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

Volume 9:

Lightning

LC 0064_18V9

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Version	Date	Details
0.1	24/11/17	Submitted for IPR
0.2	07/12/17	IPR comments addressed and submitted to CTO
1.0	12/01/18	CTO comments addressed and submitted to ETI
2.0	16/02/18	ETI and NHP3 Steering Committee comments addressed

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

1. Introduction

Lightning is a visible electrical discharge generated within thunderstorms. The discharge may occur within a cloud, between clouds, or between a cloud and the ground. The currents within lightning discharges are large, of the order of thousands of amps. It is not possible to predict exactly where or when a lightning discharge may occur. However, long-term observations of lightning or other proxy data allows the identification of locations prone to lightning activity, as well as seasons and times of day when lightning is likely to occur. Lightning is a rare phenomenon in the UK. Measurements of lightning over the UK indicate that the highest average frequency is about 1 to 2 flashes km^{-2} year^{-1} (*Cecil et al., 2014*). Occasionally, very active thunderstorms can produce much higher flash rates, over 30 flashes km^{-2} day^{-1}. Over the Democratic Republic of Congo, and Lake Maracaibo in north western Venezuela, much higher flash rates of 70 to 150 flashes km^{-2} year^{-1} have been recorded.

The greatest hazards to infrastructure assets are caused by cloud-to-ground lightning strikes, of which there are two types. Negative strikes occur between the base of a storm cloud (which has a negative charge; see *Figure 1*) and the surface. Positive strikes occur between the upper part of a storm cloud, which has a positive charge, and the surface (*Heidler et al., 2008*). The path taken by a positive discharge is longer than the path of a negative discharge, and can travel a significant horizontal distance before reaching the ground. The characteristics of these types of strikes are very different. Negative strikes consist of several individual strokes, whereas most positive strikes consist of a single stroke (*Rakov, 2003*). Negative strikes have lifetimes of the order of 10s or 100s of microseconds (one millionth of a second), whereas positive strikes have lifetimes of milliseconds (*Heidler et al., 2008*). The peak currents associated with negative strikes are usually smaller than the currents from positive strikes. The latter are therefore more damaging to structures and systems, and are thought to be responsible for starting the majority of forest fires (*Rakov, 2003*).

Positive strikes make up only a small proportion of the total number of cloud-to-ground strikes. *Schulz et al. (2005)* analysed ten years of cloud-to-ground flashes recorded between 1992 and 2001 in Austria. Their data showed that the proportion of positive strikes was largest during winter (~20%) and smallest in the summer months (~11%). *Johnson and Vaughn (1999)* cited a study of cloud-to-ground flashes recorded at the NASA Johnson Space Centre; averaged over a six-year period, 94.5% were negative and 5.5% positive. *Lyons et al. (1998)* studied cloud-to-ground flashes recorded over the USA between 1991 and 1995, focusing on strikes with peak currents of 75 kiloamps (kA) or larger. Over the entire country, 13.7% of those cloud-to-ground flashes were positive, but 70% of the positive discharges occurred in the central part of the USA. The proportion of positive lightning discharges is highly variable in space and time, and may have a seasonal dependence (*Rakov, 2003*). Currently, it is not possible to forecast accurately the numbers or proportions of cloud-to-ground strikes, or the numbers of positive strikes.

Damage to energy infrastructure from lightning falls into two categories — indirect (induced) and direct damage (*International Atomic Energy Agency, 2011*). Indirect effects of lightning strikes are *arcing** and *induced currents*. When lightning strikes an object, the point of the strike becomes vacated of charge, but the surroundings remain highly charged. Charge is released by the surrounding area to the strike point which causes current to flow. If the strike to the ground occurs in the proximity of electrical wiring or other good conductors, a high electrical surge is induced in the wiring. This surge can cause flammable materials to ignite, damage to electronics or scarring of metal surfaces.

The direct impacts of lightning strikes are caused by current flow and heat. In the UK, lightning strikes convey tens to hundreds of kA. Direct impacts can be arranged into four broad categories (which are not mutually exclusive):

1. *Physical damage:* The material around the point of the strike can be fractured or shattered. If the strike is sufficiently powerful, it could produce a hole in the structure.
2. *Fire:* Wood and other flammable materials could be ignited by a lightning strike. In the UK, strikes on houses have started fires in the roofs.
3. *Power surge:* Lightning which travels via the electrical wiring within a building will cause power surges, damaging electronic devices. The damage might be permanent. If the strike was particularly powerful, a fire could be started. Safety features in many assets would be activated, resulting in temporary loss of power to customers or loss of other services. Electronic systems some distance from the strike could be damaged if they are not adequately grounded or protected against surges.
4. *Shock wave:* When lightning has struck an object (such as a building or tree), the material can be fractured and blown outwards, shattering glass or even damaging walls. Secondary damage by flying debris could happen in some cases, depending on the power of the lightning strike and proximity of other assets.

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

Lightning strikes on or near nuclear and other types of power stations have a wide range of potential impacts (*Trehan, 2000*). Overvoltage protection devices would be operated, and transformers can be damaged. These impacts can disrupt the supply of stable offsite power required by the power station. Electrical and electronic control equipment could also be affected.

Some examples of lightning strikes on assets in the UK and their impacts are given below. On 2nd May 2002, lightning struck pylons near the Torness nuclear power station in Scotland, causing a surge that activated the safety systems and shut down both reactors (*BBC, 2002*). The reactors were restarted about five days later.

On 12th February 2005, a house in Northern Ireland was struck by lightning, damaging the roof and blowing electrical sockets from the walls (*BBC, 2005*). In May 2014, The Shard in London was hit by lightning, but was not damaged owing to its adequate protection. Lightning strikes from storms that struck power lines in south Wales in October 2014 left many homes without power for several hours (*BBC, 2014*).

During a severe storm over Tyneside on 21st June 2017, lightning struck a house causing the roof to catch fire (*Collings, 2017*). The storm also caused localised flooding and 4000 homes were left without power. On 22nd August 2017, a house in County Down, Northern Ireland, was hit by lightning, leaving a large hole in the roof.

The National Grid recorded the effects of ten different lightning strikes on the UK power network between 2004 and 2012. In all instances, a number of circuit breakers were tripped cutting off the power (*National Grid, 2015*). In some cases, the power was restored within a few minutes via *delayed auto-reclosing* (DAR). Manual restoration of power was required in other cases.

Lightning is always associated with thunderstorms. These storms need specific conditions to form, including an abundant supply of atmospheric moisture and a source of heat, which leads to instability in the atmosphere. In certain situations, the movement of air upwards over a hill can trigger the formation of a thunderstorm. As the warm air rises it expands (due to lower pressure) and cools (due to lower ambient temperatures). If cooling is sufficient then the air will become saturated and condensation will occur, which releases significant amounts of latent heat. The temperature at which the air becomes saturated is known as the *dew-point temperature*. This process results in the formation of cumulus clouds ('fluffy' or 'heaped' white clouds) which may not produce any rain if they remain shallow, as any condensed water drops will not have sufficient time to grow large enough to fall as rain.

In optimum conditions with plenty of heat and moisture, these cumulus clouds can grow very large, reaching heights in excess of 10,000 m, and extend beyond the freezing level (the altitude above ground at which the air temperature is 0 °C) so that any water droplets will freeze. Such clouds are called cumulonimbus ('thunderstorm clouds') and the freezing of the water droplets gives the cloud tops a wispy appearance. They often have flat tops as the cloud reaches the tropopause layer (which separates the troposphere and the stratosphere) and spreads out, giving the cloud the appearance of an anvil (*Figure 1*). The frozen water droplets grow more quickly than those that are still liquid, and start to fall. Warm updrafts and cooler downdrafts within thunderclouds create turbulence, resulting in collisions between water droplets and ice crystals. These collisions result in growth of the ice crystals into a range of different sizes. Ice crystals from high in the cloud fall to a lower level but can be transported upwards again by the strong updrafts, collecting layers of ice by aggregation. Some of the heavier ice particles will fall out of the cloud, where they can reach the ground as hailstones or melt into raindrops (see Volume 8 — Hail).

