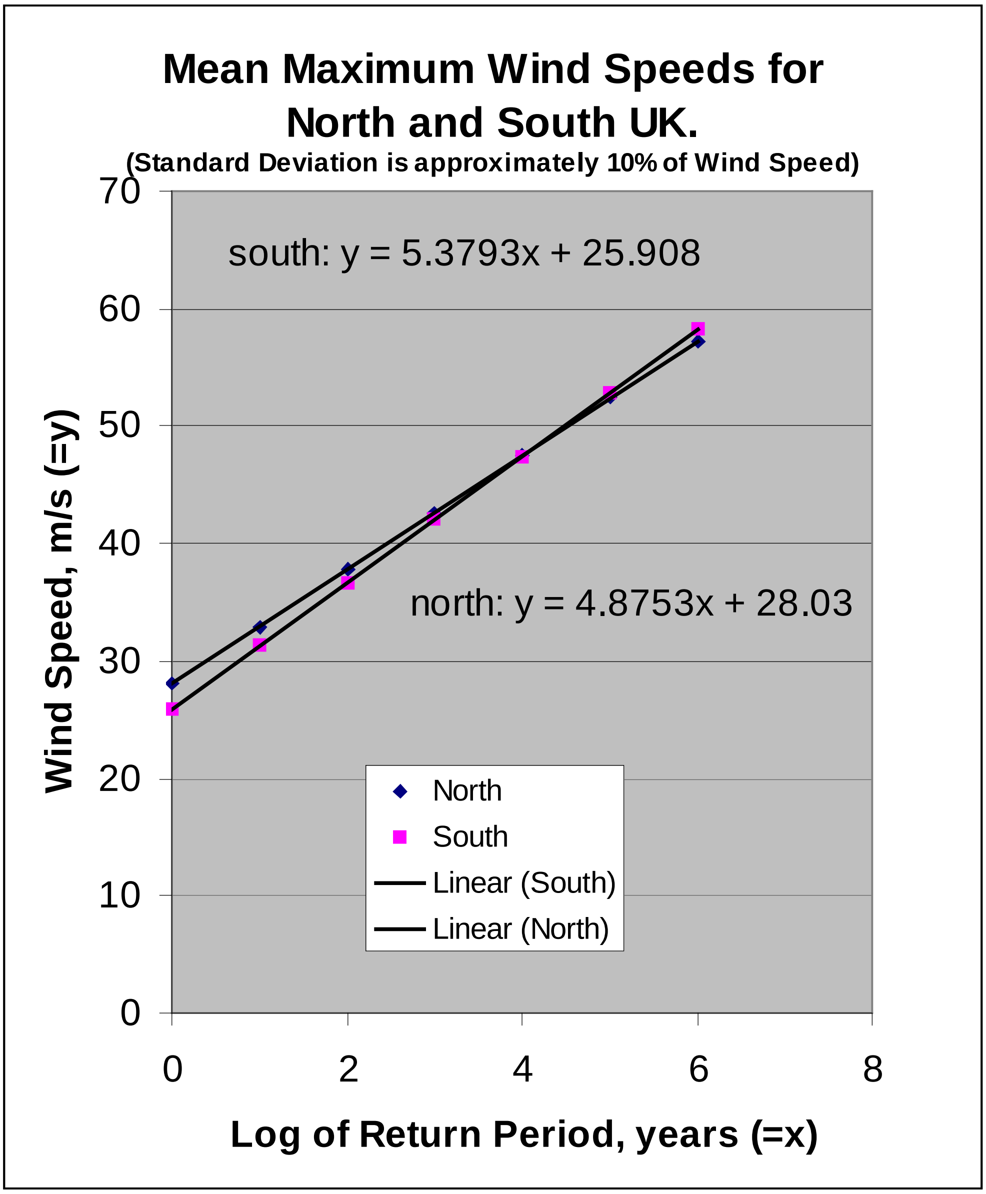
A more interesting question, then, is: what would losses there have been had Daria taken only a slightly more northerly course than it did and swept directly across London, much as winter storm Lothar roared through Paris in late 1999? What about a ``Super Daria" that is more intense and larger than the real Daria? There are many more scenarios that one might imagine. This is exactly what the event generation component of catastrophe models is designed to do: generate all types of possible, yet realistic, scenarios. Furthermore, because these events are being generated using high-speed computers, many thousands of potential events can be simulated in accordance with their relative probability of occurrence. Detailed scientific analyses are performed on the historical and geophysical data to develop the probability estimates. Through this large sample, or catalog, of simulated events, the event generation component determines the frequency, magnitude, and other primary characteristics of potential catastrophe events by geographical location.

The wind speed is always fluctuating, and thus the energy content of the wind is always changing. Exactly how large the variation is depends both on the weather and on local surface conditions and obstacles. Energy output from a wind turbine will vary as the wind varies, although the most rapid variations will to some extent be compensated for by the inertia of the wind turbine rotor.

In storms there is the possibility that wind turbines will be damaged. They are provided with over-speed protection and are designed to resist storm- force winds, but these provisions will fail with a calculable probability.

I have calculated the return periods of the mean maximum wind speed for the north and south of Great Britain. The results are given in Figure 17

Figure 17: Mean Maximum Wind speeds for North and South UK.



Wind generators are normally designed to resist the wind that has a return period of 50 years. We see that this has a velocity of just over 30 m/s, whereas at longer return periods much greater velocities are forecast: about 50 m/s with a return period of 10,000 years and, allowing for the 10% standard deviation of these predictions, around 60 m/s with a return period of 1,000,000 years. These are the mean maximum wind speeds and gusts of substantially higher velocities are to be expected (Figure 18). Tornados, with which I deal separately, produce much higher wind speeds, albeit for brief periods and over limited areas of land or sea.

Figure 18: The Highest Wind speeds Recorded in the UK.

Low-level	123 knots	Fraserburgh, Aberdeenshire

site:		13 February 1989
High-level site:	150 knots	Cairngorm (1,245 m AMSL), 20 March 1986

In the UK, the storms that generate these wind speeds cover areas equal to or greater than that of the whole country. They last on average for an entire day.

My forecasts have been made using the techniques developed at Riso Laboratory in the EU joule programme, [2] for the frequency with which storms will interrupt the UK's wind generation, for the case where the UK has 7 Gwe of installed wind generation capacity.

The verification of the structural integrity of a wind turbine structure involves analyses of fatigue loading as well as extreme loading arising from the environmental wind climate. With the trend of persistently growing turbines, the extreme loading seems to become relatively more important. The extreme loading to be assessed in an ultimate limit state analyses may result from a number of extreme load events including transient operation (start/stop sequences), faults, and extreme wind events. Examples of extreme wind events are extreme mean wind speeds with a recurrence period of 50 years, extreme wind shear, extreme wind speed gusts and extreme wind direction gusts. The present analysis addresses extreme wind turbine loading arising only from (a particular class of) extreme wind events included in the IEC-standard (IEC 61400-1, 1998) as extreme load conditions that must be considered as ultimate load cases when designing a wind turbine.

Within the framework of the IEC-standard, these load situations are defined in terms of two independent site variables - a reference mean wind speed and a characteristic turbulence intensity. The available experimental data material relates to the mean wind speed regime between 5m/s and 25m/s, and the present analysis is consequently limited to extreme wind conditions occurring during normal operation of the wind turbine. In the code these are described exclusively in terms of the turbulence intensity. In addition to the code, which is somewhat empirically based, theoretical models, based on probabilistic analysis of multi-variate random processes, exist that predict probability density functions of gust events. Also these models rely heavily on the site turbulence intensity. Thus the turbulence intensity - defined as the standard deviation of the wind speed divided by the mean wind speed - is the crucial parameter concerning modelling of this class of extreme wind conditions.

The standard deviation of the horizontal turbulence component plays a prominent role in the IEC 61400-1 formulation of the fatigue and extreme loading of wind turbines. The values for the class B turbulence intensities in the code claim to represent an 80% quantile level for a data material including measured turbulence characteristics

[2] Riso Report R 1111 EN. Gunner Chr. Larsen, Knut Ronold, Hans E. Jørgensen, Kimon Argyriadis and Jaap de Boer, 2002.

covering "all wind turbine relevant (on-shore) sites". The turbulence intensity specification in the code is thus intended to represent the turbulence characteristics of many different sites rather than to give precise information of one particular site.

IEC 61400-1 does not provide any specific information on turbulence intensities suitable for off-shore sites. Although differences in wind climates for off-shore sites definitely exist, these differences seem smaller than the mutual differences between wind climates related to on-shore sites in general, where large variations in terrain forms inevitably are represented. It is consequently expected that data from relative few off-shore sites can provide sufficient information to give a general idea of the off-shore wind climate. The extreme loading relates to atmospheric turbulence described in terms of a statistically stationary process. Gusts due to thunderstorms, tornados, down bursts etc. are not covered in this section of my analysis, but they are separately evaluated in this Report

Without the cut-out speed included in the reliability analysis, the variability in the mean wind speed would have become a much more important uncertainty source with a design point value in the range 35-40 m/sec, which is unrealistic for operation of the wind turbine. This would have led to a significantly higher failure probability in ultimate loading than the one reported here.

The results of these calculations are shown in Figure 19, which shows that the return period of wind speeds that will cause 50% of the wind turbines to fail is 2000 years. Storms that produce this wind velocity typically cover an area similar to that of the UK and it is assessed that half the wind turbines would be subjected to these wind speeds.

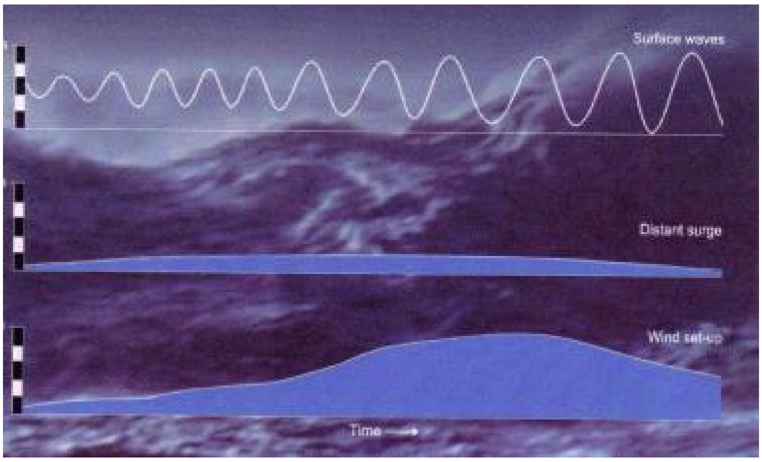
Figure 19: Design Wind Speed and Return Speed for Wind Turbine Failure.

