Programme Area: Nuclear

Project: Natural Hazards Review

Title: Review of Natural hazard characterisation methodologies

Abstract:

This document is the main deliverable of Phase 1 of the ETI project on Natural hazards containing a detailed literature review which specifies: the natural hazards which are relevant for the energy sector, classified by hazard categories; the available mature methodologies for regional and localised characterisation, as well as expert judgement regarding these methodologies; some comments on the impact(s) of climate change on natural hazards; the sectors where each natural hazard characterisation is relevant; the existing guidelines and regulatory frameworks impacting the UK; some examples of industry applications, including the estimation of climate change impacts; some trends in R&D in the characterisation of the Natural hazard; the gaps in natural hazard analysis and prediction (i.e., for example, the gaps in understanding the hazard combinations or the difficult in estimating the ligthning intensity) and the priority level of the gaps to be addressed by future work, with justification for why these gaps should be filled. All of this information will be used for scoping Phase 2 of the ETI project on Natural hazard, which aims to address the most urgent and relevant gaps.

Context:

The Natural Hazards Review project will develop a framework and best practice approach to characterise natural hazards and seek to improve methodologies where current approaches are inefficient. This is to improve energy system infrastructure design and the project is intended to share knowledge of natural hazards across sectors. The project will be completed in three stages. Phase one will focus on a gap analysis. Phase two will look at developing a series of improved methodologies from the gaps identified in phase one, and phase three will demonstrate how to apply these methodologies. Finally, phase 3 will develop a “how to” guide for use by project engineers.

ETI “Review of Natural hazard” project
Phase 1
D1
Review of Natural hazard characterisation methodologies

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Executive Summary

The goal of Phase 1 of the ETI "Review of Natural hazard" project is to provide an extensive review of the natural hazard characterization methodologies relevant for the Energy sector in the UK, together with an expert judgement on the robustness of the available methodologies and an analysis of the existing gaps to be addressed before providing an overall approach for the design of future high-value UK infrastructure in the Energy sector.

This document is the main deliverable of Phase 1 of the ETI project on Natural hazards containing a detailed literature review which specifies: the natural hazards which are relevant for the energy sector, classified by hazard categories; the available mature methodologies for regional and localised characterisation, as well as expert judgement regarding these methodologies; some comments on the impact(s) of climate change on natural hazards; the sectors where each natural hazard characterisation is relevant; the existing guidelines and regulatory frameworks impacting the UK; some examples of industry applications, including the estimation of climate change impacts; some trends in R&D in the characterisation of the Natural hazard; the gaps in natural hazard analysis and prediction (i.e., for example, the gaps in understanding the hazard combinations or the difficult in estimating the ligthning intensity) and the priority level of the gaps to be addressed by future work, with justification for why these gaps should be filled. All of this information will be used for scoping Phase 2 of the ETI project on Natural hazard, which aims to address the most urgent and relevant gaps.

Contents

Introduction

Background to the Project

Over the next three decades, the UK will be investing in a wide range of high value, long lived infrastructure assets. EDF Energy and its partners on this project are likely to be heavily involved in the shaping and design of these new assets. A robust understanding of the full range of natural hazards that will need to be considered in the design and assessment of high value energy infrastructure is a key goal.

A three-phase project has been launched by ETI with the goal of developing a consistent methodology for natural hazard characterisation in regard to the design of high value infrastructure across the energy sector. This methodology should provide a high quality design approach for improving safety, cost efficiency, and the understanding of the resilience of future energy systems and their dissemination.

In particular, Phase 1 will present a review of available information and existing mature methodologies regarding natural hazard characterisation across a wide range of energy sectors. Using this review, gaps in the data will be identified, some which will later be addressed during Phase 2. The goal of Phase 2 is to deliver a programme of small research and consultancy projects to address prioritised gaps and uncertainties identified from Phase 1, together with development and delivery of a consistent approach and methodology for the assessment of natural hazards and the design of solutions. Finally, the main aim of Phase 3 is to produce a "how to" guide to drive the engineers toward a high quality design approach for improving safety, cost efficiency. In Phase 3, the results of the whole project will be widely communicate and disseminate by an illustration of the full methodology developed in Phase 2 on two to three case studies, and via the organisation of two to three workshops. For more information, see [1].

EDF Energy R&D UK Centre is leading the consortium delivering this project. This high quality consortium includes **EDF Energy Generation, NNB Gen.Co., the Met Office, Mott MacDonald and AIR Worldwide**.

The underlying principles for gathering together the project partners were to be able to provide a strong project team ensuring the capability for covering a large number of domains in the Energy sectors as well as an exhaustive expertise on the skills required for the comprehension of a large ensemble of Natural Hazards.

EDF Energy is one of the UK's largest energy companies and its largest producer of low-carbon electricity. The company provides power to a quarter of the UK and supplies gas and electricity to over 5.5 million residential and major business customers. It is part of the EDF Group, one of Europe's largest power companies, which operates in 23 countries, employing over 157,000 staff. Research and Development is a key part of EDF Group and EDF Energy activities. EDF Energy R&D UK Centre Ltd. (RD) was formed in March 2012 in order to further strengthen its ability to deliver increasing R&D activity in the UK. EDF Energy R&D UK Centre team can call upon additional expertise from across the EDF Group. RD is leading the consortium appointing the project manager and the Chief Technologist. EDF Energy Nuclear Generation Ltd. (NG) is the owner and operator of the existing civil nuclear fleet in the UK while NNB gen. co. Ltd. (NNB), part of the EDF group, 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. EDF Energy will provide a decadal experience of characterisation of Natural Hazard mainly, but not only, due to its unique experience in Nuclear sector. Experts from Renewable sectors and others Company business units will be involved in the project.

Mott MacDonald Ltd is a global management, engineering and development consultancy and a top firm in power (Ranked number 1 in Power in the 2013 NCE Consultants File). They began working on power projects in the late 1890s and have accumulated experience in all types of generating technologies including: Conventional coal and oil fired steam plant, CHP, Diesel, Energy from waste, ICGT, OCGT, CCGT, renewables and nuclear. MMD has wide experience in natural hazard consideration spanning across different sectors, including oil and gas, water and power industry, including thermal generation and renewables. Mott MacDonald has strong links with operators in energy sectors, among them; Scottish Power, EoN, Iceland's national power company Landsvirkjun, National Grid, Shell, BP and TOTAL. For this commission, MMD is 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 in 1987 and has extensive experience characterizing natural hazards and determining their effects. Air has experience of providing global risk engineering services and providing assessments of local hazard conditions to the insurance and reinsurance markets. AIR's modelling methodologies are widely used throughout the entire property insurance and reinsurance industries and help clients meet Solvency ii regulatory certification.

The Met Office is the UK's national weather and climate service, and also provides operational predictions of space weather. It is a Trading Fund within the Department for Business, Innovation and Skills. As a world leader in providing weather and climate services, it employs more than 1,800 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 from the Government, to businesses, the general public, armed forces, and other organisations. Additionally, the Met Office Hadley Centre provides world-class guidance on the science of climate change and is the primary focus in the UK for climate science

This consortium is thus covering a wide number of Energy sectors domains and providing expertise on a large set of Natural Hazard phenomena. The credentials of the participants strongly assure the authority and quality of the final deliverables.

The main technical deliverables for Phase 1 are (D1) a review of the available information and methodologies on natural hazard characterisation and an analysis of key gaps in the available knowledge and (D4) a report including a proposed scope schedule, budget and resource profile for Phase 2.

This report is deliverable D1 of Phase 1 of the ETI project.

Content of this Report

This first deliverable of Phase 1, D1, aims to present a review of the available information and methodologies regarding natural hazard characterisation across a wide range of energy sectors. The deliverable also includes an extensive analysis of the gaps in current knowledge and an assessment of the emerging trends in R&D. Finally the report suggests a prioritization of the gaps to be treated in the next Phase of the project to go toward the definition of a high quality "how to" guide for the characterisation of natural hazards for the UK's high value energy infrastructure.

The content of the report is comprehensively summarized in several tables reported in the Appendix of this document, presenting the following information:

- A list of natural hazards which are relevant for the energy sector, classed by hazard categories
- The available mature methodologies for regional and localised characterisation, as well as expert judgement regarding the methodology
- Comments on impact climate change has on natural hazards
- A list (if applicable) of suitable and sufficient methodologies available to quantify the impact and associated uncertainties
- A list of sectors where each natural hazard characterisation is relevant
- A list of existing guidelines and regulatory frameworks impacting the UK
- Examples of industry applications, including the estimation of climate change impact
- Trends in R&D
- Gaps in natural hazard analysis and prediction
- The priority level of the gaps to be addressed with justification for why the gap should be filled

The results reported in the tables in the Appendix are discussed and analysed in the following sections, focusing on the review of available methodologies in Section 1 and on gap analysis in Section 2.

Review of Methodologies for Natural hazard Characterisation

Definitions and scope

This project is a review of the available methodologies for characterisation of natural hazards relevant for high value infrastructure design in the UK. For a project of this scale, some definition is needed to clarify the boundaries of the exercise.

A **natural hazard** may be defined as an "element of the physical environment, harmful to man and caused by forces extraneous to him", [2]. The listed hazards belong to different classes of natural phenomena including Meteorological Hazard; Marine Hazard; Hydrological and Hydro-geological Hazards; Volcanic, Seismic and Geological Hazards; Biological Hazards; and Electromagnetic Hazards. To extensively demonstrate this definition, a list of relevant natural hazards is given in the next section. This project ill deal with the characterisation of Natural Hazards
Note that the natural hazards belong to the class external hazards, generating from sources and mechanisms external to a power plant or an infrastructure to be distinguished from the internal hazard, generated within the power plant or the infrastructure. However, in the class of the external hazard, it is useful to distinguish natural hazards from man made hazards (e.g. airplane crash, accidents). In the Table 1, a simple diagram illustrates the definitions of internal, external, natural and man made hazards.

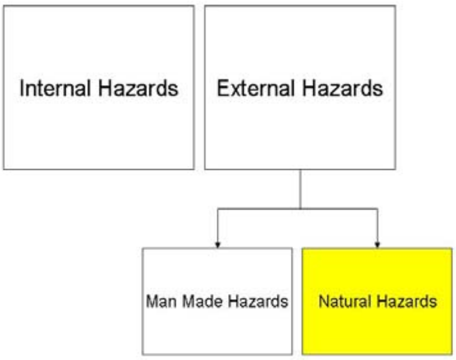

Table 1. Illustration of Hazards definition

An **extreme event** is characterized by its probability of occurrence, usually its annual probability of occurrence. The more the event is extreme, the rarer it is, thus associated to a small annual probability. For high value infrastructure design and protection, the extreme events to be estimated are usually associated to annual probability ranging from 10^{-2} to 10^{-4} and even lower for some specific applications (i.e. nuclear safety).

In particular, focusing on Meteorological Hazards, The IPCC Special Report on Extremes (SREX) defines a **climate extreme (extreme weather or climate event)** to be: “the occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable. For simplicity, both extreme weather events and extreme climate events are referred to collectively as ‘climate extremes’”, [3].

In terms of **geographical scope**, the project will focus on research regarding infrastructure based on UK land and offshore waters. However, due to the global nature of the scientific community, methodologies can come from other countries. Moreover, hazards generated outside the UK but with the potential for a knock-on effect in Britain will also be investigated (for example, the dispersion of volcanic ash in the UK generated by volcanoes in Iceland).

The definition of **high value infrastructure** is limited to energy sector infrastructure, including generation and extraction sites, networks and grid. Road networks and other civilian infrastructure not specific to the energy sector are excluded.

The energy sectors considered in this project are:

- Renewable energy (including offshore and onshore wind power, solar, wave energy)
- Hydropower generation

- Transmission and distribution networks
- Nuclear generation
- Oil and gas
- Thermal generation
- Insurance

Note that insurance, technically speaking, is not part of the energy sector. However, the insurance sector approach to natural hazards characterisation may have an impact on the investment on the energy high value infrastructures. For this reason the insurance sector has been considered here. Hydropower generation sector has been treated separately from renewable sector, due to the fact that it is a traditional sectors existing in the energy industry since long time, compared to the new renewable technologies. By transmission and distribution network, it is meant here the whole electricity grid from the generation plant to the customer, including distributed generation, even though this last sector may deserve more specific attention in the future.

The approach

In order to ensure the **widest possible coverage of all the energy sectors** the skills and capability within the consortium has been mapped to ensure coverage for all the sectors mentioned in the previous section. A preliminary check of the consortium skills were presented in the project Phase 1 proposal [4]. Partners' contributions within the project consortium ensure the fact that all the information relevant for the energy sectors listed in the previous sections is represented here. In Table 2 it is shown that all the sectors are covered by at least one consortium partner's skill.

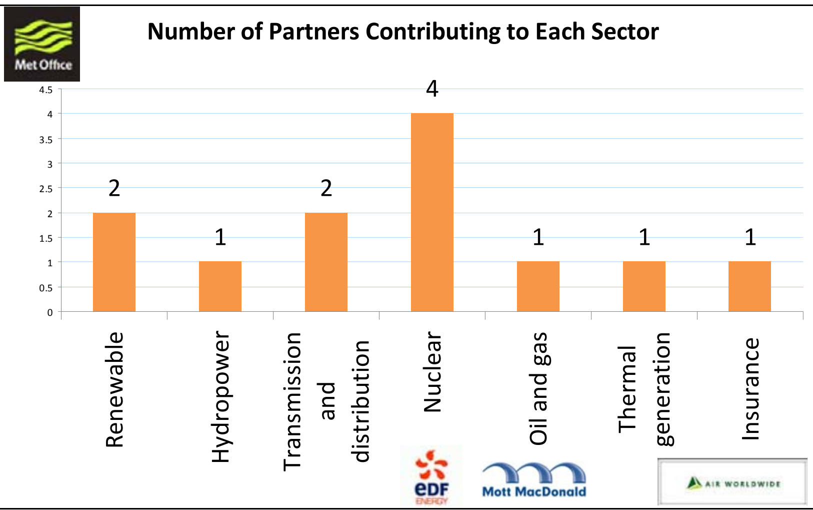

Table 2. Number of partners contributing with information to each sector

In order to ensure **the best possible coverage of the scientific literature** and knowledge, a large dataset of scientific and industrial references has been investigated in order to provide all the information reported in the Appendix. The selected approach for locating and reviewing existing mature methodologies is based on a wide review of:

- Scientific/academic literature
- National and international regulatory documents
- National and international guidelines
- Meteorological and environmental studies
- Industrial studies
- Workshop records
- European Project deliverables
- Partnership knowledge and public reports

A list of relevant references is reported at the end of this document and the list of references quoted in the table is reported in Appendix.

The literature review is supplemented with expert interviews, focused, in particular, on any blanks left in the table following the systematic review of the mentioned sources. In particular, we interviewed

- Sebastien Pelissier, EDF Energy R&D UK centre project manager of the offshore wind project, expert in renewables energy
- Sarah Levy, expert in marine renewable energy fleet design at EDF EN (Energies Nouvelles)
- Marta Nogay, project manager for wave energy and marine energy project at EDF R&D
- Scott Stransky, R&D expert on Natural hazards for the Insurance sector at AIR Worldwide, with particular expertise on Wind perils, severe thunderstorms, tropical cyclones and wildfires
- Arnaud Lenes, expert on thermal electricity generation at EDF Energy

Finally, in order to ensure **high quality of the delivered information**, a periodic Technical Quality Review has been provided by the Met Office.

List of Natural hazards

In order to better define the scope of the project, a list of 34 relevant natural hazards for the energy sector was developed. Note that this is a first important result of the project, opening the door to defining a systematic and common approach for the characterisation of natural hazards, which is the final deliverable of Phase 3.