The collisions between ice particles result in the transfer of electrical charge, and different movement rates within the cloud create separation of charge. For reasons not fully understood, small particles tend to acquire positive charges and larger particles negative charges. The smaller particles are transported to the upper parts of the cloud, while the heavier particles are pulled to the lower parts by gravity (*Figure 1*). This differential movement of charged particles creates an electrical imbalance within the cloud. When the electrical charge reaches a certain critical point (a potential difference of the order of thousands of volts), electrons flow between two areas of opposite charge to establish a channel within the cloud. The bolt of lightning follows this channel and lasts for about 0.1 milliseconds. The very large currents associated with lightning superheat the air to around 30,000 °C resulting in a brilliant flash of light that is observable.

The large amounts of heat released cause the surrounding air to expand rapidly, sending pressure waves reverberating through the clouds which are heard as thunder.

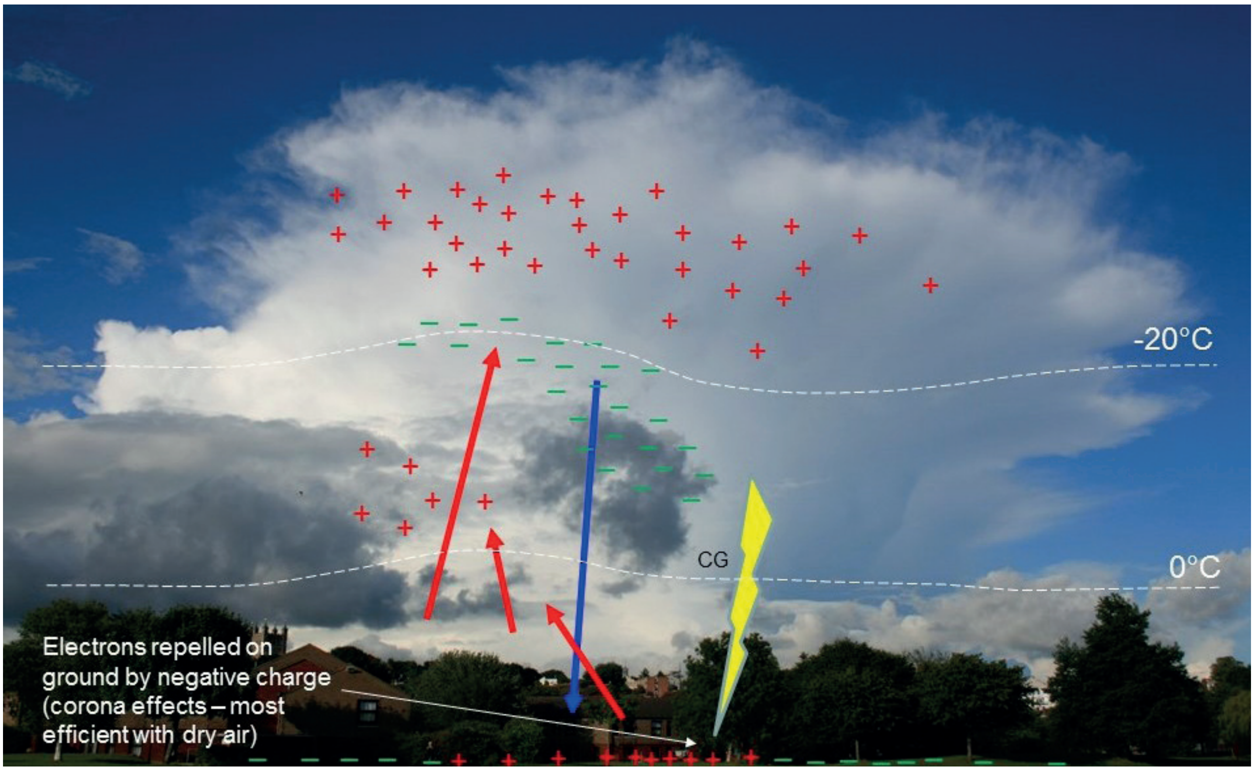

Figure 1. Illustration of charge build-up within a cumulonimbus storm cloud. The vertical red and blue arrows indicate the warm updraft and cold downdraft within the cloud respectively. The red plus signs and green minus signs indicate regions of positive and negative charge in the cloud and in the ground below the cloud. The jagged yellow arrow indicates a cloud-to-ground (CG) lightning strike. Cloud photograph courtesy of Mark Seltzer, Met Office.

The build-up of negative charge within the base of a thunderstorm repels electrons in the ground, resulting in a positive charge building up at the surface (*Figure 1*). These conditions allow lightning to occur between the cloud and the ground. The distance between the cloud and ground is larger than within the cloud, and hence a higher electrical potential is created. The currents which flow in cloud-to-ground strokes are therefore larger than inter-cloud flashes.

A map of the lightning flash density (mostly cloud-to-ground strikes) over the UK is shown in *Figure 2*, using data recorded by the Met Office's Arrival Time Difference (ATD) network (known as ATDnet) lightning location system between 2008 and 2017. Most flashes were recorded over southern and central England, with notably smaller numbers over the south west of England, Wales, Ireland and Scotland. As stated above, thunderstorms are created by heating of the surface. Consequently, lightning is most common in the warmest areas of the UK, which are the East Midlands and the south east of England.

