

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

Volume 1:

**Introduction to
the Technical
Volumes and
Case Studies**

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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.

1. Background and motivation	6
1.1 Context	6
1.2 Project aims	7
1.3 Project structure	10
1.4 Project consortium	11
2. Introduction to the energy sector, potential vulnerabilities and relevant natural hazards	14
2.1 Motivation	14
2.2 Potential vulnerabilities	16
2.3 Natural hazard characterisation	19
2.4 Summary	22
3. List of natural hazards	23
4. Format	26
4.1 Technical volumes	26
4.2 Case studies	28
5. Technical primers	31
5.1 Extreme value analysis	31
5.2 General regulatory context	34
References	39
Glossary	42
Abbreviations	43

1. Background and motivation

1.1 Context

Natural hazards have the potential to cause wide-ranging impacts on people, economies, the environment and infrastructure. In many situations, it is vital to have an understanding about the magnitude, duration and occurrence frequency of natural hazards. This ensures that people and infrastructure can be adequately protected (or where not possible, warned) to reduce the impacts of these events. These impacts are best highlighted through a couple of recent case studies: the Fukushima earthquake and tsunami in 2011 and the UK winter storms in 2013/14 and 2015/16.

On Friday 11th March 2011, an earthquake of magnitude 9.0 centred 130 km off the east coast of Japan triggered a 15 m tsunami which struck the Fukushima nuclear power plant ([World Nuclear Association, 2018](#)). This event disabled the power supply and cooling systems of three of the nuclear reactors, which led to a nuclear accident. The reactors proved robust seismically to the event but were vulnerable to the tsunami that was triggered. In total, the tsunami directly led to 19,000 deaths and caused much damage to coastal ports and towns with over a million buildings destroyed. Over 100,000 people were evacuated from areas close to the power plant for nuclear safety purposes which ensured that there were no deaths or cases of radiation sickness directly attributable to the nuclear accident ([World Nuclear Association, 2018](#)). This event highlighted not only the impact that individual hazards can have on infrastructure but also showed how the combination of different natural hazards can lead to more severe impacts than if the hazards had occurred separately. The accident also led to a worldwide safety review of nuclear stations (including those in the UK), with new protection systems, safety equipment and protocols instituted to prevent such severe consequences.

In the UK, some of the most damaging natural hazard events of recent times have been caused by storms. In December 2013, a sequence of storms striking the UK led to severe flooding in multiple areas. On 5th December, an extreme storm surge flooded several hundred homes on the east coast of England requiring the evacuation of thousands of residents ([Met Office, 2014](#)). The Thames Barrier was closed to protect London from the effects of this event. Extreme wind speeds across Scotland forced the closure of the rail network and left approximately 100,000 homes without power.

A couple of years later, Storm Desmond hit the north-west of the UK from 4th to 6th December 2015, leading to a new UK record of 341.4 mm of rainfall within a 24-hour period at Honister Pass in Cumbria ([Met Office, 2016](#)). In this situation, flooding impacts were exacerbated by pre-existing wet ground conditions; several bridges were swept away and tens of thousands of

1. Background and motivation

houses were left without power. This event was swiftly followed by Storms Eva and Frank which led to further intense flooding across the UK.

An appreciation of the risks associated with natural hazards has become even more important in recent years with the potential impacts of climate change on the environment. There have been well-observed increases in global mean temperature from pre-industrial times due to increased human-induced emissions of greenhouse gases (*IPCC, 2014*). The picture for other hazards (e.g. intense rainfall, strong wind) is often less clear and can be highly regionally dependent. However, developments in climate science are starting to permit further study of future changes for a variety of natural hazards. One particular focus is the behaviour of extremes with climate change — a changing climate can lead to ‘changes in the frequency, intensity, spatial extent, duration, and timing of extreme weather and climate events, and can result in unprecedented extreme weather and climate events’ (*IPCC, 2012*).

In the UK, the impacts of natural hazards need to be considered within the wider context of infrastructure design across different industries. In the energy sector, a wide range of energy solutions are being explored including nuclear, carbon capture and storage, and renewables including bio, wind, solar and tidal. Decarbonisation of transport requires the development of new and integrated infrastructure solutions, and decarbonisation of heat is likely to lead to changes in the use and distribution of natural gas via the gas distribution network. With investment in all these different types of energy solutions comes the need to understand the feasibility of each choice and how natural hazards will impact upon them both now and into the future, particularly given the long design lives of many energy assets. These considerations are equally important in other sectors, with new rail, road, air, manufacturing and communications infrastructure needing to be resilient to the impacts of natural hazards (including the interdependencies between new and existing infrastructure within sector and across different sectors).

1.2 Project aims

With this challenge in mind, there is clearly value in the provision of a high-quality set of documents on the characterisation of natural hazards. These documents need to be available for a wide range of natural hazards in a format that can be used by different end-users. By having a standard approach, end-users can then:

- optimise the design of infrastructure to reduce the risk of expensive unscheduled mid-life engineering works;

1. Background and motivation

- operate and maintain high-value infrastructure in a cost-effective manner, protect staff on site and in the local area and ensure resilient service to customers;
- satisfy industry-specific standards and regulation to ensure the safe operation of infrastructure.

Current methodologies used to characterise natural hazards tend to vary by hazard and industry sector. One contributory factor has been the lack of general technical guidance which encompasses a wide range of natural hazards. Documents for separate natural hazards tend to focus on specific hazards using methodology developed within the literature of a particular research area. The development of methodologies in different research areas can occur within 'silos', i.e. there is little interaction with other natural hazard research areas, leading to differing approaches to tackling similar problems.

In the academic community, natural hazard characterisation is a well-researched area; applied research is undertaken for a variety of natural hazards alongside other research (e.g. statistical modelling) which can be applied across different hazards. This highlights the importance of natural hazard characterisation but can lead to other issues; for example, if this academic research is not communicated with end-users then it can be very difficult for the new methodologies to be taken up and applied. The documents generated by the current project are anticipated to inform this link between academic research and end-user needs.

The documents presented in this project are split into a set of eleven technical volumes and five case studies (more information on the content is provided in [Section 3](#)). A brief description of the aims of each type of document is given below.

Each technical volume focuses on one type of natural hazard, or family of hazards, and aims to provide an overview of the latest science available to characterise the natural hazard(s) 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

1. Background and motivation

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 is provided for each hazard as context, but again it is advised that end-users investigate in further detail the latest developments relating to the hazard 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 case studies 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 aside from those presented. 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. As mentioned above, 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.

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.

1. Background and motivation

1.3 Project structure

This set of technical volumes and case studies has been delivered through a project consisting of three distinct phases; see [Figure 1](#).

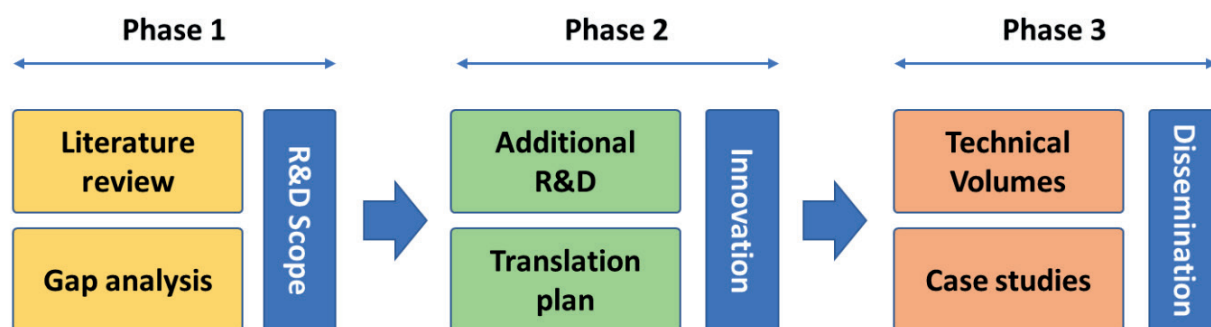


Figure 1. Schematic of the three-phase structure of this project.