Design Life, years	Design Speed, m/s	25% Above Design Speed.	Return period of 25% over design velocity, y
50	35	44	2000

Storm Surge.

The enormous mechanical forces of high waves have a colossal destructive potential, which can lead to the destruction of even solid steel and concrete structures, such as offshore installations like oil rigs and loading bays. The rise in sea levels will increase the storm surge hazard even further.

Figure 20: Illustrating the Factors Contributing to Surge, leading to rises of up to (and above) 5m in sea level.



The majority of coastal areas remain very flat even far into the hinterland. The water streaming in from the sea may therefore flood large areas, especially because even if a dam breaks, the water level in the sea - unlike in a river - does not go down and the volume of water there is virtually unlimited. In the vicinity of a breach, the rapid flow of water causes total losses, whereas some distance away damage is caused by the water level slowly rising, which on account of the corrosive quality of the salt water is more serious than the damage caused by freshwater floods.

Depending on the particular features of the coast affected, wave action and erosion of the sea bed may play an important role besides the surge itself.

The rise in sea levels will increase the storm surge hazard even further.

Basis of the Analysis of the Effects of Storm Surge on Wind Generation.

A storm surge is defined as the difference between the predicted astronomical tide and the actual height of the tide when it arrives. Two factors drive significant storm surges: the low pressure at the centre of a storm causes the sea level to bulge upwards, and more importantly, the high winds associated with a large and persistent pressure gradient can drive the water towards the shore.

On 31 January 1953, one of the strongest North Sea windstorms of the 20th century produced the highest storm surge ever recorded along much of the eastern coast of England. As the tide rose that evening, water levels reached heights not seen during at least the previous 250 years. The storm that caused the surge began to develop around midday on Thursday, 29 January as a low-pressure system located to the southwest of Iceland, with a central pressure of 1003 mb. The system proceeded to move to the northeast over the following 30 hours, deepening rapidly by 24 mb and was located to the northwest of Scotland by 6 pm GMT on Friday, 30 January. Instead of continuing on the same path, the system became influenced by the circulation around a strong anticyclone located to the west of Ireland and turned to the southeast. It entered the North Sea during the morning of 31 January, where it attained its lowest pressure of around 966 mb. The contrast in pressures between the low-pressure system and the anticyclone led to very high winds to the southwest of the storm centre, and a gust of 125 mph (56 m/s) was recorded at Costa Hill (altitude 15 m) in Orkney, the highest recorded land windspeed in the U.K. to that date. The winds caused significant damage to property and the destruction of forests in northeast Scotland, felling more trees than the annual timber-harvest.

As the storm system moved down the North Sea during the remainder of Saturday 31, high pressure continued to build over the eastern North Atlantic. Although the system was filling at the time, encroachment of the high pressure increased the pressure gradient over the North Sea, effectively squeezing the system and tightening the isobars. The strong winds pushed water into the North Sea from the Atlantic and southwards, generating the surge. The water was driven on-shore as the coasts of eastern England and the Netherlands funnel together and the sea becomes shallower, amplifying the surge along the east coast of England and then against the southwest coast of the Netherlands where it arrived during the early hours of Sunday, 1 February.The storm crossed the North Sea just two days after the full Moon, interacting with the spring tides (when the gravitational pull of the Sun and Moon combines to create the highest tide of the lunar cycle).

The high water levels and accompanying waves overwhelmed and broke through flood defences and walls all along the east coast of England during the night of Saturday 31 January.

On Saturday 31 in the morning, the storm claimed its first casualties when the Princess Victoria ferry, on passage from Stranraer in Scotland to Larne in Ireland, sank with the loss of 133 lives. Flood warnings for the east coast were issued late that morning, however there was no national coordinated system for distributing these warnings at the time. The danger mark on the Norfolk coast of 2.5 m (8 feet) above mean sea level was surpassed at 6 pm and within half an hour the sea level had risen a further 1 m (3 feet), giving a surge-height of 3.6 m. The sea level rose up to 0.6 m (2 feet) higher than recorded during the previous 80 years and for many sections of coast it remains the highest recorded surge in the North Sea.

This gives us an estimate of 100 years as the return period for a surge of height 3.5 m.

A government inquiry into the causes of the floods identified that along the 1,600 km (1,000 miles) of east coast affected there were 1,200 flood defence breaches, 647 square kilometers (160,000 acres) of land flooded, 307 people died and 24,000 houses were damaged, of which 500 were totally destroyed. Around 200 industrial facilities were also damaged by floodwater.

Among the worst affected areas was the low-lying Canvey Island in the Thames Estuary, which was completely inundated, the death toll was later confirmed at 58.

Water flooded up to 8 km (4 miles) inland around Cley on the north Norfolk coast, and to a depth of 1.8 m (6 feet) in the town centre of Kings Lynn. It was not just coastal communities that were at risk, as the surge travelled inland from The Wash along the Rivers Ouse and Nene, causing both rivers to overflow and break their banks. Along the south bank of the River Thames defences were breached, and the floodwater reached the top of embankments in the City and through Westminster.

The overall financial cost of the disaster at the time is difficult to quantify, as accurate records were not collated. A month after the flood, the Home Secretary, Sir David Maxwell Fyfe, estimated the material cost of the damage to be £40 - £50 million: equivalent to around £1 billion in 2003 values. However this does not include the impact of interrupted business activity or the costs of relocation. Flood was not a general insurance coverage at the time, and therefore the proportion of costs repaid by insurance was very small.

The spectre of a major storm surge flood in London led to the construction of the Thames Flood Barrier near Woolwich, which became operational in 1982. The barrier was initially designed to protect against extreme tidal surge events with a return period of up to 1 in 1,000 years until 2030.

Three hundred miles, or 45% of the dikes in southwest Netherlands were damaged. The floodwaters inundated 47,300 buildings, of which 9,215 were destroyed. A large quantity of livestock was killed, and infrastructure was severely disrupted with many roads submerged and damaged. Damage in the Netherlands was estimated at the time to be 1 billion guilders (250 million Euro), with 350 million guilders (90 million Euro) damage caused to the flood defences.

U.K. Storm Surge probabilistic catastrophe analysis model.

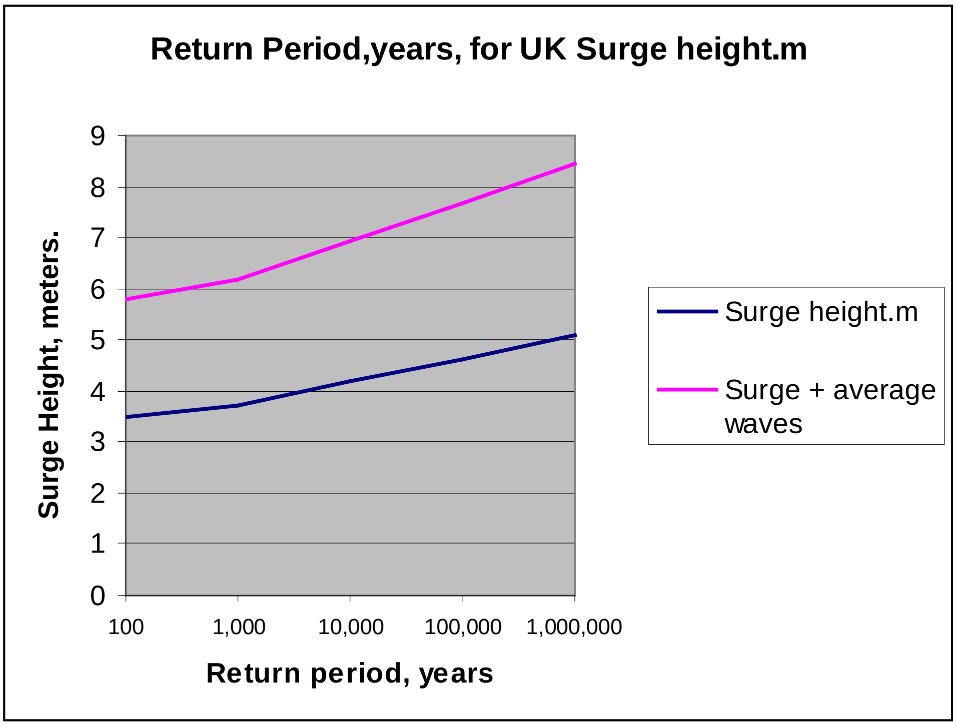
The analysis upon which I base the forecasts for Wind Generation explored a range of alternative combinations of tides arriving with the surge, including high tides even higher than those experienced on the night of 31 January 1953. It derives from the RMS U.K. Storm Surge model, which treats failures probabilistically according to surge height and wave action, using fragility curves appropriate to the construction type, height, and quality of each structure. By combining synthesised scenarios of varying probability, estimates of possible flood event losses are derived, each with their associated relative probabilities. Results are given in Figure 22, from which it is deduced that the return period for surges in which will damage or destroy half the wind-generators on the east or west coast of Great Britain is 1,250 years. That is to say, a frequency of 0.0004/year for the east coast and 0.0004/year for the west coast. These surges will be topped by waves that frequently exceed a height that will damage the rotors of the wind generators.

Figure 21 shows that it is the East Coast of England and Scotland together with the Welsh Coast of the Irish Sea that are the sectors subject to surge. Significantly many offshore and on shore wind farms are planned for these very regions.

Figure 21: Storm Surge Coastal Areas, UK and Nearby Continental Europe. (dotted lines along coasts}.

The insured property loss from all these possible scenarios, involving different states of tide and failure scenarios, ranges from £5 million to more than £2 billion. The probability-weighted average `expected' loss is £470 million with a return period of 40 years. This represents a significant reduction from the return period of loss reconstructed from the 1953 flood footprint, which is 750 years. However, rising sea-levels and continued subsidence of the southeast corner of England, together with the sea bed on which the offshore wind generators will be situated, which is associated with the recovery of land-levels after the Ice Age, act to increase the risk of high level storm surge year on year.

Figure 22: Return Period for UK Storm Surge.



Tornado.

The UK suffers more Tornados per square mile than any other country in the world.