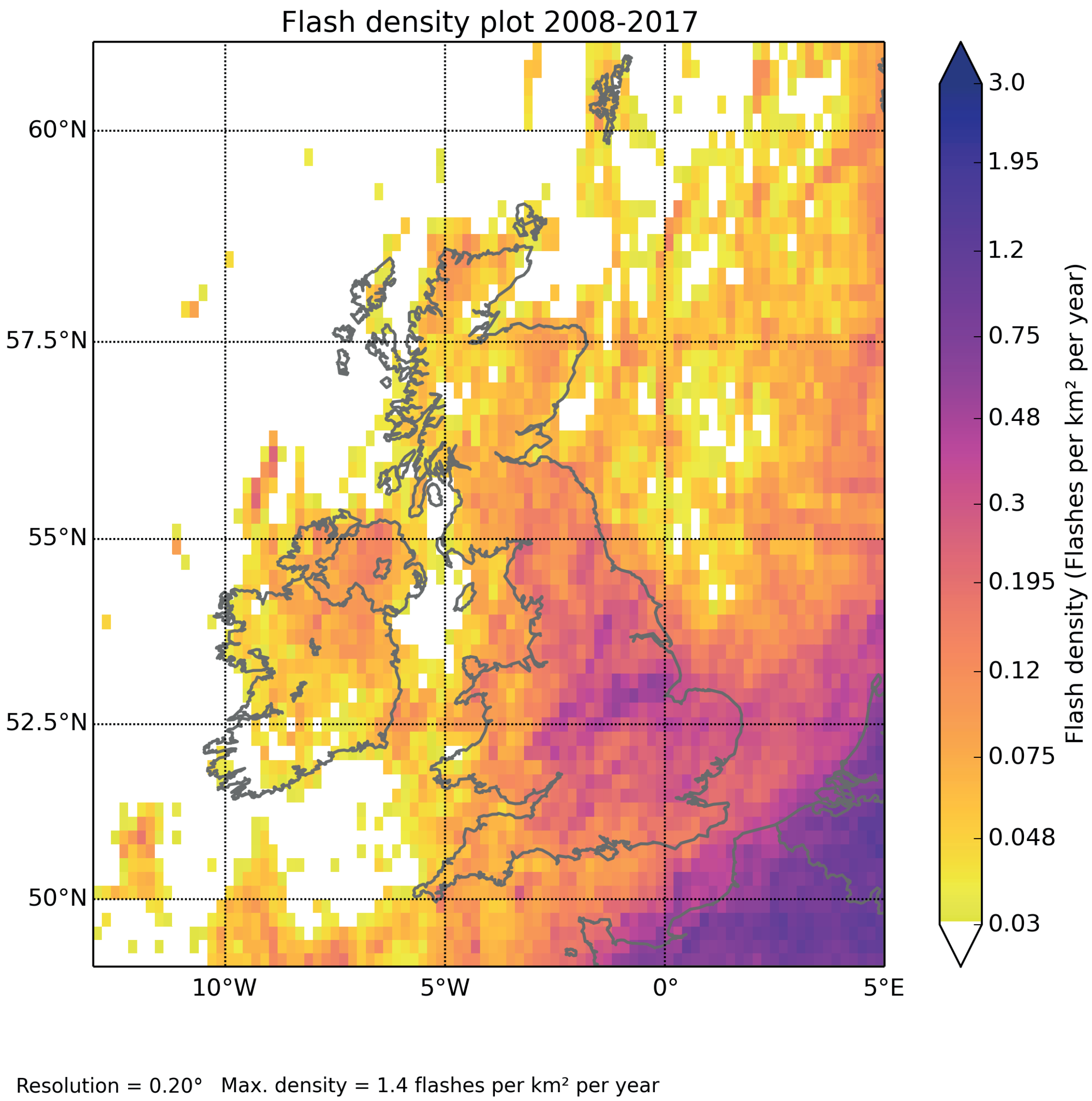

Figure 2. Mean lightning flash density over the UK derived from the Met Office ATDnet lightning location system. The data were recorded between January 2008 and December 2017. The units are flashes per km² per year.

In the UK, lightning is most common in the summer months, when conditions are optimal for the formation of thunderstorms (*Figure 3*). Most lightning occurs, on average, between about 15:00 and 22:00 (*Owens et al., 2015*). During the summer months, lightning can occur at any time of day, but is still most common between the aforementioned times. The times when the largest numbers of strikes are recorded varies between storms. For example, in a storm which affected the north west of England on 20th July 2016, the largest numbers of strikes occurred between 05:00 and 07:00.

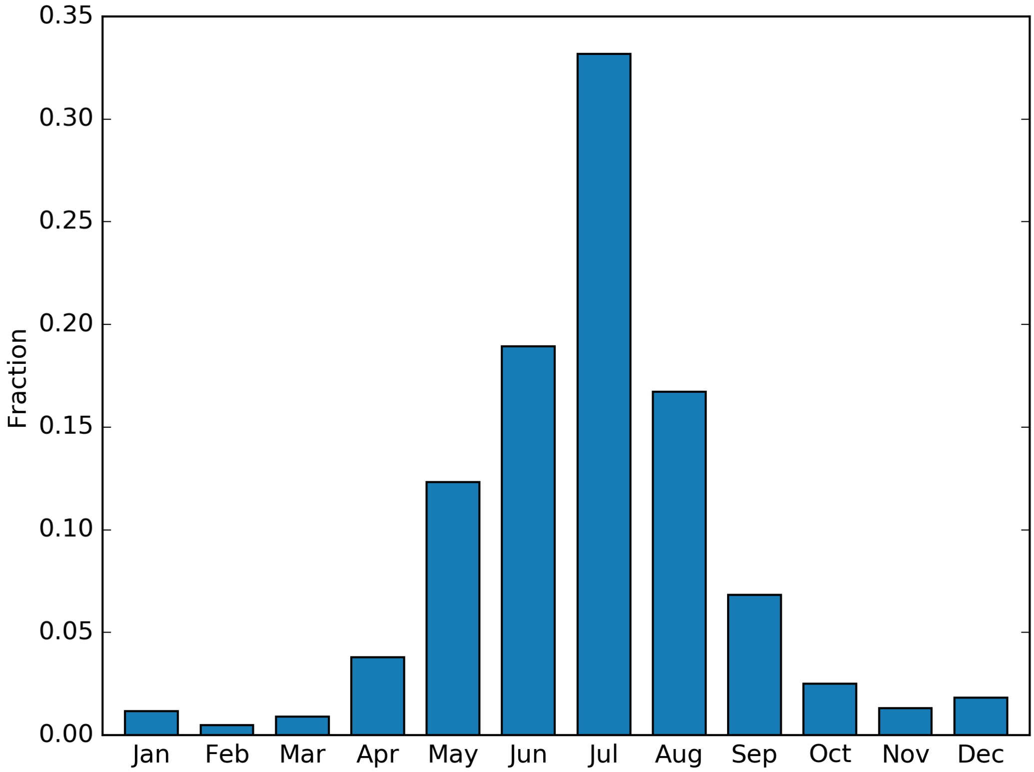

Figure 3. Fraction of lightning flashes per month recorded by ATDnet between 2008 and 2017.

Lightning currents are not measured directly, but are estimated from the strength of the electro-magnetic waves detected at aerials and the location of the strike. There is a large uncertainty (up to 36%) in the estimated currents of individual strikes. The ionised path length taken by a lightning strike cannot be measured, so a standardised length is used. Currents higher than 300 kA have probably never occurred in temperate regions (*Rousseau et al., 2015*). The very high currents in the British Standard (up to 600 kA) have been derived via extrapolation of distribution functions of measured lightning currents (*BSI, 2011*), but were not actually measured. Some measurements of currents in excess of 300 kA have been reported in Japan (*Rakov, 2003*).

Cooray and Rakov (2012) estimated the upper and lower limits of the largest negative first return stroke peak current from lightning discharges. They estimated the upper limit for the negative current to be 300 kA in temperate regions, such as the UK. The lower limit was estimated to lie between 1.5 and 3.0 kA, with a most probable value of 2 kA. *Cooray and Rakov (2012)* also noted that the peak current would be reduced by tall buildings and vegetation over land, and that the highest currents were most likely to be observed over water. Protection against a current of 300 kA would seem to be adequate. The next edition of the lightning protection standard (edition 3) is expected to retain a maximum current of 300 kA and remove the entries relating to higher currents (*Rousseau et al., 2015*). The upper limit of 300 kA may also be applied to positive strikes.

A non-exhaustive list of datasets of lightning flashes that include the UK are summarised in *Table 1*. Some datasets are focused on the UK, others are continental or global in scale. These datasets have been constructed from a variety of different instruments and are described in more detail in the following sections. Only the raw data from the Optical Transient Detector (OTD) are freely available. After the descriptions of the lightning datasets, an alternative method for estimating lightning strike frequencies based on days of thunder (called *keraunic numbers*) is given.

Table 1. Summary of lightning datasets that include the UK.

Dataset	Period	Accuracy of strike location over UK	Estimate of current?	Availability
ATDnet[1]	January 2008 to present	2 km	No	On request[§]
EA Technology[2]	1989 to present	100 m	Yes	On request[§]
LINET[3]	2004 to present	ca. 150 m	Yes	On request[§]
EUCLID[4]	2004 to present	< 500 m	Yes	On request[§]
WWLLN[5]	Aug 2004 to present	ca. 5 km	Unclear	Via subscription[§]
OTD[6]	May 1995 to March 2000	ca. 10 km	No	Freely available

[1] *https://www.metoffice.gov.uk/learning/making-a-forecast/first-steps/thunderstorms* (accessed on 12th January 2018).
[2] *https://www.eatechnology.com/technical-services/lightning-protection-and-location/lightning-location-system/* (accessed on 12th January 2018).
[3] *https://www.nowcast.de/en/lightning-detection-products/real-time-lightning-data.html* (accessed on 12th January 2018).
[4] *http://www.euclid.org/* (accessed on 12th January 2018).
[5] *https://wwlln.net/new/* (accessed on 12th January 2018).
[6] *https://lightning.nsstc.nasa.gov/data/data_otd.html* (accessed on 12th January 2018).
[§] *A charge would be made for the data*

3.1 ATDnet: Met Office Arrival Time Difference network

The Met Office has operated a lightning detection system since 1987, but the current ATDnet has only been in place since December 2007 (*Anderson and Klugmann, 2014*). The ATDnet system detects very low frequency (VLF) radio waves or ***sferics*** (radio atmospheric signals) emitted by lightning. These VLF sferics can propagate over considerable distances, so that only a small number of sensors are required to provide continuous coverage over Europe. The locations of lightning strikes can be triangulated using a network of sensors that time the arrival of individual lightning strikes (*Figure 4*).