In Phase 1, there was a detailed review of the available methodologies which can be used to characterise natural hazards. This was important to ensure that the final technical volumes accounted for the latest best practice across various industries. It was also necessary to assess where knowledge gaps existed within the current state-of-the-art.

Phase 2 sought to address the gaps identified in Phase 1 through further research. A list of fifteen gaps were identified through Phase 1: hail; lightning; biological fouling; space weather; hazard combinations; low sea temperature; earthquake; climate change; numerical modelling; volcanic ash; tornadoes; liquefaction; tsunamis. Many of these gaps were not considered in Phase 2 as they either: (i) would have a low impact on UK infrastructure; (ii) could not be fully addressed within the timescale of the project; (iii) were already being addressed by ongoing programmes within the scientific community. Some of the topics not considered for further research in Phase 2 have been included as related hazards within certain technical volumes (see [Table 2](#)). Out of the fifteen gaps, five natural hazards were taken forward:

- hail;
- lightning;
- space weather;
- marine biological fouling;
- hazard combinations.

The latest developments in the methodology behind natural hazard characterisation were highlighted, and a consistent methodology was agreed upon to be taken forward to the technical volumes.

1. Background and motivation

Phase 3 has focused on creating and disseminating the technical volumes and case studies which can be used by a wide range of end-users across different industries. The final technical volumes provide summaries of relevant good practice for the characterisation of natural hazards using the consistent methodology outlined in Phase 2.

1.4 Project consortium

The first edition of *Enabling Resilient UK Energy Infrastructure: Natural Hazard Characterisation Technical Volumes and Case Studies* has been funded by the Energy Technologies Institute (ETI) and authored by EDF Energy R&D UK Centre, with 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 (IMechE) and Institution of Chemical Engineers (IChemE) to exploit the intellectual property. This enables these organisations to make these documents available and also update them as deemed appropriate.

The consortium assembled for the delivery of this project ([Figure 2](#)) was chosen to contain experts on the characterisation of natural hazards from different organisations. These partners could call upon a range of experience from many years of work within the field. The consortium was led by the EDF Energy R&D UK Centre, supported by EDF Energy Nuclear Generation, EDF Energy Nuclear New Build, Mott MacDonald, Air Worldwide and the Met Office.

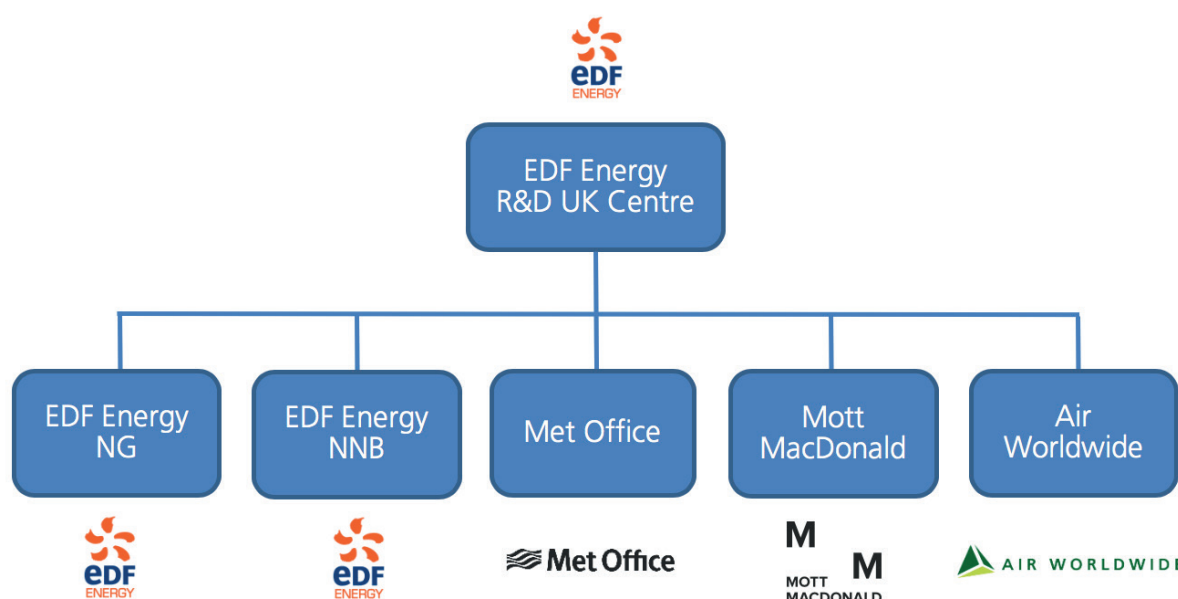


Figure 2. Structure of the project consortium.

Abbreviations: EDF Energy Nuclear Generation (NG); EDF Energy Nuclear New Build (NNB).

1. Background and motivation

EDF Energy is one of the UK's largest energy companies and its largest producer of low-carbon electricity. EDF Energy is part of the EDF Group, one of Europe's largest power companies, which operates in 23 countries and employs over 157,000 staff. Research and development is a key part of EDF Group and EDF Energy activities. The EDF Energy R&D UK Centre was formed in March 2012 to strengthen its ability to deliver R&D activity in the UK. The EDF Energy R&D UK Centre team work closely with experts from across the EDF Group. EDF Energy Nuclear Generation is the owner and operator of the existing civil nuclear fleet in the UK. EDF Energy Nuclear New Build has been established with the mission of delivering the first new nuclear power station in the UK in over 20 years at Hinkley Point, and planning for new development at the Sizewell site.

The Met Office is the UK's national meteorological service, and a Trading Fund within the Department for Business, Energy and Industrial Strategy. It employs around 1700 people at 60 locations throughout the world and is recognised as one of the world's most accurate forecasters. Forecasts are delivered to a huge range of customers including the government, businesses, the general public, and armed forces. The Met Office's forecasting capability also includes operational predictions of space weather. Additionally, the Met Office is a world leader in climate research and services, working with organisations around the world to advance global understanding of the past, current and future climate.

Mott MacDonald is a global management, engineering and development consultancy and a top firm in power projects (ranked number 1 in 'Power in the 2013 NCE Consultants File'). It began working on power projects over a century ago and has accumulated experience in all types of generating technologies including conventional coal and oil-fired steam plants, combined heat and power, diesel, energy from waste, open/combined cycle gas turbine plants, renewables and nuclear. The company has wide experience in natural hazard characterisation across different sectors, including oil and gas, water and power industry, thermal generation and renewables. Mott MacDonald has strong links with operators in energy sectors, including Scottish Power, EoN, Iceland's national power company Landsvirkjun, National Grid, Shell, British Petroleum and Total. For this project, Mott MacDonald has been able to draw on a wide resource pool of expertise covering an extensive range of engineering disciplines and associated technology.

Air Worldwide founded the catastrophe modelling industry over 30 years ago and has extensive experience characterising natural hazards and determining their effects. It has experience of providing global risk engineering services, and providing assessments of local hazard

1. Background and motivation

conditions to the insurance and reinsurance markets. Air Worldwide's modelling methodologies are widely used throughout the property insurance and reinsurance industries, and help clients meet Solvency ii regulatory certification.

These documents have undergone an independent peer review process and a full review by the Chief Technical Officer of EDF Energy. In addition, a steering committee comprised of industry experts (including representatives from IChemE, IMechE, ONR and external consultants) has provided feedback on all of the documents, which has been incorporated into the final versions.