The list of hazards was divided into 8 classes, as listed below:

- Meteorological
- Marine
- Hydrological and hydrogeological
- Volcanic, seismic, and geological
- Biological
- Electromagnetic
- Combinations
- Other

Each of the individual natural hazards is placed into one of the above classes. The hazards are presented below, grouped within their respective classes.

Meteorological:
- Extreme rainfall
- Frazil (including ice flow)
- Extreme and very rapid changes in temperature
- High extreme ambient air temperatures
- Low extreme ambient air temperatures
- Extreme high water temperature
- Extreme low water temperature
- Extreme snow (including sticking snow, snow avalanches, icing, hard rime)
- Extreme wind
- Tornadoes
- Lightning
- Hailstones
- Humidity (including mist and fog)

Marine:
- High tide/extreme sea level/extreme surge
- Wind generated waves (long or short fetch)
- Tsunami
- Extreme low sea level

Hydrological and hydrogeological:

- River flood
- Flood due to dam failure
- Drought
- Extreme Groundwater level

Volcanic / seismic / geological:

- Offshore or onshore landslide
- Sediment transport and sandbank
- Geological instabilities (i.e. sinkholes, liquefaction, land slippage, etc.)
- Sandstorm (including dust storm and volcanic action)
- Earthquake

Biological:

- Marine biological hazard (i.e. marine growth or jellyfish and seaweed clogging of water intakes)
- Animals (including for example, rodent infestation)

Electromagnetic:

- Space weather (including solar flare, Natural EMP)
- Solar UV

Combinations:

- Hazard combinations

Other:

- Forest fire
- Meteorite impact

Decisions had to be made to define the list of the relevant natural hazard, including the aggregation or the disaggregation of single hazard in groups (ex: snow or geological instabilities). The similar phenomena were merged in a single group where possible in order to simplify the list. If similar phenomena were analysed in the past using different techniques or in different context, they were not merged. For example, tornadoes and wind has been separated because of the specific literature existing on Tornadoes phenomena while geological instabilities such as sinkhole or liquefaction were gathered together for sake of simplicity.

Sectors impacted by the listed Natural hazards and Examples of Industrial applications

Different energy sectors may consider the impacts of different natural hazards in the design and operation of high value infrastructure, depending on the impact of the given extreme natural event on aspects of their business.

In the attached table (see Appendix)(column "Sectors impacted" and "Examples of industrial applications"), some impacts of each hazard on the different sectors are considered and examples of applications to the most relevant sectors are highlighted. This mapping detailed exercise is not exhaustive but it gives a general idea on which hazards are considered in the different sectors and allows the reader to drawn some conclusions on the hazards the most considered and on the sectors the most active in the hazards characterisation.

In Table 3, coverage in terms of natural hazard considered in each sector is given.

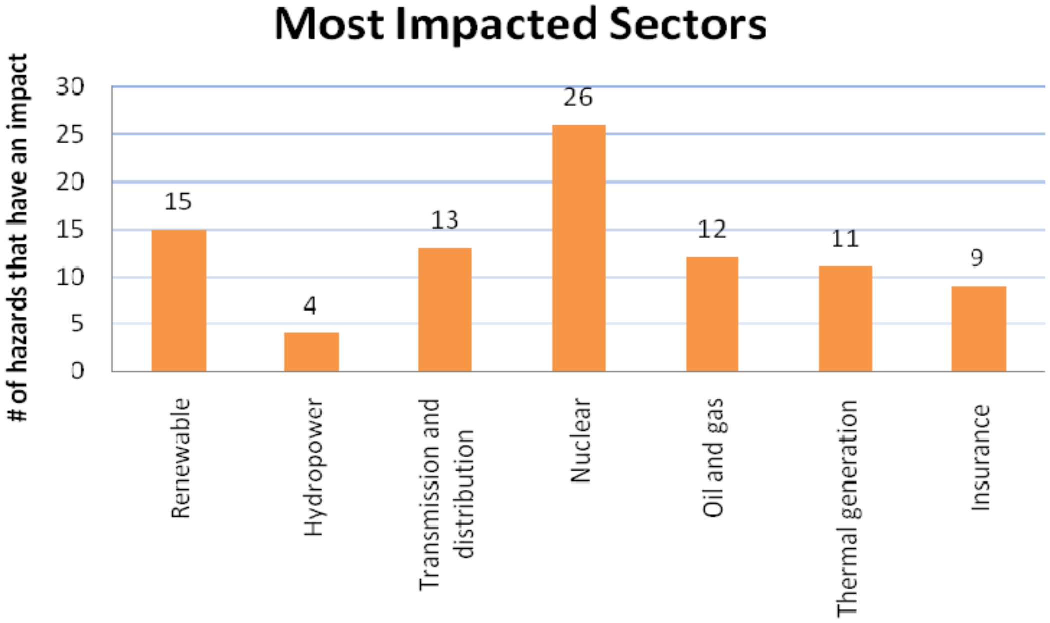

Table 3. Coverage of number of natural hazard for each sector

26 out of the 34 natural hazards are considered in the nuclear sector. This shows that the maximum number of different hazards considered in the nuclear sector for nuclear safety.

The complete information can be found in the table in the Appendix, but in order to give few examples of impacts, tsunamis are mentioned for the nuclear industry because of the associated risk of flooding for the nuclear platform. Extreme snow is a relevant hazard in transmission and distribution sector because of the risk of having sticking snow on the electric wires, potentially leading to breakage of the wires. Extreme wind is mentioned for renewables in terms of damaging the wind turbines. Earthquake is the hazard which is covered in the largest number of sectors (essentially all of them). According to AIR Worldwide, as reported in the attached table (see Appendix) "all insurable property lines of business can be affected by earthquake."

Table 4 presents the list of hazards in combination with the number of sectors they impact; the complete information is available in the table in the Appendix.

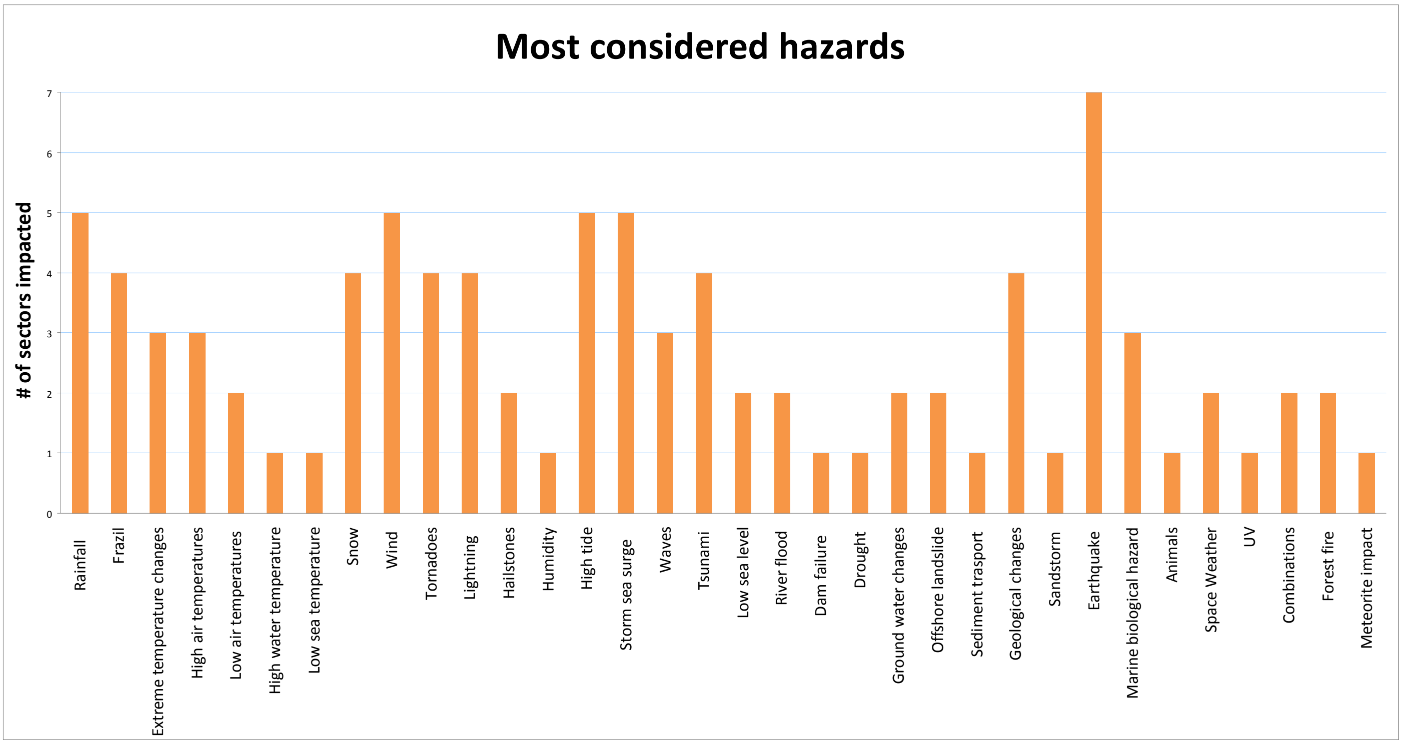

Table 4. Number of sectors impacted by each hazard

It is useful to note that a small number of hazards are considered in almost every sector (at least 5 sectors). These are rainfall, wind, snow, extreme sea level and storm surge, and earthquake. This allows for the definition of a short list of particularly relevant hazards, which are basically the traditional hazards largely considered in scientific literature. This point confirms as well that the list proposed in the previous section is relevant, that the main hazards have been mapped together with more specific hazards, and that it is now possible to converge towards a systematic and common approach.

A specific comment must be made for hazard combinations. Even though few sectors (nuclear and renewable in our survey) are already considering this emerging hazard, it is clear that the consideration of the simultaneous occurrences of extreme phenomena for design purposes has been introduced across the energy industry.

The impact and, as a consequence, the return level of the hazard considered depends on the sector. Again, one can observe that the nuclear industry is leading the exercise because of the need for estimating extreme events associated with a 10^{-4} annual probability, while in other sectors (e.g. renewables) the estimation usually stops at 10^{-2} annual probability. 10^{-4} seems to be a kind of maximum extrapolation limit. In the insurance sector, for example, AIR Worldwide’s stochastic modelling techniques can estimate events up to probabilities of 10^{-4}.

Among the example of industrial applications, we have references to the safety cases produced for nuclear safety, insurance series studies, and commissioned studies for different sectors. For example, for the nuclear sector the Met Office produced reports for the EDF Energy nuclear fleet for the estimation of extreme rainfall and other meteorological hazards, while EDF Energy produced periodic safety reviews studies for the characterisation of several natural hazard characterisations. The insurance sector produced series of industrial facility codes, the 400-series that can be used to assess the vulnerability to several natural hazards of over 60 different large industrial facility types. (see the Appendix of this document for complete information). Other mentioned industrial studies are, for example, (i) the DEFRA (Department for Environment, Food & Rural Affairs) Report on the threat posed by tsunami to the UK and (ii) the Royal Academy of engineering report on the extreme space weather impact on engineered systems and infrastructure.

Literature Review of the Available Methodologies Including Expert Judgement

Depending on the class of natural hazard and on the sector, different methodologies have been suggested for hazard characterisation in the past. In the attached table (see Appendix) (columns “Available Mature Methodologies” and “Expert Judgement”), these methodologies are reported together with expert judgement on their robustness.

The methodologies mentioned for characterizing the hazards in the list are presented below:

- Extreme Value Analysis (EVA), [5], stationary and non-stationary versions
- Statistical Methods based on EVA (EVA with salinity, linear method for tornadoes, JPM (Joint Probability Method), [6])
- Regional Frequency Analysis (RFA), [7]
- Spatial distribution analysis and geospatial studies
- Deterministic approaches (PMP (Probable Maximum Precipitation),[8], maximum scenarios)
- Numerical modelling (Finite element analysis, weather, climate and atmospheric models, hydrodynamic and ocean models, tsunami models, hydrological models, hydraulic models)
- Stochastic modelling (Monte Carlo)
- Laboratory testing
- Use of international codes, catalogues, or standards

The traditional application of the EVA has been distinguished from the application of the EVA within more complex statistical frameworks (Statistical Methods Based on EVA). For example for the estimation of extreme sea level EVA is used within the Joint Probability Method for characterising the probability of occurrence of extreme surges. Technically speaking the “Use of international codes, catalogues or standard” is not a methodology itself, because the results contained in these catalogues are obtained using specific methodologies, often EVA. However, the use of these codes reflects a very common engineer practice, thus it was decided to list it independently.

The use of some particular methodologies for a given sector may be driven by existing guidelines or regulatory frameworks. For example, in France, for the estimation of the extreme sea level for the protection of nuclear power plant, the security authority, in a regulatory document dating back to 1984, [9], (in French and now updated by [10]) suggested the use of the EVA. This has been driving the use of such an approach for several years in this domain.

Two main classes of methodologies were defined to analyze the results. One is the class of purely statistical approaches similar to Extreme Value Analysis (EVA), including extensions such as statistical methods based on EVA, RFA, and geospatial studies. The other is the class of numerical (often stochastic) approaches, including deterministic approaches and numerical modelling. Almost all the mentioned approaches belong to one of these classes. Note that both classes of approaches are theoretically able to deal with the spatial extent of the hazard characterisation: purely statistical approach via techniques like geostatistics or RFA, numerical approaches because of the spatial extent and resolution of the available numerical models. Obviously each specific phenomenon is characterized by specific spatial variability and extension, which can be more or less difficult to take into account (i.e. strong spatial variability for convective rainfall versus smooth spatial variability for temperature).

In Table 5, the methodologies used for hazard characterisation are shown in relation to the number of hazards to which each methodology applies; the details being available in the attached table (see Appendix). For example, 17 individual hazards are characterised using EVA in the current practices across various sectors.

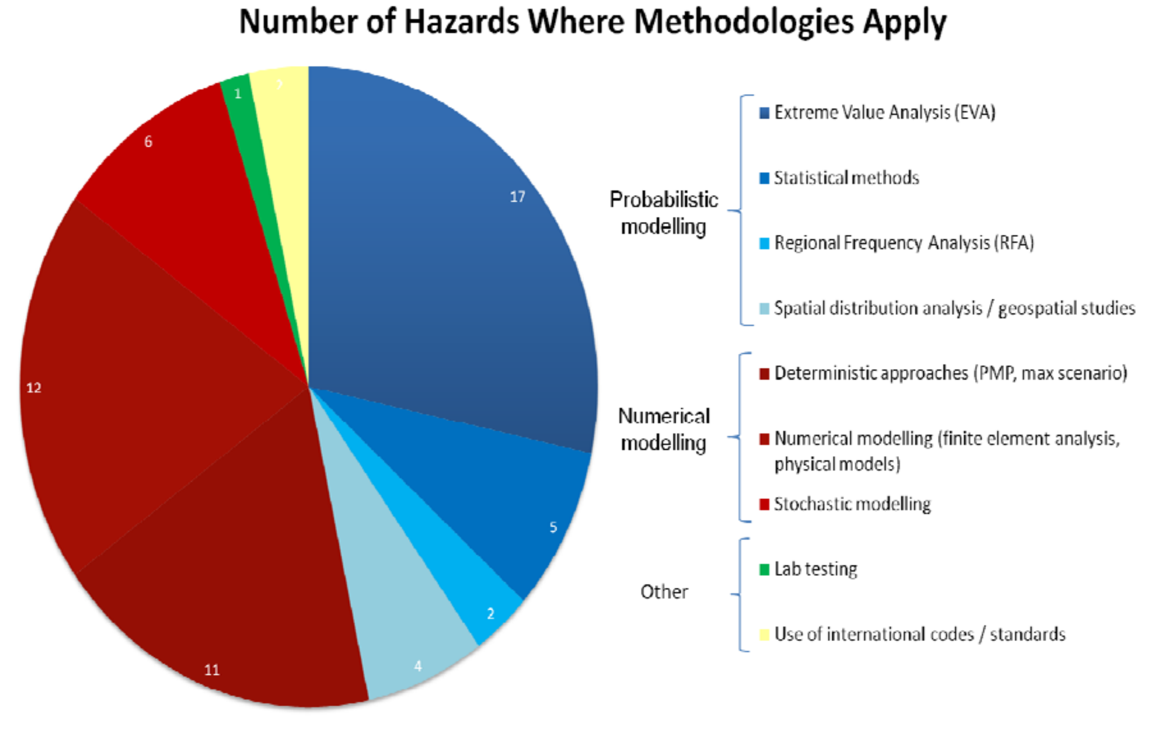

Table 5. Main methodologies for characterisation

A first general comment on the reliability of the existing methodologies is the warning on the difficulty of observing and correctly measuring some extreme phenomena. Some examples are the difficulty on measuring lightning intensity or the lack of data for extreme rainfall at few minutes' resolution.