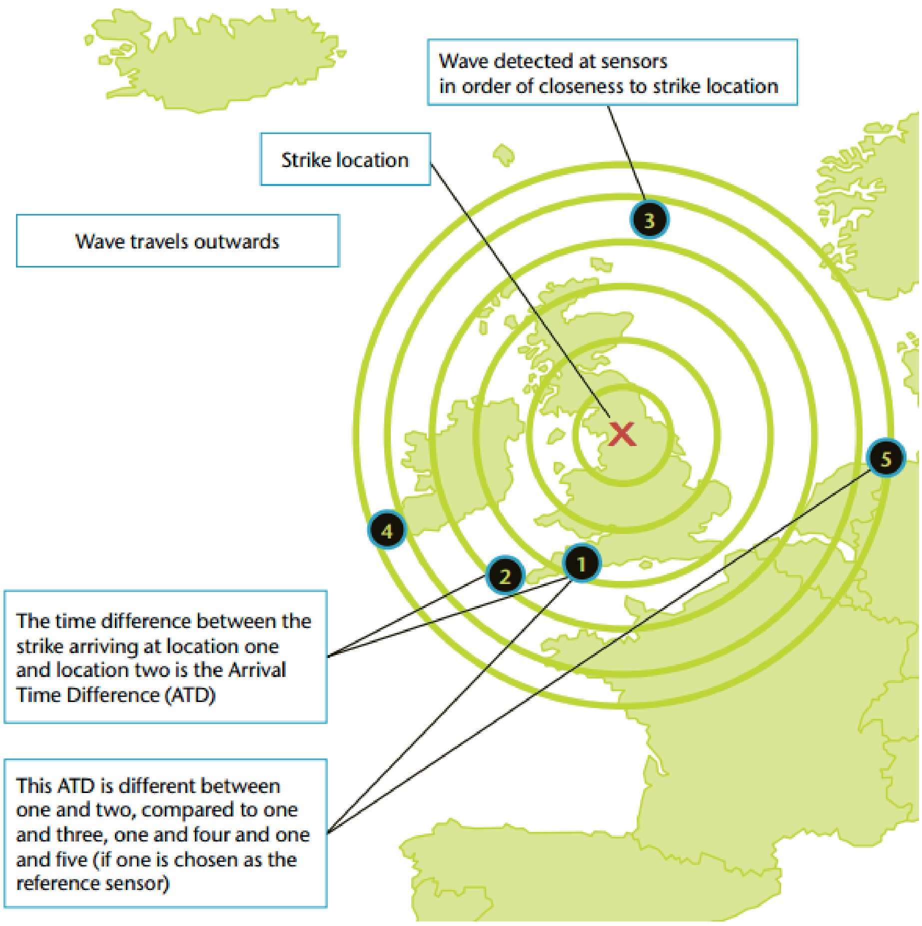

Figure 4. Diagram illustrating the operation of the Met Office's ATDnet lightning location system. (© Crown Copyright Met Office 2018)

The differences in the arrival times of these strikes at the sensor stations are used to calculate the lightning's location using an ATD technique (*Figure 4*). The ATD network system is capable of sensing lightning strikes continually over a wide and varied geographical area but is optimised for detection within the UK. Most other lightning detection networks (*see Table 1*) use a similar method to ATDnet to detect and locate lightning strikes.

The location accuracy of ATDnet is lower than other networks, being about 2 km over the UK, owing to the small number of sensors used. ATDnet predominantly detects cloud-to-ground (CG) strokes. The energy and polarisation of sferics created by CG return strokes mean that they can travel more efficiently and are more likely to be detected at longer ranges than typical inter-/intra-cloud (IC) discharges (*Anderson and Klugmann, 2014*).

3.2 EA Technology

The lightning detection network operated by EA Technology is based on six sensors located around the UK, and is designed to have optimal accuracy over the UK. This network records cloud-to-ground strikes only. The sensors used are different to those in ATDnet (they detect higher frequency sferics), and allow the current of the strikes and their polarity to be estimated. Over 25 years of lightning data have been archived. These data were used to create maps of numbers of lightning flashes per year over the UK within British Standards BS EN 6651 and BS EN 62305.

3.3 LINET: Lightning Detection Network

LINET consists of over 100 sensors in 17 countries across Europe, with the highest density of sensors in Germany (*Uglešić et al., 2010*). Two sensors are located in the UK, near Southampton and Manchester (see Figure 2 of *Betz et al., 2009*). The sensors detect low frequency (LF) and VLF as well as very high frequency (VHF) signals. VLF signals are used by many networks to detect CG strokes. VHF methods allow the detection of within-cloud or cloud-to-cloud discharges (*Betz et al., 2009*). Over the UK, the sensor density is lower than in Germany, so most of the lightning detected will be CG strokes. LINET has been active from 2004, although the sensors in Germany were upgraded and increased in number in 2006. The currents associated with lightning strokes can also be estimated using these sensors.

3.4 EUCLID: European Cooperation for Lightning Detection

The European Cooperation for Lightning Detection (EUCLID) is a collaboration among national lightning detecting networks with the aim of identifying and detecting lightning across the European area (*Poelman et al., 2016; Schulz et al., 2016*). As of December 2014, the EUCLID network consists of 147 sensors across Europe, of which seven are located in the UK and three in the Republic of Ireland (see Figure 1 of *Schulz et al., 2016*). From 2006, several upgrades to the sensors, processing and software were made. The UK sensors are operated by a private consultancy firm. Some of the data may also form part of the World Wide Lightning Location Network (WWLLN).

3.5 WWLLN: World Wide Lightning Location Network

The WWLLN is a ground-based lightning detection network with global coverage which began in 2004 (*Virts et al., 2012*). WWLLN (as of October 2012) consists of 68 sensors located around the world, of which two are located in the UK. These sensors monitor VLF radio waves for lightning sferics, and have a relatively high detection threshold for power. Hence, WWLLN preferentially detects strong cloud to ground strokes.

3.6 OTD: Optical Transient Detector

The OTD was an optical imager that detected momentary changes in cloud brightness caused by lightning (*Christian et al., 2003*). Optical transients that are similarly located in space and time are grouped into flashes. The OTD was mounted on board the Orbview-1/Microlab satellite and was operational between May 1995 and March 2000 (*Cecil et al., 2014*). The inclined orbit of the satellite meant lightning could be detected between 75°N and 75°S. Observations at any given point on the Earth's surface could only be made for a few minutes a day. The lightning data from many orbits of the OTD could be used to estimate the average lightning density. However, given the highly variable nature of storms which produce lightning, and the lack of continual measurements, the true lightning density would not be captured (*Anderson and Klugmann, 2014*). The OTD sensor cannot distinguish between cloud-to-ground and inter-/intra-cloud lightning *(Price, 2009)*. The raw OTD data from individual orbits as well as gridded datasets of flash densities derived from the orbits are freely available. These datasets are described in more detail by *Cecil et al. (2014)*, together with details on how the datasets may be accessed.