The largest tornado outbreak in Britain is also the largest tornado outbreak known anywhere in Europe. On November 21, 1981, 105 tornadoes were spawned by a cold front in the space of 5.25 hours. Excepting Derbyshire, every county in a triangular area from Gwynedd to Humberside to Essex was hit by at least one tornado, while Norfolk was hit by at least 13. Very fortunately most tornadoes were short-lived and also weak (the strongest was around T5 on the TORRO Tornado Scale) and no deaths occurred.

Evidence that UK tornados are capable of damaging offshore structures is provided by the fact that, on December 28, 1879, all 74 lives were lost when a passenger train plunged from the Tay Bridge (Tayside) into the Tay Estuary, when the middle section of the bridge collapsed. Although the bridge was poorly constructed and had already been weakened in earlier gales (including the pre-existing winds at the time of the tragedy), the ultimate failure is believed to have been caused by two or three waterspouts, that is to say tornados over the water, which were sighted close to the bridge immediately before the accident.[3]

A tornado is a violently-rotating column of air which is usually in contact with the parent thunderstorm - although as many as a third occur without thunder. In the centre of a tornado, winds are actually very light and may descend towards the ground - just like the eye of a hurricane.

A tornado will typically last for a few minutes, track across the land for 2 to 5 kilometres (roughly 1 to 3 miles) and will have a diameter of 20 to 100 metres (roughly 20 to 100 yards). Windspeeds are in the order of 72 to 113 miles per hour - that is, T2 or T3 on the Tornado Intensity Scale. At the more extreme end, some tornadoes track for over 100 kilometres, are over 1 kilometre wide and have winds in access of 300 miles per hour (T10) - such tornadoes are extremely rare, anywhere in the world.

In contrast, a hurricane is an intense area of low pressure that only forms in the tropics where the sea surface temperature is at least 27 degrees Celsius. A hurricane has a diameter of around 100 miles, has mean windspeeds which must average at least 73 mph (by definition), and can last for several days - but will rapidly decay on making landfall.

Measuring Tornado Intensity

In the late 1960's, Dr. Theodore Fujita, of the University of Chicago, first developed a scale for classifying tornadoes. The Fujita Scale, or simply FScale, classifies tornadoes based on their rotational wind speeds and on the damage caused both to man-made structures and to vegetation. The index ranges from F0, representing tornadoes that result in only minimal damage, to F5, the most severe category of tornado causing "incredible" damage. A tornado's intensity will typically change during its brief life. Along a single tornado's path, then, it is not unusual to observe F2 damage at one point, F3 at another, and just F1 at a third. Because tornadoes generally last only minutes and, more often than not, occur out of the range of weather stations or anemometers (instruments used to measure wind speeds), assigning an Fscale classification is often an inexact science. When wind speed observations exist, the task is relatively straightforward. When no measured wind speeds are available, scientists and engineers must estimate wind speeds from observed damage.

A similar measure, the Tornado Intensity Scale was devised by Dr. Terence Meaden of Bradford-on-Avon, Wiltshire, Great Britain, in 1972. This ranges from T0 to T10, with each point representing a range of windspeed, just like the Beaufort Scale (in fact, the Tornado Intenstiy Scale is based directly on the Beaufort Scale). T0 to T3 are weak tornadoes, T4 to T7 are strong tornadoes and T8 to T10 are violent tornadoes. T10 = F5.

[3] Tornado and Storm Research Organisation. Head of TORRO:- Prof. Derek M. Elsom.Geography Dept.Oxford Brookes University.Gypsy Lane.Headington.Oxford. Oxfordshire OX3 OBP.

On average, 33 tornadoes are reported each year in the United Kingdom. This average is based on a 30 year period, though in reality the actual yearly figures may vary dramatically from year to year.

Most tornado reports are from the Western Midlands, Eastern Midlands, Central-Southern England, South-Eastern England and East Anglia. Some occur in South-Western England, North-Western England, North-Eastern England and Wales. Tornadoes are rare in Northern Ireland and Scotland, Figure 23.

Figure 23: Tornado Intensities in the UK and Western Europe. The darker the shade of green, the higher the intensity.

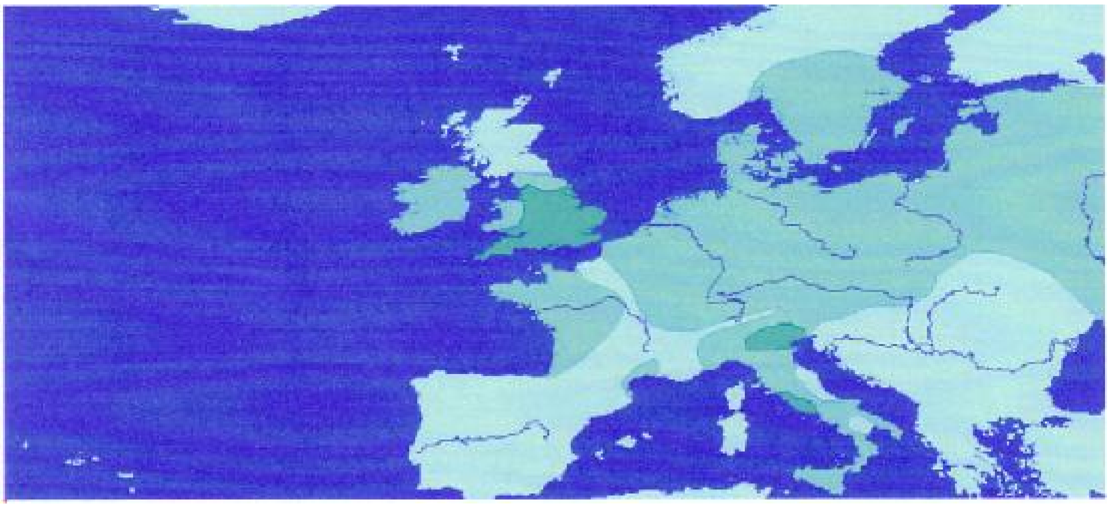


Figure 24: % of Tornados having stated intensity or less.

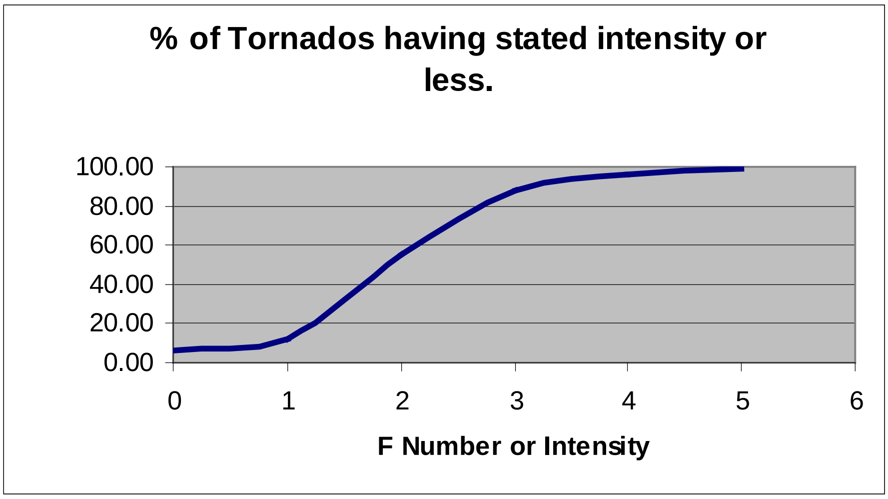
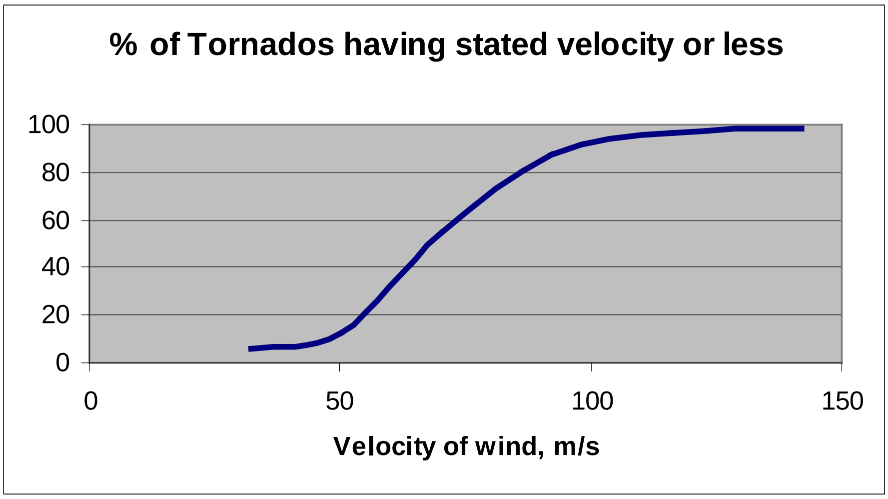


Figure 25: % of Tornados having stated velocity or less

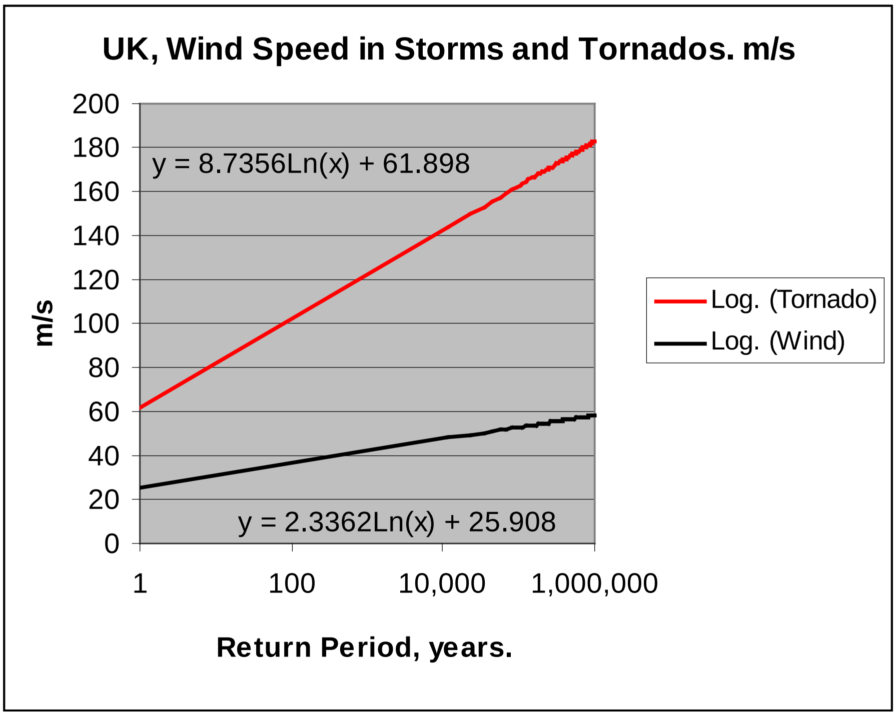


Two tornadoes in Britain are known to have reached F4 or T8; their antiquated nature necessitated great caution in assigning intensities, so it is possible that they may have been even stronger.

