Enabling Resilient UK Energy Infrastructure: Natural Hazard Characterisation Technical Volumes and Case Studies

Volume 8:

Hail

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This document forms part of the Energy Technologies Institute (ETI) project 'Low Carbon Electricity Generation Technologies: Review of Natural Hazards', funded by the ETI and led in delivery by the EDF Energy R&D UK Centre. The aim of the project has been to develop a consistent methodology for the characterisation of natural hazards, and to produce a high-quality peer-reviewed set of documents suitable for use across the energy industry to better understand the impact that natural hazards may have on new and existing infrastructure. This work is seen as vital given the drive to build new energy infrastructure and extend the life of current assets against the backdrop of increased exposure to a variety of natural hazards and the potential impact that climate change may have on the magnitude and frequency of these hazards.

The first edition of *Enabling Resilient UK Energy Infrastructure: Natural Hazard Characterisation Technical Volumes and Case Studies* has been funded by the ETI and authored by EDF Energy R&D UK Centre, with the Met Office and Mott MacDonald Limited. The ETI was active from 2007 to 2019, but to make the project outputs available to industry, organisations and individuals, the ETI has provided a licence to the Institution of Mechanical Engineers and Institution of Chemical Engineers to exploit the intellectual property. This enables these organisations to make these documents available and also update them as deemed appropriate.

The technical volumes outline the latest science in the field of natural hazard characterisation and are supported by case studies that illustrate how these approaches can be used to better understand the risks posed to UK infrastructure projects. The documents presented are split into a set of eleven technical volumes and five case studies.

Each technical volume aims to provide an overview of the latest science available to characterise the natural hazard under consideration within the specific volume. This includes a description of the phenomena related to a natural hazard, the data and methodologies that can be used to characterise the hazard, the regulatory context and emerging trends. These documents are aimed at the technical end-user with some prior knowledge of natural hazards and their potential impacts on infrastructure, who wishes to know more about the natural hazards and the methods that lie behind the values that are often quoted in guideline and standards documents. The volumes are not intended to be exhaustive and it is acknowledged that other approaches may be available to characterise a hazard. It has also not been the intention of the project to produce a set of standard engineering 'guidelines' (i.e. a step-by-step 'how to' guide for each hazard) since the specific hazards and levels of interest will vary widely depending on the infrastructure being built and where it is being built. For any energy-related projects affected by natural hazards, it is recommended that additional site- and infrastructure-specific analyses be undertaken by professionals. However, the approaches outlined aim to provide a summary of methods available for each hazard across the energy industry. General advice on regulation and emerging trends are provided for each hazard as context, but again it is advised that end-users investigate in further detail for the latest developments relating to the hazard, technology, project and site of interest.

The case studies aim to illustrate how the approaches outlined in the technical volumes could be applied at a site to characterise a specific set of natural hazards. These documents are aimed at the less technical end-user who wants an illustration of the factors that need to be accounted for when characterising natural hazards at a site where there is new or existing infrastructure. The case studies have been chosen to illustrate several different locations around the UK with different types of site (e.g. offshore, onshore coastal site, onshore river site, etc.). Each of the natural hazards developed in the volumes has been illustrated for at least one of the case study locations. For the sake of expediency, only a small subset of all hazards has been illustrated at each site. However, it is noted that each case study site would require additional analysis for other natural hazards. Each case study should be seen as illustrative of the methods outlined in the technical volumes and the values derived at any site should not be directly used to provide site-specific values for any type of safety analysis. It is a project recommendation that detailed site-specific analysis should be undertaken by professionals when analysing the safety and operational performance of new or existing infrastructure. The case studies seek only to provide engineers and end-users with a better understanding of this type of analysis.

Whilst the requirements of specific legislation for a sub-sector of energy industry (e.g. nuclear, offshore) will take precedence, as outlined above, a more rounded understanding of hazard characterisation can be achieved by looking at the information provided in the technical volumes and case studies together. For the less technical end-user this may involve starting with a case study and then moving to the technical volume for additional detail, whereas the more technical end-user may jump straight to the volume and then cross-reference with the case study for an illustration of how to apply these methodologies at a specific site. The documents have been designed to fit together in either way and the choice is up to the end-user.

The documents should be referenced in the following way (examples given for a technical volume and case study):

ETI. 2018. *Enabling Resilient UK Energy Infrastructure: Natural Hazard Characterisation Technical Volumes and Case Studies,* Volume 1 – Introduction to the Technical Volumes and Case Studies. IMechE, IChemE.

ETI. 2018. *Enabling Resilient UK Energy Infrastructure: Natural Hazard Characterisation Technical Volumes and Case Studies,* Case Study 1 – Trawsfynydd. IMechE, IChemE.

Contents

Hailstones are a solid form of precipitation formed within large convective storms (i.e. thunderstorms). They are produced by the freezing of ***supercooled**** water droplets onto ice particles by ***riming***. The ice particles grow further via collision with water droplets and other ice particles to form hailstones. Most hailstones which reach the ground in the UK are small, typically with diameters less than 10 mm. Smaller hailstones do require consideration, principally due to the hazard created when a depth of hail settles on the ground or on the roof of a structure. The depth of hail is also important as, like snow, the weight could cause roofs of buildings to collapse.

However, much larger hailstones (diameters greater than 50 mm) are occasionally produced by violent storms. These hailstones can cause considerable damage. The types of asset that may be damaged via a hail event include:

- crops;
- cars/vehicles;
- roofs;
- windows;
- exterior wall cladding;
- solar panels;
- Heating, Ventilation, and Air Conditioning (HVAC) units.

Historically, perhaps the most destructive British hailstorm, taking account of intensity and areal extent, occurred on 9th August 1843 between the Cotswolds and the Norfolk Broads. In North Oxfordshire slate roofs were 'pounded to pieces', in Cambridge an enormous quantity of glass was smashed at colleges and in public buildings, and in Norfolk the devastation of agricultural crops was so complete that a local council levied a special voluntary rate of local taxation (*Webb and Elsom, 1994*).