3.7 Indirect estimates of lightning flash rates: isokeraunic maps

If direct observations of lightning flash rates are unavailable, the average flash rate can be estimated using maps of days of thunder heard. The keraunic number is the average number of days per year when thunder can be heard. A thunderstorm day is a day on which a human observer hears at least one instance of thunder. The days of thunder heard do not distinguish between cloud-to-ground and other types of lightning (e.g. cloud-to-cloud, or inter-cloud). A day of thunder could mean a single thunderclap was heard, or a much larger number. In some cases, lightning can be observed but no thunder heard by an observer.

An isokeraunic map consists of contours showing areas with similar numbers of days of thunder per month or per year. These maps are created from days of thunder collected over several decades (30 years being fairly typical). An example isokeraunic map based on UK days of thunder for 1971 to 2000 is shown in *Figure 5*. The annual average number of cloud-to-ground strikes per square kilometre per year (N_G) can be estimated from the days of thunder (T_d) using the following equation (*Anderson et al., 1984*):

$$N_G = 0.04 \times T_d^{1.25}$$

An alternative (and simpler) equation is sometimes used (*DEHN, 2014*):

$$N_G \approx 0.1 \times T_d$$

To take an example for illustrative purposes, using T_d values of 6 and 8 for Teesmouth (the site for Case Study 4, estimated from *Figure 5*), the estimated number of cloud-to-ground strikes from the first equation is in the range 0.4 to 0.5 per km^2 per year. These estimates are larger than the numbers of flashes recorded by ATDnet (*Figure 2*), where the average flash density over Teesmouth is in the range 0.1 to 0.3 flashes per km^2 per year.

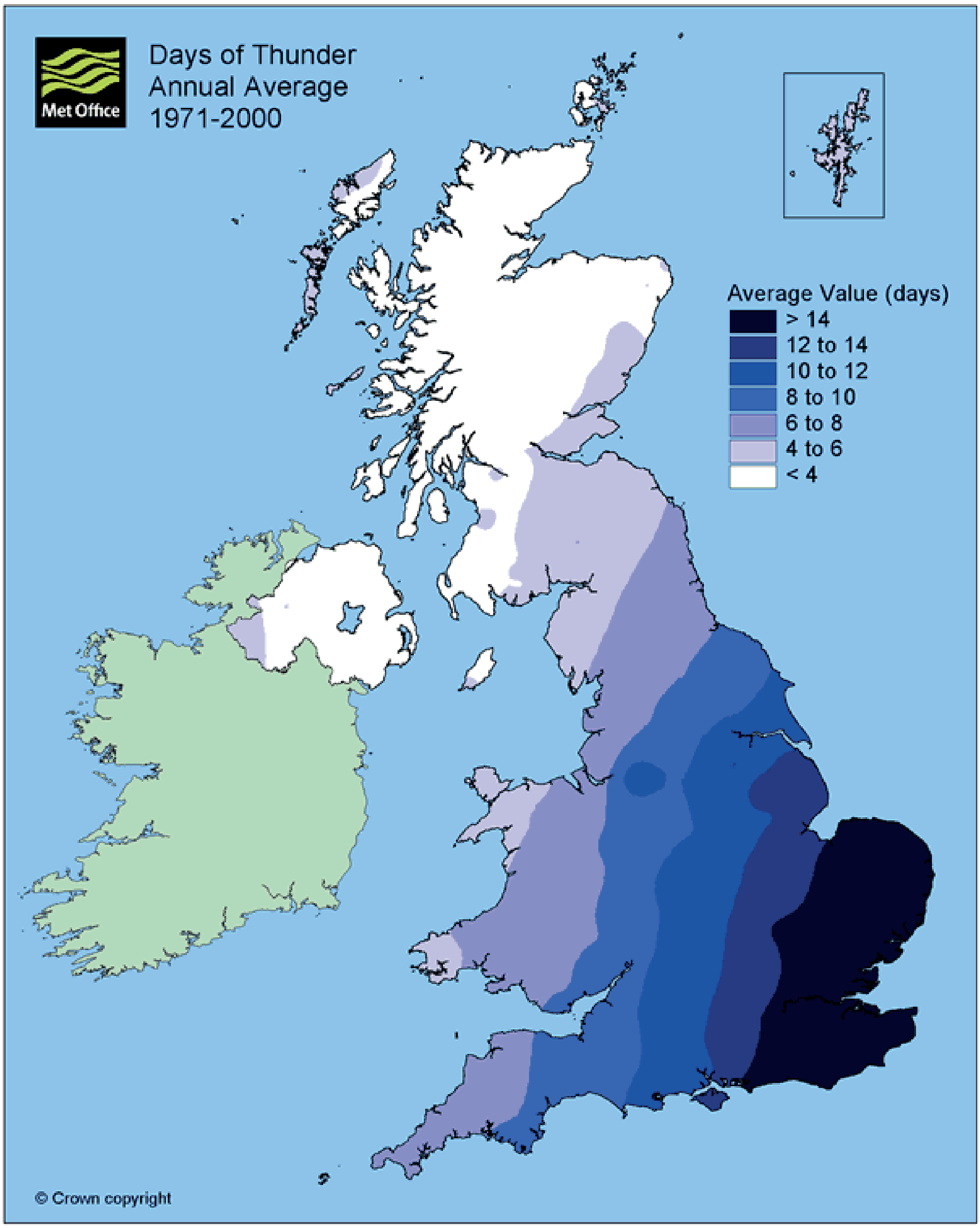

Figure 5. Isokeraunic map for the UK showing annual average numbers of days with thunder. (© Crown Copyright Met Office 2018)

3.8 Models

Equations relating lightning flash rates to cloud top heights and other meteorological data available from climate models have been developed over the past 25 years. *Price and Rind (1992, 1993)* derived simple equations giving lightning flash rates as a function of the cloud top heights of convective clouds. These equations were derived from observations of lightning flash rates and convective cloud top heights in various parts of the USA. Lightning flash rates over land were proportional to the fifth power of the cloud heights. *Price and Rind (1992)* also produced an alternative equation relating lightning flash rates to *Convective Available Potential Energy* (CAPE). The maximum vertical speed within an updraft inside a convective cloud is related to CAPE; thus, larger values of CAPE indicate a greater potential for higher flash rates. This latter equation was used to derive lightning flash rates from climate model data that underpinned the United Kingdom Climate Projections 2009 (UKCP09) (*Met Office, 2010*). Lightning flash rates have been calculated within the Met Office high resolution weather forecast model (UKV) from the vertical mass flux of ice particles within a cloud, which is used as a proxy for charge separation (*Wilkinson and Bornemann, 2014*).

Very detailed models have also been used to study lightning production from individual storms. These models simulate the build-up of electrical charge within clouds and the subsequent electric field (*Mansell et al., 2005; Mansell et al., 2010*). These models are too complex to be used within climate models, and have only been used to study individual storms.

The exact mechanisms behind lightning production, and the factors which control the proportions of cloud-to-ground and inter-/intra-cloud lightning, are not fully understood. For example, on 18th July 2014, a storm which clipped Exeter had a base at 600 millibars (which is very high) but still produced about 90% cloud-to-ground lightning. Other very similar storms (e.g. 16th July 2015) only generated cloud-to-cloud or inter-cloud flashes. More research is needed to understand the reasons for the different proportions of cloud-to-ground lightning between storms, together with other factors, such as vertical wind shear, the freezing level height and production of small ice particles within the storm cloud.

In this section, two different methods for estimating the number of lightning strikes per year on an asset are presented. The first method is described in British Standard BS EN 62305-2 (*BSI, 2012*), and the second is summarised by *Hasbrouck (1996)*. It is important to note that any calculation of strike frequency is very uncertain and should be used cautiously.