- The first, also Britain's earliest known tornado, occurred on October 23, 1091. The church at St. Mary le Bow in central London was badly damaged, with four rafters - each 7.9 m long (converted from the reported 26 ft) - being driven into the ground (composed of heavy London Clay) with such force that only 1.2 m (converted from the reported 4 ft) protruded above the surface. Other churches in the area were demolished, as were over 600 (mostly wooden) houses.

- On September 22, 1810, another T8 tornado tracked from Old Portsmouth to Southsea Common (Hampshire) also causing immense damage - although no deaths, it is believed. Some houses were completely levelled and many others were so badly damaged that they had to be demolished; chimneys were blown down and the lead on a bank roof was "rolled up like a piece of canvas and blown from its situation".

Figure 26: Return periods for Wind Speeds in UK Storms and Tornados.



Predicting the Damage due to Tornados

Within cyclones, wind speeds generally increase with height. The air spirals upward to the central core of the tornado to merge with the airflow in the parent cloud at the top. Structural failures occur even in well engineered commercial structures. Structures also sustain damage from airborne debris that act as missiles. These are usually pieces of already damaged structures that are picked up by the force of wind and carried sometimes great distances. The high-speed rotating winds of a tornado can turn almost anything into a missile. To estimate the damage and associated losses from these perils, models use damageability relationships, or damage functions, which have been developed over a period of many years. Post-disaster field surveys provide first-hand data on how structures perform when subjected to such extreme weather conditions. These data are incorporated into the modes through the subsequent calibration and testing of the damageability relationships.

My estimates for the effects of tornados on the reliability of wind generation in the UK were arrived at by the same methods as for the effects of storms. Even the most up-to-date building codes do not require that buildings and structures such as wind turbines be able to withstand the extreme winds of violent tornadoes. Accordingly it is clear that tornados capable of damaging a wind generator occur somewhere in the UK every year. The frequency with which wind generators are damaged by tornados are therefore dominated by the fact that the area affected by a tornado is small- smaller than a windfarm. The likelihood that one of the damaging tornados that occur in a given year will occur where there is a wind farm is therefore low.

Hail.

Figure 27 shows that the intensity of the risk presented by Hail, in the UK, is greatest in the southern part.

For the recent period from 1981 to 2000 potentially damaging hail (TORRO intensity of H1 or more on a scale of 1 to 10) was reported on between 6 and 28 days each year with an average annual frequency of 15 days in Great Britain .Analysis of TORRO's database of more than 800 hailstorms which reached an intensity of H3 or more reveals that the early summer experiences the highest proportion of such storms, with more than half (52%) occurring in June or July. Around three-quarters of all these hailstorms (77%) occurred between May and August, with June experiencing the peak monthly frequency (29%).

The area most frequently affected by hail damage extends from Lancashire, Greater Manchester, and Merseyside, south-eastwards to the counties in and around the Thames Valley (Berkshire, Bedfordshire, Buckinghamshire, Hertfordshire, Oxfordshire) and Greater London, and to parts of East Anglia (Cambridgeshire, Essex and Suffolk).

The earliest known severe hailstorm in Britain occurred at Wellesbourne in Warwickshire in May 1141 and was at least H3 in intensity. However, there are believed to have been one or more fatalities caused by hail - which would infer very large stones and hence a much higher intensity rating.

On September 22, 1935, an H6 hailstorm tracked 335 km from the west-south-west from Newport (Gwent) to Mundesley (Norfolk). It is likely that the true length was longer still, as the storm probably tracked along the Bristol Channel for some distance before reaching Newport, as well as continuing over the North Sea after Mundesley. Several hailstorms have reached H7 in Britain, but only one H8 has been recorded. On May 15, 1697, a H8 hailstorm tracked from Hitchin to Great Offley (Hertfordshire) - although this makes a track length of only 5 km, the true hail swathe must have been much longer.

The heaviest hailstone recorded in Britain fell from the H7 storm which tracked 150 km from West Wittering (West Sussex) to Maldon (Essex) on September 5, 1958 - the stone, which fell on Horsham (Sussex), weighed 141 g. However, descriptions from older accounts which do not usually quote weights clearly indicate that significantly heavier stones have fallen in Britain (even when suspected exaggeration is taken in to account).[4]

[4] For further details see Webb, J. D. C, Elsom, D. M, and Reynolds, D. J (2001) Climatology of severe hailstorms in Great Britain, Atmospheric Research 56, pp 291-308

Figure 27: Hail. Purple Shading.

Figure 28: Frequency with which Hail storms of various intensities will strike wind farms in the UK in 2015.

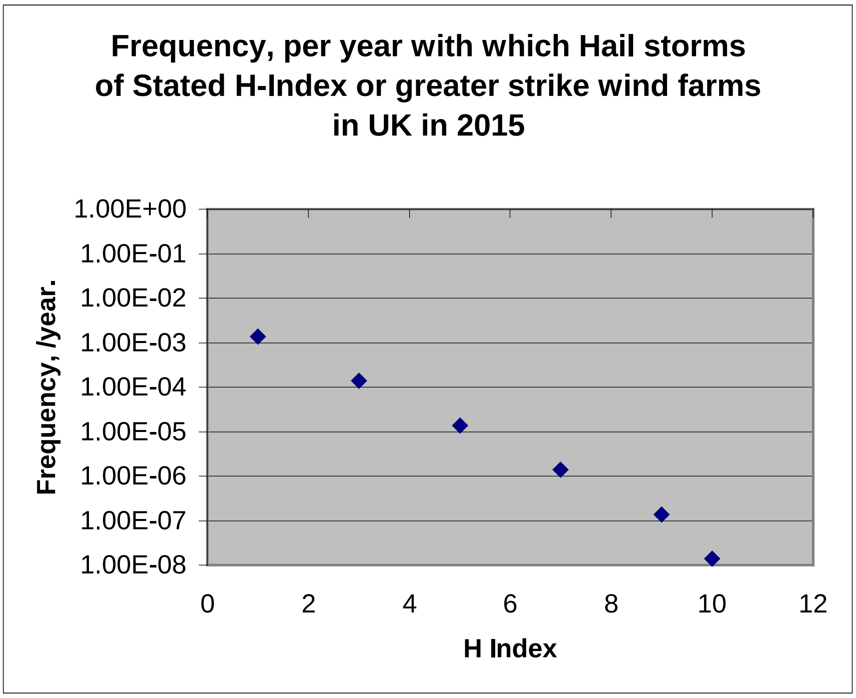


Figure 28 shows the calculated frequency with which hailstorms of the stated H Index or greater will strike wind farms in the UK in 2015.

Damage to 10% of the turbines on a windfarm will be produced by hailstorms of intensity H9 or greater. This means that, for hail, the frequency with which 10% of a single wind farm, say a loss of 10Mwe, will occur in 2015 is 0.000,0001/year.

High Sea.

Figure 29: High Seas (dark blue), Storm Tracks (black arrows), Tornado intensity (green) and limit of ice-bergs (white triangles)- shows that High Seas affect the coasts of the UK. Figure 29 shows the return periods for waves of various heights for the UK coastal areas. I have estimated their effect upon the security of supply of wind generation in the UK, using the probabilistic methods of the present Report.

The enormous mechanical forces of high waves have a colossal destructive potential, which can lead to the destruction of even solid steel and concrete structures, such as offshore installations like wind generators, oil rigs and loading bays.

Waves with a return period of 1,000 years have a mean height of 6.6 metres and a standard deviation of 10% of this height, that is to say 0.66 metres. A proportion of such waves will damage the rotating airfoils of off shore wind turbines, leading to a loss of the order of 1%.

Figure 29: High Seas (dark blue), Storm Tracks (black arrows), Tornado intensity (green) and limit of ice-bergs (white triangles)

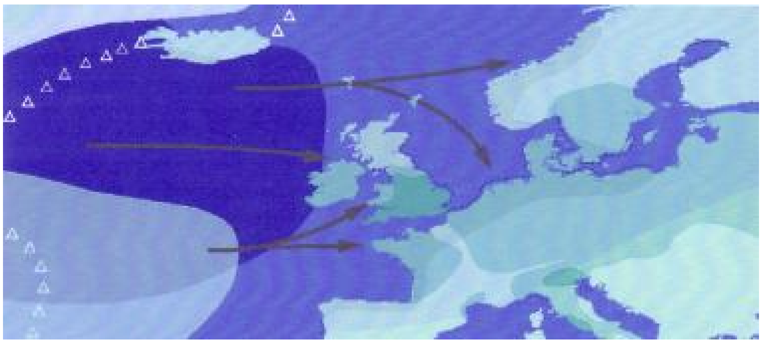
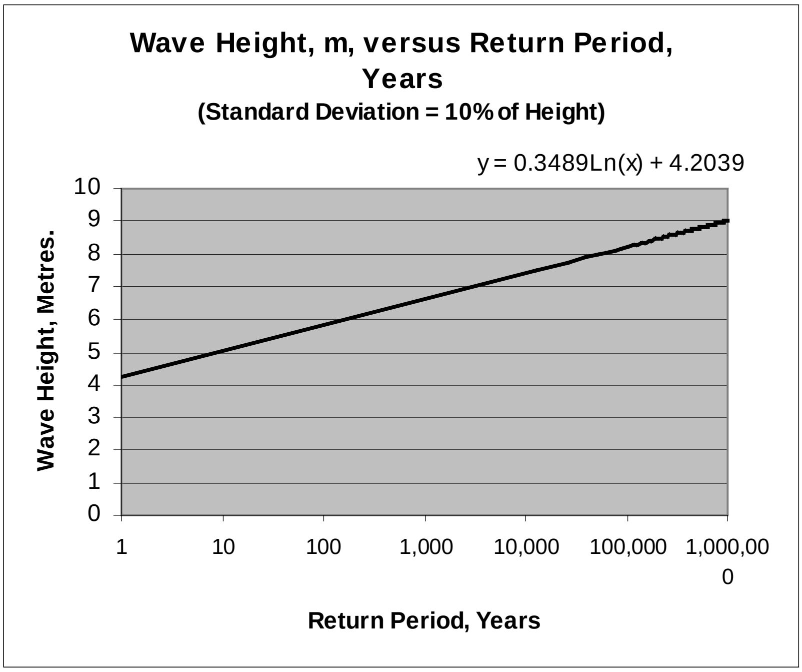


Figure 30: Wave Height, East and West Coasts of Great Britain, versus Return Period.