2.1 Motivation

The energy sector in the UK encompasses many different types of energy generation and customers. The current picture of energy generation is provided in [Table 1](#). In total during 2016, 338.6 TWh of electrical energy was generated across the UK ([BEIS, 2017](#)), spread across four broad groups: coal, nuclear, gas and renewables.

Table 1. Amount of electrical energy generated during 2016 and the percentage change from 2015.
(Source: [BEIS, 2017](#))

Generated from	2016 (TWh)	Change from 2015 (%)
Coal	30.7	−59.4
Nuclear	71.7	+2.0
Gas	143.4	+43.4
Renewables	82.8	−0.9

The current picture is of an energy mix which is highly reliant on coal and gas generation, creating significant CO₂ emissions. This is exacerbated by the fact that many nuclear power plants across the UK are close to the end of life, and therefore will not be available to continue the current supply of low-carbon baseload power in the near future.

Alongside this current picture, the 21st Conference of Parties (COP21) — which took place in Paris in 2015 — achieved a universal, legally-binding global climate agreement. The main goal of this agreement is to keep global warming below 2 °C, with efforts to keep global warming below 1.5 °C strongly encouraged. This agreement has set the agenda in the energy sector to move towards a feasible low-carbon energy system. Analysis by the ETI suggests that, combined with approaches to improve efficiencies and reduce energy demand, an optimum transition involves decarbonisation of electricity generation first, followed by decarbonising heat. Decarbonisation of transport is expected to be more gradual, beginning with an increase in consumer uptake of hybrid and electric passenger vehicles.

Historically, coal generation has provided a large proportion of the electrical energy used within the UK, with eight working power plants across the UK. However, the drive to reduce carbon emissions to combat damaging climate change has led to a reduction in the use of coal over recent years. This is confirmed by the steep decline in generation from 2015 to 2016 and the general downward trend over recent years ([BEIS, 2018](#)).

Around 40% of the gas production in the UK comes from fields in the North and Irish Seas, with the reliance on imported gas from continental Europe slowly increasing as the aforementioned reserves start to deplete. The discovery of a reported 200 trillion cubic feet of untapped gas under Lancashire in 2012 may increase the amount of available gas in the UK ([Energy UK, 2018](#)).

Nuclear power currently produces and has the potential to continue to provide low-carbon baseload generation for the UK. Currently, there are 15 nuclear reactors at many different sites across the UK, most of which are close to the end of their life. In June 2011, eight sites were chosen across the UK for potential new build projects.

Renewables have the potential to provide 20 to 50% of energy generation for the UK in the near future ([ETI, 2015a](#)). There are many different types of renewable generation (e.g. offshore/onshore wind, tidal, solar power) which are developed to varying levels. At the moment (as of 2018), the main driver is to reduce the costs associated with renewables to make them a more competitive option in the current market. These renewable generation solutions must be developed to try to reduce carbon emissions; however, they are intermittent and as such must be paired with development in baseload generation or energy storage.

The anticipated trend in the energy sector is towards small-scale and low-carbon technology with large-scale low-carbon technologies (e.g. nuclear) still having a role to play in the future ([ETI, 2015b](#)). This will be driven by improving technological innovation and reductions in the costs for building this type of infrastructure. This is likely to be accompanied by more complex flows of energy and a growing number of players in the energy market.

Irrespective of the specific mix of generation sources, it is clear that multiple sources are required and therefore many different types of infrastructure will need to be built. It is a costly process to replace existing assets with the necessary low-carbon generation infrastructure. As such this must be done correctly, first time. In particular, it is necessary to account fully for the impacts of natural hazards when building this new infrastructure. A few examples of specific natural hazards that need to be considered for two different types of infrastructure are given below.

Nuclear

Due to the nature of the power generation, a failure caused by a natural hazard can have a very wide-ranging impact and damage estimates are difficult to forecast. As such, this type

of infrastructure needs to be protected against low-probability, high-impact events. In the UK, most nuclear plants have been built at the coast (all future potential new build sites identified in the current National Policy Statement, NPS 6-EN, are coastal) which means they are particularly susceptible to coastal hazards including *marine biofouling*. Future plans include the potential to construct nuclear plants (e.g. small modular reactors) inland (ETI, 2015b) which will be susceptible to a different set of natural hazards.

Renewables

The term 'renewable energy' refers to a broad range of generation types including offshore/onshore wind, solar, and tidal power. Each of these types of generation is open to impacts from different natural hazards. Wind-power assets may be susceptible to extreme wind events and other forms of extreme weather. For offshore wind farms, there are also coastal hazards such as wave heights and currents, which will not only impact upon infrastructure but also on the safety of workers on site. Marine biofouling can also have an impact on offshore structures. Tidal infrastructure is located in coastal regions by definition and an assessment of the impacts that coastal hazards may have on this type of infrastructure is important.

These examples show that natural hazards do and will impact upon all types of energy infrastructure now and in the future; further examples are provided in the technical volumes and case studies. These impacts will happen irrespective of the specific mix of energy generation into the future. As such, it is important to consider the impact that natural hazards could have upon energy infrastructure, and the potential vulnerabilities within the system.

2.2 Potential vulnerabilities

To this point there has been a broad discussion of the energy sector as a whole and the specific natural hazards which can have a large impact on this sector. This consideration has been taken into account when finalising the list of hazards included within the final documents; see *Section 3* for more details. However, a specific discussion of potential vulnerabilities within the energy sector has not yet been provided. These are investigated in more detail below.

Broadly, natural hazards can have a direct impact upon different stages of the energy supply chain. For certain energy industries (e.g. oil and gas), this can start with the extraction of resources. Whether these activities are onshore or offshore, natural hazards are likely to have an impact on the efficiency of operations and the safety of workers on site.

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

The safety and operation of energy generation assets must be considered. Natural hazards can directly affect the potential to generate energy. In most situations, the occurrence of a natural hazard will reduce energy generation for all types of generation infrastructure. However, the impact does not necessarily always have to be negative; for example, high wind speeds (albeit not too extreme) can lead to increased output from offshore and onshore wind generation.

It is not just generation capacity that is affected by natural hazards; the transmission of power across the UK can also be affected. For example, extreme wind speeds can damage or blow over transmission infrastructure, such as pylons, which can lead to power failures. This can be an especially important issue for isolated communities which are highly dependent on specific transmission infrastructure. However, the impact on transmission is not necessarily limited to localised issues. For example, past extreme space weather events have been known to cause power failures in a large proportion of the grid due to geomagnetically induced current.

Different sectors within the energy industry provide different levels of protection to natural hazards. This is often driven by the risks associated with the impact of a natural hazard. For example, the negative impacts of the failure of a nuclear power plant have the potential to be exceptionally serious, so there are very stringent safety regulations within this sector. When the failure of a specific piece of infrastructure is less likely to cause a large impact, the associated infrastructure is likely to be protected to a lower level. As such, a natural hazard of a specific magnitude striking different pieces of infrastructure can lead to different probabilities of failure.