4.1 British Standard 62305-2

The method described in the British Standard requires the average number of cloud-to-ground lightning strikes for the location of interest (variable N_G in the equation below). Values of N_G can be obtained from the various lightning datasets described in *Section 3*, or estimated from isokeraunic maps (*Section 3.7*). The number of direct lightning strikes per year (N_D) can be estimated using equation A4 in BS EN 62305-2:

$$N_D = N_G \times A_D \times C_D$$

where:

N_G is the lightning flash to ground value
A_D is the collection area in km^2
C_D is the structure location factor

N_G may be estimated from maps of numbers of lightning flashes (such as *Figure 2*). From *Figure 2*, the highest number of flashes is 0.48 to 0.75 flashes per km^2 per year. The collection area A_D is proportional to the height of the building (*DEHN, 2014*). For an isolated rectangular building, if the height is H, then the collection area extends to a distance equal to $3 \times H$ around the perimeter of the roofline. If the length and width of the building are L and W, then the collection area A_D is calculated using the equation below (*DEHN, 2014*):

$$A_D = L \times W + 2 \times (3 \times H) \times (L + W) + \pi \times (3 \times H)^2$$

The structure location factor C_D considers the influence of the surroundings (other buildings, terrain, trees, etc.). For example, if the building is isolated, C_D has a value of 1. C_D is less than 1 if there are other buildings or trees nearby, as they help to reduce the risk of a direct strike. However, if the building is isolated and located on top of a hill or other local high point, C_D is assigned a value of 2 owing to the increased risk of a direct strike.

For the calculation of the frequency of a strike exceeding a specified peak current (e.g. 100 kA or 200 kA), the value of N_D calculated above needs to be multiplied by a factor P_B given in the British Standard (Section B3 in BS EN 62305-2) for a given lightning protection level (LPL). For LPL I (200 kA), $P_B = 0.01$. For LPL III to IV (100 kA), $P_B = 0.05$.

Using the oil storage facility from Case Study 4 as an example, and values of C_D given in Table 3.2.3.1 of the lightning protection guide (*DEHN, 2014*):

L, $W = 500$ m, $H = 16.5$ m
$A_D = 0.357$ km^2
$C_D = 0.5$ (owing to proximity of nearby buildings)
$N_G = 0.2$ flashes per km^2 per year (from *Figure 2*)
Hence: $N_D = 0.2 \times 0.357 \times 0.5 = 0.036$

For the oil storage facility at Teesmouth, 0.036 direct strikes per year would be expected, or about one strike every 28 years (see Case Study 4 — Teesmouth for more details).

4.2 Hasbrouck method

An alternative method for the calculation of the probability of a lightning strike on an asset was described by *Hasbrouck (1996)*. The method is based on lightning current data recorded in the USA and other empirical relationships representing lightning phenomena; similar equations would ideally be derived using lightning current data for the UK. Lightning datasets that include an estimation of the current are EA Technology (*Section 3.2*), LINET (*Section 3.3*) and EUCLID (*Section 3.4*).

This calculation of strike frequency requires the following information: the length, width and height of the asset, the annual average lightning flash rate for the asset's location, plus estimates of the lightning currents. A sample calculation is shown below for an oil storage depot located to the north-west of Seal Sands within Teesmouth at 54.636°N, 1.212°W (OS National Grid NZ509270). This depot consists of ten oil storage tanks, nine of which are arranged in a 3 × 3 grid. The area enclosed by the nine tanks is about 500 m by 500 m. The height of these tanks is unknown, so the largest tank height reported by *Penman et al. (1967)*, 54 ft (16.5 m) has been used.

The probability of a lightning strike is calculated using the equations (1) to (6) below from *Hasbrouck (1996)*. In these equations, *l*, *w* and *h* are the length, width and height of the asset (in m) respectively. *Fg* is the ground flash density (flashes per km^2 per year). The peak current per decile, *Ipk*, is also required. The probability of a strike is calculated separately for ten deciles of lightning peak currents (equations (1) to (4)), which are then summed to give an estimate of the overall probability (equation (5)).

(1) Ds = lightning *striking distance* = $10 \times Ipk^{0.65}$
(2) r = radius of *attractive area* = $\sqrt{(2 \times Ds \times h - h^2)}$
(3) AA = attractive area/decile = $(l + 2r) \times (w + 2r) - 10 \times [(4 - \pi)/4] \times r^2$
(4) PO = *strike probability*/decile = $AA \times (0.1 \times Fg) \times 10^{-6}$
(5) Cumulative probability (PC) = sum of PO over all deciles
(6) Return period = $1/PC$

From *Figure 5*, the lightning flash density over Teesmouth is in the range 0.12 to 0.2 flashes km^{-2} yr^{-1}, with a slightly higher range (0.2 to 0.3 flashes km^{-2} yr^{-1}) located to the south. The calculations below use the higher value of 0.3 flashes km^{-2} $year^{-1}$.

The peak current per decile, *Ipk*, is required in equation (1). Peak currents per decile for lightning strikes in the UK are not known. Lightning peak currents are not available from the ATDnet system. They have been estimated by operators of other UK lightning networks which use different types of sensors (for example, *Lees (1997)*), but these data are not readily available. For the purposes of the example probability calculation, the peak currents estimated for the USA listed by *Hasbrouck (1996)* are assumed to be applicable to lightning strikes in the UK. The variables in equations (1) to (4) are calculated for each decile and are summarised in *Table 2* with their respective units. The peak currents per decile used by *Hasbrouck (1996)* are also listed.

The overall probability of a lightning strike is the sum of the strike probabilities per decile, which in the example in *Table 2* is 0.109. The reciprocal of this number is the average strike frequency, 9.1 years. Hence, the oil depot at Teesmouth, on average, would be expected to be struck by lightning once every 9 years. If the lower ground flash density of 0.2 flashes per km^2 per year is used, the return period of a strike is 14 years.

The estimates of the strike frequency using the two methods do not agree well. The method described in the British Standard produces an estimated strike frequency of 1 in 28 years, whereas the method described by *Hasbrouck (1996)* produces frequencies of 1 in 9 and 1 in 14 years. These two methods are very different in their approach, so some disagreement is likely. One possibility is that the lightning currents listed in *Table 2* are higher than would be measured over the UK. If these currents were smaller, the estimated strike frequency would be larger.

Table 2. Example calculation of probability of a lightning strike on an asset at Teesmouth, using the method described by Hasbrouck (1996).

Decile	Peak current, *Ipk* (kA)	Lightning striking distance, *Ds* (m)	Radius of attractive area, *r* (m)	Attractive area per decile, *AA* (m^2)	Strike probability per decile, *PO‡*
1	6	32.05	28.02	307,503.38	0.009
2	13	52.97	38.42	329,571.00	0.010
3	18	65.45	43.45	340,394.78	0.010
4	23	76.76	47.55	349,286.32	0.010
5	28	87.23	51.05	356,934.89	0.011
6	35	100.84	55.28	366,219.14	0.011
7	45	118.74	60.38	377,525.50	0.011
8	57	138.46	65.55	389,067.35	0.012
9	77	168.35	72.69	405,168.93	0.012
10	112	214.78	82.56	427,747.27	0.013
				Sum	0.109

‡These probabilities have been rounded to three decimal places. Their total may not equal the sum shown in the final row.

Extreme value analysis (EVA) has not been applied to lightning flash data for two main reasons: (i) the data series from ATDnet and OTD are fairly short (eight and five years respectively) and may contain very few extremely high flash rates; (ii) EVA might give unrealistically high flash rates as it is a statistical method and is not physically based.

5. Related phenomena

There are no particular minor phenomena associated with lightning as outlined in this technical volume. It is possible that lightning could occur in combination with other phenomena; for more information on this see Volume 12 — Hazard Combinations.

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

There is no specific legislation relating to lightning; however, knowing that lightning cannot be prevented or avoided, the options for risk reduction are directed to protection and mitigation, as the consequences of lightning strikes can be minimised with appropriate design techniques. For such considerations, there exists an International Standard IEC 62305, which is implemented in the UK as BS EN 62305:2011, Parts 1 to 4, 'Protection against lightning'. This standard was a result of a significant overhaul of lightning protection standards at the time and its application is considered as international good practice. BS EN 62305 recognises that lightning effects on systems can be divided into direct (physical) and indirect (electromagnetic) effects including:

- structural protection (e.g. burning and eroding, blasting, and structural deformation);
- shock waves and magnetic forces produced by the associated high currents;
- surge protection (external surges, internal surges, use of lightning protection zones);
- earthing, bonding and shielding;
- flashover;
- electromagnetic interference (EMI).