More recently, the most widespread occurrence of severe hail in Britain occurred on 7th June 1996. Following an early heatwave with temperatures of 33 °C in London, spectacular thunderstorms deposited large hailstones, typically 25 to 50 mm in diameter, along a series of ***swaths*** which included several medium to large towns such as: Sherborne, Dorset; Salisbury, Wiltshire; Cambridge and Luton, Bedfordshire. There was extensive damage to glasshouses, vehicle bodywork, etc. Indeed, in most years there are at least one or two incidents of locally

*All technical terms marked in blue can be found in the Glossary section.

severe damage by hail over 25 mm in diameter. In 2001, hailstones up to 30 to 40 mm across caused considerable damage to car bodywork and horticultural glass in parts of Kent and East Sussex on 27th June and in Lincolnshire on 25th August.

Whilst no evidence of damage to power infrastructure could be found in the UK, a solar farm in Texas, USA was damaged by a hailstorm where the hailstones were described as 'baseball sized' (between 72 and 74 mm in diameter).

It is necessary for plant and infrastructure designers and operators to plan for extremes and future trends in hailstorm events. In this technical volume, different data and methods for characterising the hail hazard are outlined. However, it is recommended that engineers carry out individual studies for their specific design, operation and location. These studies should consider the severity of storms (maximum hailstone size and impact energy) expected for various return periods, and from that, the risk of:

- roof collapse;
- missile impact from hailstones;
- blockage of intakes;
- injury/death to humans or animals.

Hailstones are a solid form of precipitation formed within large convective storms (i.e. thunderstorms). They are produced by the freezing of supercooled water droplets onto ice particles by riming. The ice particles grow further via collision with water droplets and other ice particles to form hailstones. Ice particles formed by riming are called hailstones if they have diameters greater than 5 mm; particles smaller than this are described as *graupel*. Hail accounts for only a small amount of the total precipitation from the cloud, and so is almost always accompanied by rain. When hailstones become too heavy to be supported by the updraughts within the cloud, they fall from the cloud to the ground. As they descend, some melting of hailstones occurs when they encounter temperatures above freezing. Smaller hailstones can melt fully before they reach the ground, but larger hailstones will fail to melt fully and will therefore persist for long enough to reach the ground.

Historical data suggest that the seasonal distribution of hailstorm events is highest in May, June and July, and the geographical distribution gives an event frequency highest in the south-east of the UK.

Two distinct phenomena associated with hail are investigated in this technical volume:

- large hailstones, with the potential to cause damage from their size and impact energy;
- accumulation of hailstones on the ground and roofs.

Most hailstones which reach the ground in the UK are small, typically with diameters less than 10 mm. However, much larger hailstones (diameters greater than 50 mm) are occasionally produced by violent storms. These hailstones can cause damage to crops, buildings and vehicles, windows, external wall cladding, solar panels, and HVAC units.

Large hailstones (greater than 15 mm in diameter) are likely to cause damage to property when they strike the ground, as for example in Leicester in 2012 (*Clark and Webb, 2013*). However, smaller hailstones can also cause significant damage and disruption. In June 1982, two separate hailstorms in Bristol and Ludlow, Shropshire produced large quantities of pea-sized hail which buried the streets to a depth of around 10 cm, possibly more in some areas (*Sanderson et al 2015*). Another severe hailstorm on 16th October 2006 deposited large hailstones up to 20 to 22 mm diameter in Padstow, North Cornwall, to depths of a few centimetres (*Webb et al., 2009*). The total rainfall which accompanied this storm was not exceptional, as the storm passed over Padstow relatively quickly, although some localised flooding did occur. A more severe event occurred in Ottery St Mary, Devon in October 2008, where a localised hailstorm buried the town in up to 30 cm of hail, blocking drains and exacerbating the flooding caused by the intense rainfall which accompanied this storm (*Clark and Webb, 2011*).

A review of the very large hailstone events from the historical records suggests that an extreme hailstone for the UK (a 1 in 500-year event) would have a diameter of the order of 110 mm (see *Sections 3* and *4* for more information). If this hailstone was spherical and had an average density of 900 kgm^{-3} (900 kgm^{-3} is the maximum density for hail), it would weigh nearly 0.63 kg. The greatest hailstone diameter ever recorded anywhere in the world was 200 mm in Vivian, South Dakota, USA, on 23rd July 2010.

Hail can also cause damage by accumulating on surfaces, such as roofs, with the resultant weight causing damage to the structure. The maximum expected weight of hail on the ground, based on a depth of 30 cm and a density of 900 kgm^{-3}, is 270 kgm^{-2}. Note that a maximum loading for snow based on *EN 1991-1-3 (2003)* is 276 kgm^{-2}; this value is for the Scottish Highlands at an altitude of 1000 m.

However, note also that there are gaps in the research conducted within this project for both the depth of hail and the diameter of hailstones. This is principally because accurate information was difficult to obtain. For depth of hail, it is assumed that the loadings for snow will be bounding.

Research undertaken during this project on the topics of hailstone and hailstorm characterisation has formed the basis of the guidance provided in this report. This has included work carried out by the Met Office to assess maximum hailstone sizes, including a statistical extreme value analysis (EVA) and work done by AIR Worldwide in developing a stochastic catalogue of simulated hail events over the UK. The stochastic catalogue contains 10,000 years of simulated hail data, where each year in the catalogue dataset represents a statistically generated representation of the potential hail activity for a year in the UK.

There are two types of events represented within the catalogue — *microevents* and *macroevents*. Microevents are the individual hail swaths with properties including the location, swath size (i.e. footprint), maximum hailstone size and hail impact energy (HIE). Macroevents are groups of microevents initiated on the same day, or over multiple days, produced within the same weather system passing over the UK.