To this point, the potential interdependencies within the system have not been considered. For example, the interaction between generation and transmission infrastructure has the potential to create a feedback loop during natural hazards. Many energy generation assets require energy from the grid to ensure safe operation. If a natural hazard affects the transmission to power infrastructure, this will have an impact upon the power generation capacity itself. This highlights the importance of considering potential interdependencies within the total energy system, and how these could manifest themselves during a natural hazard event. As discussed in [Section 2.1](#), the total energy requirements of the UK are satisfied through a combination of different energy generation sources. If a natural hazard causes an impact upon a particular generation asset, e.g. by requiring an unplanned load reduction at a nuclear power plant, other sources of generation will be required to cover the power deficit. For some intermittent sources, this will not be a large issue. However, for larger infrastructure which provides a greater proportion of the

total power, the loss of this generation ability could have a great impact on other infrastructure. In the modern world, information communications technology (ICT) sits at the heart of all major infrastructure projects and needs to be considered carefully in relation to interdependencies, as it has the potential to impact drastically on the robustness of infrastructure during natural hazards. The performance of ICT will affect the ability to detect, recognise and act when extreme natural hazard events occur, so that those in control are still able to perform their functions. As such, it is likely to be necessary to consider a range of different factors which are not directly on-site; for example, ensuring power supplies are sufficiently robust, there is some degree of redundancy for ICT, and that staff can access emergency control centres during extreme events.

These interdependencies become especially important when different assets are affected by the same natural hazard. Although localised hazards are unlikely to cause damage to multiple pieces of infrastructure, larger events (e.g. low-pressure systems tracking over the Atlantic towards the UK) have the potential to impact upon multiple locations. In this situation, there will be less resilience in the total energy system and the natural hazard can stress the system further.

The spatial and temporal characteristics of each natural hazard will have a great impact upon the damage that can be done within the energy sector. Localised events may only cause issues for particular pieces of infrastructure, but are unlikely to cause wider issues to the whole energy sector. On the other hand, an extreme event that covers a large spatial area is likely to cause greater stress within the system as a whole.

It is also important to consider the temporal characteristics to understand better the *vulnerability* of the system. An event which happens in isolation could have an effect on a particular piece of infrastructure, but with the appropriate protection measures, is unlikely to be a large issue. However, clusters of events have the potential to cause much more damage if the system is not given enough time to recover from one event to the next. Clusters of events (multiple events of the same hazard or multiple different hazards) have been observed for a wide number of different natural hazards. In many situations, this is caused by specific overarching conditions which increase the probability of an event occurring, such as the positive phase of the North Atlantic Oscillation (NAO) which is associated with stronger westerlies tracking across the Atlantic Ocean, bringing warmer and stormier conditions across the UK. The first event striking a region is likely to cause damage, but may not cause a failure. If a second event then occurs, the system is already in a stressed state and there is an increased chance of the second event leading to a failure. For example, an initial extreme rainfall event may increase the groundwater

level and saturate the ground to a point where a secondary rainfall event leads to widespread flooding as there is more water run-off than usual.

Clusters of separate events have the potential to cause damage to different infrastructure. However, it is also necessary to understand the vulnerability to persistent single events such as heatwaves and droughts. In these situations, as for the examples of clustered events, an event may not initially cause damage but, as it persists, in time the likelihood of a failure increases. An example could be given for heating, ventilation and air-conditioning units used within many different types of infrastructure. These systems are designed to cool hot air, and singular hot days are usually well within the operating capacity. But heatwaves can stress such units, especially if combined with increased humidity. This can reduce the cooling capacity and finally lead to a failure if such an event persists over a very long period.

The vulnerabilities of the energy system to single hazards have been well discussed and natural hazard characterisation approaches for single hazards are well developed, with extensions to account better for temporal and spatial characteristics currently being a large area of research. However, vulnerabilities can be the result of multiple hazards which affect a particular site or set of sites at the same time. So vulnerabilities in the energy system to these hazard combinations must be taken into account. Different types of hazard combinations can have a very different impact on the infrastructure under consideration. Mapping the effects that hazard combinations have on the energy system as a whole is a very challenging task, especially given the interdependencies discussed earlier. It is still an open question as to how to do this rigorously and robustly, but progress is being made. Historically, joint hazards have been considered and research in this area is available. A full analysis of larger-scale multi-hazard events is very important to understand better the vulnerabilities in the energy system, and is an important area of future research.

There are certain hazards or combinations of hazards where the vulnerabilities in the energy system are not well known and in certain situations it may not be possible to validate their impacts adequately. One example is the impacts of space weather events, which up until very recently were not well understood. In recent years, improvements in the amount of data available to analyse the vulnerability of certain components to this hazard have allowed a clearer characterisation. Consideration of a wide variety of hazards can be made, but there is always the chance of observing a type of hazard that is completely unexpected for which the vulnerabilities will not have been well assessed.

2.3 Natural hazard characterisation

So far, the potential vulnerabilities of the energy sector have been discussed, including issues of interdependencies between systems and over space and time. However, this project is focused on disseminating knowledge on the characterisation of natural hazards as opposed to addressing directly some of the issues raised. So where can the process of characterisation help to address the vulnerability of the energy system? The process of characterisation of natural hazards can be used within safety analysis and operation of different infrastructure. More specifically, it can be focused on:

- the initial build of infrastructure;
- adaptation over time to account for new hazards and the effects of climate change;
- ongoing safety assessment and operational considerations, including asset management protocols and the implementation of appropriate operating procedures.

During the initial build of any infrastructure it is important to characterise the impact that natural hazards may have on safety and operations. Decisions need to be made as to what level of protection is going to be provided against natural hazards and whether there are any hazards that can be screened out (for being either very unlikely to occur, or very unlikely to impact upon the infrastructure under consideration). A rigorous characterisation of natural hazards ensures that these decisions are robust and provide the level of protection that they should.

An important decision to be made during the initial build phase is what level of protection should be considered and implemented. This will depend on the asset, its vulnerability to the natural hazard, and the rarity of the natural hazard under consideration. Further to these considerations, the potential for future adaptation also needs to be taken into account should the magnitude of the frequency of the natural hazard alter (e.g. increasing sea levels could lead to a higher probability of coastal flooding).

An initial important consideration is the projected lifetime of the type of infrastructure. If it is short then there is less need to protect the infrastructure against long-term changes due to climate; if it is longer, it is necessary to consider the best way to protect the infrastructure against future climate change. The consideration of the impact that climate change may have on the asset at the construction and planning stage allows for the relevant protection to be built initially. However, building this amount of protection may be costly and there is a risk of overprotection for many years. This risk could be compounded by the fact that further research in the field of climate science could alter estimates of the effect of future climate change. Also, advances in technology may make providing protection in the future less expensive. Building protection to

cope with current natural hazards with the option to include additional protection later can overcome these issues, but requires a careful adaptation strategy.

Irrespective of the decisions taken at the initial build stage of infrastructure, the process of natural hazard characterisation is also important within the context of periodic safety review and asset management protocols. This process is vital for any infrastructure project to ensure that the safety measures taken initially are still valid and provide the appropriate level of protection. In many industries, this type of review is undertaken every five to ten years, although the regularity will depend upon the infrastructure under consideration. This process also permits the application of the latest technical approaches published in the research literature. The research area of natural hazard characterisation is evolving as new models and approaches are developed and translated into an industry context. In many situations, these approaches allow for more certain and robust estimates of *return levels* of natural hazards, which need to be filtered through into safety review processes and asset management protocols.

Natural hazard characterisation is not only important for new build infrastructure projects. Existing energy infrastructure assets in the UK also require approaches for natural hazard characterisation to ensure that this infrastructure is robust to any natural hazard that may strike the UK in the near future. However, they pose a slightly different problem as many of these projects were built using earlier techniques for characterising natural hazards which have since been supplanted and were not built with future climate change in mind. As such, the process of periodic safety review is especially important for these pieces of infrastructure.

Throughout this section, the focus has broadly concerned the use of natural hazard characterisation within the context of safety assessment. However, it can also provide an important contribution to operational aspects. For example, at coastal power plants there is not only interest in what a 1 in 100-year marine ingress event looks like, but also in how an early-warning system could be developed to give people on site as much time as possible to adapt to an emerging event. In this role, the focus is less on standard statistical approaches for assessing the occurrence frequency of events, and more on predicting general conditions which could lead to a damaging event.