The collected expert judgements on the robustness and reliability of the different methodologies show a low degree of confidence on the traditional purely statistical approaches, such as EVA, which are defined as having poor robustness for extreme extrapolation, particularly when relying on short series of data. A mentioned limit for these approaches is the underuse of physical knowledge of the phenomena, indeed the choice of the probability law traditionally used to estimate the probability of occurrence of the extreme values are not based on physical arguments, neither are the estimated parameter of this laws. Another limit is linked to the underuse of available data (at different location and from different sources).

Some methods are mentioned which can be applied to increase their robustness. Concerning the underuse of physical knowledge, the law parameters could be linked to physically based co-variables, for example. In order to use more available data methods such as Regional Frequency Analysis (RFA), or the use of historical data were applied in the past. Historical data refers to measures of intensity of extreme events occurred in the past which were not measured using standard techniques but which can be reconstructed by alternative approach. For example, it is possible to estimate the discharge of a flood occurred centuries ago studying historical documents describing the flood or analyzing sediments layers on the river bed. This data may be used in cases such as flooding risk estimation, while RFA is more frequently used when classifying cases such as extreme storm sea surges or extreme rainfall.

Statistical models with physical constraint and approaches relying on the use of Numerical modelling (i.e. Stochastic simulations) seem to be judged as more robust even though they can be difficult to apply for very complex systems (i.e. biological hazards or tsunamis).
Finally, during the discussion within this project, it has been stressed that "confidence in numerical models can be high, if the appropriate model is being used. […]. EVA can also yield useful results if the extremes are not extrapolated too far […]. Both methods are models, not reality, and should always be treated as such." according to AIR Worldwide.

Comments on Existing Guidelines and Regulatory Frameworks

Regulatory frameworks, guidelines, standards and reference maps of hazard intensity were widely developed and used across the sectors and for different natural hazards. The term “guidelines” indicates suggested engineering guidelines advising on the methodology to use for the characterisation of a given Natural hazard, while a “regulatory framework” is a compulsory regulation indicating the return level to be estimated and sometimes the methods to use for characterising the hazard. “Reference maps” of hazard intensity such as Eurocodes contain the estimation of the intensity for given hazards and given return period. Eurocodes exist, for example, for snow, extreme wind or earthquakes. For the sake of simplicity all these documents are listed together here. The goal is to provide a large list of sources suggesting approaches and methodologies. The huge amount of codes and guidelines are grouped here based on the institutions producing them.

In order to give an idea of the institution producing the guidelines and to suggest some relevant document to the reader, a list including institutions, guidelines series and some stand alone guideline documents is given here:

- Nuclear sectors guideline including International Atomic Energy Agency (IAEA), tern European Nuclear Regulators Association (WENRA) and the Office for Nuclear Regulation (ONR).
- British Standards (BS)
- Solvency II rules for insurance sector
- American Petroleum Institute (API) guidelines
- International Electrotechnical Commission (IEC) guidelines
- Lloyds Syndicates
- Eurocodes
- National Grid Technical Specifications
- Garrad Hassan (Off shore wind design) guidelines
- DNV Offshore Standard (DNV OS)
- Construction Industry Research and Information Association (CIRIA)
- Sewers for Adoption
- American Society of Civil Engineers (ASCE) guidelines
- Department for Environment, Food, and Rural Affairs (DEFRA) guidelines
- International Building Code (IBC)
- National Fire Protection Agency (NFPA)
- Planning Policy Statement 25 from UK government
- Uniform Building Code (UBC)
- The Flood Estimation Handbook (CEH)
- TORnado and storm Research Organisation (TORRO)

Some sets of regulatory frameworks and guidelines are designed specifically for a given industry. For example, the IAEA, WENRA, and ONR guides are used by the nuclear sector. API standards are used by the oil and gas sector, while the Solvency II Directive is used by the insurance sector. Other sets, however, may be used by a wide variety of sectors, such as the Eurocodes, IEC, and British Standards. In Table 6, the number of hazard covered by each class of guidelines is reported.

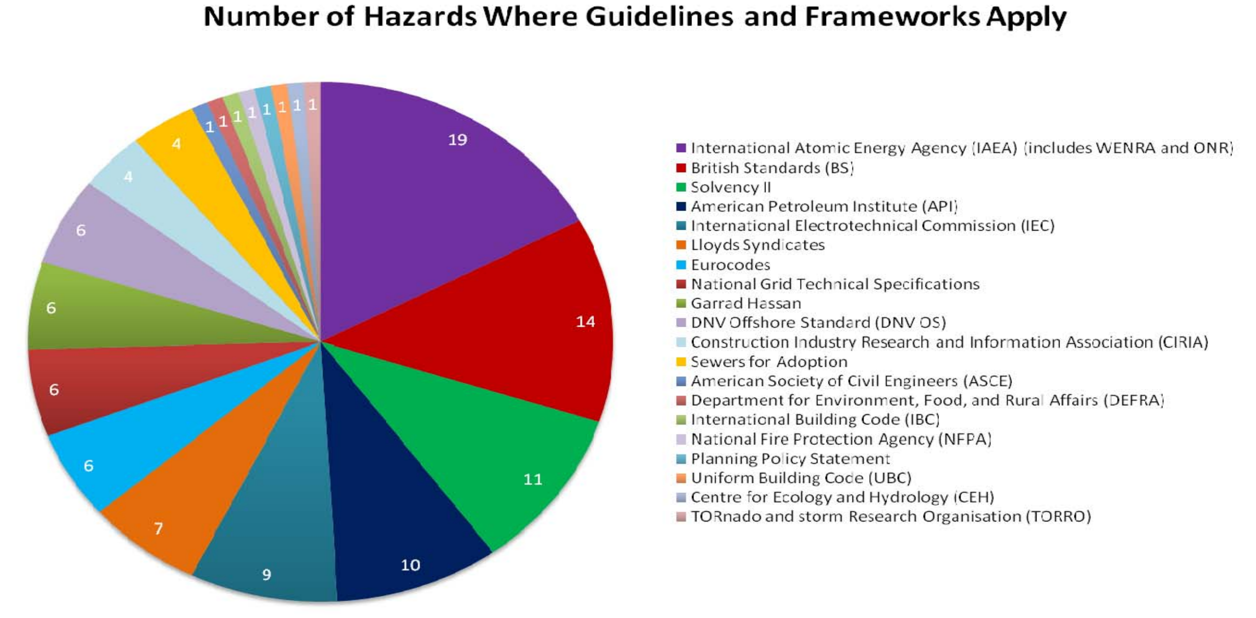

Table 6. Distribution of guideline and framework classes

The fact that the IAEA guidelines for the nuclear sector cover more natural hazard than any other guidelines is another clue of the fact that the maximum number of natural hazards are identified in the nuclear sector.

Additionally, a wide range of standards may be applied to a given hazard. If we consider rainfall, relevant guidelines for its estimation might be Planning Policy Statement 25 (PPS25), BS EN 752, BS 12056, Sewers for Adoption, CIRIA guides, National Grid Technical Specifications, BS EN 50341, BS 61936, and BS 7671, and this list could perhaps be extended.
In the attached table (see Appendix) (column "Existing guidelines and regulatory frameworks"), all the relevant guidelines and regulatory frameworks documents are listed including the actual references.

Climate change impacts

Climate extremes are rare events which occur as a result of variability in the climate system. As such, natural climate variability is an important factor governing extremes, and will continue to be so in the future. However, the available evidence also indicates that climate change is modifying the frequency, intensity, spatial extent, duration and timing of some extreme weather and climate events, and can result in unprecedented extreme weather and climate events. Conceptually, changes in extremes can be linked to changes in a combination of the mean, variance and shape of the probability distribution of weather and climate events. It is also important to note that some climate extremes are the result of compound processes and accumulation of weather or climate events that are not extreme when considered independently, [3]. An example was the stormy weather experienced by the UK during winter 2013/14, [11], the individual storms were not necessarily particularly extreme, but the clustering and persistence of the storms was highly unusual.

The most recent set of climate change projections for the UK was produced for UKCP09 - the UK Climate Projections 2009, [9]. This is the fifth generation of climate scenarios for the UK, and provides the most comprehensive UK climate change scenarios to date, based on leading climate science (from the Met Office Hadley Centre), which, for the first time, systematically incorporates and quantifies some of the key uncertainties associated with climate modelling. In particular, whereas previous climate change projections have been based on the outputs of one model - giving a single projection for a particular variable, time slice and emissions scenario – UKCP09 provides probabilistic climate projections for the UK.

The motivation behind this is to explore the uncertainty in climate projections which arises from the following:

- Uncertainty in future greenhouse gas emissions (we cannot know for certain our future greenhouse gas emissions, therefore projections are produced under three different plausible emissions scenarios)
- Natural climate variability (natural factors, both internal and external to the climate system, can cause the climate

to vary even in the absence of any human influence; some of these factors are included in UKCP09)
- Modelling uncertainty (sampled in part by using variants of the Met Office Hadley Centre's climate model, and in part by using information from other centres' climate models)

By using our best understanding to incorporate and explore climate natural variability and modelling uncertainty in a systematic way, UKCP09 provides probabilistic projections for a range of meteorological variables (e.g. mean/maximum/minimum temperature, precipitation, and wind) at 25km resolution across the UK.

A detailed list of key findings from UKCP09 is reported as a stand alone paragraph in the Appendix of this document. Moreover, in the columns "Climate Change Impacts" and "Uncertainties on climate change impact" of the attached table (see Appendix) some discussions are reported on the impact of climate change for each natural hazard.

Hazard Combinations

The subject of hazard combinations requires a special section. Historically and generally again today, the general practice is to treat each natural hazard separately, in terms of both characterising its impacts and protecting against those impacts.

However, in particular after the Japanese tsunami in 2011, the consideration of hazard combinations is becoming more and more of a requirement in terms of regulatory frameworks and guidelines. The specific combination observed during the Japanese tsunami was the sequential occurrence of earthquake and a tsunami wave. It is worth to note that here we will use the word "combination" to indicate not only the simultaneous occurrence of two or more different hazard but also the sequential occurrence of different hazards (i.e. the Japanese tsunami)

Again, the nuclear industry is the leader in this field, with general requirements from ONR in the UK, [12], WENRA, [13, 14] and IAEA, [15-17].

There is not yet a consensus within the scientific community regarding the actual degree of dependence between the hazards mentioned in the list. This lack of agreement is holding back the definition of the most appropriate methodologies to be applied for the estimation of the probability of occurrence of hazard combinations.

This issue is tackled in the insurance domain via numerical platform models where risk can be quantified for a location or multiple locations across multiple perils, [18]. In the scientific community and in industry, the use of multivariate analysis is being explored, [19, 20].

The lack of a systematic methodology for hazard combinations characterisation currently represents a major gap.

Trends in R&D

In order to capture the gaps and to anticipate the direction of future R&D development, an overview of the trends in R&D is given in the attached table (see Appendix) on the column "trends in R&D" for each hazard in the list.

This includes general trends in shifting from pure probabilistic approaches to the use of numerical modelling and trends for improving the robustness, reducing the uncertainty, and taking into account climate change in the EVA approaches. Just to give few examples: a trend towards using meteorological parameters in addition to statistical techniques for the tornado hazard characterization and a trend in coupling meteorological and hydrodynamical models for the simulation of storm surges are mentioned. In the statistical approach side, Nonstationary EVA is mentioned as an emerging R&D trend for extreme temperature characterisation, while RFA (Regional Frequency Analysis) is mentioned for extreme sea level.

Gap Analysis

Exploring the existing gaps

A list of existing gaps in the currently available methodologies for natural hazard characterization has been drafted, gathering together the experience and feedback from the partners, the interviews and the literature analysis. We report here the gaps mentioned by the consortium partners and emerging from expert interviews and discussions. They are fully reported in the attached table (see Appendix) in the column "Identified gaps". For each gap, it is reminded (i) the impact of the concerned hazard on high value infrastructures, (ii) the nature of the gap, (iii) the consequences of the gaps in the existing methodologies and the risks associated in not addressing the gaps.

The highlighted existing gaps are grouped depending on the hazard classes defined above:

Meteorological

1. **High resolution rainfall.** Within the Power industry there is an appreciation of the consequences to plant operation that high intensity rain fall can initiate. An example of this would be conventional plant trip resulting from water Rainfall on short duration may be critical. To enable design of suitable drainage to mitigate risk further knowledge on frequency of events is required. Very few observations are available for high resolution rainfall (1 to 15 minutes) indeed and the traditional methods, such as EVA, which strongly rely on observations may produce very uncertain results fro very extreme (up to 10^{-4} annual probability) In particular, short duration extreme rainfall is critical in urban hydrology and drainage system design due to their ability to cause flash flooding. As long as this gap is not addressed the risk of over or under design of drainage system exist, leading to potential cost for expensive mid-life drainage systems modifications.

2. **Extreme winds** may knock over trees which in turn damages power line. Moreover wind creates a load on the structures and may generate projectiles potentially damaging the infrastructures. There is high uncertainty in the estimation of extreme winds. Recent work has revealed inconsistencies between EVA estimations and Eurocodes estimations. The available observed data series for wind are generally short. The impact of climate change on extreme winds is also not very clear. The failure in addressing quickly these gaps may lead to over or under design requiring expensive mid-life modifications.

3. **Low water temperature.** Low sea o river water temperature may lead to the formation of frazil ice and floating ice which could damage the water infrastructure and clogging the heat sinks of power plants. A precise judgement on the lowest possible values for sea temperature and on the ice formation mechanism on the sea and the river should be sought. Addressing this gap would allow a more reliable forecasting of frazil formation, reducing damages and probability of power plant shutdown. Leaving this gap open decreases the forecasting capability and increase the probability damages and shutdown.

4. **Lightning** strikes may damages power lines, electric devices. The lack of reliable measure for lightning intensity means that extreme lightning estimations are very uncertain. Not addressing this gap prevents an actual estimation of the lightning maximum intensity and thus increasing the risk of over or under design.

5. **Hailstones** may damage building roofs and infrastructures. There is some uncertainty around the atmospheric physics and formation of frozen precipitation; the fact that hail is an emerging risk, and the potential better quantification of the size distribution of hail with better understanding of physics, highlight the lack of a robust methodology for hailstone characterisation. Not addressing this gap prevents an actual estimation of the maximum hailstones size and loads and thus increasing the risk of over or under design.