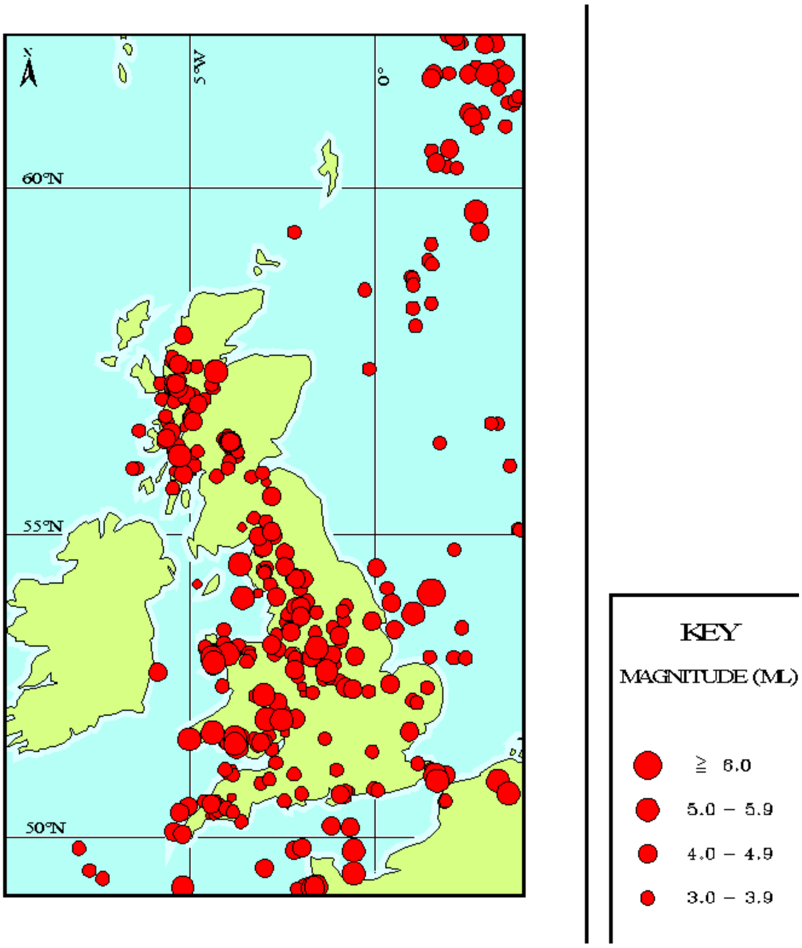


Earthquake

The UK is not a country generally associated in the public mind with earthquakes. However, while the UK is nowhere near in the same league as high seismicity areas such as California and Japan, it nevertheless has a moderate rate of seismicity, sufficiently high to pose a potential hazard to sensitive installations such as dams, wind generators and chemical plants.

Figure 31: Regions of Raised Seismic Intensity, UK and Continent, The darker the yellow colour, the more seismically active the zone.

Figure 32: Earthquakes in the UK and its coastal waters.



The spatial distribution of earthquakes in the UK is neither uniform nor random. For example, in Scotland most earthquakes are concentrated on the west coast, between Ullapool and Dunoon, with the addition of centres of activity near the Great Glen at Inverness and Glen Spean, and a small area around Comrie, Perthshire, and extending south to Stirling and Glasgow. The Outer Hebrides, the extreme north and most of the east of Scotland are virtually devoid of earthquakes. For the north-west of Scotland the absence of early written records, the small population, and the recent lack of recording instruments means that there may be a data gap in the context of an apparent event in 1925, possibly near Ullapool, with magnitude probably about 3½ ML, for which there are no first-hand reports. However, many other parts of Scotland, especially south of the Highland line, are quite well-documented, at least since 1600, and therefore the lack of earthquakes is genuine.

Further south a similar irregularity is seen. If one draws a quadrilateral from Penzance to Holyhead to Carlisle to Doncaster, most English and Welsh earthquakes will be included within it. The northeast of England seems to be very quiet; almost aseismic. The southeast has a higher rate of activity, with a number of earthquakes which seem to be "one-off" occurrences. The most notable example of these is the 1884

Colchester earthquake, a magnitude 4.6 ML event which was the most damaging British earthquake in at least the last 400 years, and yet which occurred in an area (Essex) otherwise more or less devoid of earthquakes from the earliest historical period up to the present day (Musson et al 1990). There are also important centres of activity near Chichester and Dover. The former produced a swarm-like series of small, high-intensity earthquakes in the 1830s and was active again in 1963 and 1970.

Offshore, there is significant activity in the English Channel and off the coast of Humberside. Because only the larger events in these places are likely to be felt onshore, the catalogue in the pre-instrumental period is probably under-representative of the true rate of earthquake activity in these zones. Even after the introduction of seismometers, offshore earthquakes may still have gone unnoticed on account of the distance to the nearest instruments. The Central Grabens of the North Sea are now known to be active features, only because of the improvements in instrumental monitoring over the last fifteen years.

The whole of Ireland is practically free of earthquakes. This is clearly a real phenomenon and not a product of reporting - as Ware, as early as the 17th century, remarks in describing an earthquake (probably Welsh) felt in Dublin in 1534, *"... qui casus adeo rarus est in Hibernia, ut quando contingit, inter prodigia habeatur"* [loosely, which is such a rare thing in Ireland that when it happens it is considered a wonder].

Certain centres can be identified as showing typical patterns of activity. For example, the Caernarvon area of north-west Wales is one of the most seismically active places in the whole UK. Both large and small earthquakes, usually accompanied by many aftershocks, occur at regular intervals. The most recent of these larger events was the earthquake of 19 July 1984 (5.4 ML), which was one of the largest ever UK earthquakes to have an epicentre on land and had a very protracted aftershock sequence. Two further felt earthquakes have occurred there since, on 29 July 1992 (3.5 ML) and 10 February 1994 (2.9 ML). It is tempting to ascribe several early earthquakes of unknown epicentre (eg that of 20 February 1247) to this area just because it seems to be such a favoured site for large earthquakes.

In South Wales, on the other hand, although a line of epicentres of significant events can be traced from Pembroke (an earthquake in 1892) to Newport (active in 1974), only the Swansea area shows consistent recurrence, with significant earthquakes occurring in 1727, 1775, 1832, 1868 and 1906. (Given this periodicity it may be that a further earthquake in this area is due in the near future.) The Hereford-Shropshire area has also produced large earthquakes in 1863, 1896, 1926 and 1990, but none of these share a common epicentre.

The area of the Dover Straits is particularly significant because of the occurrence there of two of the largest British earthquakes in 1382 and 1580 (both of magnitude about 5¾ ML). Since 1580 the only earthquakes there have been much smaller, raising the question of whether there is a danger of another 1580-style earthquake in the near future. The area may be structurally continuous with a zone of activity running east through Belgium, in which case it could be argued that stress in this area since 1580 has been released further east. This does not rule out another 1580-type earthquake in the future, but it is impossible to estimate how soon it might occur.

In the north of England seismic activity occurs over a more or less continuous area from Leicester to Carlisle. The most prominent centres of repeating activity here are the upper end of Wensleydale (with significant earthquakes in 1768, 1780, 1871, 1933 and 1970) and to a lesser extent the Skipton area.
What is remarkable is the lack of correlation between this pattern and the structural geology of the UK.

The boundaries between areas of moderate or high seismicity and areas of very low seismicity do not correspond to any major structural feature; for instance the sharp dividing line running SE from Inverness. And the major boundaries are not clearly reflected in the pattern of seismicity either as dividing lines between zones of differing rates of seismicity nor as lineations marked by earthquakes. It seems likely that the pattern of seismicity may be influenced by the distribution of ice during the last glaciation - certainly for Scotland this appears to be the case.

The distribution of British earthquakes in time

Earthquakes are not rare in the UK, as Figure 33 shows there have been ten in March 2003.