Information is provided on the swath, or elliptical footprint, of each microevent. This is in the form of the end points of both axes of the elliptical footprint as well as the lengths of these axes (in km). The final set of information is the HIE for the microevent as well as the maximum hailstone size (hail diameter) within that microevent.

3.1 Hailstone Intensity Scale

In 1986, the Tornado and Storm Research Organisation (also known as TORRO) developed an international Hailstorm Intensity Scale (see *Table 1*) and have used this to characterise around 2500 hailstorms known to have occurred in Great Britain since the first documented such event of 1141 AD. The scale extends from intensities H0 (hard hail) to H10 (super hailstorms) and is used within this report to quantify hail events. The most intense British hailstorm, in Hertfordshire on 15th May 1697, reached intensity H8. Note that this scale is not widely used.

Table 1. The Tornado and Storm Research Organisation Hailstorm Intensity Scale.

Intensity	Intensity category	Typical hail diameter (mm)
H0	Hard hail	5
H1	Potentially damaging	5 to 15
H2	Significant	10 to 20
H3	Severe	20 to 30
H4	Severe	25 to 40
H5	Destructive	30 to 50
H6	Destructive	40 to 60
H7	Destructive	50 to 75
H8	Destructive	60 to 90
H9	Super hailstorms	75 to 100
H10	Super hailstorms	>100

3.2 Maximum historical hailstone sizes

Observations of maximum hailstone sizes for the UK are primarily held by the Tornado and Storm Research Organisation. The Tornado and Storm Research Organisation has made available for public use a quick-view of historical hail events from 2002 up to 2006 which provides information on dates, intensity, size and location. The Tornado and Storm Research Organisation has also made information publicly available on hail extremes that have occurred in the UK. This information includes the most intense hailstorm and the heaviest hailstone, plus a list of the 50 most damaging hailstorms from 1650 to 2018, with locations and intensity. The full Tornado and Storm Research Organisation database of recorded events is available to research bodies and to full Tornado and Storm Research Organisation members. Membership of the Tornado and Storm Research Organisation is available by contacting a Tornado and Storm Research Organisation administrator or making a request in the Tornado and Storm Research Organisation Members Forum (*TORRO, 2018*). Regular summaries of damaging hailstorms in Britain and Ireland are published in the journals *Weather* and the *International Journal of Meteorology.*

Many historical events producing very large hailstones have been summarised by the Tornado and Storm Research Organisation. Additional events are described in other publications, such as the books by *Russell (1893)* and *Brazell (1968)*, and letters published in the scientific journals *Philosophical Transactions* (e.g. *Halley, 1697a*; *Halley, 1697b*; *Lhuyd, 1697*; *Thoresby, 1711*) and *Quarterly Journal of the Royal Meteorological Society* (e.g. *Harding, 1897*; *Marriott, 1888*; *Marriott, 1889*). The earliest storm for which observations of very large hailstones are available occurred in May 1697, when hailstones with diameters around 110 mm fell to the ground

(*Tailor, 1697*). Since this time, there has been a second event producing hailstones with diameters of 100 mm or more (15th July 1808; *Clark, 2004*), and possibly a third (22nd September 1935; *Bilham, 1938*). Events in the UK which produced very large hailstones, where the diameters of the hailstones are known or can be estimated, are summarised in *Table 2*.

Table 2. Very large hailstone events recorded in the UK, where the diameters of the hailstones are known or can be estimated.

Date	Location	Max. hailstone diameter (mm)	Reference
4th May 1697	Great Offley and Hitchin, both in Hertfordshire	~113	*Tailor (1697)*
19th August 1800	Oxfordshire, Buckinghamshire, Bedfordshire	70 to 90	*Webb et al. (2009)*
15th July 1808	Templecombe, Langport, both in Somerset	109	*Clark (2004)*
12th May 1811	Bonsall, Derbyshire	~72 to 97	*Russell (1893)*
9th August 1843	Cotswolds, Norfolk Broads	80+	*Webb and Elsom (1994)*
18th to 19th July 1926	Gwennap, Cornwall	~83	*Webb et al. (2009)*
22nd September 1935	Holme, Cambridgeshire	70 to 80	*Webb et al. (2009)*
5th September 1958	Horsham, West Sussex	80	*Clark (2004)*

Note that historical records (recent as well as those further back in time) almost always record the maximum hailstone diameters observed. It is very rare for a distribution of hailstone sizes to be noted. The Tornado and Storm Research Organisation database is also biased towards 'damaging' hailstones (those with diameters greater than 15 mm). Events with smaller hailstones are rarely recorded, except when the quantity of hailstones is sufficient to cover the ground. The largest hailstones described are those noted by human observers. It is possible some storms produced even larger hailstones which were either not observed, or broke up on impact with the ground.

It is possible that other events producing extremely large hailstones with diameters greater than 100 mm have occurred in the past, but any records of these events have been lost or the hail fell in sparsely populated areas and thus was not recorded. *Webb and Elsom (1994)* provide a list of the most severe hailstorms which have occurred in the UK from 1800, but do not give the sizes of the hailstones.

3.3 Data gathered for analysis

When undertaking an EVA for hail, the Tornado and Storm Research Organisation hail database records between September 1961 and July 2010 were used. Of 428 hail events in the Tornado and Storm Research Organisation dataset, 181 included actual hailstone diameters and only these were included in the analysis. Data from several other sources were used to supplement the information from the Tornado and Storm Research Organisation. The numbers of reports containing hailstone diameters (or observations from which a diameter could be calculated) from the various sources are summarised in *Table 3*. Overall, diameters of hailstones from 232 separate storms were available for analysis. In a few cases, the same storm is described by two or more different sources.

Table 3. Sources of historical hailstone size data for hailstorms in the UK.