From an operational perspective, it is also important to consider the safety of on-site staff in the event of a natural hazard. Undertaking important operations during such an event can be very dangerous and care must be taken to ensure the safety of all staff members. As an example, extreme sea states can make it difficult to send staff out to offshore structures to deal with safety

issues, or even to undertake routine maintenance work. Natural hazard characterisation can help by providing analysis of the likely duration of such events, to ensure that staff are not sent into situations that are potentially hazardous.

2.4 Summary

The UK energy sector is a very dynamic environment where several different types of generation areas interact to meet the country's energy requirements. Broadly, there is a shift towards small-scale and low-carbon generation driven by improving technology and the reduction in costs of these types of infrastructure.

Irrespective of the type of infrastructure under consideration, it is clear that natural hazards have an impact and therefore the infrastructure may be vulnerable. These vulnerabilities differ greatly between infrastructure types, but cannot be considered only in isolation. There are a lot of interdependencies within the energy system as a whole (and indeed between the energy system and other systems such as transport and ICT), and therefore natural hazards have the potential to impact multiple pieces of infrastructure and cause impacts that may not be foreseen if only considering the separate infrastructure. Such impacts must be considered not only for single hazards impacting on different spatial and temporal scales, but also for combinations of different hazards. This highlights the need for robust and reliable natural hazard characterisation techniques across a wide range of natural hazards. The hazard characterisation process should be undertaken for safety assessment for current- and future-build infrastructure including any procedures required for periodic safety review. However, it need not be restricted to safety assessment as natural hazard characterisation can also provide useful information for operational concerns that occur on site.

There is significant potential value in providing detail on the specific natural hazards that should be considered for the UK, as the country's existing energy infrastructure is to be decarbonised, overhauled or replaced by 2050. This step is important as there is a very long list of natural hazards that could be considered, but not all of these will be relevant to the UK. In this way, it will be ensured that the current set of documents provide information about the most relevant natural hazards that could affect UK infrastructure.

3. List of natural hazards

The technical volumes and case studies are designed to give a comprehensive overview of approaches for characterising a wide range of natural hazards. The documents focus on natural hazards which affect the energy sector in the UK. This choice is made to ensure a manageable set of hazards with a non-negligible probability of affecting UK infrastructure (where the definition of non-negligible is not fixed and is likely to change depending on the type and lifetime of the infrastructure under consideration).

When drafting the list of natural hazards to consider, certain assumptions were made and certain hazards were excluded as it was not feasible to provide guidance for all hazards. The main criteria for inclusion were:

- Does the hazard affect sites across the UK?
- Is there a non-negligible probability of a specific hazard occurring?
- Is there an appropriate amount of available information on the hazard in question?
- If there is little information, would additional research provide additional information?
- Is it appropriate to undertake this research within the timeframe of the project?

A wide variety of natural hazards were assessed using these criteria. For example, the occurrence and severity of hurricanes is important within a global context, but hurricanes themselves do not affect sites in the UK (although their remnants can strike the UK as low-pressure systems during hurricane season). Certain hazards, such as direct meteorite strike, have not been considered within the project due to their extremely low probability of occurrence and localised effect. However, the potential of a tsunami triggered by a meteorite strike has been considered as this event has a higher probability of affecting infrastructure.

Natural hazards for which there was little information prior to this project were identified as knowledge gaps within the early phases of the project. Five of these hazards were taken forward for additional research during Phase 2 of the project. Some of the other hazards considered during this process (see [Section 1.3](#) for a list) were disregarded as there was little additional information available or it was not feasible to undertake additional research within the timeframe of the project.

The application of the broad criteria above has allowed the definition of the scope of the technical volumes. There are twelve volumes in total: a single introductory volume (this volume) and eleven volumes outlining the characterisation of different classes of natural hazards. The final list of volumes is provided below and represents a comprehensive list of natural hazards that currently affect UK infrastructure:

3. List of natural hazards

- Volume 1 — Introduction to the Technical Volumes and Case Studies
- Volume 2 — Extreme High and Low Air Temperature
- Volume 3 — Extreme Wind
- Volume 4 — Extreme Precipitation
- Volume 5 — River Flooding
- Volume 6 — Coastal Flooding
- Volume 7 — Seismic, Volcanic and Geological Hazards
- Volume 8 — Hail
- Volume 9 — Lightning
- Volume 10 — Space Weather
- Volume 11 — Marine Biological Fouling
- Volume 12 — Hazard Combinations

Five of these hazard classes (Volumes 8 to 12) were identified as knowledge gaps during Phase 1 of the project and additional research was undertaken in Phase 2 to address these gaps. This work feeds directly into the technical volumes and case studies.

The other six hazard classes (Volumes 2 to 7) were chosen as they represent important hazards which can impact infrastructure across the UK. More information is available for each of these hazards and the research fields are more developed. For these technical volumes, current relevant good practice across industries and academia is summarised and the appropriate methodologies applied at case study sites.

The hazards under consideration have been grouped to ensure that similar hazards are considered within the same volume. In particular, hazards with similar initiating events or similar impacts have been grouped to ensure they can be addressed holistically within the same volume. Volume 2 encompasses extreme high and low air temperature, extreme temperatures for rivers, seas and lakes as well as *frazil ice* formation and wildfires. Volume 3 includes the characterisation of tornadoes, and Volume 4 contains a brief discussion of the likelihood and occurrence of extreme snow.

The impact of flooding has been split between river and coastal sources (Volumes 5 and 6 respectively). From the perspective of natural hazard characterisation, the separate hazards within each of these broad classes can be very different. For coastal flooding, environmental variables such as high tide, extreme sea level, storm surges and wind-generated waves are the most common hazards which can impact on infrastructure. Less common factors

3. List of natural hazards

that can cause a large impact are tsunamis, landslides, meteorite impacts, low water levels and sediment transport phenomena. The impacts from river flooding are quite different, with flooding due to dam failure, extreme groundwater level, extreme surface water level, drought and sediment transport causing issues. For this reason, it is natural to consider coastal and river flooding as separate hazards.

Seismic, geological and volcanic hazards (Volume 7) have been included within the same volume as these can all be attributed to a similar root cause. These hazards are also often considered within similar existing regulatory frameworks.

The hazard combination volume (Volume 12), by definition, contains assessments of a range of natural hazards and how they interact. This includes an assessment of the different types of interactions and methods that can be used to model joint-hazard scenarios.

The natural hazards contained within the other volumes are all naturally split as they constitute separate hazards. As such, separate volumes have been provided for hail, lightning, space weather, and marine biological fouling (Volumes 8 to 11).

4.1 Technical volumes

For each natural hazard, the volumes aim to serve a wide variety of end-users, but are mainly focused on more technically able end-users. Broadly, each volume introduces the hazard under consideration, providing a definition and description of the phenomenon including a discussion of important past observed events. A summary of available data sources is given as well as a summary of the best current methodologies for modelling the hazard under consideration. There is a discussion of existing regulations and how these may develop in the future, and of potential changes in the severity and occurrence of each natural hazard under future climate change. Each volume follows the general structure described below.

Introduction

A general description of the hazard or family of hazards to which the considered natural hazard belongs. A set of past examples of occurrences and impacts to energy infrastructure provides additional context. A summary of how the hazard under consideration deviates from average values is given and, if appropriate, a discussion of potential physical limits is also provided.

Description of main phenomena

A clear description of the list of phenomena generating the natural hazards. A general statement of the global occurrence and severity of each natural hazard may be provided, especially for hazards with little observational data across the UK. However, more attention is given to the regional occurrence of each hazard across the UK, as this is the focus of the project.