As a result, other standards applicable to lightning protection design may be invoked, such as:

- IEC 61000 Series: Electromagnetic compatibility (EMC);
- IEC 62561 Series: Lightning protection system components;
- IEC 60099: Surge arresters;
- IEC 61643 Series: Low-voltage surge protective devices;
- BS7430: Code of practice for protective earthing of electrical installations.

The emphasis of BS EN 62305 is on risk assessment to determine the extent of lightning protection to be specified for different classes of structure according to the type of loss associated with them. BS EN 62305:2011, Part 2 describes a detailed method of risk assessment that will enable a given installation to be assigned one of four possible lightning protection levels, the highest being LPL I, which is likely to be the most appropriate for energy infrastructure installations. Each level defines a set of maximum values for lightning parameters. During an assessment for extreme lightning flashes, consideration should be given to use of the parameters depending on which type of protection is being sized (for example, peak current, maximum charge or specific energy).

Users of the standard are encouraged to design the elements of protection against the various possible effects of lightning strikes on or near to a structure, to form an integrated lightning protection system for their installation. To do this, the other parts of BS EN 62305:2011 can be used to determine protection for physical damage and hazards to life (Part 3) and for electrical /electronic systems within structures (Part 4).

As well as the standards themselves, guidance notes and papers are available from lightning specialist companies and elsewhere in the public domain.

The approach of the nuclear industry to natural hazards is described in the general regulations description in Volume 1 — Introduction to the Technical Volumes and Case Studies. Under the ONR Safety Assessment Principles (SAPs) (*ONR, 2014*), simple compliance with codes and standards may not necessarily provide a sufficient safety substantiation for nuclear plants, and asks operators to apply codes and standards as a minimum, recognising that risks must be as low as reasonably practicable (ALARP) and severe accidents are considered.

Specifically for nuclear plants with respect to the lightning hazard, Annex 5.3 of the technical assessment guide for external hazards (*ONR, 2017* states: "Lightning cannot readily be defined in terms of a magnitude frequency relationship. Instead, a justification against the appropriate British Standard (BS EN 62305 Series. Protection against lightning) is considered a minimum requirement." This statement recognises that, currently, there is no established method of defining a lightning event with annual exceedance probability (AEP) of 10^{-4}.

The statement that use of the British Standard is a **minimum** requirement is reinforced in the 2014 SAPs. Since the LPL I lightning parameters may not represent a 10^{-4} AEP event, nuclear power plant designers, contractors and operators may need to consider producing the equivalent of a hazard severity/frequency curve to define a design basis. Such a curve would incorporate site-specific data (e.g. as described in *Section 4*) as well as an examination of events that are greater than those addressed by BS EN 62305. Additional studies beyond those undertaken for this project would need to be conducted to determine the appropriate data.

Irrespective of achieving standards compliance, a demonstration of the effectiveness of the protection measures provided by application of the design code (in terms of nuclear safety) against a derived lightning design basis may be required, along with a demonstration that the risks are ALARP.

For non-nuclear facilities, British Standards can be applied in most situations. Examples of exceptions (from BS EN 62305) being:

- railway systems;
- vehicles, ships, aircraft, offshore installations;
- underground high pressure pipelines;
- pipe, power and telecommunication lines placed outside the structure.

For systems related to energy infrastructure, additional standards often exist outside the UK (and are commonly adopted for use within the UK), though there is no guarantee that they are totally consistent with extant British Standards with which they might overlap.

For example, the oil and gas sector has specific concerns with respect to lightning strikes to large tanks (API RP 545 applies) and there are standards from the National Fire Protection Association (NFPA 780), Underwriters Laboratories (UL 96, 96A and 467) and FM Global.

7.1 Improved forecasts of lightning risk for the UK

The Met Office is currently developing a lightning risk product using ensemble forecasts based on a high-resolution (2.2 km) weather forecast model (*Hagelin et al., 2017*). Forecasts using twelve versions of the high resolution forecast model are executed to predict the weather 54 hours ahead. Meteorological data from these forecasts are then used to drive the Convection Diagnostics Procedure (CDP) (*Hand, 2002*). The CDP is separate to the forecast models and calculates the risk of many weather hazards including lightning. The lightning risk is based on CAPE, precipitation rates, the instability of the atmosphere and several metrics derived from cloud properties. The lightning risks from all twelve versions of the model are combined to calculate the probability of each of five levels of lightning risk, which range from 'no risk' to 'very likely'. The final categorical risk value is selected based on tuned probability thresholds for each risk level.

7.2 Observations of lightning flashes

The *Geostationary Operational Environmental Satellites* (GOES) are a series of four satellites to be launched and operated by the US National Oceanic and Atmospheric Administration (NOAA). The GOES-R series will provide advanced imagery and atmospheric measurements of the Earth's weather, including real-time mapping of total lightning activity. The first satellite, GOES-R, was launched in 2016, and the second, GOES-S, is due to be launched in 2018.

The European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) is planning to launch a new series of satellites in 2021. This series is known as the *Meteosat Third Generation*. A Lightning Imager (LI) aboard four of these satellites will measure total lightning (intra-cloud and cloud-to-ground flashes). The instrument will bring full hemispheric near real-time total lightning detection capabilities. The LI will complement the two geostationary lightning mappers on the GOES-R and GOES-S satellites, thus contributing towards near global coverage.

The Met Office is planning to replace the ATDnet system with a new lightning detection network, the Lightning Electromagnetic Emission Location via Arrival-time-difference (LEELA). This network will use a new generation of sensors and be able to distinguish between cloud-to-cloud and cloud-to-ground lightning. A larger number of sensors will be deployed to improve the accuracy of the locations of lightning flashes. Lightning current and polarity data may also be provided.

7.3 Climate change effects

The impact of climate change on lightning activity is highly uncertain. Observations and many climate model simulations all suggest that lightning activity would increase under a warming climate, although a recent study by *Finney et al. (2018)* suggests a decrease in flash rates would occur (see below). Lightning ignitions of fires in the north west of Canada and Alaska recorded between 1975 and 2015 had increased over this period by an average of 2.2% per year (*Veraverbeke et al., 2017*). Statistical relationships between climate variables (temperature, precipitation and convective precipitation) and lightning, ignitions, and burned area were derived from the observations. These relationships were combined with future climate data for the period 2050 to 2074. Increases in lightning activity and associated ignitions relative to the period 1980 to 2004 were projected (*Veraverbeke et al., 2017*).

Simple models of lightning flash rates have been used with data from climate models to project possible changes in lightning flash rates under a warming climate. Note that these simple lightning models do not take into account the role played by aerosols and cloud condensation nuclei in the generation of lightning. *Price and Rind (1992)* derived a simple model of lightning flash rates based on cloud top heights. *Price and Rind (1994)* applied this simple model to cloud height data from a global climate model simulation. Lightning flash rates over latitudes 50°N to 60°N were projected to increase by 1.5% under a climate with roughly doubled concentrations of carbon dioxide (630 parts per million). A study of cloud-to-ground lightning strikes in the USA, which used a different lightning model, estimated that the strike rates would increase by 12% for every 1 °C rise in global mean air temperature (*Romps et al., 2014*).

Price and Rind (1992) also derived a relationship between CAPE and lightning flash rates. This relationship was combined with CAPE from an ensemble of eleven regional climate model simulations which underpinned the UKCP09 (*Murphy et al., 2009*) to project future changes in lightning over the UK (*Met Office, 2010*). The number of days with lightning was projected to increase in all four seasons by the 2080s, with the largest increases of two days in the summer. Similar increases were projected in autumn in southern England and parts of Wales. However, there was considerable variation in the projected increases between the eleven models (*Met Office, 2010*).