Source	Time period	Number of hail events
The Tornado and Storm Research Organisation hail database	1961 to 2010	181
Russell (1893)	1800 to 1893	22
Brazell (1968)	1840 to 1964	8
Philosophical Transactions	1697 to 1711	5
Quarterly Journal of the Royal Meteorological Society	1888, 1889, 1897	3
Webb and Elsom (1994)	9th August 1843	1
Clark (2004)	July 1808	1
Smith (2007)	24th June 1897	1
Webb et al. (2009)	1800 to 1897	7
Clark and Webb (2013)	28th June 2012	1
Photographs found on the internet	1st and 15th July 2015	2

3.4 Stochastic hail catalogue

Hailstone size data from the Tornado and Storm Research Organisation covering the period 1980 to 2013, including details of the dates, locations, intensity and limited footprint information of historical UK hail events were used to create a stochastic hailstone catalogue. Some additional observational data were obtained from the European Severe Weather Database (ESWD) maintained by the European Severe Storms Laboratory (ESSL).

The ERA-Interim data from the European Centre for Medium-Range Weather Forecasting (ECMWF), covering the period 1979 to 2013, were used to develop the atmospheric model. ERA-Interim is a gridded reanalysis dataset which contains information on various atmospheric parameters such as wind speed, pressure, humidity, etc. The data are derived via a technique that combines observations with numerical weather prediction model runs to provide estimates of the past atmospheric state. By combining some of these atmospheric parameters it is possible to identify when conditions are suitable for severe thunderstorms and hail to occur. Additional information on ERA-Interim can be found at *ECMWF (2018)*.

The ERA-Interim data have been used in conjunction with the Weather Research and Forecasting (WRF) model, a numerical weather prediction model, to simulate atmospheric conditions over the UK for the period 1979 to 2013. The WRF model produces the atmospheric variables necessary to determine the probability of hail on each day over the UK at a resolution of 16 km.

From these data, AIR Worldwide has developed a stochastic catalogue of simulated hail events over the UK. The catalogue contains 10,000 years of simulated hail data, where each year in the catalogue dataset represents a statistically generated representation of the potential hail activity for a year in the UK.

The analysis is based on atmospheric modelling, not historical observation. Although no definitive methodology currently exists for estimating atmospheric activity on an event-by-event basis, the approach used in this study was derived from AIR Worldwide's research on how to best represent detailed, event-level information about severe thunderstorm activity. This is achieved by using data on the past atmospheric state in a regression model that calculates the likelihood of hail occurring given the atmospheric conditions.

3.5 Spatial distribution of hail events

Figure 1 shows the location of hailstorms in the UK as contained in the Tornado and Storm Research Organisation data covering 1981 to 2010, along with the locations of the limited number of UK hailstorms contained within the ESWD. The historical datashow that the majority of hailstorms have been observed in the south east of the UK and the frequency decreases in the north and west of the UK. Very few hailstorms were recorded in Scotland and Ireland over this period. The results of the stochastic study are in general agreement with the spatial distribution of hail events in the historical record.

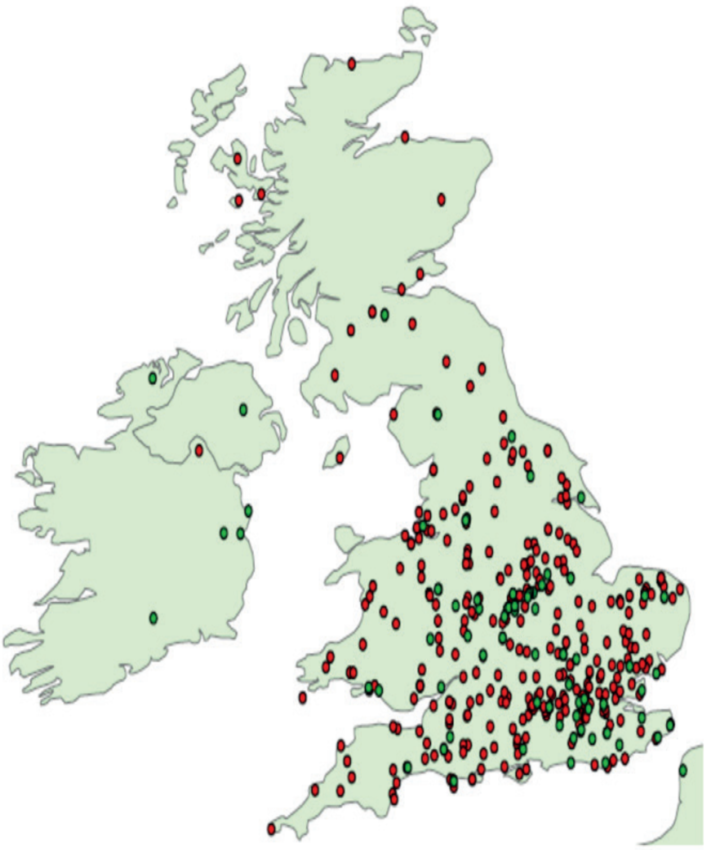

Figure 1. Location of historical hail events (the Tornado and Storm Research Organisation events in red, ESWD events in green), 1981 to 2010.

In order to assess hazards, engineers need to know about the likelihood of the hazard occurring and the severity/consequence of the event, should the event happen. This section outlines the different appropriate methodologies used to obtain these risk estimates.

4.1 Maximum hailstone size for the UK based on historical data

It is considered unlikely that the design of any (non-nuclear) infrastructure project within the UK should need to withstand hail events which produce hailstones greater than 110 mm in diameter. The 110 mm hailstone event is a rare occurrence, and is approximately the size of the largest hailstone ever recorded in the UK. The vast majority of hail events are of much lower intensity. *Figure 2* reveals that, based on the Tornado and Storm Research Organisation data, the majority of events had a hail intensity of category H2, with almost 60% of events falling into this category (see *Table 1*). This translates into a hailstone diameter of 10 to 20 mm. Additional work reveals that longer datasets continue to show this predominance of hail events with an intensity of H2.