6. Extreme winds generated by a **Tornado** may knock over trees which in turn damages power line. Moreover wind creates a load on the structures and may generate projectiles potentially damaging the infrastructures. Some uncertainties exist around the formation and recording of Tornadoes; for example there could be an under-reporting effect producing a mismatch of tornado frequency between urban and countryside areas. As for the extreme winds estimation, the failure in addressing quickly this gap may lead to over or under design requiring expensive mid-life modifications. However, the probability of Tornados occurrences is lower than extreme wind occurrences in the UK.

Marine

7. Tsunami may damage coastal infrastructure, including power grids, power plants and other infrastructures. Very limited data and knowledge exist around **tsunami** modelling, in particular on the coupling of geological earthquake models and hydrodynamic models. If these gaps are not addressed, design of coastal protection structure may be inadequate and fail in case of extreme tsunami event. However, the probability of occurrence of a Tsunami on the UK coast seems to be low.

Hydrological and hydrogeological

Volcanic, seismic, and geological

8. **Earthquake** may damage the structural integrity of a large set of infrastructures. Ground motion: improvements to the deterministic methods are being investigated by European partners, but would not be readily transferrable to the UK context. Moreover, there is a lack of UK ground motion prediction equations – but, due to the UK's low seismicity, this is unlikely to be resolved. In this framework this gaps may be unresolved for a while in the UK. Current practice seems to adequately cover the hazard and the risk of not addressing this gap in Phase 2 of this project seems low.

9. **Liquefaction, sinkholes and ground motion** may damage a large set of infrastructures. There is a lack of geological mapping of the potential for these phenomena in the UK. Note that some related information may be collected from the British Geological Survey, http://www.bgs.ac.uk/products/geosure/home.html.

10. There is a lack of knowledge on potential **Volcanic ash effects** on the UK due to volcanic eruptions elsewhere in Europe. Volcanic ash may impact several sectors including air transportation. The impact on Energy sector will be limited to the occlusion of filter on the air filtering machine. The actual impact of volcanic ash should be demonstrated and thus the risk of not addressing this gap in Phase 2 of this project seems low.

Biological

11. **Biological** materials may clog up the water intake of power plants. However, the blooming of marine biological species and the actual parameters driving this phenomenon are not completely understood. Moreover, the transportation of biological species by waves and currents is complex and would benefit from in-depth modelling. The development of suitable biological models is thus needed, together with hydrodynamics models. If the bio and physical mechanism should turn out to be too complex, a stochastic modelling of the probability of occurrence of this hazard depending on meteorological variables is a promising way to be explored. Mitigation measures are also poorly known; for example, alternatives to chlorination for biofouling control would be welcome. If not addressed the risk of observing clogging of power plant water intake and damage on off shore infrastructure can not be reduced by early warning, appropriate mitigation measures and adapted design.

Electromagnetic

12. Electromagnetic inferences generated by **Space Weather** event may have an impact and damage micro electronic control system and thus damage engineered systems and infrastructure A gap exists regarding the estimation of the intensity of an extreme space weather event and providing a methodology to assess the sensitivity of the electronics and/or EMI (Electro Magnetic Inferences) protection systems against it. This need is pushed by the increased use of microprocessors in safety systems. If not addressed the existing risk of damage on electric control system can not be reduced by appropriate mitigation measures and adapted design.

Combinations

13. **Hazard combinations** may generate a large range of issue to high value infrastructure and power plant. The nature of the issue will depend on the nature of the hazards that will be occurring together. However, a clear understanding of the actual probability of simultaneous occurrences of coupled hazards (e.g. low water temperature and extreme wind) is not always available. Moreover there is no one widely accepted approach, in particular for characterizing hazard combination associated to very extreme (up to 10^{-4} annual probability of exceedence) probability. Some numerical modelling techniques can account for hazard combinations such as wind and surge. The risk for not address this gaps is that potential combination of natural hazard may remain

unknown, preventing to reduce the risk by mitigation measure or appropriate design. The failure in addressing quickly this gap may lead as well to over or under design requiring expensive mid-life modifications.

Other

General Gaps

14. **Numerical modelling** could be used instead of or in conjunction with EVA when a physical knowledge of the phenomena could yield a better prediction (i.e. snow simulation, storm modelling or extreme wind simulation). The introduction of more physical knowledge of the process in the probabilistic approach, (for example see weather type approaches, [21], for rainfall) could be very beneficial in some sectors. The risk of not taking into account this gap is to miss some useful information for the characterization of some natural hazards.

15. The impact of **climate change** on some hazards (in particular meteorological hazards) may change the probability of occurrence of some extreme events. However, the scenarios simulated by the global circulation models are manifolding and uncertain. This science topic definitely needs more investigation and the actual impact of climate change of some specific hazard is not yet known (for example, biofouling, high resolution extreme rainfall). The risk in not addressing this gap is that important uncertainties in the impact of climate change may lead as well to over or under design requiring expensive mid-life modifications.

Prioritization of the existing gaps

These gaps will be prioritized following a list of common criteria. A preview of this list is given here.

- Industrial prioritization (i.e. is the gap important from an industrial point of view? What is the prioritization of this gap from the industrial partners?)
- Scientific community prioritization (i.e. does the gap represent an important lack of scientific knowledge in the understanding or modelling of the phenomenon in question? Is the scientific community already carrying out research on that gap?)
- Urgency (Does the gap need to be solved quickly in order to avoid industrial risk or in order to optimize industrial procedures?)
- Feasibility of the project duration (Is it reasonable to address the gap within the timescale and the budget of the ETI Phase 2 program?)
- Transferability to the "how to" guide (Is it reasonable to suggest a "how to" procedure and to make the results available for industrial applications within the timescale and the budget of the ETI Phase 2 program?)

A prioritization exercise with all the partners (except the Met Office, given its TQA role in the project) assigning values varying from 0 to 10 for each of these criteria and for each of the listed gaps has been carried out. A simple exercise is also carried out assigning a given number of points to each gap depending on the rank occupied in each partner's classification. For example, one should assign, for each partners ranking, 10 points to the first gap, 5 to the second, 3 to the third and so on. Summing the points obtained by each gap on the different partners ranking, one could obtain a final gap ranking.

This simplified exercise is most robust, smoothing the different significance that the partners associated to the absolute notation.

Prioritization results

The results of the exercise are shown in Table 7. Following the prioritization exercise **5 major gaps** relevant to be addressed in the Phase 2 of the project are suggested at the end of the session.

The choice of the number comes for the detailed analysis of the prioritization results. A clear difference in the gap classification may be seen in the Table. Hazard combination is first (1) in the ranking no matter the ranking method adopted. Behind this the list of the following six gaps (2-7) is found having similar notes: biological, wind, lightning, hailstones, rainfall and space weather. Note that their actual relative positions depend on the ranking criteria. Among the first 7, Rainfall and Wind were dismissed and the details are given in the following paragraphs.

1	**Hazard combinations**	203	50	34	45	34	40
2	**Extreme winds**	202	30	42	50	30	50
3	**High resolution rainfall**	195	38	28	42	42	45
4	**Hail**	188	42	40	40	32	34
5	**Ligthning intensity**	187	45	36	38	38	30
6	**Biological**	184	38	45	32	45	24
7	**Space weather**	180	40	50	36	26	28
8	**Low sea temperature**	158	32	38	34	28	26
9	**Earthquake**	142	28	32		50	32
10	**Climate Change**	128	22	30		40	36
11	**Numerical modelling**	82	18	26			38
12	**Volcanic ash**	70	38		32		
13	**Tornadoes**	26	26				
14	**Liquefaction**	24	24				
15	**Tsunami**	20	20				

Table 7. Hazard prioritization results. P1 to P5 represents the 5 consortium partners involved in the exercise.

Details on the reason why the top 5 gaps got better score that the others are given here. These considerations are extracted from the detailed analysis of the prioritization exercise done by the partners.

The "**hazard combination**" gap is on the top of the list for both cases. It is put in top places but almost all the partners. It is explained by the fact that there is lack of common methodologies on this topic, and by the fact that the recent Fukushima incident considerably raised the profile of this issue. A first hazard combinations screening would be very useful for industrial application. The hazard combination got indeed high notes in "transferability to the industry" item. One of the partners stated that "the output should be readily easy to apply" and "a shot term resolution of the question would be appropriate". The definition of a better knowledge on the probability of hazard combination will allow delivering and operating high value energy infrastructure assets more cost effectively and more reliably with greater overall system resilience.

The **biological hazards** gap is an emerging risk with a considerable lack of knowledge on how relevant phenomena occur, and on the potential effect of climate change on these phenomena. It is identified by two out of five contributors as the second most important hazard. Note that, however, energy infrastructures located far from the sea shore may not be affected by this hazard. The

Lightning and hail are, relatively speaking, also emerging hazards for which common approaches do not exist, but where fruitful transfer of knowledge form one sector to another could deliver high quality results at the project timescale (i.e. from insurance to industry). They got good notes in the "transferability to the industry" criterion, showing that a focused and short R&D effort could delver ready to use results on these topics. The definition of a specific approach for the estimation of lightning intensity and hailstones size is an important step in the definition of an overall methodology allowing delivering and operating high value energy infrastructure assets more cost effectively and more reliably with greater overall system resilience

Space Weather is also an emerging hazard; although its impact on energy sector infrastructure has been assessed at a high level, see [22], it has not yet been examined in detail. For Space Weather as well, addressing the gaps in their characterization methodology will allow to deliver and operate high value energy infrastructure assets more cost effectively and more reliably with greater overall system resilience.

Concerning Rainfall, Wind and the gaps from (8-15) positions, note that these gaps definitely exist and deserve to be solved in the next future. However, (i) the impact of the next future infrastructure design for non solving these gaps are lower than for other gaps, (ii) the Phase 2 timescale is not the appropriate timescale for these gaps resolutions or (iii) the Phase 2 of this project may not be the most appropriate framework for the resolution of these gaps, because of on-going works in scientific community. In particular, following on of the partners "**Earthquake** is adequately covered by current practice". There was consensus on the fact that **Climate Change** is widely investigated by the scientific community and that the Phase 2 of the project will not bring extra knowledge compared to the existing reports. **Numerical Modelling** is too generally defined and not identified as a single appropriate hazard, thus it could be out of the scope of the study. Volcanic ash dispersion was identified as a gap potentially impacting other industries out of the Energy sectors (e.g.

aviation), but with the actual impact on the energy sector must be still demonstrated. **Tornadoes, Liquefaction** and **Tsunami** get little attention from the partners. Tornadoes and Tsunami characterization techniques exist and this hazard may be less relevant for the UK compared to the other. Gaps in **Wind** estimations caught the attention of the consortium partners because of the lack of long data series for use in EVA and the uncertainty around how climate change could affect wind, as well as for the potentially important impacts of wind on various aspects of the energy sector. Gaps on wind characterization, in particular, lack of coherence between different sources of extreme wind estimations are highlighted as a main gap by several partners. However, it is also mentioned that several R&D programs are going on in the scientific community on this point. At the same time the estimation of extreme **Rainfall** at very high resolution may be challenging and the existing methodologies based on EVA show some limitations. As mentioned for wind, other research programs are ongoing in this area and methodologies are available, (e.g. [23]) even if it is conservative and sometimes inappropriate for use in particular analyses.

We, therefore, suggest the following **five main gaps could be addressed in Phase 2**:

- **Hazard combinations**
- **Biological**
- **Space Weather**
- **Lightning**
- **Hail**

Conclusions

This report introduces the context and relevance of existing design guidelines, industry specifications, reference studies and regulatory frameworks. In particular, the following aspects have been analysed:

- A list of natural hazards which are relevant across the energy sector
- The available mature methodologies for their characterisation, as well as expert judgement regarding these methodologies
- A high-level assessment of the projected impacts of climate change on natural hazards
- A list of sectors for which characterisation of each natural hazard is relevant, including several example of industrial applications
- A list of existing guidelines and regulatory frameworks affecting the UK
- Some comments on the recent trends in R&D projects for the characterisation of natural hazards
- Gaps in natural hazard analysis and prediction
- The priority level of the gaps to be addressed with justification for why these gaps should be addressed

The main conclusions are the following:

a. It was possible to define a common list of natural hazards relevant across different sectors in the energy domain

b. Even though sectors may traditionally look at different return levels and specific natural hazards, depending on the impact, the methodologies used are generally consistent across sectors

c. Some gaps exist and need to be addressed

d. Given the solution of some existing gaps, the final goal of the project (namely to have a common and systematic approach for the characterisation of natural hazards across the energy sectors) can be achieved.

In particular, we suggest researching 5 main potential gaps to be addressed in Phase 2: **hazard combinations, biological hazards, space weather, lightning, hail**.

It is shown how addressing these gaps in the Phase 2 will permit to define a high quality, systematic approach to the natural hazard characterization. This approach will be illustrated in Phase 3 and it will allow delivering and operating high value energy infrastructure assets more cost effectively and more reliably with greater overall system resilience

We are confident that in the following phases of the project, these gaps can be addressed and a “how to” guide for supporting future studies in the energy sector can be delivered.

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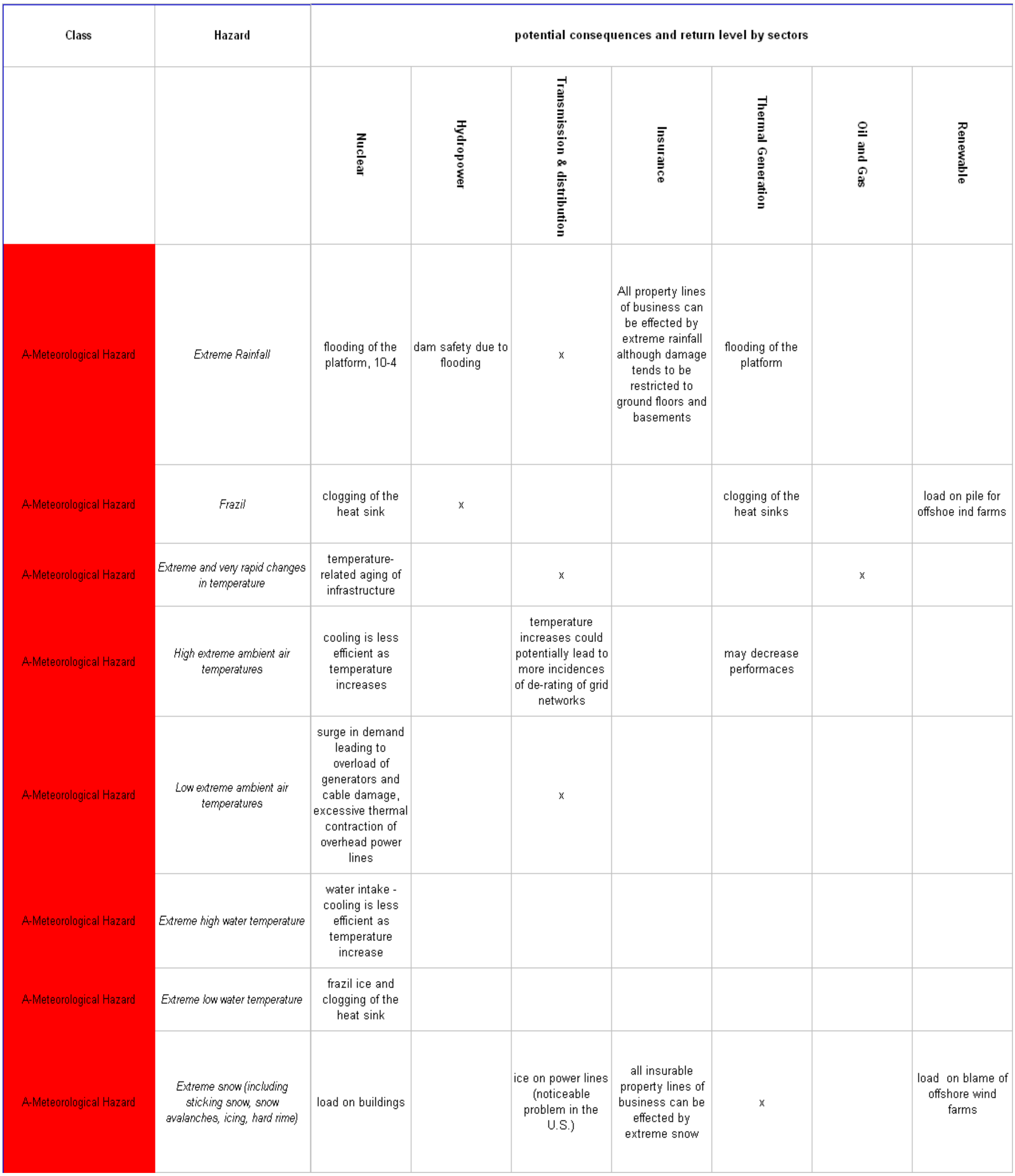
Appendix