Observations, measurement techniques and modelling tools

A description of available data for each natural hazard including measurement techniques and modelling tools for each of the main phenomena. This contains a non-exhaustive list of potential datasets and sources of information which could be accessed for the characterisation of the natural hazard under consideration. It includes the main publicly-available datasets, and also outlines commercial datasets that are available for purchase by companies wishing to undertake natural hazard assessments. The amount of available data may vary widely depending on the hazard under consideration and the maturity of the research area for each hazard. Wherever possible, available data for past important severe events outlined in the previous sections are highlighted. The focus is on data available for the UK.

Methodologies

A description of the currently available and robust methodologies for the characterisation of natural hazards, including the best practice and new developments from recent research. For each hazard

under consideration a list of methodologies is provided to highlight the different approaches available for the characterisation of the hazard. For the identified knowledge gaps (Volumes 8 to 12), the results from Phase 2 of the project are used to outline the best methodology. All appropriate methodologies are described briefly and a balanced discussion of the relative merits and drawbacks of each approach is provided. Recommendations on the application of different methodologies (including their theoretical and practical limitations) is also given to ensure that any methodology can be used correctly. Finally, to link through to the previous section, each volume contains a discussion of the data required to apply each methodology robustly.

Related phenomena

A short description of the list of other natural phenomena related to the natural hazard under consideration within the volume; for example, a discussion of the likelihood and impacts of flooding caused by extreme precipitation. This description includes a brief physical description of the process, available observational data, and approaches for the characterisation of these related phenomena. For certain hazards, there may not be many related phenomena resulting from the main hazard under consideration, and this is discussed if appropriate. A summary of related phenomena provided in each volume is included in [Table 2](#).

Regulation

An overview of existing regulations for characterising the hazard which have the greatest relevance for each specific natural hazard under consideration. In particular, this section aims to reference the most relevant existing regulatory frameworks for the UK. This includes references to any particular return levels and occurrence probabilities currently used in industrial practice, and a discussion of specific methodologies mentioned in existing regulatory documents. This helps to assess how the proposed methodologies differ from the current best practice within regulatory documents and ensure that the methodologies proposed in this project are widely applicable. The focus of the regulation section is on the UK and specifically the energy sector.

Emerging trends

A brief assessment is provided of how the hazard could change into the future. Specifically, it is necessary to discuss how the severity and occurrence of each natural hazard may change with anticipated future climate change. As part of this discussion, the ability of climate models to simulate each hazard should be noted, as this has a large effect on the ability to obtain reliable climate change projections. This section may also include a summary of new and emerging methodologies that are becoming available for the characterisation of natural

hazards, but are currently not mature enough for full inclusion within the technical volumes. Finally, a discussion of the future regulation landscape is also provided where appropriate.

4.2 Case studies

The technical volumes are supported by a set of five individual case studies. These case study reports provide illustrative site-specific examples of the natural hazards and practical examples showing how the approaches outlined in the respective technical volumes should be applied. The case study sites have been chosen to span different location types. They are:

1. Trawsfynydd, in Wales, as representative of an inland case study.
2. Dounreay, in Scotland, as representative of a site with onshore and offshore infrastructure.
3. Hunterston industrial estate, in Scotland, as representative of a coastal area.
4. The Teesmouth industrial area, in England, as representative of an estuarine environment.
5. The Cottam power station, in England, as representative of an inland riverside site.

At each case study site, a specific set of natural hazards is considered. This is not to say that other hazards cannot occur at each site, but this has been done to focus the case studies and avoid unnecessary repetition; see [Table 2](#) for the hazards and their corresponding case studies.

Table 2. List of technical volumes and the hazards under consideration within each, along with the respective case studies for each hazard.

Volume	Hazard	Content	Applicable case study
1	-	Provides an executive summary on the background of the project. This includes an introduction to the natural hazards and motivation for the project.	-
2	Extreme high and low air temperature	Mainly describes high and low air temperature. Related phenomena include extreme high and low water temperatures, frazil ice formation, wildfires and enthalpy.	Trawsfynydd
3	Extreme wind	Focuses on extreme wind and tornadoes. Related phenomena include sandstorms.	Dounreay
4	Extreme precipitation	Focuses on extreme rainfall. Related phenomena include extreme snow, ice, fog, mist and humidity.	Dounreay
5	River flooding	Characterises floods arising from fluvial sources.	Cottam
6	Coastal flooding	Covers high tide, extreme sea level, storm surges, and wind-generated waves.	Dounreay and Teesmouth
7	Seismic, volcanic and geological hazards	Considers earthquakes, volcanic-ash dispersion and geological instability. Related phenomena include tsunamis.	Trawsfynydd
8	Hail	Covers hail only.	Teesmouth
9	Lightning	Covers lightning only.	Teesmouth
10	Space weather	Focuses on the effects of geomagnetically induced current. The solar energetic particle hazard is a related phenomenon.	Hunterston
11	Marine biological fouling	Covers marine species which clog up and grow around coastal or offshore facilities.	Dounreay and Hunterston
12	Hazard combinations	Investigates the combined impacts of potential hazards occurring close together in space and/or time.	Trawsfynydd

4. Format of the technical volumes and case studies

The case studies sit alongside the technical volumes to illustrate how the methodologies from the volumes can be utilised in practice. Each case study is organised into subsections where the natural hazards selected for a given case study are characterised. Some sites and hazards may have little or no observed data, so at least one example case study is included to illustrate how to proceed in these circumstances. The reports are structured as described below.

Introduction

General introduction to the site which is the basis for the case study. This includes an overview of past natural hazard events that have occurred at the site, and a short description of the geography and climatology of the site. This section also includes a discussion of the existing facilities and any future plans, where known, for the site.

Characterisation of the natural hazards

An overview of available data at the case study site for the characterisation of the selected hazards under consideration. The different methodologies highlighted in the respective volumes are mentioned and applied (where appropriate) to the available data at the site. This analysis aims to include an estimate of the probability of the natural hazard occurring, and includes design recommendations where possible. In situations where certain approaches cannot be applied, there is a discussion of the choice of methodology. This also includes a discussion of the limits and assumptions made when obtaining the final results. This context helps to explain the usefulness and limits of the different methodologies outlined in the respective technical volume, and reduce the risk of misinterpretation of the approach or outcomes.

Conclusion

Each case study finishes with a summary of the analysis together with any relevant comments on regulations, specific requirements or caveats that may apply. If any information is available about likely changes in the risk with future climate change then this is provided.

The process of characterising different natural hazards usually requires specific technical methods for specific hazards. However, there are some aspects which are consistent across different hazards. This section aims to provide a primer for two aspects in particular: (i) extreme value analysis; (ii) general regulatory context. The idea is to avoid unnecessary repetition within the technical volumes and case studies by outlining the broad concepts here. This allows the separate technical volumes and case studies to focus on detailing any more advanced methods and regulatory documents which pertain to a specific natural hazard of interest, without needing to repeat the introductory material provided in this section.

5.1 Extreme value analysis

Extreme value analysis (EVA) is a statistical approach that models only the most extreme values in an observational record and provides a framework for quantifying extreme levels (extreme values) and extrapolating out to extremes beyond those seen in the observational record; for readers desiring more information on general statistical techniques, the following guides are suggested — [Coppola \(1999\)](#); [Crawley \(2005\)](#). Extreme value models are specifically designed to allow for the model to provide estimates of the magnitude of very rare events and to quantify the robustness of these estimates. These models attempt to overcome many potential issues that can arise when attempting to model extreme values, such as:

- observations of extreme events are by definition rare, which means there are few available data;
- practical applications often require extrapolation beyond the maximum value previously observed;
- standard statistical models (e.g. the normal distribution) fit well to the body of a statistical distribution (i.e. values near the mean) but can provide poor fits to extreme values;
- different statistical models with a similar fit to the body of the distribution can lead to very different extrapolations.