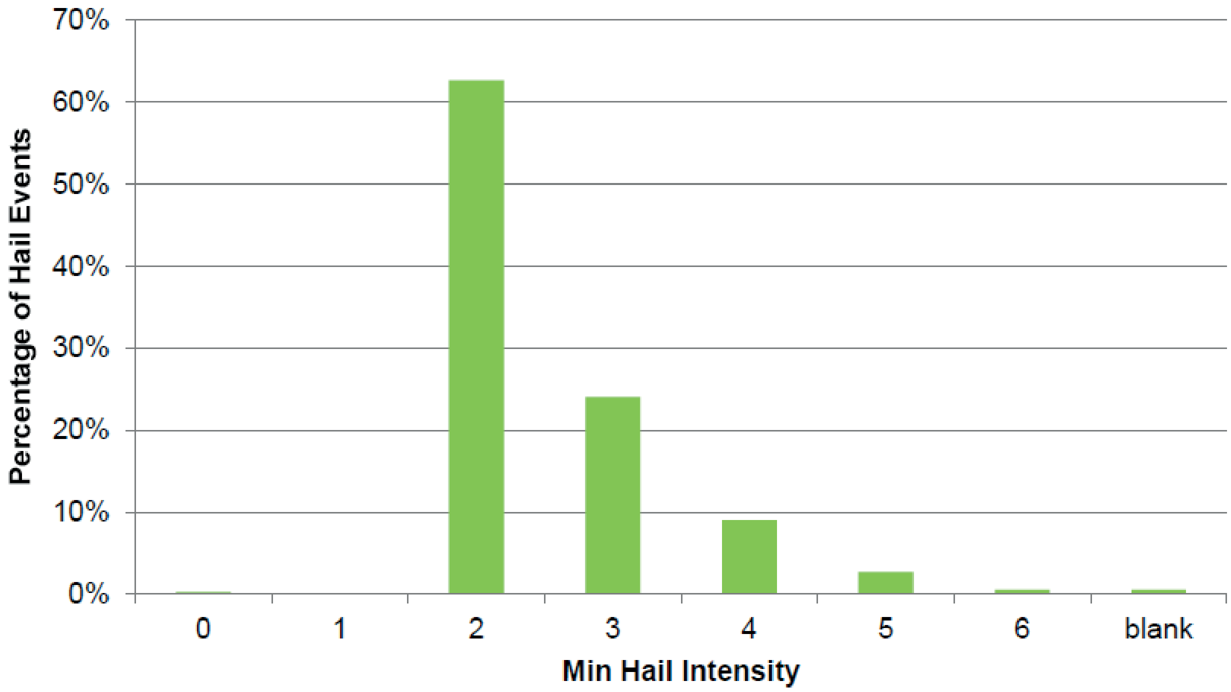

Figure 2. Distribution of hail intensity from the Tornado and Storm Research Organisation data 1981 to 2010 ('blank' represents events where no information on hail intensity was provided in the Tornado and Storm Research Organisation data). (Source: the Tornado and Storm Research Organisation)

4.2 Extreme value analysis

An EVA was carried out with extreme value distributions fitted to observations of maximum hailstone sizes. The EVA model provides estimates of hailstone diameters for selected return periods for the UK. For example, a hailstone with diameter *d* would have a return period of *m* years; an alternative way of expressing the same result is that the probability of a hailstone with diameter greater than *d* occurring in any given year is equal to 1/*m*.

From the EVA, a hailstone with a diameter of 110 mm (comparable to the largest stone ever witnessed in the UK) would have a regional return period for the whole of the UK of approximately 500 years; that is, a hailstone of this size would be expected to occur, on average, once every 500 years somewhere in the UK. Alternatively, the probability of such a hailstone being produced in any given year, somewhere in the UK, is 1/500 = 0.002. Therefore, 110 mm is considered to represent the largest hailstone size that could reasonably be expected to occur somewhere in the UK over any reasonable facility operational lifetime (with the possible exception of very long-life facilities such as nuclear waste repositories).

The EVA also identifies 121 mm as the best estimate for the maximum hailstone diameter that could be expected on a 1000-year return frequency. The probability of a hailstone equal to or greater than 121 mm falling anywhere in the UK is therefore 0.001 in any given year. Note that this assessment considers the entire UK, and that the likelihood of the extreme hailstone event occurring at a specific site is considerably lower.

Specific calculated (rather than observed) return frequencies are given in *Table 4*. The largest possible hailstone size estimated is 216 mm, which is almost certainly not a realistic value given the historical record and the results from atmospheric modelling.

Table 4. Estimated maximum hailstone diameters for return periods between 5 and 1000 years.

Return period (years)	Hailstone diameter (mm)	95% confidence	Approximate Tornado and Storm Research Organisation intensity
5	39	29 to 50	H5
10	54	36 to 72	H6
20	67	41 to 93	H7
50	82	45 to 119	H8
100	92	46 to 138	H9
200	101	47 to 156	H10
500	113	45 to 180	H10
1000	121	43 to 198	H10
∞	216	-	H10

Extreme value analysis is discussed in more detail within Volume 1 — Introduction to the Technical Volumes and Case Studies.

4.3 Stochastic catalogue – frequency and spatial distribution

As outlined in *Section 3.4*, AIR Worldwide has developed a stochastic catalogue of simulated hail events over the UK. The stochastic catalogue contains 10,000 years of simulated hail data, where each year in the catalogue dataset represents a statistically generated representation of the potential hail activity for a year in the UK.

For each event contained within the stochastic catalogue, a specific set of information is provided on the location and intensity of the event. An example of an entry in the stochastic catalogue is shown in *Table 5*. The first column provides a unique number used to identify the macroevent (which may be comprised of one or more microevents) followed by information on when each microevent occurred. In *Table 5*, macroevent 1 contains a single microevent, whereas macroevent 2 consists of two microevents. The 'year' column contains the stochastic year of the microevent and as such will range from 1 to 10,000. The month and day of the microevent enables the seasonality of the hail events to be captured. Information is provided on the swath, or elliptical footprint, of each microevent. This is in the form of the end point of the elliptical footprint as well as the lengths of these axes (in km). The final set of information is the HIE for the microevent as well as the maximum hailstone size (hail diameter) within that microevent.