Table

Class	Hazard	Parners with skills						Available Mature Methodologies	Expert judgements on available methodologies, including associated uncertainties, credibility limits
		EDF Energy R&D UK Centre	EDF Nuclear Generation	Nuclear New Build	Met Office	Mott MacDonald	AIR Worldwide		
A-Meteorological Hazard	*Extreme Rainfall*	x	x	x	x	x	x	(1) PMP (Probable Maximum Precipitation); Regional Analysis Pooling and Intensity duration curves method [32]; (2) Stationary EVA; (3) Coupled Global Circulation Model with Meoscale Numerical Weather Prediction Models [19], (4) Monte Carlo Approaches [33]	(1) PMP: Mature methodology, large subjectivity, large uncertainties, usually associated with the 10-4 annual frequency event; (2) EVA: Mature methodology, not adapted for high resolution rainfall, does not use physical knowledge, huge uncertainties due to the small amount of data at the local scale, need to allow for different characteristics of site location compared to weather station location
A-Meteorological Hazard	*Frazil*		x		x	x		(1) Finite Element Analysis; (2) Comptuational Methods for Ice Flow Simulation (Kallen-Brown, J., 2011) [26]; (3) EVA on low temperature	Methodology (2) provides a means of modelling ice flows taking density variations into account.
A-Meteorological Hazard	*Extreme and very rapid changes in temperature*		x		x	x			
A-Meteorological Hazard	*High extreme ambient air temperatures*	x	x		x	x		Stationary and non-stationary EVA for air temperature (4.4 IAEA [7])	Stationary EVA (see comment given for EVA on rainfall) Non-stationary EVA can provide unrealistic projections when the trends detected on the past series are projected too far in the future
A-Meteorological Hazard	*Low extreme ambient air temperatures*	x	x		x	x		EVA for air temperature(4.4 IAEA [7])	Stationary EVA (see comments given for EVA on rainfall)
A-Meteorological Hazard	*Extreme high water temperature*	x	x		x	x		Stationary and non-stationary EVA	Stationary EVA (see comments given for EVA on rainfall) Non-stationary EVA can provide unrealistic extrapolation when the trends detected on the past series are extrapolated to the future
A-Meteorological Hazard	*Extreme low water temperature*	x			x			Stationary EVA with due account of salinity	Recent reports cannot confidently fix a value for extreme low sea temperature. Only an upper bound 10-4p.a. value can be provided.
A-Meteorological Hazard	*Extreme snow (including sticking snow, snow avalanches, icing, hard rime)*	x	x	x	x	x		(1)Stationary EVA for snowpack (4.4 IAEA [7]); (2) Numerical Weather Prediction Models, (3) eurocodes	Stationary EVA (see comments given for EVA on rainfall)

Class	Hazard	Climate change impacts	Uncertainties on climate change impacts
A-Meteorological Hazard	*Extreme Rainfall*	Possible increase in extreme rainfall since a warmer climate holds more water. Increase in frequency (Tab IV-1 IAEA), increase in annual maxima and decrese in return period [15]	Very uncertain, may change regionally, natural variability makes it hard to predict [14], influenced by seasons and North Atlantic Oscillation [15], Not currently enough data to estimate degree of impact especially regarding frequency
A-Meteorological Hazard	*Frazil*	Possible increase [17]; Decrease in ice duration and seasonal ice cover [22]	Uncertain due to limited available data [22]
A-Meteorological Hazard	*Extreme and very rapid changes in temperature*	Impossible to quantify fom climate models	Impossible to quantify fom climate models
A-Meteorological Hazard	*High extreme ambient air temperatures*	Warmer and more frequent hot days/nights over most land areas / warm spells and heat waves (Tab IV-1 IAEA); Increased average annual temperature and daily average maximum temperature [14]	Virtually certain / very likely (Tab IV-1 IAEA); Lower confidence in model capability at regional scales (IPCC AR5 [13]); 4/5 stars confidence [14]
A-Meteorological Hazard	*Low extreme ambient air temperatures*	Decreased frequency of cold winters and cooler springs (but severe cold seasons can still occur) [14]	Lower confidence in model capability at regional scales (IPCC AR5 [13]); 3/5 stars confidence due to natural variation [14]
A-Meteorological Hazard	*Extreme high water temperature*	Projected increase in global mean temperatures [23]	Not regionally uniform [23]
A-Meteorological Hazard	*Extreme low water temperature*	Climate change projected to warm the sea temperature in future (but cold sea temperatures could still occur) [12]	Changes in transport currents may result in local cooling even if the global mean heat content is rising (IPCC AR5)
A-Meteorological Hazard	*Extreme snow (including sticking snow, snow avalanches, icing, hard rime)*	Climate change projected to warm the air temperature in future, but severe cold spells with the risk of snow could still occur [12]	Insufficient timeseries of data to be able to identify trends rather than natural variability

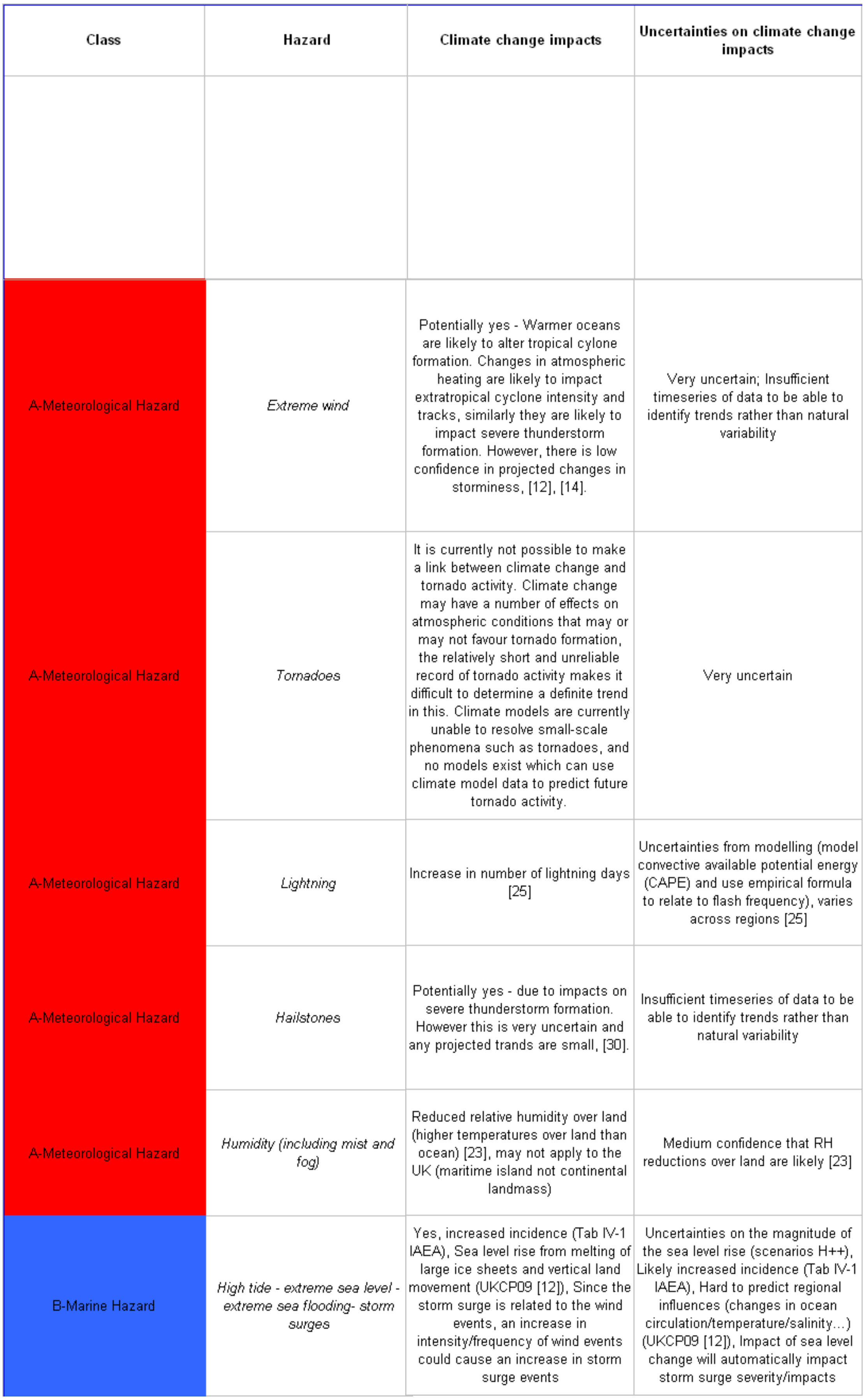


Class	Hazard	potential consequences and return level by sectors						
		Nuclear	Hydropower	Transmission & distribution	Insurance	Thermal Generation	Oil and Gas	Renewable
A-Meteorological Hazard	*Extreme Rainfall*	flooding of the platform, 10-4	dam safety due to flooding	x	All property lines of business can be effected by extreme rainfall although damage tends to be restricted to ground floors and basements	flooding of the platform		
A-Meteorological Hazard	*Frazil*	clogging of the heat sink	x			clogging of the heat sinks		load on pile for offshoe ind farms
A-Meteorological Hazard	*Extreme and very rapid changes in temperature*	temperature-related aging of infrastructure		x			x	
A-Meteorological Hazard	*High extreme ambient air temperatures*	cooling is less efficient as temperature increases		temperature increases could potentially lead to more incidences of de-rating of grid networks		may decrease performaces		
A-Meteorological Hazard	*Low extreme ambient air temperatures*	surge in demand leading to overload of generators and cable damage, excessive thermal contraction of overhead power lines		x				
A-Meteorological Hazard	*Extreme high water temperature*	water intake - cooling is less efficient as temperature increase						
A-Meteorological Hazard	*Extreme low water temperature*	frazil ice and clogging of the heat sink						
A-Meteorological Hazard	*Extreme snow (including sticking snow, snow avalanches, icing, hard rime)*	load on buildings		ice on power lines (noticeable problem in the U.S.)	all insurable property lines of business can be effected by extreme snow	x		load on blame of offshore wind farms

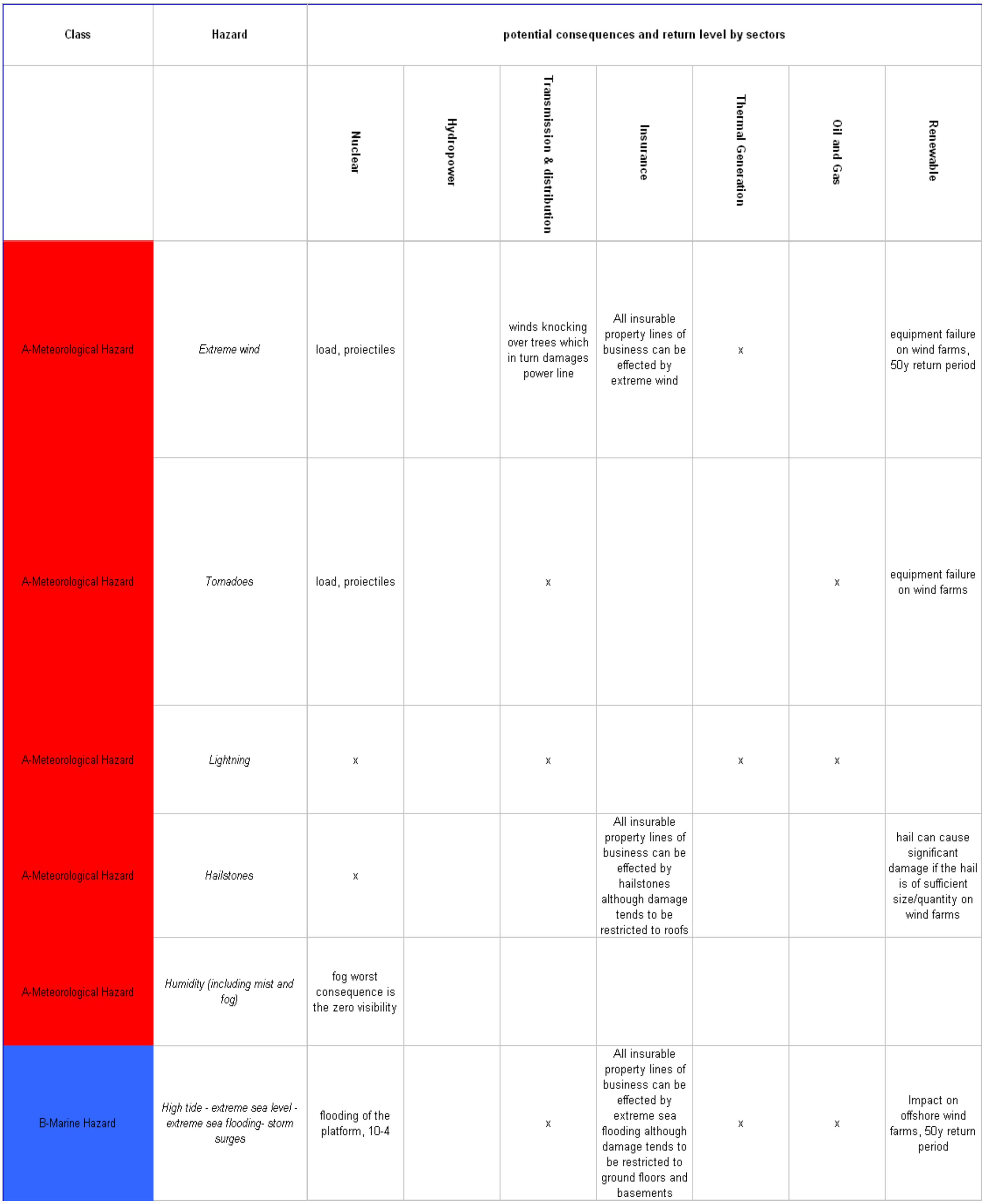
Class	Hazard	Existing Guidelines and regulatory frameworks impacting the UK	Example of industrial application	trends in R&D
A-Meteorological Hazard	*Extreme Rainfall*	The Flood estimation Handbook [32]; Flood Risk statement, IH124; Models require validation for use in Solvency II and Lloyds synidcates must report exposure in relation to Realistic Disaster Scenarios, IAEA**, Planning Policy Statament 25 (PPS25), BS EN 752, BS 12056BS EN 50341, BS 61936, BS 7671, Sewers for Adoption, CIRIA guides, National Grid Techical Specifications	Nuclear: Met Office reports for EDF Energy, Established Flood Risk Assessment techniques across NG fleet, Flood estimation Handbook used to for roof drainage project for Hartlepool and Heysham power stations.	Stochastic Modelling [34], Weather type approaches [33]
A-Meteorological Hazard	*Frazil*			
A-Meteorological Hazard	*Extreme and very rapid changes in temperature*	BS 6399, BS EN 50341, Eurocodes, National Grid Technical Specifications, API STD 520, 594, 600, 602 AND 607.	EDF NG PSR studies	Non-stationay EVA, Climate models scenarios improvement
A-Meteorological Hazard	*High extreme ambient air temperatures*	EVA for air temperature(4.4 IAEA [7]), BS 6399, BS 5400, BS EN 50341, BS 61936, BS 7671; Eurocodes ; National Grid Technical Specifications	EDF NG PSR studies	Non-stationay EVA, Climate models scenarios improvement
A-Meteorological Hazard	*Low extreme ambient air temperatures*	EVA for air temperature (4.4 IAEA [7]); BS 6399, BS 61936, BS 7671 BS 5400, BS EN 50341; Eurocodes ; National Grid Technical Specifications	EDF NG PSR studies	
A-Meteorological Hazard	*Extreme high water temperature*		Established Flood Risk Assessment techniques across NG fleet	
A-Meteorological Hazard	*Extreme low water temperature*		Nuclear studies for NPP in France and UK	
A-Meteorological Hazard	*Extreme snow (including sticking snow, snow avalanches, icing, hard rime)*	EVA for snowpack (4.4 IAEA [7]); British Standards: BS6399-3 (now withdrawn), BS EN 1991-1-3; Eurocodes, BSI Codes, Models require validation for use in Solvency II, National Grid Technical Specification, EN 50341, BS7354, CP 3, ONR Safety Assessment Principles	EDF NG Commissioned Studies with Met Office, Hazard Safety Cases, Periodic Safety Reviews, resilience/ defence in depth, and the continual management of the overall commercial and nuclear safety risk.	