Figure 33:This map created at Tuesday March 25 08:42:25 GMT 2003

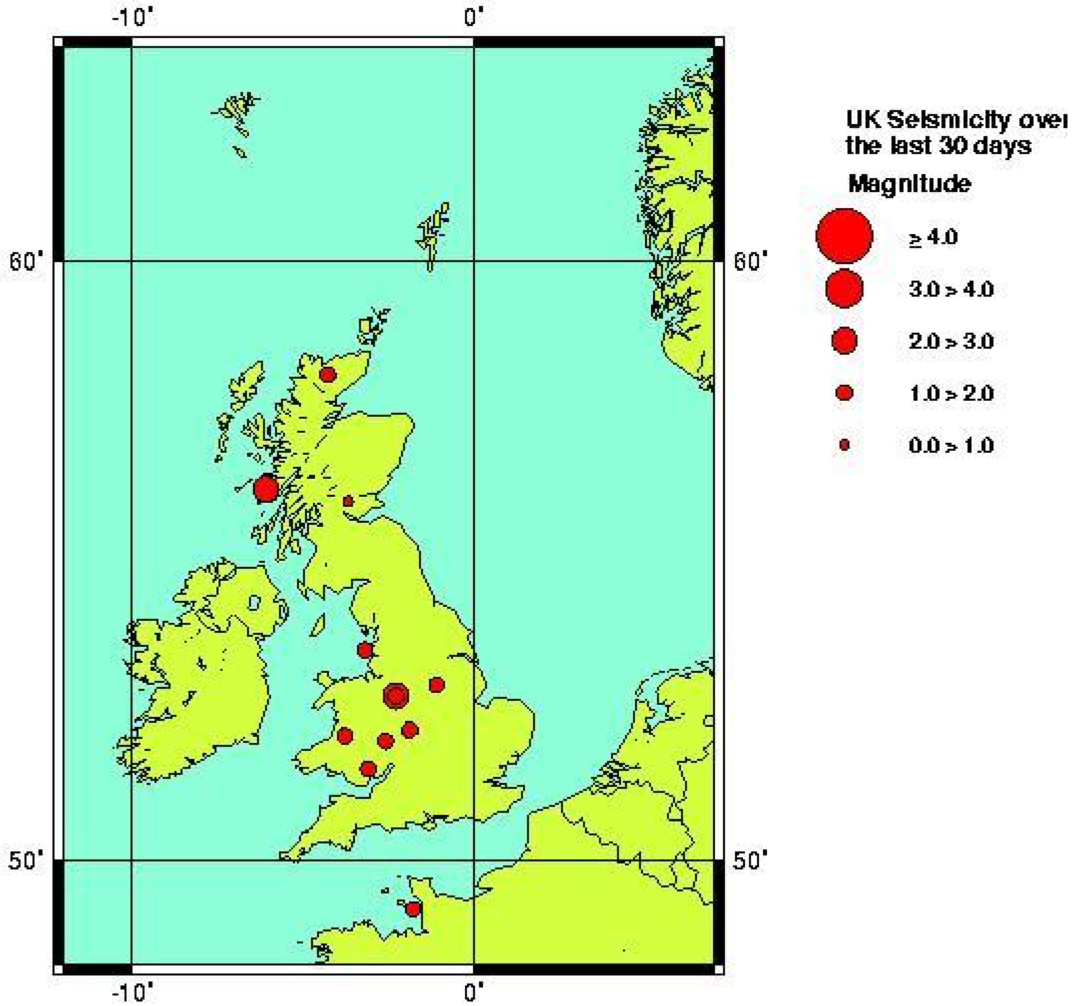
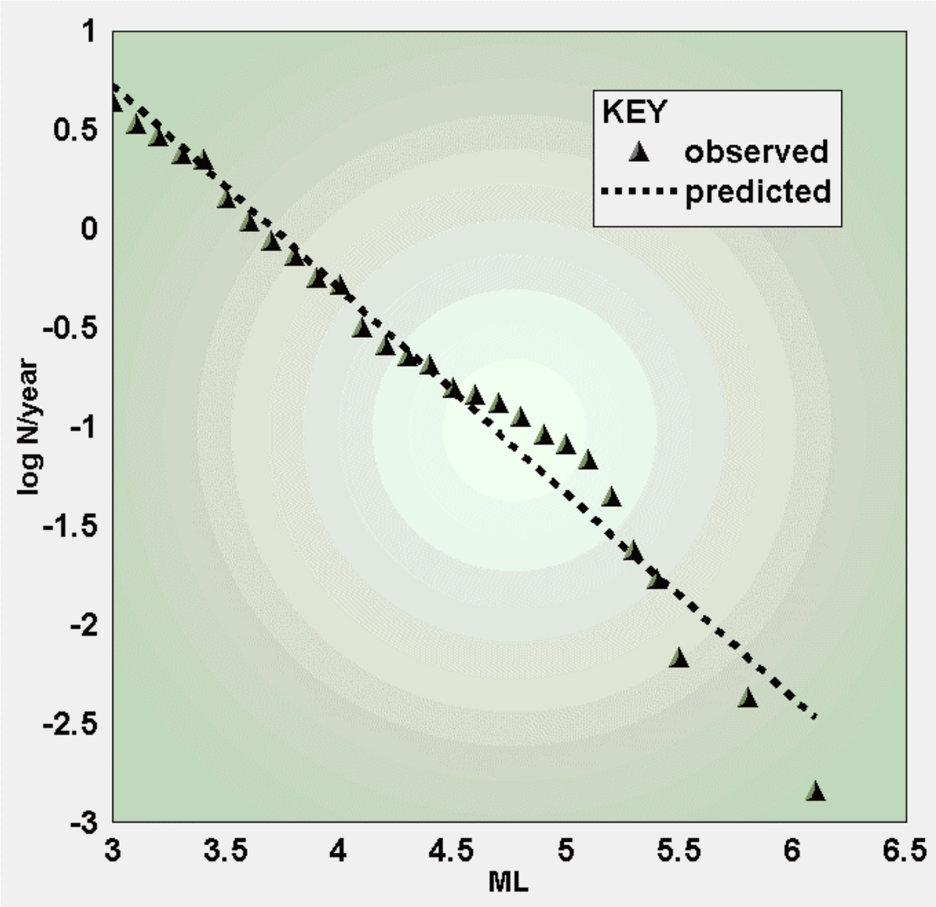


Figure 34: Frequency of Exceedance Versus UK Earthquake Intensity.



It has long been realised that larger earthquakes occur less frequently than smaller earthquakes, the relationship being exponential, ie roughly ten times as many earthquakes larger than 4 ML occur in a particular time period than earthquakes larger than magnitude 5 ML. This can be expressed by the Gutenberg-Richter formula

log N = a - b M

where N is the number of earthquakes per year exceeding a given magnitude M. The constant a reflects the absolute level of seismicity in an area, and the value of b has generally been found to be consistently close to 1.0.

This holds true for the UK for the area 10o W to 2o E and 49o N to 59o N. This deliberately excludes the northern North Sea area which is of high seismicity and completely under-represented in the catalogue before 1970 because of the impossibility of detecting smaller events in this area before that date. A least-squares regression to the UK data of Figure 34 gives the relationship

$$\log N = 3.82 - 1.03\ M$$

One can therefore draw the following conclusions about average recurrence - the UK may expect:

- an earthquake of 3.7 ML or larger every 1 year
- an earthquake of 4.7 ML or larger every 10 years
- an earthquake of 5.6 ML or larger every 100 years.

Seismic hazard calculations

Seismic hazard calculations in regions of low seismicity, such as the UK, are generally based on probabilistic methodology. Probabilistic seismic hazard assessment (PSHA) uses a combination of interpreted geological and seismological data to calculate the probability that a certain level of ground motion will be exceeded, or not exceeded, in a given period of time. This methodology can be divided into three principal components as follows:

(i) Definition of a set of seismic source zones which define the geographical variation of earthquake activity. These source zones are based on the distribution of observed seismic activity together with geological and tectonic factors and represent areas where the seismicity is assumed to be homogenous; ie there is an equal chance that a given earthquake will occur at any point in the zone.
(ii) An understanding of earthquake recurrence with respect to earthquake magnitude, as described above.
iii) An attenuation relationship is required which defines what ground motion should be expected at Location A due to an earthquake of known magnitude at Location B. The rate at which the strength of shaking decreases with distance from an earthquake's epicentre varies regionally and has to be calculated or estimated. Peak ground acceleration (pga) is the measure of earthquake shaking most used by engineers in this country. However, it has two disadvantages - firstly, the attenuation of pga in the UK is very poorly known, and secondly, pga is actually not a particularly good measure of the actual expectation of damage. A useful alternative is intensity, which is an expression of ground shaking in terms of its effects. The attenuation of intensity in the UK is very well documented, and intensity is directly proportional to damage, making it a very meaningful parameter.

The intensity attenuation model used here is expressed by the formula

$I = 3.32 + 1.44\ ML - 3.34 \log R$

where ML is local magnitude and R is hypocentral distance in kilometres. The data that I have used to produce this formula are found in Musson [5] .

Seismic hazard studies in the UK in the past have been mostly single-site studies for particular installations. The first attempt to look at hazard for the UK as a whole using the PSHA methodology was conducted by Ove Arup around 1991. This study calculated hazard at eleven representative sites in the UK. Following this, a study to produce contour maps of UK seismic hazard was commissioned by the Department of Trade and Industry. In this study the computer code SUNMIC was used, which allows a "logic tree" model to be applied to the hazard, by which uncertainty in input parameters can be modelled by the inclusion of multiple choices each with a weighting value).

One of the innovations used in this study was the approach taken to source zone modelling. If several significantly different source zone models are included in a logic tree model without regard for their combined effect, the result tends to be that the conflicting source zones smear one another out into a semi-uniform distribution of hazard; meaningfulness is lost. In this study, two mutually supportive zone models were constructed; one consisted of relatively broad zones based chiefly on the general regional trends observed in the seismicity data. The second consisted of much smaller zones closely placed around sites of known large earthquakes, the size of these zones being roughly related to the degree of uncertainty in the epicentral location. The result of the combination of these two models was a hazard map in which the general areas where earthquakes might be expected to occur would have higher hazard, but within these, spots where such earthquakes had occurred in the past were picked out as having locally higher hazard values.

[5] Musson, R.M.W., 1994a. A catalogue of British earthquakes, BGS Technical Report No WL/94/04.