Table 5. Example of the stochastic catalogue showing the information provided on the footprint and intensity of each event.

Event ID	Year	Month	Day	Focus 1 Lat	Focus 1 Lon	Focus 2 Lat	Focus 2 Lon	Length (km)	Width (km)	HIE (J/m²)	Hail dia (mm)
1	1	4	27	51.2142	−1.0983	51.05214	−1.35432	0.235192	0.05694	21.99119	27.005
2	1	5	1	54.7158	−6.1225	54.60775	−6.35787	0.18662	0.067967	3.6992	25.400
2	1	5	1	52.2658	−1.5673	51.87323	−2.10673	0.518054	0.06571	237.1627	51.850

The model predicted that a total of 181,159 microevents would occur throughout the UK over the 10,000-year simulation period, or roughly 18 per year. The model also predicted a total of 89,633 macroevents, or roughly 9 per year.

The simulated numbers of days with hail over the UK from the catalogue are shown in *Figure 3*. The distribution of hail events is similar to that derived from the Tornado and Storm Research Organisation data (*Figure 1*), but the areas with the highest numbers of hail events are biased towards the centre-west of the UK. The map in *Figure 3* can be used to estimate the number of days per year that hail events would be expected to occur for any location within the UK. For example, in the far north of Scotland it can be shown that hail events are very unlikely, with an expectation of no more than 0.02 per year, or once every 50 years on average.

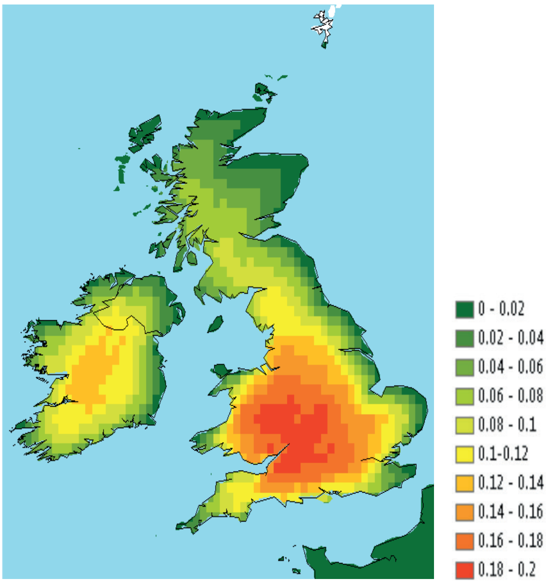

Figure 3. Hail occurrence rates in days per year from the simulated event set on a 0.2° x 0.2° grid.

The spatial pattern of hail events shown in *Figure 3* is similar to that derived from a longer period (75 years) of observed historical hail events (*Figure 4*). However, note that the distributions of observed hail events in *Figure 4* are partially biased towards populated areas. More hail events will tend to be recorded in areas that have been consistently and densely populated than in rural areas.

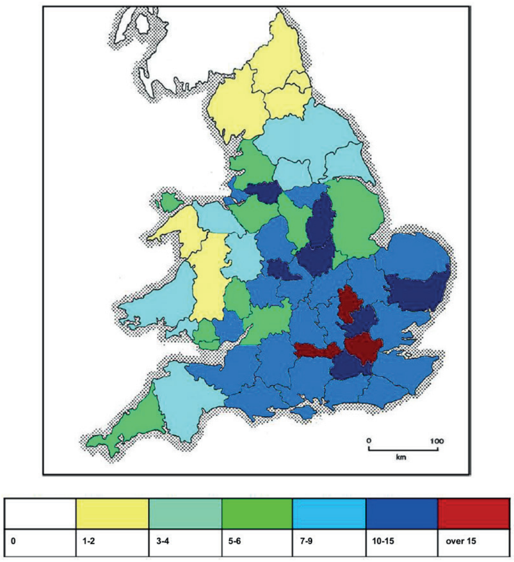

Figure 4. Number of hailstorms containing hail greater than 15 mm in diameter over the period 1930 to 2004. Figure reproduced from Webb et al. (2009).

4.4 Stochastic catalogue – intensity and spatial distribution

The stochastic study also included an assessment of return values for specific large and energetic hail events based on location. The data were assessed to estimate the maximum HIE and hailstone diameter (for the largest hailstone produced in any particular microevent), during a 100-year period, at each map grid point. HIE is a proxy for the damage potential of hail and accounts for both vertically falling hail and hail being blown horizontally. Within the calculation of the HIE, an integral is included to capture the potential damage due to the varying hailstone sizes that are observed in any hail event.

This dataset can be used to identify the 100-year return frequency hail event for any location in the UK based on its latitude and longitude. An example dataset for the area near to the position of 54.7°N latitude and 1.1°W longitude (in the Teesside area, North East England) is provided in *Table 6*. Note that the location is coastal, and locations out at sea are not recorded.

Table 6. Estimates of the 100-year return period event in terms of maximum hail size and HIE for an illustrative location; see Case Study 2 – Teesmouth for full illustrative case study.

Latitude	Longitude	HIE	Size (mm)
54.4	−1.2	640.9127197	40.98266602
54.4	−1	532.8094482	36.4472847
54.4	−0.8	459.7098999	33.83612442
54.6	−1.4	571.548584	38.85761642
54.6	−1.2	478.8620911	35.25530243
54.6	−1	437.3329773	32.97930145
54.6	−0.8	390.7367554	31.4099865
54.8	−1.4	429.4350586	33.41501236
54.8	−1.2	391.2633057	32.36249542
55	−1.4	408.3479614	32.02875137

This analysis shows that the maximum diameter hailstone in the general area during a nominal 100-year period is expected to be of the order of 44.5 mm.