Class	Hazard	Identified gaps	Prioritisation and justification why the gaps should be addressed
A-Meteorological Hazard	*Extreme Rainfall*	Very few observation available for high resolution rainfall (15 minutes), available methods not adapted, new R&D needed .	Short duration extreme rainfall estimation are critical in urban hydrology, drainage system design and they can cause flash flood. They cause huge damages. Pluvial flooding can be more damaging than fluvial
A-Meteorological Hazard	*Frazil*		
A-Meteorological Hazard	*Extreme and very rapid changes in temperature*		
A-Meteorological Hazard	*High extreme ambient air temperatures*		
A-Meteorological Hazard	*Low extreme ambient air temperatures*		
A-Meteorological Hazard	*Extreme high water temperature*		
A-Meteorological Hazard	*Extreme low water temperature*	A more precise judgement on the lowest value should be sought	
A-Meteorological Hazard	*Extreme snow (including sticking snow, snow avalanches, icing, hard rime)*	Modelling moving towards numerical due to greater computing power; The effect of combined hazard	Some uncertainty around atmospheric physics and formation of frozen precipitation; Medium priority Existing safety cases are based on the consequences of failure being tolerable

Class	Hazard	Parners with skills						Available Mature Methodologies	Expert judgements on available methodologies, including associated uncertainties, credibility limits
		EDF Energy R&D UK Centre	EDF Nuclear Generation	Nuclear New Build	Met Office	Mott MacDonald	AIR Worldwide		
A-Meteorological Hazard	*Extreme wind*	x	x	x	x	x	x	(1) Stationary EVA (Pareto, Weibull); (2) Eurocodes; (3) Probabilistic Monte-Carlo simulation approach deriving a stochiastic catalogue of parameters from scientifically adjusted historical distributions. Numerical models and climate models can also be used	(1) Huge uncertainties due to the small amount of data at the local scale, not adapted for short series, does not use physical knowledge, up to 10-2; (3) Robust methodology for characterizing hazard over an extended period of time
A-Meteorological Hazard	*Tornadoes*	x	x	x	x	x	x	(1) Stationary EVA (Pareto, Weibull); (2) Linear methods (observations per area etc in Met Office reports) utilised to estimate frequencies; (3) TORRO estimation of return period vs intensity (tornado inventory) based determination of the frequency of occurrence for stated levels of tornadic wind-force in particular nominated zones	(1) Huge uncertainties due to the small amount of data at the local scale, not adapted for short series, does not use physical knowledge, up to 10-3
A-Meteorological Hazard	*Lightning*			x	x	x	x	Estimated annual frequency of exceedance (calculating lightning strike frequency) (4.35 IAEA [7])	Strike intensity is a very uncertain measure to be used cautiously
A-Meteorological Hazard	*Hailstones*				x	x	x	(1) Probabilistic Monte-Carlo simulation approach deriving a stochiastic catalogue of parameters from scientifically adjusted historical distributions; (2) Met Office work [16]	Yes, methodology produces scientifically plausible hail stone swathes for characterizing hazard over an extended period of time
A-Meteorological Hazard	*Humidity (including mist and fog)*				x	x		EVA of extreme wet bulb temperature available	Do not combine the output from extreme air temperature with that of the wet bulb. Taking the extreme values from both and assuming that they could occur at the same time is not necessarily an appropriate approach
B-Marine Hazard	*High tide - extreme sea level - extreme sea flooding- storm surges*	x	x	x	x	x	x	(1) Stationary EVA - Direct Method; (2) JPM (Joint Probability Method); (3) Numerical model - Princeton ocean model, SLOSH, Deltares for the North Sea as examples; (4) Regional Frequency Analysis	(1), (2) see comment given for EVA on rainfall; (3) Various numerical models can represent water levels due to storm surge with good accuracy, (4) more robust than EVA



Class	Hazard	Climate change impacts	Uncertainties on climate change impacts
A-Meteorological Hazard	*Extreme wind*	Potentially yes - Warmer oceans are likely to alter tropical cylone formation. Changes in atmospheric heating are likely to impact extratropical cyclone intensity and tracks, similarly they are likely to impact severe thunderstorm formation. However, there is low confidence in projected changes in storminess, [12], [14].	Very uncertain; Insufficient timeseries of data to be able to identify trends rather than natural variability
A-Meteorological Hazard	*Tornadoes*	It is currently not possible to make a link between climate change and tornado activity. Climate change may have a number of effects on atmospheric conditions that may or may not favour tornado formation, the relatively short and unreliable record of tornado activity makes it difficult to determine a definite trend in this. Climate models are currently unable to resolve small-scale phenomena such as tornadoes, and no models exist which can use climate model data to predict future tornado activity.	Very uncertain
A-Meteorological Hazard	*Lightning*	Increase in number of lightning days [25]	Uncertainties from modelling (model convective available potential energy (CAPE) and use empirical formula to relate to flash frequency), varies across regions [25]
A-Meteorological Hazard	*Hailstones*	Potentially yes - due to impacts on severe thunderstorm formation. However this is very uncertain and any projected trands are small, [30].	Insufficient timeseries of data to be able to identify trends rather than natural variability
A-Meteorological Hazard	*Humidity (including mist and fog)*	Reduced relative humidity over land (higher temperatures over land than ocean) [23], may not apply to the UK (maritime island not continental landmass)	Medium confidence that RH reductions over land are likely [23]
B-Marine Hazard	*High tide - extreme sea level - extreme sea flooding- storm surges*	Yes, increased incidence (Tab IV-1 IAEA), Sea level rise from melting of large ice sheets and vertical land movement (UKCP09 [12]), Since the storm surge is related to the wind events, an increase in intensity/frequency of wind events could cause an increase in storm surge events	Uncertainties on the magnitude of the sea level rise (scenarios H++), Likely increased incidence (Tab IV-1 IAEA), Hard to predict regional influences (changes in ocean circulation/temperature/salinity...) (UKCP09 [12]), Impact of sea level change will automatically impact storm surge severity/impacts



Class	Hazard	potential consequences and return level by sectors						
		Nuclear	Hydropower	Transmission & distribution	Insurance	Thermal Generation	Oil and Gas	Renewable
A-Meteorological Hazard	*Extreme wind*	load, projectiles		winds knocking over trees which in turn damages power line	All insurable property lines of business can be effected by extreme wind	x		equipment failure on wind farms, 50y return period
A-Meteorological Hazard	*Tornadoes*	load, projectiles		x			x	equipment failure on wind farms
A-Meteorological Hazard	*Lightning*	x		x		x	x	
A-Meteorological Hazard	*Hailstones*	x			All insurable property lines of business can be effected by hailstones although damage tends to be restricted to roofs			hail can cause significant damage if the hail is of sufficient size/quantity on wind farms
A-Meteorological Hazard	*Humidity (including mist and fog)*	fog worst consequence is the zero visibility						
B-Marine Hazard	*High tide - extreme sea level - extreme sea flooding- storm surges*	flooding of the platform, 10-4		x	All insurable property lines of business can be effected by extreme sea flooding although damage tends to be restricted to ground floors and basements	x	x	Impact on offshore wind farms, 50y return period

Class	Hazard	Existing Guidelines and regulatory frameworks impacting the UK	Example of industrial application	trends in R&D
A-Meteorological Hazard	*Extreme wind*	OW [1,2,9], British Standards BS6399-2 (now withdrawn), BS EN 1991-1-4; Engineering Science Data Unit (ESDU) Wind Engineering Series guides, BSI Codes, Eurocodes, National Grid Technical Specification, EN 50341, BS 61936, BS 7671, IEC 61400, Models require validation for use in Solvency II and Lloyds synidcates must report exposure in relation to Realistic Disaster Scenarios, BS7354, CP 3, CP 3-2, ONR Safety Assessment Principles	Hazard Safety Cases, Periodic Safety Reviews, resilience/ defence in depth, and the continual management of the overall commercial and nuclear safety risk. EDF NG Commissioned Studies with Met Office ; AIR 400 series occupancy coding using component based damage functions	Moving to numerical/physical based modelling rather than statistical based modelling due to the increase in computer power; Regional Frequency Analysis
A-Meteorological Hazard	*Tornadoes*	OW [1,2,9], TORRO Guidelines, IAEA Safety Guides IEC 61400, API STD 600, Models require validation for use in Solvency II, ONR Safety Assessment Principles	Hazard Safety Cases, Periodic Safety Reviews, resilience/ defence in depth, and the continual management of the overall commercial and nuclear safety risk.	Trend towards using meteorological parameters in addition to statistical techniques. Increasing use of numerical methods for vulnerability analysis. Eg Computational fluid dynamics
A-Meteorological Hazard	*Lightning*	Estimated annual frequency of exceedance (calculating lightning strike frequency) (4.35 IAEA [7]), BS 6651, BS 62305, BS 61936, BS 7671, BS7354; IEC 61400, IEC 61400, IEC 60079; API STD 607, API RP 2003		
A-Meteorological Hazard	*Hailstones*	Models require validation for use in Solvency II	AIR 400 series occupancy coding using component based damage functions	
A-Meteorological Hazard	*Humidity (including mist and fog)*			
B-Marine Hazard	*High tide - extreme sea level - extreme sea flooding- storm surges*	OW [1,2,9]; Models require validation for use in Solvency II and Lloyds synidcates must report exposure in relation to Realistic Disaster Scenarios; United Kingdom Climate ImpactsProgramme, UKCIP, BS PD 8010	Established Flood Risk Assessment techniques across NG fleet - embedded into safety cases and covered under PSR; AIR 400 series occupancy coding using component based damage functions	Storm modelling coupling meteorological and hydrodynamical models; Increase in the use of Numerical modelling; Paleodata

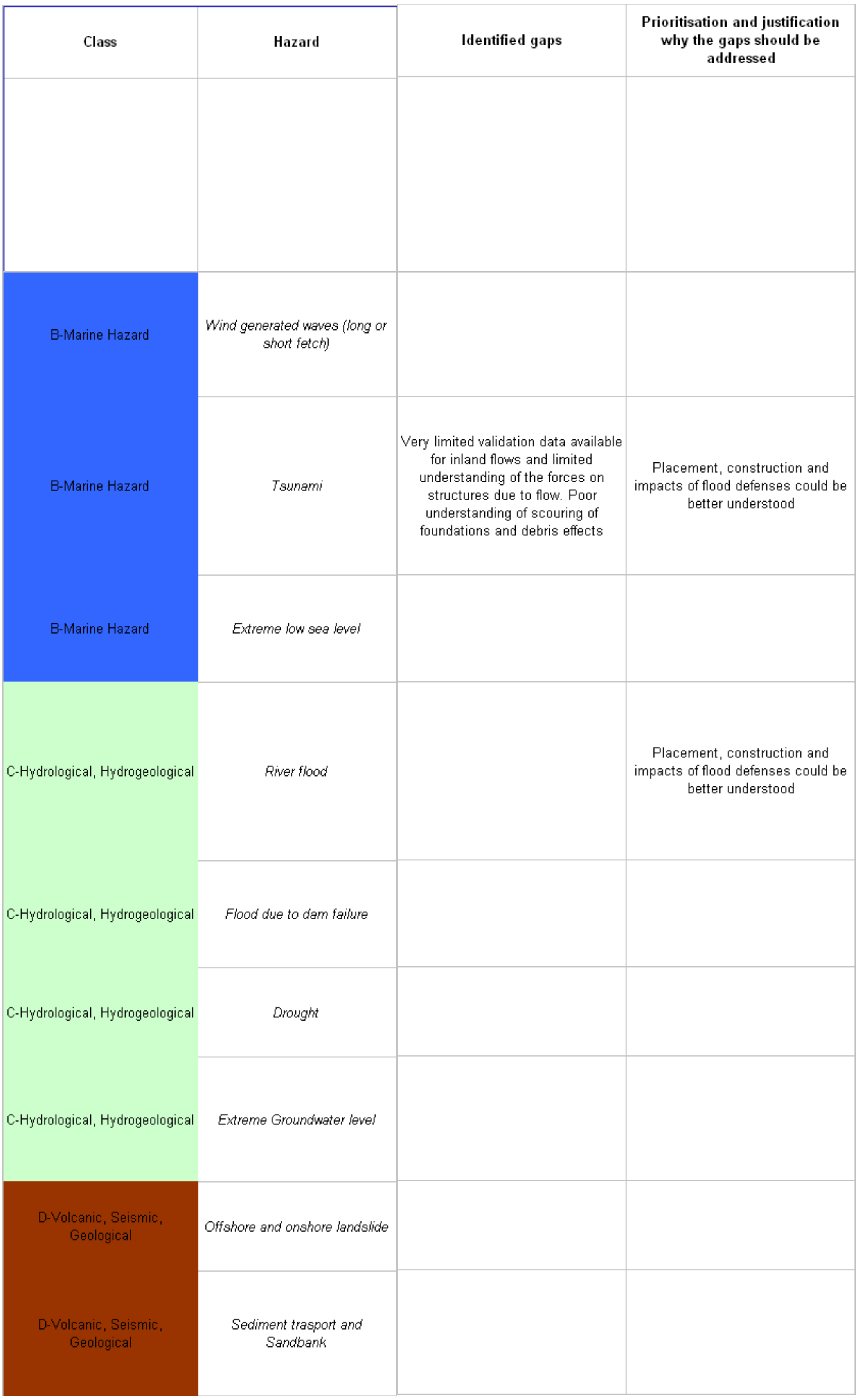
Class	Hazard	Identified gaps	Prioritisation and justification why the gaps should be addressed
A-Meteorological Hazard	*Extreme wind*	The effects of the North Atlantic Oscillation (NAO) and jet strength on extreme winds; The effects of climate change on extreme winds; Is there a theoretical upper limit to extreme wind speeds due to atmospheric characteristics? Investigation on the applicability of EVA results, and how to compare them with the equivalent values derived in the Eurocodes	May be included in hazard combination; High Priority:An under-estimation of extreme winds (and hence wind pressure loads) could undermine nuclear safety cases and challenge the claimed lines of protection e.g. in the event of partial collapse of buildings, loss of cladding, interaction threats, the formation of wind-blown missiles etc.
A-Meteorological Hazard	*Tornadoes*	Some uncertainty around formation of tornadoes; The effects of under-reporting. Due to the effects of mismatch of population between urban and countryside areas.	High Priority:An under-estimation of extreme winds (and hence wind pressure loads) could undermine nuclear safety cases and challenge the claimed lines of protection e.g. in the event of partial collapse of buildings, loss of cladding, interaction threats, the formation of wind-blown missiles etc.
A-Meteorological Hazard	*Lightning*	EVA not applied to the existing data	
A-Meteorological Hazard	*Hailstones*	Some uncertainty around atmospheric physics and formation of frozen precipitation, Emerging risks, very little knowledge	Could better quantify size distribution of hail with better understanding of physics
A-Meteorological Hazard	*Humidity (including mist and fog)*		
B-Marine Hazard	*High tide - extreme sea level - extreme sea flooding- storm surges*	Lack of high resolution input terrain data and computational power required to utilise high resolution data. Poor understanding of scouring of foundations and debris effects	Placement, construction and impacts of flood defenses could be better understood