Seismic hazard results

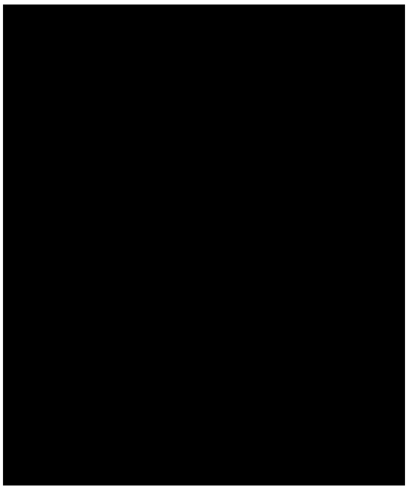
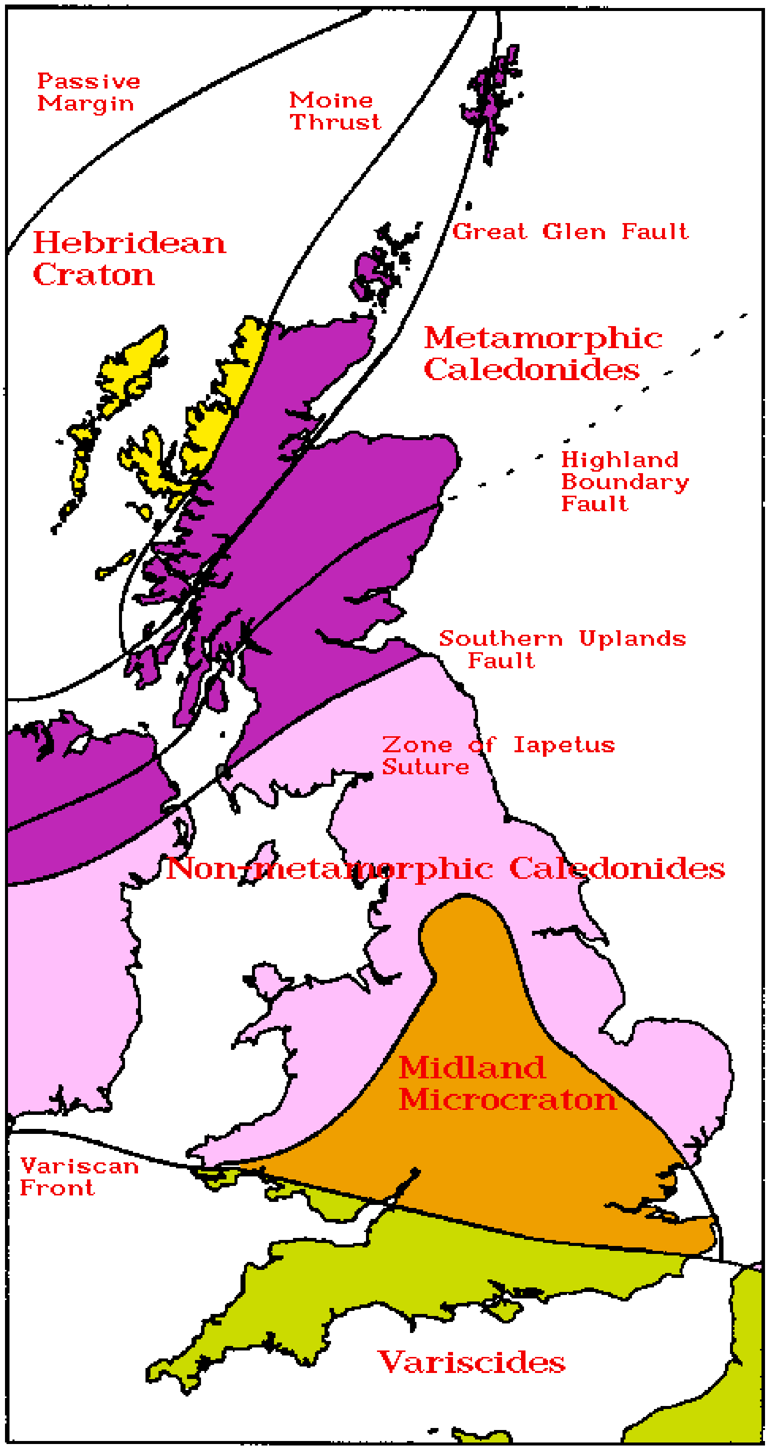


Figure 35 Seismic Hazard Map of the UK.

Figure 36: Tectonic Map of the UK, for comparison with Seismic Hazard Map.



A sample hazard map of the UK is shown in Figure 35.

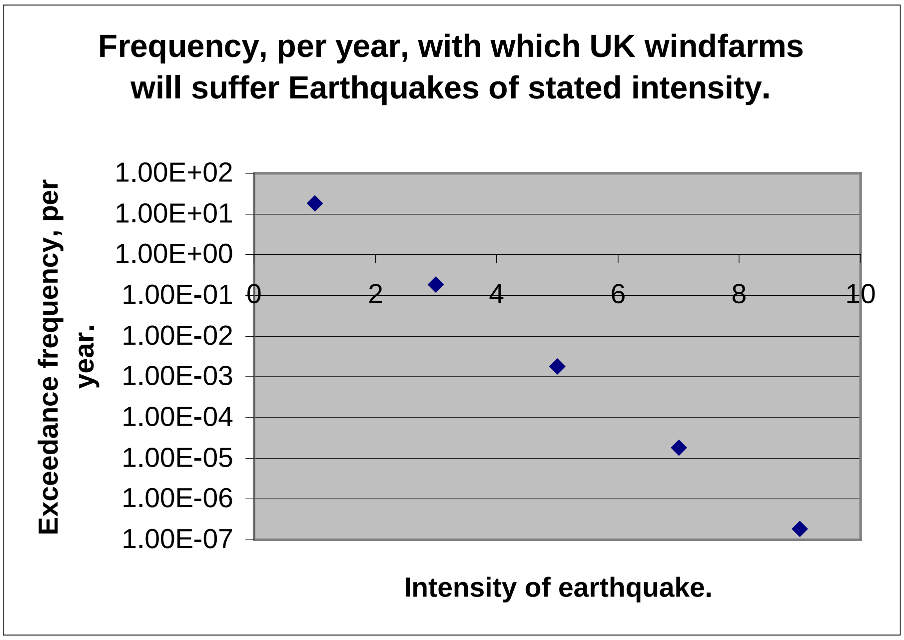
The map shows intensities that are 90% likely not to be exceeded in 50 years - equivalent to a return period of 475 years.

As might be expected, the areas of highest hazard parallel the areas where earthquakes have been most common in the past, but particularly those places where repeated earthquake activity has been highly localised - this localisation has a pronounced effect on the hazard calculations compared to areas where the seismicity, while high, is more diffuse and less repetitive. The zones where hazard is higher than average encompass the W Highlands of Scotland, an arc running from Carlisle to Pembroke, NW Wales and W Cornwall. The places in the UK with lowest seismic hazard are Northern Ireland (especially the western counties) and outlying parts of Scotland, including the Orkneys and Outer Hebrides.

The actual values of hazard are not particularly high, since the predicted intensity for the higher zones is only 6 EMS. In other words, even in areas of relatively high exposure to earthquakes in the UK, if a facility has a life of 50 years there is only a 10% chance that it will experience shaking equivalent to intensity 6. Moving briefly from hazard to risk, if we take as a guideline that probably less than 5% of buildings of normal construction (eg conventional brick houses) will be damaged in a place when the intensity there is 6, the probability of damage for a single house in 50 years is therefore less than 0.5%.

The indices so arrived at are shown in Figure 1 and the Exceedance frequency with which windfarms will suffer earthquakes of various intensities, in 2015, is shown in Figure 37.

Figure 37: Exceedance Frequency with which UK Windfarms will suffer earthquakes of stated intensity in 2015.



Machinery Breakdown.

Machinery such as the generator in a wind turbine is normally very reliable and will have breakdown between once and ten times in 10,000 years of operation. I have here assumed a return period of 1,000 years for machinery breakdown. This gives, with nearly 100% certainty, a loss of 0.1% of wind generation capacity. I have shown this separately in Figure 2 and have not plotted it in Figure 3.

Annex: Maps.

Figure 38: UK offshore Wind farms, planned and in operation.

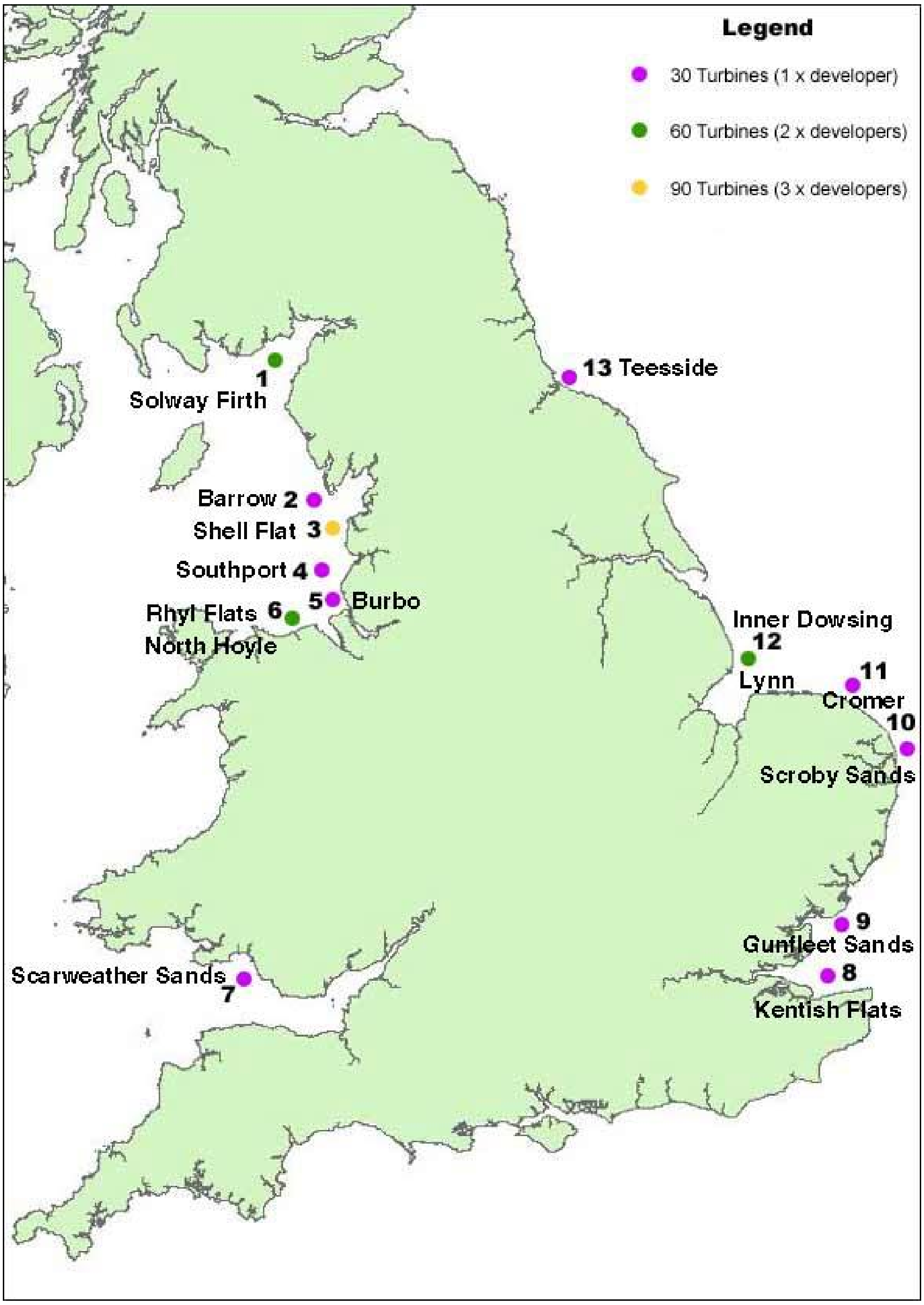


Figure 39. Onshore Wind Farms in the UK, operating and planned.

Figure 40: Location of Carno Wind Farm, Welshpool or Montgomeryshire, Mid-Wales.