4.5 Seasonality

Although perhaps not as relevant as hailstorm intensity or frequency, it may also be appropriate to consider the seasonality of hail events. It is conceivable that infrastructure project activities may benefit from scheduling to minimise the likelihood of adverse impacts from hail events.

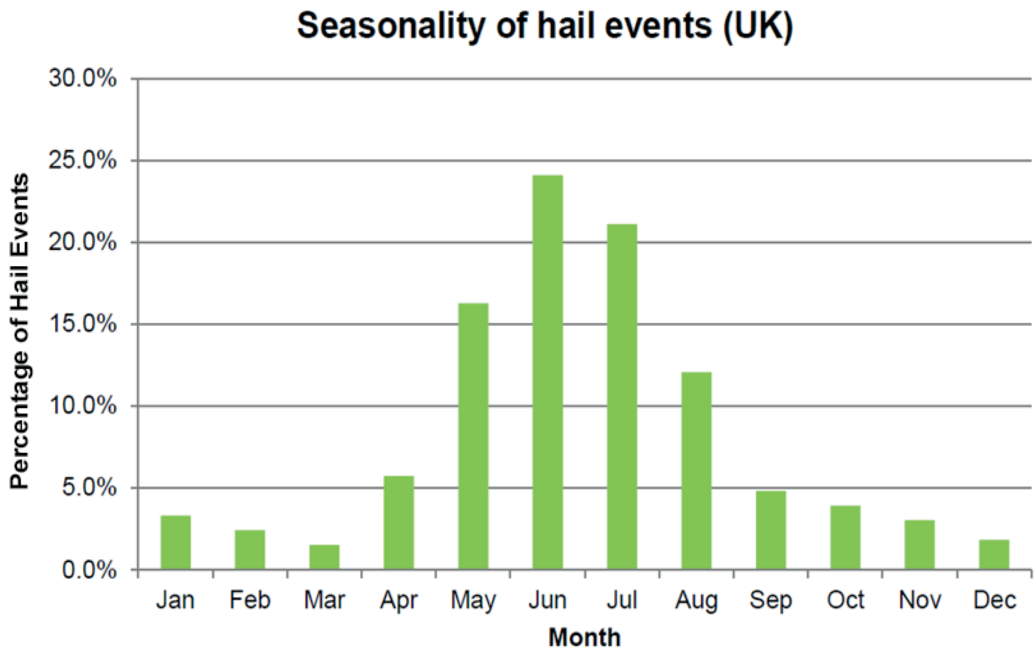

Figure 5. Seasonality of hail events in the UK, derived from the Tornado and Storm Research Organisation data from 1981 to 2010.

From the historical data in *Figure 5*, the peak in hail activity in the UK occurs in the summer months, most notably in June and July. In the period 1981 to 2010, almost 25% of the observed events in this period occurred in the month of June. Additional studies produced by the Tornado and Storm Research Organisation using longer periods of the observation data also reveal this peak in hail events in June and July. Additionally, *Webb et al. (2009)* revealed that hailstorms of intensity H5 or greater favour the month of July, rather than June.

There are no direct secondary/triggered phenomena associated with hail. However, hail is sometimes present as a combined hazard with other weather phenomena. These are described briefly below. For more information on general approaches for characterising multi-hazard events then please see Volume 12 — Hazard Combinations.

Hail and rain

Hail and rain are produced together in cumulonimbus clouds. There are few measurements of rain and hail from the same storm. Those available indicate that hail mostly forms just a few percent of the total precipitation, and rarely exceeds 10%.

Hail and wind

Hailstones can be produced alongside strong winds. Most hail in the UK is formed in thunderstorms, but hail can also be created in convective systems embedded in weather fronts. Some of the most severe hailstorms which occurred in Britain were accompanied by strong surface winds, although winds associated with other severe hailstorms were light. A study of hailstones in the UK used a regional climate model with a horizontal resolution of 25 km, which is too low to simulate the gust fronts and strong winds which can accompany convective storms. No studies of hailstones and accompanying winds are known.

Hail and temperature

Hail is formed in convective storms, and so mostly occurs during the warmer months (May to September) in the UK, although hail with diameters greater than 15 mm is occasionally formed in the remainder of the year. Hailstones with diameters greater than 40 mm have not been observed between January and April in the UK, and almost all of the events were recorded between May and September. Many of the major hail events recorded in the UK between 1800 and 1998 were associated with high temperatures (26 to 35 °C), and of those the majority occurred when temperatures were at least 30 °C.

Although most large hailstones are produced when temperatures are high, there is no direct causal relationship between high temperatures and the presence of hail.

Hail and lightning

Hailstorms are almost always accompanied by lightning, but lightning often occurs without any hail. Lightning associated with a hailstorm which struck North Cornwall on 16th October 2006 damaged a house and railway signals. The large hailstones which damaged property in Leicestershire in June 2012 was accompanied by lightning with very high flash rates. There is no apparent correlation between lightning intensity and hailstone sizes, but a formal study has not been carried out. However, lightning flash rates at locations when large hailstones fell to the ground could be compared with flash rates when no hail occurred.

6. Regulation

In this section, specific guidance is provided on regulatory instruments, codes and standards applicable to the hail hazard. For more information on general regulatory considerations, please see Volume 1 — Introduction to the Technical Volumes and Case Studies.

It is incumbent on designers, constructors/installers and operators to provide evidence that appropriate good practice has been applied. This includes compliance with appropriate design codes and standards. Note that the information below was relevant at the time of writing, and that the reader should confirm the status of current standards.