Class	Hazard	Parners with skills						Available Mature Methodologies	Expert judgements on available methodologies, including associated uncertainties, credibility limits
		EDF Energy R&D UK Centre	EDF Nuclear Generation	Nuclear New Build	Met Office	Mott MacDonald	AIR Worldwide		
B-Marine Hazard	*Wind generated waves (long or short fetch)*	x	x		x	x		(1) Stationary EVA; (2) Hydrodinamical modelling using extreme wind as input	(1) Huge uncertainties due to the small amount of data at the local scale, not adapted for short series, does not use physical knowledge, up to 10-3; (2) Depending on the methodology used for the wind estimation
B-Marine Hazard	*Tsunami*	x	x		x	x	x	Enhanced TUNAMI model used by AIR. Report on threat posed by tsunami to the UK by DEFRA [18]	Existing numerical models can be very accurate in their prediction of water levels from tsunami inundation. However, this is very dependant upon the quality and accuracy of the underlying digital terrain model/ bathymetry. Validations based on field-measured water velocities are limited in number.
B-Marine Hazard	*Extreme low sea level*	x	x		x	x		(1) stationary EVA - Direct Method; (2)JPM (Joint Probability Method)]	(1), (2) Huge uncertainties due to the small amount of data at the local scale, not adapted for short series, does not use physical knowledge, up to 10-3, not valid for sites with large tidal range
C-Hydrological, Hydrogeological	*River flood*	x	x		x	x	x	(1) EVA, (2) Coupled Global Circulation Model with Mesoscale Numerical Weather Prediction Models [19] Hyrological and run off geenration with flood routing models (3) Statistical Stochiastic Simulation Approach	(1) Huge uncertainties due to the small amount of data at the local scale, not adapted for short series, does not use physical knowledge, up to 10-3, not valid for sites with large tidal range; (2) uncertainities on the parametrization and link between the hydrological cycle and the atmosphere
C-Hydrological, Hydrogeological	*Flood due to dam failure*	x	x			x		Hydraulic modelling of the flood consequence of a dam breaking	Well assessed modeling. However, the estimation of the probability of dam breaking is a uncertain exercise
C-Hydrological, Hydrogeological	*Drought*	x	x		x	x		Stationary EVA	Huge uncertainties due to the small amount of data at the local scale, not adapted for short series, does not use physical knowledge
C-Hydrological, Hydrogeological	*Extreme Groundwater level*		x			x		hydrogeological modelling	
D-Volcanic, Seismic, Geological	*Offshore and onshore landslide*		x			x		coupling landslide and hydrodynamic models at this continental scales semms to be very complex and time consuming for the moment	Unpredictable
D-Volcanic, Seismic, Geological	*Sediment trasport and Sandbank*		x			x		Regional Ocean Model System General Length Scale Approach (Tidal Asymmetry and Residual Circulation Over Linear Sandbanks and their Implication on Sediment Transport: A Process-Oriented Numerical Study)	Used separately ROMS and GLSA provide horizontal and vertical movements, respectively.

Class	Hazard	Climate change impacts	Uncertainties on climate change impacts
B-Marine Hazard	*Wind generated waves (long or short fetch)*	Potential impact [11]	Very uncertain and linked to the wind evolution, very variable across regions and need long time series to differentiate between change and annual variability (UKCP09 [12])
B-Marine Hazard	*Tsunami*	Yes - rising sea levels will enhance Tsunami hazard, by increasing the baseline sea water level	Uncertainties as to magnitude of sea level rises
B-Marine Hazard	*Extreme low sea level*		
C-Hydrological, Hydrogeological	*River flood*	Yes, climate change could lead to more frequent and intense rainfall events. Sea level rise will affect the lower tidal reaches of rivers making fluvial flooding more likely	Uncertainties on how climate change will effect rainfall patterns. Very local effect
C-Hydrological, Hydrogeological	*Flood due to dam failure*	Possible increase in failure occurences due to increasing in extreme rainfall [29]	Uncertainty from dependence on projected increases in frequency and magnitude of extreme precipitation events [29]
C-Hydrological, Hydrogeological	*Drought*	Area affected by drought increases (water availability decreases) (Tab IV-1 IAEA); Projected increased frequency of extremely dry summers [14]	Likely (Tab IV-1 IAEA); 2/5 stars confidence due to low resolution of projection models [14]; local and regional effects
C-Hydrological, Hydrogeological	*Extreme Groundwater level*	Potentially yes, due to the potential increase in extreme rainfall. However the link between extreme rainfall and extreme ground water level may be impacted by other factors.	Dependent on climate change effects on amount/timing of precipitation and humidity/temperature - hard to account for topography/vegetation/soil properties in model [28]
D-Volcanic, Seismic, Geological	*Offshore and onshore landslide*		
D-Volcanic, Seismic, Geological	*Sediment trasport and Sandbank*	Potential impact; Projected increase in sediment yield due to rainfall amplification through catchment runoff [31]	Models are still uncertain and don't account for temporal / spatial / altitudinal variation [31]

Class	Hazard	potential consequences and return level by sectors						
		Nuclear	**Hydropower**	**Transmission & distribution**	**Insurance**	**Thermal Generation**	**Oil and Gas**	**Renewable**
B-Marine Hazard	*Wind generated waves (long or short fetch)*	flooding of the platform, 10-4				x		impact on waves energy farms, offshore wind power, 50y return period
B-Marine Hazard	*Tsunami*	flooding of the platform, 10-4		x			x	wind power, 50y return period
B-Marine Hazard	*Extreme low sea level*	water intake acces to cooling water, 10-4						stability of the pile for offshore wind farms
C-Hydrological, Hydrogeological	*River flood*			x	All insurable property lines of business can be effected by river flooding although damage tends to be restricted to ground floors and basements	x	x	
C-Hydrological, Hydrogeological	*Flood due to dam failure*						x	
C-Hydrological, Hydrogeological	*Drought*					x		
C-Hydrological, Hydrogeological	*Extreme Groundwater level*	x					x	
D-Volcanic, Seismic, Geological	*Offshore and onshore landslide*						x	Potential impact of landslide on offshore wind fams pile stability
D-Volcanic, Seismic, Geological	*Sediment trasport and Sandbank*	potential clogging of water intake by sand						

Class	Hazard	Existing Guidelines and regulatory frameworks impacting the UK	Example of industrial application	trends in R&D
B-Marine Hazard	*Wind generated waves (long or short fetch)*	OW [1,2,9], Nuclear [7]	Established Flood Risk Assessment techniques across NG fleet - embedded into safety cases and covered under PSR	Numerical modelling Regional Frequency Analysis (Weiss, 2015)
B-Marine Hazard	*Tsunami*	Models require validation for use in Solvency II and Lloyds synidcates must report exposure in relation to Realistic Disaster Scenarios; API ST 594	EDF NG Safety Cases and PSR; AIR 400 series occupancy coding using component based damage functions; Department for Environment, Food and Rural Affairs (DEFRA) Report: The Threat Posed By Tsunami To The UK, Study Commissioned by Defra Flood Management, 2005	Movement towards numerical simulation. Trends for 3D simulation for detailed site specific analyses; Numerical modelling; Paleodata
B-Marine Hazard	*Extreme low sea level*		Studies for NPP along France and UK shoreline	
C-Hydrological, Hydrogeological	*River flood*	Sewers for Adoption; CIRIA (Framework for assessing uncertainty in fluvial flood risk mapping (721); Culvert design and operation guide (C689)); Models require validation for use in Solvency II and Lloyds synidcates must report exposure in relation to Realistic Disaster Scenarios; API STD 610; BSI BS EN 12285-2	AIR 400 series occupancy coding using component based damage functions	Increasing resolution of digital terrain models and use of lower resolution, higher extent global models; Use of paleodata
C-Hydrological, Hydrogeological	*Flood due to dam failure*	Sewers for Adoption; CIRIA (Framework for assessing uncertainty in fluvial flood risk mapping (721); Culvert design and operation guide (C689)); BSI BS EN 12285		
C-Hydrological, Hydrogeological	*Drought*		EDF NG Safety Cases and PSR	
C-Hydrological, Hydrogeological	*Extreme Groundwater level*	Sewers for adoption; CIRIA; API STD 610; BSI BS EN 12285	EDF NG Safety Cases and PSR	
D-Volcanic, Seismic, Geological	*Offshore and onshore landslide*	BS PD 8010		
D-Volcanic, Seismic, Geological	*Sediment trasport and Sandbank*			



Class	Hazard	Identified gaps	Prioritisation and justification why the gaps should be addressed
B-Marine Hazard	*Wind generated waves (long or short fetch)*		
B-Marine Hazard	*Tsunami*	Very limited validation data available for inland flows and limited understanding of the forces on structures due to flow. Poor understanding of scouring of foundations and debris effects	Placement, construction and impacts of flood defenses could be better understood
B-Marine Hazard	*Extreme low sea level*		
C-Hydrological, Hydrogeological	*River flood*		Placement, construction and impacts of flood defenses could be better understood
C-Hydrological, Hydrogeological	*Flood due to dam failure*		
C-Hydrological, Hydrogeological	*Drought*		
C-Hydrological, Hydrogeological	*Extreme Groundwater level*		
D-Volcanic, Seismic, Geological	*Offshore and onshore landslide*		
D-Volcanic, Seismic, Geological	*Sediment trasport and Sandbank*		

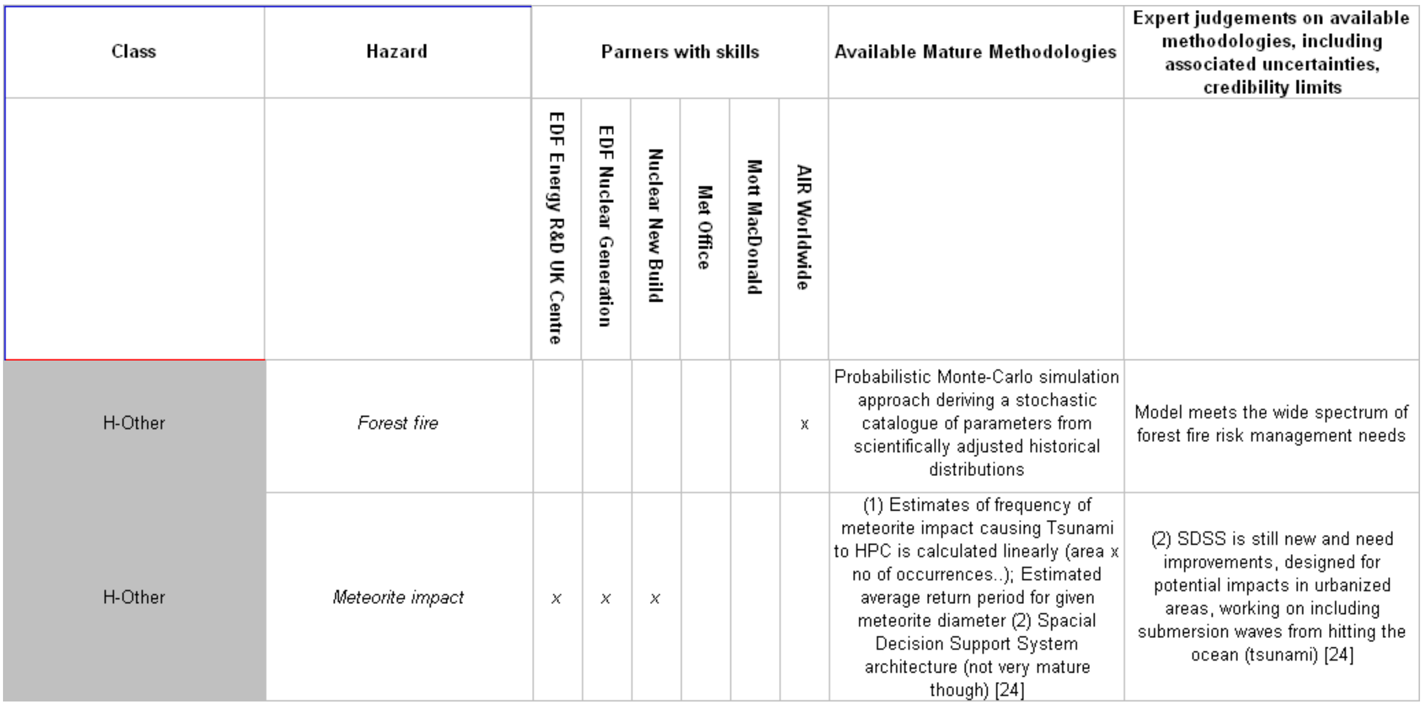
Class	Hazard	Parners with skills						Available Mature Methodologies	Expert judgements on available methodologies, including associated uncertainties, credibility limits
		EDF Energy R&D UK Centre	EDF Nuclear Generation	Nuclear New Build	Met Office	Mott MacDonald	AIR Worldwide		
D-Volcanic, Seismic, Geological	*Geological instability , sinkholes, liquefaction, land slippage, etc*		x			x	x	Spatial Distribution Analysis (F/ Gutierrez, A.H. Cooper, K.S. Johnson, 'Identification, prediction and mitigation of sinkhole hazards in evaporite karst areas', 2008)	Limited amounts of data (spatial and temporal distribution of sinkholes, and conditioning factors). Assumes future subsidence phenomena will have the same probability and rate as past activity. Areas of low activity/no monitoring will not have the capability to predict occurences
D-Volcanic, Seismic, Geological	*Sandstorm (including dust storm and volcanic action)*		x			x		Atmospheric modelling of volcanic ash dispersion	Large uncertainties on the estimation of the return period of the extraction
D-Volcanic, Seismic, Geological	*Earthquake*		x			x	x	Probabilistic Seismic Hazard Assessment carried out in 4 steps: (1) Earthquake catalogue / tectonic review (2) Seismic source model development (3) Ground motion prediction equations (4) Hazard calculations. (5) In UK there are established PSHA techniques used to derive hazard. (6) Probabilistic Monte-Carlo simulation approach deriving a stochiastic catalogue of parameters from scientifically adjusted historical distributions [20]	As with all hazards, there are large uncertainties, but this is regarded as best practice. A large reliance is put on suitably qualified and experienced engineers making judgements on equation calibration and source data, which could be regarded as too subjective. Uncertainties are covered by expert illicitation and inherent conservatism in methodology. Existing techniques fairly well established, credible and backed up by significant research in the wider scientific community
E-Biological	*Marine biological hazard*	x	x			x		(1) EDF NG Prediction and control techniques; (2) Stationary EVA	(1) Complex physics including biological behavior, hydrodynamics, temperature and meteorology, very site dependent; (2) Huge uncertainties due to the small amount of data at the local scale, not adapted for short series, does not use physical knowledge
E-Biological	*Animals (including, for example rodent infestation)*					x			
F-Electromagnetic Hazard	*Space weather (including solar flares, Natural EMP)*	x	x		x			Peak over threshold EVA using (CLIMAX GLM?) provide fluence rates for return periods up to 10,000yr r.p.	Huge uncertainties due to the small amount of data at the local scale, not adapted for short series, does not use physical knowledge, up to 10-3
F-Electromagnetic Hazard	*Solar UV*					x		Laboratory testing of panels	Simulations run in labs are dependent on using a variety of lamps to provide similar UV exposure from the sun. Potential impacts listed to the right may not be directly from UV exposure but it is difficult to separate these.
G-Combinations	*Hazard Combinations*	x			x	x		(1) AIR's Touchstone modelling platform – risk can be quantified for a location or multiple locations across multiple perils; (2) Geospatial studies – can use shapefiles to represent regions of unmodelled risks e.g. sinkholes, where accumulating locations within these shapefiles aids in the quantification/identification of potential risk	To be investigated