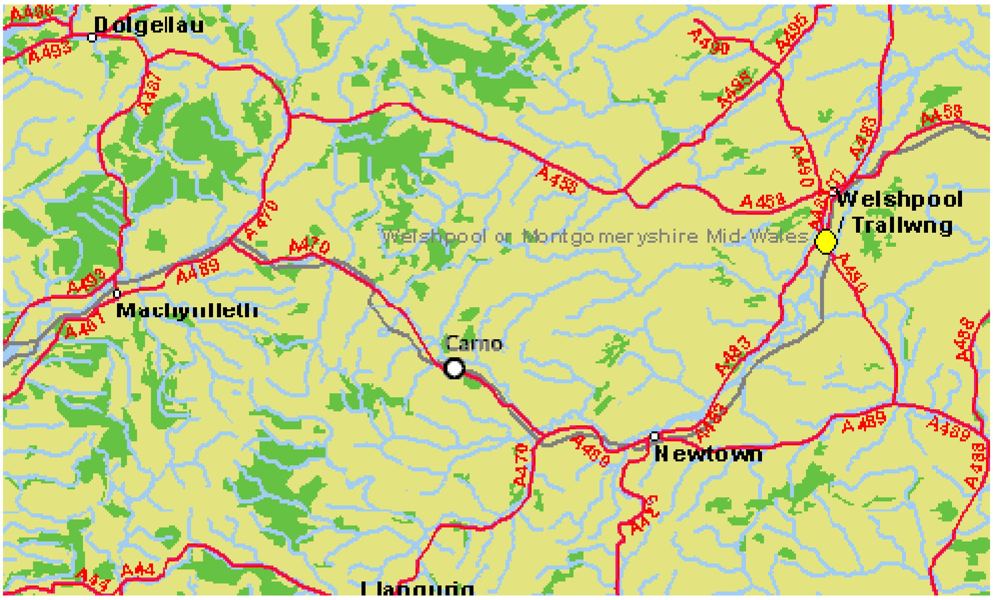


Figure 41: Carno Wind Farm: Site Map.

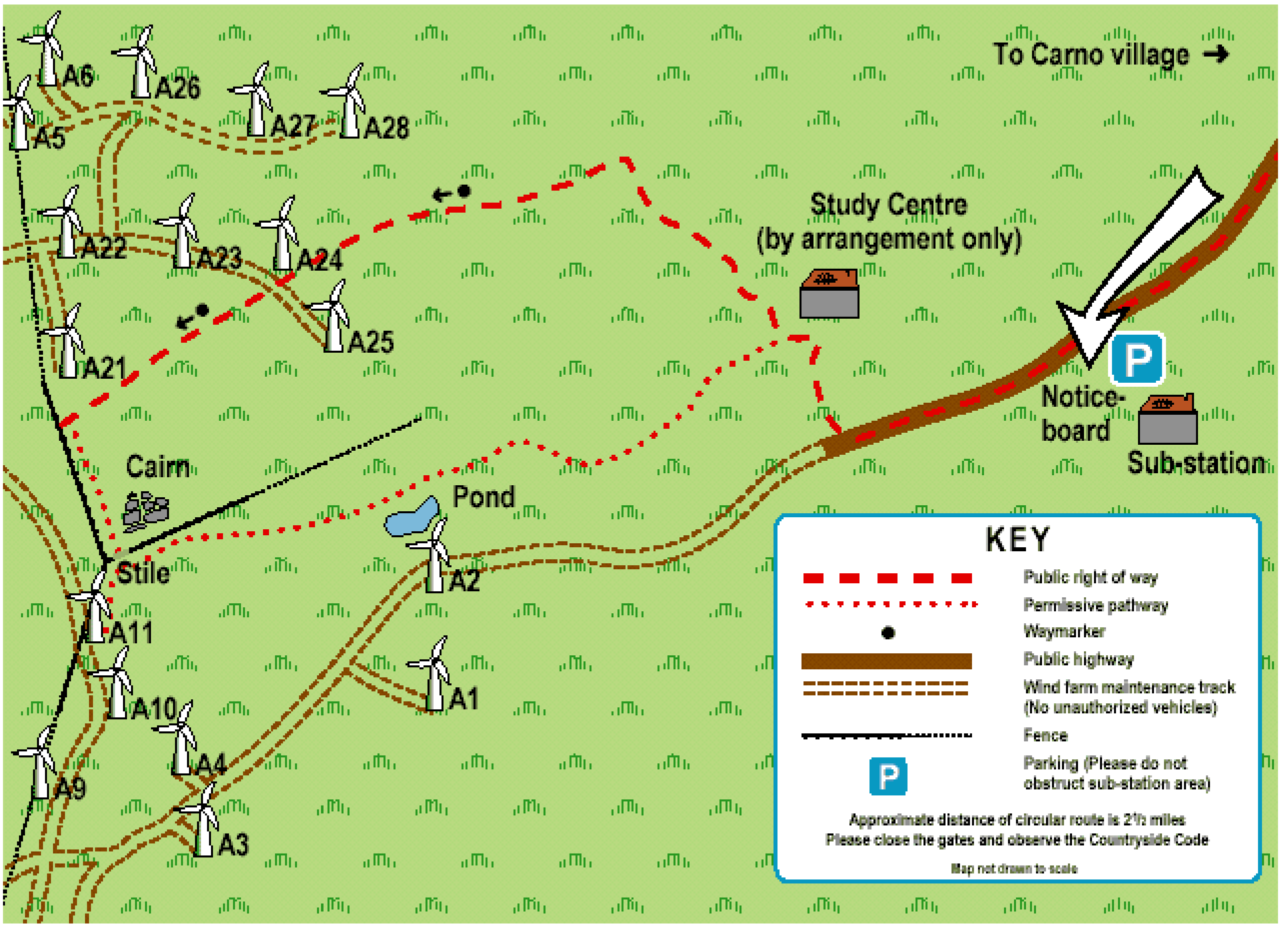
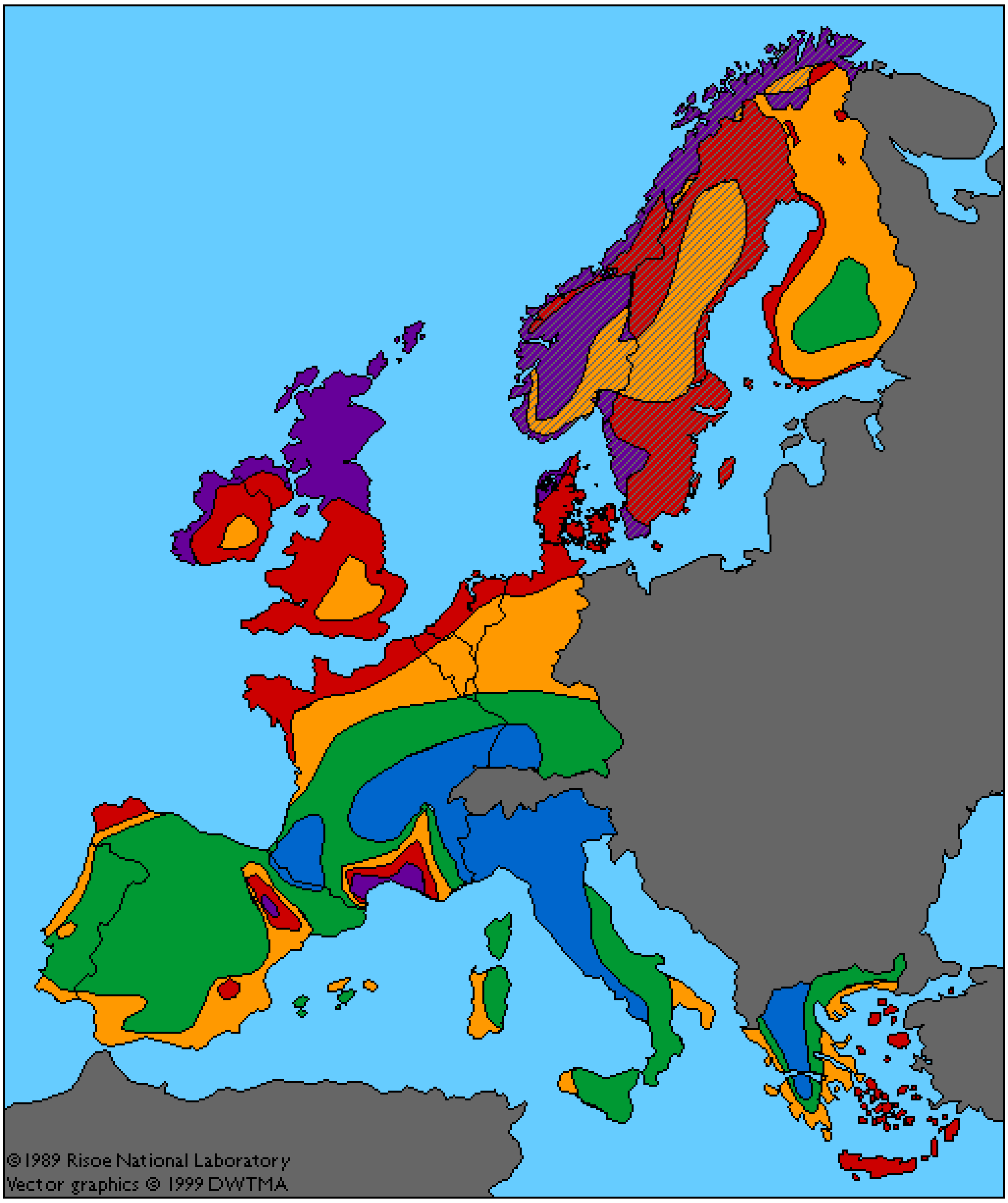


Figure 42: Wind Map of Western Europe.



Wind Resources at 50 (45) m Above Ground Level

Colour	Sheltered terrain	Open plain	At a sea coast	Open sea	Hills and ridges

	m/s	W/m²	m/s	W/m²	m/s	W/m²	m/s	W/m²	m/s	W/m²
	>6.0	>250	>7.5	>500	>8.5	>700	>9.0	>800	>11.5	>1800
	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0-8.5	400-700
	<3.5	<50	<4.5	<100	<5.0	<150	<5.5	<200	<7.0	<400
			>7.5							
			5.5-7.5							
			<5.5							

This wind map of Western Europe was originally published as part of the European Wind Atlas. The details on how to interpret the colours are given in the legend above. The data for Norway, Sweden and Finland are from a later study, and are calculated for 45 m height above ground level, and assume an open plain. The purple zones are the areas with the strongest winds while the blue zones have the weakest winds. The dividing lines between the different zones are not as sharp as they appear on the map.