There is no specific legislation relating to hail, and design standards are somewhat limited. Some guidance is provided by the following standards:

- ASTM F320-16 *Standard Test Method for Hail Impact Resistance of Aerospace Transparent Enclosures.*
- ASTM E822-92(2015) *Standard Practice for Determining Resistance of Solar Collector Covers to Hail by Impact With Propelled Ice Balls.*
- ASTM E1038-10(2015) *Standard Test Method for Determining Resistance of Photovoltaic Modules to Hail by Impact with Propelled Ice Balls.*
- BS EN 61215-1:2016 *Terrestrial photovoltaic (PV) modules. Design qualification and type approval. Test requirements.*
- BS EN 61215-1-1:2016 *Terrestrial photovoltaic (PV) modules. Design qualification and type approval. Special requirements for testing of crystalline silicon photovoltaic (PV) modules.*
- BS EN 61215-1-2:2017 *Terrestrial photovoltaic (PV) modules. Design qualification and type approval. Part 1–2. Special requirements for testing of thin film Cadmium Telluride (CdTe) based photovoltaic (PV) modules.*
- BS EN 61215-1-3:2017 *Terrestrial photovoltaic (PV) modules. Design qualification and type approval. Part 1–3. Special requirements for testing of thin film amorphous silicon based photovoltaic (PV) modules.*
- BS EN 61215-1-4:2017 *Terrestrial photovoltaic (PV) modules. Design qualification and type approval. Special requirements for testing of thin film $Cu(In,Ga)(S,Se)_2$ based photovoltaic (PV) modules.*
- BS EN 13583:2012 *Flexible sheets for waterproofing, Bitumen, plastic and rubber sheets for roof waterproofing. Determination of hail resistance.*
- BS EN 1991-1-3:2003 *Eurocode 1 — actions on structures. General actions — Snow loads.*

The effects of climate change on the frequency of hail and sizes of hailstones are unclear. *Webb et al. (2009)* examined the numbers of events with hailstone diameters greater than 15 mm in the UK between 1930 and 2004. The number of events with hailstones greater than 15 mm appeared to have increased since the mid-1980s, although the numbers of events after 1995 were similar to those recorded in the mid-1930s. *Webb et al. (2009)* repeated this analysis for events with hailstone diameters greater than 40 mm using observations between 1800 and 2004. The numbers of events, summed over five-year intervals, varied between 1 and 14 but there was no clear trend with time. The interannual variability in the numbers of both types of events was very large.

Sanderson et al. (2015) used a regional climate model simulation to drive a simple hail model which estimates maximum hailstone sizes under given conditions. These models were used to investigate changes in hailstone characteristics over the UK between the present day and the 2050s. The results suggested that there would be fewer days with damaging hail (hailstone diameters greater than 15 mm) in the future. This decrease in the number of days with hailstones was caused by fewer storms producing hailstones. The spatial patterns of damaging hailstones for the present-day and future climates were very similar. Most of the events occurred over central and southern England, with fewer events over northern England, Scotland and Ireland. There was a suggestion that the numbers of events with small hail and graupel (2 to 5 mm) might become more frequent in the future, but the high variability in the modelled numbers of these events obscured any trend.

Hail and rain

The effects of climate change on the combined hazard of hailstones and rain in the UK are unclear. The results of *Sanderson et al. (2015)* show that hail and rainfall are projected to continue to occur together under a warming climate, but events with damaging hail would be less frequent. The hail model (*Fawbush and Miller, 1953*) only estimates maximum hailstone sizes, and so it is not possible to say whether the proportion of the total precipitation falling as hail would change in the future. The hail model does not estimate the numbers or mass of hailstones, and thus cannot distinguish a light fall of hail from a very intense hail fall.

Hail and wind

Marsh et al. (2009) calculated parameters conducive for the development of severe thunderstorms using data from a single global climate model simulation for the 21st century. Their results suggested that there would be little change in the frequency of environments under which severe storms occur over northern Europe during the 21st century. This approach is limited by the extent to which variability of the environments captures actual severe weather variability. Although the environment may be conducive to storms, it is not possible to say whether a storm would or would not occur; most often, severe weather events do not occur even if the environment is favourable (*Tippett et al., 2015*).

Overall, the results discussed in this section suggest that the combined risk of hail and strong winds could decrease in the future. The frequency of storms producing damaging hailstones is projected to decrease (*Sanderson et al., 2015*). There is no evidence for an increase in wind gust speeds in recent years (*Hewston and Dorling, 2011*) or numbers of tornadoes which could be attributed to climate change (*Kirk, 2014*). The conclusion reached here is highly uncertain owing to the very small number of relevant studies and lack of suitable models. It is important to note that, to date, no study has modelled both hailstones and wind gusts.

Hail and lightning

The three studies which have reported climate change effects on lightning for the UK suggest that lightning will become more frequent in the future. The single study of climate change effects on hail over the UK suggests that large hailstones will become less frequent in the future. The studies above suggest that the combined hazard of lightning and large hail could become less frequent in the future under a warming climate, but changes in the occurrence of lightning accompanied by smaller hailstones and graupel are unclear. It is important to stress that these conclusions are drawn from a very small number of studies, and thus are highly uncertain.

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Graupel

Ice particles less than 5 mm in diameter.

Macroevent

Groups of microevents initiated on the same day, or over multiple days, produced within the same weather system.

Microevent

The individual hail swaths with properties including the location, swath size (i.e. footprint), maximum hailstone size and hail impact energy.

Riming

When ice crystals collide with supercooled droplets, freezing on contact and sticking together.

Supercooled

To cool a liquid below its freezing point without solidification or crystallization.

Swath

The footprint of a hailstorm.

Abbreviations

ASTM	American Society for Testing and Materials
ECMWF	European Centre for Medium-Range Weather Forecasting
ERA	European Reanalysis
ESSL	European Severe Storms Laboratory
ESWD	European Severe Weather Database
EVA	Extreme value analysis
HIE	Hail impact energy
HVAC	Heating, Ventilation, and Air Conditioning
TORRO	Tornado and Storm Research Organisation
WRF	Weather Research and Forecasting

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