Extreme value theory states that a sample of extreme values follows a given probability distribution from a known family of probability distributions. Two main approaches exist for modelling extreme values:

Block maxima

The idea is to select the largest observation in each given time block (often taken to be a year in length) and then fit a generalised extreme value (GEV) distribution to the set of extreme observations. For environmental data, a block is often chosen as a year to negate the effects of seasonality.

Threshold exceedance models

All observations above a certain high threshold are used to fit a form of the generalised Pareto distribution (GPD). There may be several or no extreme observations in each year and *non-stationarity* might have to be modelled using a variable threshold.

Compared to a block maxima method, threshold models make better use of available data as several extremely high observations, occurring in the same time period, may be discarded if using the block maxima method. As data are at a premium when modelling extremes, threshold exceedance approaches are more commonly used when undertaking EVA. However, the threshold exceedance approach introduces other issues which are discussed in more detail below.

EVA is based upon asymptotic theorems which only hold true for sufficiently extreme values. The choice of what constitutes a sufficiently extreme value is often difficult and subjective. For block maxima approaches, the maxima of a block of a certain length are modelled; as an example, if a time block of a year is chosen then the extreme values used would be annual maxima. For threshold exceedance models, an appropriate threshold must be chosen which defines which values are extreme. There is no specific level at which this must be set and the choice is subjective. Statistical approaches exist to select a sensible value of the threshold ([Coles, 2001](#); [Northrop et al., 2016](#)); in some situations, the appropriate level may be clear from the physical context.

An underlying assumption of EVA is that the data being modelled are independent. This is not always a realistic assumption, especially with environmental extremes, where large values can cluster (e.g. consecutive high temperature observations during heatwave events). When modelling using block maxima, any potential temporal dependencies are negated (providing that sufficiently large block lengths are chosen). When modelling using threshold exceedances it is possible to model multiple clustered extreme observations. By using all these exceedances, final inferences are likely to be too certain (with confidence intervals that are too narrow) as all exceedances will be treated as if they are independent. One approach commonly used to overcome this effect is declustering ([Coles, 2001](#); [Ferro and Segers, 2003](#)), where exceedances are split into clusters and the peak of each cluster is modelled (often called the peaks-over-threshold approach). More recent academic papers have started to explicitly model this dependence through time ([Fawcett and Walshaw, 2012](#); [Winter and Tawn, 2016](#)).

Different approaches can be used to undertake statistical inference for extreme value models (e.g. derive estimates for the parameters of an extreme value distribution). The standard approach is to use maximum likelihood estimation; it is possible to fit extreme value models using method of moments and Bayesian approaches too. For more information on inference see [Coles \(2011\)](#).

The fitted univariate extreme value model can then be used to obtain estimates of specific extreme levels. The most useful quantity depends on the context and application under consideration. One commonly used quantity is the T -year return level. The T -year return level is defined as the value that is expected to be exceeded on average once every T years. This definition is the most common, but the terminology can sometimes be open to confusion. It is important to note that it is not true that once a T -year return level has been observed, the next exceedance will occur in another T years; consecutive T -year events can occur. The T -year return level can also be difficult to interpret under climate change, as the T -year return level at the current time is likely to differ from the T -year return level in the future.

An equivalent terminology is the use of annual exceedance probabilities. This notation is simply a restatement of the previous terminology; in each year, the probability of exceeding a specific level (the T -year return level) is $1/T$. Therefore the T -year return level can also be defined as the event with an annual exceedance probability of $1/T$. By referring to exceedance probabilities on an annual basis, it is made clearer that there is a small probability of an event each year (even for very rare events). Both terminologies are used widely across statistical and applied literature and can be used interchangeably. For the benefits described above, where practical the annual exceedance probability convention has been used in the technical volumes and case studies. However, output from programming packages often uses the return period convention, so this convention has been used where appropriate.

Non-stationarity of environmental extremes needs to be accounted for when using EVA. Climate change is an important non-stationarity consideration and is likely to ensure that the T -year return level at the current time is likely to differ from the T -year return level in the future. However, it is also necessary to consider processes that can vary in magnitude over time (e.g. warmer conditions in the summer than in the winter). When using block maxima approaches, many within-year non-stationarities are negated (all, if using an annual block size). However, when using threshold exceedance approaches it may be necessary to use varying thresholds or pre-process the data ([Eastoe and Tawn, 2009](#); [Jonathan et al., 2013](#)). Another popular approach is to use some underlying process as a covariate within extreme value models ([AghaKouchak](#)

et al., 2013; Winter et al., 2016). An example of such an approach is using global mean temperature increases as a proxy for climate change.

It is important to understand the limit of statistical modelling using EVA. The further into the tail of a distribution that an extrapolation is made, the larger the uncertainty associated with a return level estimate. For example, the UK nuclear regulator expects nuclear power plants to be resilient to a natural hazard event that happens on average once in every 10,000 years. In many situations, the analysis may be based upon up to 30 years of data which can lead to return values that have associated large uncertainties, and in the worst-case scenario may not provide any useful information for the practical application under consideration. It should also be noted that EVA is a purely statistical approach and as such is very dependent on the data that are supplied for the modelling; if data quality is poor and the length of observation series are short then it is very difficult to obtain reliable estimates using EVA. In addition, the statistical approach may not account for any physical constraints associated with the data, if the original observational records contain no or few records that approached the physical boundary. Loose rules of thumb exist for deciding the amount of data required to undertake EVA, but none of them represents a definitive rule and they should be treated with caution.

Current academic research is starting to focus on more advanced statistical models which can make better use of multiple sources of data to reduce uncertainty (*Cooley et al., 2007; Weiss et al., 2014*). There has also been a push to start incorporating more information about the physical processes into statistical models. These approaches are noted but are not used in the technical volumes or case studies, as they are not mature.

5.2 General regulatory context

Energy infrastructure installations in the UK are generally subject to a framework of legislation, regulatory instruments, codes and standards. These have various intentions, some of which are to ensure that the activities carried out do not undermine safety, health, the environment or continuity of supply. In this section, there is a focus on safety-related legislation as it can be considered to be overarching and to represent good practice for the sector.

For safety regulation, the Health and Safety at Work etc. Act 1974 (also referred to as HSWA, the HSW Act or the 1974 Act) is the primary piece of legislation covering occupational health and safety in Great Britain (*HM Government, 1974*). The Health and Safety Executive (HSE), with local authorities (and other enforcing authorities such as the Environment Agency) is

5. Technical primers

responsible for enforcing the Act and a number of other Acts and statutory instruments relevant to the working environment. Statutory instruments are pieces of secondary legislation made under specific Acts of Parliament. They cover a wide range of subjects, including control of asbestos at work, diving, escape and rescue from mines, ionising radiation, and working at height.

The concept of 'reasonably practicable' lies at the heart of the British health and safety system. It is a key part of the general duties of the Health and Safety at Work etc. Act 1974 and many sets of health and safety regulations that the HSE and local authorities enforce. HSE's policy is that any proposed regulatory action (Regulations, Approved Codes of Practice (ACOPs), guidance, campaigns, etc.) should be based on what is reasonably practicable, i.e. to reduce risk to As Low As Reasonably Practicable (ALARP). In some cases, however, this may not be possible because the Regulations implement a European directive or other international measure that adopts a risk control standard different from 'reasonably practicable' (i.e. different from what is ALARP) ([HSE, 2018a](#)).