Class	Hazard	Climate change impacts	Uncertainties on climate change impacts
D-Volcanic, Seismic, Geological	*Geological instability , sinkholes, liquefaction, land slippage, etc*	Potentially yes, due to changes in extreme rainfall, there could be changes in the occurrence of landslides. Landslides are infact trigerred by extreme or long duration rainfall, [35].	
D-Volcanic, Seismic, Geological	*Sandstorm (including dust storm and volcanic action)*		Very dependent on climate change effects on precipitation, wind, and temperature, varies by location [27]
D-Volcanic, Seismic, Geological	*Earthquake*		
E-Biological	*Marine biological hazard*	Potentially yes, changing and increasing of marine species du to the sea water temperature increase [12]	Uncertain - ongoing data collation and assessment
E-Biological	*Animals (including, for example rodent infestation)*		
F-Electromagnetic Hazard	*Space weather (including solar flares, Natural EMP)*		
F-Electromagnetic Hazard	*Solar UV*	Potentially yes, changes in the UV will depend on several factors including relative humidity (the change of which is extremely uncertain and expected to not change much, except over continental land areas where water is limited)	Very Uncertain
G-Combinations	*Hazard Combinations*	Potentially yes, depending on the single hazards involved	Uncertain

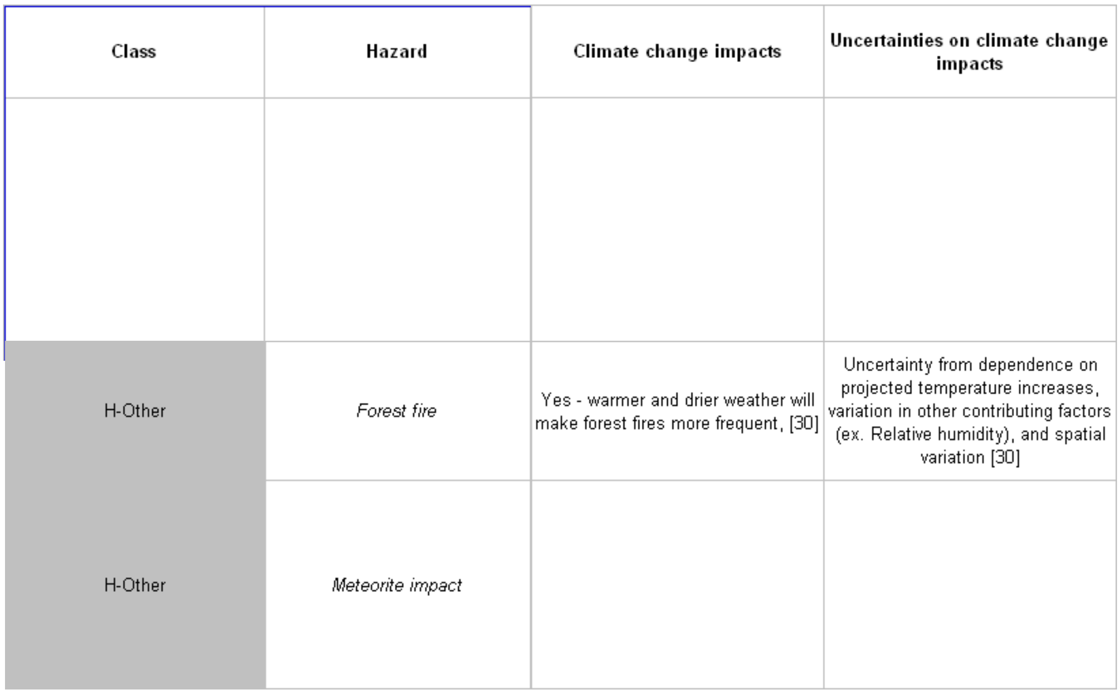
Class	Hazard	potential consequences and return level by sectors						
		Nuclear	**Hydropower**	**Transmission & distributio**	**Insurance**	**Thermal Generation**	**Oil and Gas**	**Renewable**
D-Volcanic, Seismic, Geological	*Geological instability , sinkholes, liquefaction, land slippage, etc*		x	x			x	x
D-Volcanic, Seismic, Geological	*Sandstorm (including dust storm and volcanic action)*	blockage of air filetrs by volcanic ash, 10-4						
D-Volcanic, Seismic, Geological	*Earthquake*	structural integrity	x	x	All insurable property lines of business can be effected by earthquake	x	x	x
E-Biological	*Marine biological hazard*	water intake acces to cooling water					x	loadon offshore wind farms structures
E-Biological	*Animals (including, for example rodent infestation)*			x				
F-Electromagnetic Hazard	*Space weather (including solar flares, Natural EMP)*	electronic control		Transmission system, electric control systems)				
F-Electromagnetic Hazard	*Solar UV*							Solar - browning, adhesion, and debonding of solar panels
G-Combinations	*Hazard Combinations*	depending on the combination						for offshore wind: combination of wave, tides and wind, (50 years return period + margins

Class	Hazard	Existing Guidelines and regulatory frameworks impacting the UK	Example of industrial application	trends in R&D
D-Volcanic, Seismic, Geological	*Geological instability , sinkholes, liquefaction, land slippage, etc*	API STD 594; API STD 600		
D-Volcanic, Seismic, Geological	*Sandstorm (including dust storm and volcanic action)*			
D-Volcanic, Seismic, Geological	*Earthquake*	SSHAC US guidance, Eurocodes, UBC 97, ASCE 4-98, IBC 2000, Models require validation for use in Solvency II and Lloyds synidcates must report exposure in relation to Realistic Disaster Scenarios, API STD 594, API STD 600	AIR 400 series occupancy coding using component based damage functions	Improvements to the deterministic methods are being investigated by European partners, but would not be readily transferrable to UK context Use of kinematic modelling to help constrain tail of the gutenberg-richter relationships. Use of next generation attenuation relationships
E-Biological	*Marine biological hazard*	Very little specific guidance - overarching safety principles on maintaining cooling water availability; API STD 594; API STD 600; API STD 602; BS PD 8010	Studies across EDF NG fleet & global nuclear	Development of biological models, hydrodynamics models, stochastic models
E-Biological	*Animals (including, for example rodent infestation)*	BS 61936; BS 7671		
F-Electromagnetic Hazard	*Space weather (including solar flares, Natural EMP)*		Extreme space weather impact on engineered systems and infrastructure, Royal Academy of engineer (2013)	
F-Electromagnetic Hazard	*Solar UV*			
G-Combinations	*Hazard Combinations*	OW sea combination in [1], ONR requirements in the UK, [3], WENRA requirement, [4, 5] and IAEA requirements, [6-8]		Numerical modelling

Class	Hazard	Identified gaps	Prioritisation and justification why the gaps should be addressed
D-Volcanic, Seismic, Geological	*Geological instability , sinkholes, liquefaction, land slippage, etc*	Lack of liquifaction potential geological maps	Understand locations with liquifaction potential
D-Volcanic, Seismic, Geological	*Sandstorm (including dust storm and volcanic action)*		
D-Volcanic, Seismic, Geological	*Earthquake*	Lack of UK ground motion prediction equations - but due to low seismicity unlikely to be resolved. Effect of groundwater changes on existing fault reactivation? Lack of historic data for large earthquakes in the UK and UK specific ground motion prediction equations. Lack of understanding how earthquakes effect tall structures in the UK	Better understanding of potential range of ground motions for UK sites would be desirable
E-Biological	*Marine biological hazard*	Lack of systematic understanding; Jellyfish blooming phenomena not really clear; Effect of climate change on marine biofouling; Alternatives to chlorination as suitable biofouling control ?	Emerging risk, very little knowledge
E-Biological	*Animals (including, for example rodent infestation)*		
F-Electromagnetic Hazard	*Space weather (including solar flares, Natural EMP)*	A gap exists to confirm the extreme fluence rates and provide a methodology to assess the sensitivity of the electronics and/or EMI protection systems against the fluence rate]	emerging risk, very little knowledge
F-Electromagnetic Hazard	*Solar UV*		
G-Combinations	*Hazard Combinations*		Lack of robust methodology; Covers all the range of natural hazard; Caused dramatic accidents (Fukushima)



Class	Hazard	Parners with skills						Available Mature Methodologies	Expert judgements on available methodologies, including associated uncertainties, credibility limits
		EDF Energy R&D UK Centre	EDF Nuclear Generation	Nuclear New Build	Met Office	Mott MacDonald	AIR Worldwide		
H-Other	*Forest fire*						x	Probabilistic Monte-Carlo simulation approach deriving a stochastic catalogue of parameters from scientifically adjusted historical distributions	Model meets the wide spectrum of forest fire risk management needs
H-Other	*Meteorite impact*	*x*	*x*	*x*				(1) Estimates of frequency of meteorite impact causing Tsunami to HPC is calculated linearly (area x no of occurrences..); Estimated average return period for given meteorite diameter (2) Spacial Decision Support System architecture (not very mature though) [24]	(2) SDSS is still new and need improvements, designed for potential impacts in urbanized areas, working on including submersion waves from hitting the ocean (tsunami) [24]



Class	Hazard	Climate change impacts	Uncertainties on climate change impacts
H-Other	*Forest fire*	Yes - warmer and drier weather will make forest fires more frequent, [30]	Uncertainty from dependence on projected temperature increases, variation in other contributing factors (ex. Relative humidity), and spatial variation [30]
H-Other	*Meteorite impact*		

Class	Hazard	potential consequences and return level by sectors						
		Nuclear	Hydropower	Transmission & distribution	Insurance	Thermal Generation	Oil and Gas	Renewable
H-Other	*Forest fire*	x			All insurable property lines of business can be effected by forest fire	x		
H-Other	*Meteorite impact*	sea waves caused by meteorite impact causing flooding of the platform, 10-7						

Class	Hazard	Existing Guidelines and regulatory frameworks impacting the UK	Example of industrial application	trends in R&D
H-Other	*Forest fire*	NFPA for Fire Risk Assessment, Models require validation for use in Solvency II, API RD520, API STD 594, API STD 600, API STD 607, IEC 60331, IEC 60332, IEC 60079, Multiple NFPA standards.		
H-Other	*Meteorite impact*			

Class	Hazard	Identified gaps	Prioritisation and justification why the gaps should be addressed
H-Other	*Forest fire*		
H-Other	*Meteorite impact*		

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Detailed list of key findings from UKCP09

The key findings from UKCP09 are described below, for the 2080s, under the Medium emissions scenario, relative to a 1961-1990 baseline:

- Mean daily maximum temperatures increase everywhere. Increases in the summer average are up to 5.4ºC (2.2 to 9.5ºC) in parts of southern England and 2.8ºC (1 to 5ºC) in parts of northern Britain. Increases in winter are 1.5ºC (0.7 to 2.7ºC) to 2.5ºC (1.3 to 4.4ºC) across the country.
- Changes in the warmest day of summer range from +2.4ºC (–2.4 to +6.8ºC) to +4.8ºC (+0.2 to +12.3ºC), depending on location, but with no simple geographical pattern.
- Mean daily minimum temperature increases on average in winter by about 2.1ºC (0.6 to 3.7ºC) to 3.5ºC (1.5 to 5.9ºC) depending on location. In summer it increases by 2.7ºC (1.3 to 4.5ºC) to 4.1ºC (2.0 to 7.1ºC), with the biggest increases in southern Britain and the smallest in northern Scotland.
- Central estimates of annual precipitation amounts show very little change everywhere at the 50% probability level. Changes range from –16% in some places at the 10% probability level, to +14% in some places at the 90% probability level, with no simple pattern.
- The biggest changes in precipitation in winter, increases up to +33% (+9 to +70%), are seen along the western side of the UK. Decreases of a few percent (–11 to +7%) are seen over parts of the Scottish highlands.
- The biggest changes in precipitation in summer, down to about –40% (–65 to –6%), are seen in parts of the far south of England. Changes close to zero (–8 to +10%) are seen over parts of northern Scotland.
- Changes in the wettest day of the winter range from zero (–12 to +13%) in parts of Scotland to +25% (+7 to +56%) in parts of England.
- Changes in the wettest day of the summer range from –12% (–38 to +9%) in parts of southern England to +12% (–1 to +51%) in parts of Scotland.
- Relative humidity decreases by around –9% (–20 to 0%) in summer in parts of southern England — by less elsewhere. In winter changes are a few percent or less everywhere.
  Summer-mean cloud amount decreases, by up to –18% (–33 to –2%) in parts of southern UK (giving up to an extra +16 Wm^{-2} (–2 to +37 Wm^{-2}) of downward shortwave radiation) but increase by up to +5% (zero to +11%) in parts of northern Scotland. Changes in cloud amount are small (–10 to +10%) in winter.
- Projected changes in storms are very different in different climate models. Future changes in anticyclonic weather are equally unclear.
- For some variables it was not possible to provide probabilistic climate projections. This includes snowfall, lightning, and fog. In these cases, projections from the Met Office Hadley Centre regional climate model have been provided.
- There is no assessment in UKCP09 of how the urban heat island effect may change.
- It is very unlikely that an abrupt change to the Atlantic Ocean Circulation (Gulf Stream) will occur this century.

This statement has been used, together with other literature sources to fulfil the column "Climate Change Impacts" of the table reported I the Annexe. In the table the impact of climate change are mentioned for every single hazard on the hazard list.

Glossary and List of Abbreviations

- **EVA** Extreme Value Analysis
- **RFA** Regional Frequency Analysis
- **PSR** Periodic Safety Review
- **EMI** Electro Magnetic Inferences
- **NNB** Nuclear New Build
- **OW** Offshore Wind
- **PSHA** Probabilistic Seismic Hazard Assessment
- **SSHAC** Senior Seismic Hazard Assessment Committee
- **HPC** Hinkley Point C
- **NG** EDF Energy Nuclear Generation
- **FEH** Flood Estimation Handbook
- **TORRO** TORnado and storm Research Organization
- **ONR** Office for Nuclear Regulation
- **WENRA** Western European Nuclear Regulators Association
- **IAEA** International Atomic Energy Agency
- **Frazil**: Frazil ice is a collection of loose, randomly oriented needle-shaped ice crystals in water. It resembles slush and has the appearance of being slightly oily when seen on the surface of water.