Eight different lightning parameterisations were driven by data from a global climate model by *Clark et al. (2017)*, and used to infer changes in lightning flash rates. Two parameterisations projected a small decrease, but their spatial correlations with observed flash rates and patterns were the lowest, which reduces confidence in their projections. The remaining parameterisations projected increases in lightning flash rates, although the actual increases varied between the different methods.

The effects of climate change on lightning have been assessed during this project using three versions of the Hadley Centre regional climate model HadRM3. These three versions had different sensitivities to increasing levels of greenhouse gases. A 'high sensitivity' model would project a larger increase in global temperatures to a given change in greenhouse concentrations compared with a 'low sensitivity' model. Meteorological data from these three simulations were used to estimate the heights of the tops of convective clouds and the height of the zero degree isotherm (see *Figure 1*) using the CDP (*Hand, 2002*). Lightning flash rates were estimated using the simple model of *Price and Rind (1992, 1994)*. The depth of cloud between the zero degree isotherm and the cloud top is used to estimate the proportion of cloud-to-ground strikes following *Price and Rind (1993, 1994)*.

The numbers of individual days with lightning were projected to increase as the climate warms. There was some evidence for increases in the number of events with two, three and four consecutive days of lightning over Scotland. However, there was no clear evidence for similar increases in other regions of the UK, nor for events with five or more consecutive days.

The model projections analysed in this project also suggested the area of land affected by lightning in Scotland could increase during winter in the future. The results for the other parts of the UK and other seasons were less clear. The variability in the land area experiencing cloud-to-ground strikes in a given year was very high in all areas.

However, a recent study by *Finney et al. (2018)* suggested that global average lightning flash rates could decrease in a warming climate. They compared projected flash rates for 2100 using the simple model of *Price and Rind (1992)*, which is based on cloud top heights, with a newer model which relates lightning flash rates to the upward flux of ice within a cloud. Using the newer model, lightning flash rates were projected to decrease throughout the tropics and much of southern Europe, owing to a modelled decrease in cloud ice content. Small increases in flash rates were projected over much of North America and non-tropical parts of Asia. These increases were mostly smaller than those projected using the model based on cloud top heights (*Price and Rind, 1992, 1994*). These results highlight the fact that projected changes in lightning flash rates from climate change are very uncertain.

Cooray and Rakov (2012) showed that the peak current of a negative strike to the ground was proportional to the channel length (i.e. the distance travelled by lightning between the cloud and ground). If the altitude of the base of thunderstorm clouds were to increase as the climate warms, the channel length taken by lightning would also increase, and so peak current of cloud-to-ground strikes would be expected to be larger. This simple argument assumes little or no change in the background electric field. There are no known studies of how the heights of the bases and depths of convective clouds could change under a warming climate, or how the electric fields within those clouds might change.

In 2018, a new set of updated climate projections for the UK (United Kingdom Climate Projections 2018, or UKCP18) will be launched (*UKCP Project, 2018*), which will replace the older UKCP09 projections (*Murphy et al., 2009*). UKCP18 will include a small ensemble of very high resolution climate simulations executed at 2.2 km resolution. These simulations will include lightning flash rates derived using the same model employed by *Wilkinson and Bornemann (2014)* to forecast lightning. It is intended to analyse these new lightning data and compare the results with ATDnet and existing projections once the very high resolution climate projections have been released.

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Arcing

A luminous current discharge that is produced when a very large current flows through air between two conductors, or a conductor and the ground. Arcing releases large amounts of concentrated radiant energy in a fraction of a second, resulting in extremely high temperatures, which in turn can cause fires to start, or an explosion of debris outwards.

Attractive area

If an area beneath a storm cloud were perfectly flat, lightning would strike any part with equal probability. A conductive object has an attractive area larger than the ground area it occupies, which is a function of its height and ground surface area. The total attractive area looks like the difference between the whole area occupied by the asset extended on each side by the attractive radius, and the areas between the individual assets.

Convective Available Potential Energy (CAPE)

Represents the amount of buoyant energy available to move a parcel of air vertically. The higher the CAPE value, the more unstable the air mass and the amount of energy available to promote storm growth and associated hazards such as large hailstones, torrential rainfall and lightning.

Delayed auto-reclosing (DAR)

A method for automatically resetting a circuit breaker and restoring power quickly without the need for manual intervention. The majority of faults on overhead power lines are transient (e.g. a power surge caused by a lightning strike). Once the fault has tripped a circuit breaker, an auto-recloser will reset the breaker after a short delay. The time delay and the number of recloses allowed before the breaker is locked out are both adjustable. If the breaker becomes locked out, it must be reset manually. An automatic reset will restore power much more quickly than a manual reset.

Dew-point temperature

The temperature at which a sample of air, when cooled, would become completely saturated (i.e. the relative humidity is 100%). The dew-point temperature is always lower than or equal to the air temperature.

Geostationary Operational Environmental Satellite (GOES)

A series of four satellites operated by NOAA. The GOES-R series provide advanced imagery and atmospheric measurements of the Earth's weather, oceans and environment, real-time mapping of total lightning activity, and improved monitoring of solar activity and space weather. GOES-R was launched in 2016, and the three remaining satellites (GOES-S, GOES-T and GOES-U) are scheduled for launch in 2018, 2020 and 2024 respectively.

Induced currents

Induced currents and voltages are caused by electromagnetic coupling between the field generated by a lightning stroke and a conductor. An electric current results in a second conductor when it is placed in an area where there is already an electric current (i.e. a lightning stroke).

Keraunic number

Defined as the average number of days per year when thunder can be heard at a given location. The annual number of lightning strikes can be estimated from keraunic numbers using empirically-derived equations.

Meteosat Third Generation

This will consist of four imaging and two sounding satellites, and will be operated by the EUMETSAT. These satellites will scan the full Earth disc every ten minutes at very high spatial resolutions, from 2 km to 0.5 km. The data from these satellites will be used to improve very short-range forecasts (up to six hours ahead) of high-impact weather such as thunderstorms and fog.

Sferics

Following a lightning discharge, radio waves known as sferics are emitted over a broad spectrum of frequencies (from a few kHz to several tens of kHz). These sferics are detected by networks of surface-based sensors and used to locate lightning flashes.

Strike probability

The probability of a strike for a given lightning current decile based on the attractive radii and striking distances. The probability is larger for deciles with higher peak currents. The overall strike probability is found by summing probabilities for the ten current deciles.

Striking distance

The stepped leader's final jump to the conductive object, and varies with the amount of charge and return-stroke peak current. Hence, a greater striking distance is associated with a larger amplitude return stroke.

AEP	Annual exceedance probability
ALARP	As low as reasonably practicable
ATD	Arrival Time Difference
ATDnet	Arrival Time Difference network
CAPE	Convective Available Potential Energy
CDP	Convection Diagnostics Procedure
CG	Cloud-to-ground
DAR	Delayed auto-reclosing
EUCLID	European Cooperation for Lightning Detection
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
EMC	Electromagnetic compatibility
EMI	Electromagnetic interference
EVA	Extreme value analysis
GOES	Geostationary Operational Environmental Satellites
IC	Inter-/intra-cloud discharges
LEELA	Lightning Electromagnetic Emission Location via Arrival-time-difference
LI	Lightning Imager
LF	Low frequency
LINET	Lightning Detection Network
NOAA	National Oceanic and Atmospheric Administration
OTD	Optical Transient Detector
SAP	Safety Assessment Principle
UKCP09	United Kingdom Climate Projections 2009
UKCP18	United Kingdom Climate Projections 2018
VHF	Very high frequency
VLF	Very low frequency
WWLLN	World Wide Lightning Location Network

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