The term 'reasonably practicable' is used to allow regulators to set goals for duty-holders, rather than being prescriptive. It can be challenging to decide if a risk is ALARP, as judgement is required. Making sure that a risk has been reduced to ALARP is about weighing the risk against the sacrifice needed to further reduce it. The decision is weighted in favour of health and safety because the presumption is that the duty-holder should implement the risk reduction measure unless there is a gross disproportion between the risk and the sacrifice. Most cases are decided by referring to existing relevant good practice that has been previously established; novel hazards may require further discussion with stakeholders.

In addition to showing that reasonably foreseeable risk is tolerable and has been reduced to ALARP — via the implementation of appropriate design criteria, hazard protection, and mitigation measures — an assessment will also include evidence that relevant good practice has been applied. This includes compliance with appropriate design codes and standards. A great deal of guidance is provided by the HSE on what ALARP justifications are and on how they should be produced ([HSE, 2018b](#)). The HSE document *Reducing Risks, Protecting People* ([HSE, 2018c](#)) provides a good discussion on the issues of ALARP and sets out how the statutory bodies responsible for the administration of the HSWA approached the decisions about the management of risk that are required of them under the Act.

COMAH

The HSWA and associated secondary legislation relate to a variety of different hazards that could cause safety issues. However, these guidance documents focus on the risks posed by natural hazards. A specific example of relevant legislation relating to natural hazards is the Control of Major Accident Hazards (COMAH) Regulations 2015 ([HM Government, 2015](#)). The COMAH regulations includes the following requirement from schedule 3 of the legislation: 'Identification and accidental risks analysis and prevention methods —

- a detailed description of the possible major accident scenarios and their probability or the conditions under which they might occur including a summary of the events which may play a role in triggering each of these scenarios;
- natural causes; for example, earthquakes or floods.'

Legislation specific to a particular industry or topic can be identified using the HSE website ([HSE, 2018d](#); [HSE, 2018e](#)). Two examples are provided below concerning how general regulation is applied to different types of energy infrastructure. Where appropriate, specific pieces of legislation associated with specific natural hazards are listed within each technical volume to provide additional detail.

Nuclear

The UK nuclear regulatory regime is regulated by the Office for Nuclear Regulation (ONR), under the HSWA and the Energy Act 2013 (TEA); HSWA applies to conventional and nuclear safety whereas TEA applies to nuclear only. In addition to the HSWA and TEA, the following exist:

- Nuclear Installations Act 1965 (NIA) — sections of the NIA are relevant statutory provisions of TEA (not HSWA). Licences are granted (and licence conditions attached) under the NIA.
- Ionising Radiations Regulations 1999 (IRR) — these are statutory instruments under Section 15 of HSWA.

The UK nuclear regulatory regime requires facilities to assess risks posed by external hazards, and generally expects infrastructure to withstand the design basis event, which is an event with a return period of 10,000 years (i.e. annual exceedance probability of 10^{-4}). Guidance on assessing external hazards for the UK nuclear industry is provided by the ONR in *Nuclear Safety Technical Assessment Guide* NS-TAST-GD-013 Revision 6 ([ONR, 2018](#)). It should be noted that Technical Assessment Guides are not regulations, but represent the ONR's approach to regulation associated with the subject area. The basis of ONR permissioning is the ALARP principle within the nuclear site licence framework. The NS-TAST-GD-013 guide primarily

provides guidance to inspectors and thus includes some direction as to what assessments would be deemed acceptable by the ONR regarding external hazards and natural events. It should be noted that NS-TAST-GD-013 is currently undergoing a significant revision.

NS-TAST-GD-013 also expects the licensee to carry out beyond design basis analysis (BDBA), with hazards arising from meteorological hazards derived for frequencies with an annual exceedance probability of less than 10^{-4} , and the results presented as a hazard curve. The aim is to show that there are no *cliff edge effects* (discontinuities) just beyond the design basis. Some new build nuclear licensees are adopting an annual exceedance probability of 10^{-5} as a suitable just BDBA level. The ONR expects licensees to select a suitable beyond design basis level and provide justification that it meets the intent of the safety assessment principles and the advice provided in this section.

Offshore infrastructure

The offshore industry regulation is similar to COMAH regulation, with both requiring that accident risk, including that associated with meteorological and natural causes, is evaluated with respect to likelihood and consequence, and that appropriate measures are taken to control the risks. Neither regulation stipulates the methodologies to be used nor specifies a particular hazard level to withstand (e.g. 1 in 100-year event), with safety justification based on the ALARP principle.

The Health and Safety Executive website ([HSE, 2018f](#)) provides information on the main legislation that is used to regulate the offshore oil and gas industry. It is stated that operators/owners must:

- prepare a safety case that demonstrates they have the ability and means to control major accident risks effectively and have it accepted by HSE;
- consult the installation's safety representatives in the preparation, revision or review of the safety case;
- operate the installation in compliance with the arrangements described in the current safety case;
- implement effective measures to prevent uncontrolled releases of flammable or explosive substances;
- maintain the integrity of the installation's structure, process plant, temporary refuge and all other equipment;
- maintain the integrity of the wells and the pipelines throughout their lifecycle (this applies to well operators and pipeline operators);
- prepare a plan for dealing with an emergency should one occur.

5. Technical primers

A description of any environmental, meteorological and seabed limitations on safe operations, and the arrangements for identifying risks from seabed and marine hazards such as pipelines and the moorings of adjacent installations, is also required.

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Cliff edge effects

A situation where a small change in some input variable can lead to a large (and often irreversible) change in an output variable. Here, the natural hazard intensity would be an input variable and the impact on a piece of infrastructure would be the output variable.

Frazil ice

A collection of loose, randomly oriented, needle-shaped ice crystals in water. It forms in open, turbulent, supercooled water, which means that it usually forms in rivers, lakes and oceans, on clear nights when the weather is colder, and air temperature reaches -6°C or lower. Frazil ice is the first stage in the formation of sea ice.

Marine biofouling

The undesirable growth of marine organisms (both plants and animals) on man-made structures that are submerged for a sustained period; e.g. boats, buoys, jetties and piers, and the bases of offshore installations such as oil rigs and wind turbine foundations.

Non-stationarity

Here, defined as a time series of data with properties which change over space or time. A common example in the natural hazards context is the impact of climate change; climate change is likely to lead to higher future temperatures and as such a time series of global mean temperature values is likely to exhibit non-stationarity. Non-stationarity will often have to be explicitly accounted for when undertaking statistical modelling to ensure a well fitted model.

Return level

The T -year return level is defined as the value that is expected to be exceeded on average once every T years. It is equivalent to an annual exceedance probability (AEP) of $1/T$.

Vulnerability

In this context it refers to an assessment of the anticipated threat to infrastructure that a natural hazard event may pose. Different parts of the energy system can be vulnerable to different types of natural hazard at different intensities and temporal/spatial scales.

Abbreviations

ACOPs	Approved Codes of Practice
ALARP	As Low as Reasonable Practicable
BEIS	Department for Business, Energy and Industrial Strategy
BDBA	Beyond design basis analysis
COMAH	Control of Major Accident Hazards Regulations 2015
COP21	21 st Conference of Parties
ETI	Energy Technologies Institute
EVA	Extreme value analysis
GEV	Generalised extreme value (distribution)
GPD	Generalised Pareto distribution
HSE	Health and Safety Executive
HSWA	The Health and Safety at Work etc. Act 1974
IChemE	Institution of Chemical Engineers
ICT	Information communications technology
IMechE	Institution of Mechanical Engineers
IPCC	Intergovernmental Panel on Climate Change
IRR	Ionising Radiations Regulations 1999
NAO	North Atlantic Oscillation
NIA	Nuclear Installations Act 1965
ONR	Office for Nuclear Regulation
TEA	The Energy Act 2013



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