Enhancing Resilience in UK Energy Networks – What are the future weather and climate risks to energy network infrastructure?

Final Report - Part One

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CS-NOW

Climate services for a net zero resilient world

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About CS-N0W

Commissioned by the UK Department for Energy Security and Net Zero (DESNZ), Climate Services for a Net Zero Resilient World (CS-N0W) is a 4-year, £5.5 million research programme, that will use the latest scientific knowledge to inform UK climate policy and help us meet our global decarbonisation ambitions.

CS-N0W aims to enhance the scientific understanding of climate impacts, decarbonisation and climate action, and improve accessibility to the UK's climate data. It will contribute to evidence-based climate policy in the UK and internationally, and strengthen the climate resilience of UK infrastructure, housing and communities.

The programme is delivered by a consortium of world leading research institutions from across the UK, on behalf of DESNZ. The CS-N0W consortium is led by Ricardo and includes research **partners Tyndall Centre for Climate Change Research**, including the Universities of East Anglia (UEA), Manchester (UoM) and Newcastle (NU); institutes supported by the **Natural Environment Research Council (NERC)**, including the British Antarctic Survey (BAS), British Geological Survey (BGS), National Centre for Atmospheric Science (NCAS), National Centre for Earth Observation (NCEO), National Oceanography Centre (NOC), Plymouth Marine Laboratory (PML) and UK Centre for Ecology & Hydrology (UKCEH); and **University College London (UCL)**.

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1. Executive Summary

This report is Part 1 of the Final Report for Work Package D3 Enhancing Resilience in UK Energy Networks (WPD3) of the Climate Services for a Net Zero resilient world (CS-N0W) programme. The remit of this Work Package is to support DESNZ (BEIS as it was when the project started and the invitation to tender (ITT) was issued) in improving UK energy resilience – in line with BEIS Departmental Objective 4.3 “Ensure our energy system is reliable and secure” – by improving Departmental understanding of climate risks to UK energy network infrastructure, including cascading and systemic risks.

This report presents the work done in answering question 2 of the ITT namely: “what are the future weather and climate risks to energy network infrastructure, assets, and processes, including cascading and systemic risks? This work should quantify risks where possible, look at timescales of 5, 10, 20, and 30 years from now. The work should identify the role of critical energy infrastructure in propagating these cascading and systemic climate risks in the UK.”

In this report, we present an assessment of four key hazards for distribution networks identified during interviews with Distribution Network Operators (DNOs). These include windstorms, hot spells, cold spells and wet spells. Specifically, we assess metrics that indicate the intensity of these events: the maximum wind speed in windstorms, the maximum temperature in hot spells, the minimum temperature in cold spells, and the accumulated rainfall in wet spells. Results are presented in Chapters 6 and 7 for the seven electricity and four gas DNOs outlined in Chapter 3, and are based on the UK Climate Projections 2018 (UKCP18) Representative Concentration Pathway 8.5 (RCP8.5) scenario which is a high-emissions future scenario in which we assume global GHG emissions will continue to increase towards the end of the 21st century and no mitigation measures are used to reduce them as outlined in Chapter 4. We compare three time periods: 1980-2000, 2020-2040, and 2060-2080.

We have presented the results in terms of maximum intensity of a particular weather variable for different Return Periods (RPs). The RPs were estimated by fitting a Generalised Pareto Distribution (GPD) to the whole 12-member ensemble in each of the three time slices separately, giving 240 years of data for each time slice. The GPD was fitted to the most extreme 240 events in the dataset. Uncertainties have also been estimated by applying a non-parametric bootstrapping approach.

The main findings of the report are as follows:

- Windstorms intensify in a future warmer climate, but mainly in the 2060-2080 period. However, the projections vary for different DNO areas and not all DNOs may expect to see this increased intensity. For instance, increases are found for those in the west and north of the UK while the southeast has little or no change.
- Hot spells will increase in intensity and frequency in all DNO areas. For example, events occurring every 20 years in the 1980-2000 time period, are projected to occur every 5 years in the 2020-2040 period and every 1-2 years in the 2060-2080 period.
- Cold spells are projected to reduce in intensity for all DNO areas in that the minimum temperatures during these cold spells are projected to increase. Generally, an event occurring once every 10 years on average in the 1980-2000 period is projected to occur once every 50 years in the 2020-2040 period and far less frequently in the 2060-2080 period.
- Wet spells are generally projected to increase in their intensity in that future wet spells will mostly have higher accumulated rainfall totals. The increases vary across each DNO area with some seeing increases in both the 2020-2040 and 2060-2080 period, others only seeing the increase in the far future while those in the southeast see no projected change.

Results imply that faults related to wind, high temperatures and rainfall will increase in the future. However, the event intensities that are assessed here represent only one of many contributing factors of impacts that occur in these events (e.g. wind driven risk is modulated by wind direction, seasonality and soil moisture – trees are less resistant to winds from a non-prevailing direction, catch wind more when in leaf, and uproot more easily in wet soils). We recommend that there is a need to understand and better quantify such contributions to help inform future risk assessments of what variables to assess in order to provide the best guidance possible.

2. Introduction

Extreme weather poses a large risk to energy network infrastructure in the UK. In particular, strong winds, flooding, as well as extremely cold and hot temperatures can damage assets within the electricity and gas distribution networks and lead to power outages with possible cascading effects that compromise the availability and function of other essential services. Anthropogenic climate change, driven by greenhouse gas emissions, has already led to an increase in the frequency of flooding and extremely high temperatures in the UK. Future projections indicate that these extremes, including windstorms, will increase in intensity and frequency in the future with likely adverse consequences for energy infrastructure. As we move away from fossil fuels to reduce greenhouse gas emissions, the demand placed on electricity distribution networks from electric vehicles, heating and air conditioning will only increase, requiring upgrades to infrastructure to increase capacity and to ensure resilience. To ensure our future networks maintain resilience, we need to know:

1. the type of weather extremes that infrastructure will face,
2. what effects increased demands for electricity and gas will have and
3. how new network assets and configurations contribute to this resilience.

This report, as part of the CS-N0W project, sets about laying the foundations for such work by providing and assessing climate data for regional operators for 7 electricity and 4 gas distribution network operators. It can be used to consider bullet point 1 above (weather extremes) by providing a baseline to study how other changes (increased demand and changes in energy network configurations) may affect resilience. This work is part of the CS-N0W programme which aims to enhance the scientific understanding of climate impacts, decarbonisation, and climate actions and to improve accessibility to the UK's climate data. Additionally, the project envisages that the outputs will contribute to evidence-based climate policy both in the UK and internationally, and strengthen the climate resilience of UK infrastructure, housing and communities. It proposes to meet these aims through the use of the latest scientific knowledge to inform UK climate policy and help the UK meet its global decarbonisation ambitions. The remit for WPD3 of the CS-N0W programme is to support DESNZ in improving UK energy resilience – in line with DESNZ Departmental Objective 4.3 "Ensure our energy system is reliable and secure" – by improving Departmental understanding of climate risks to UK energy network infrastructure, including cascading and systemic risks. In line with this objective, this report presents the work done in answering question 2 of the ITT namely: "what are the future weather and climate risks to energy network infrastructure, assets, and processes, including cascading and systemic risks? This work should quantify risks where possible, look at timescales of 5, 10, 20, and 30 years from now. The work should identify the role of critical energy infrastructure in propagating these cascading and systemic climate risks in the UK."

Alongside DESNZ objectives, the DEFRA climate change Adaptation Reporting Power (ARP), set out in the Climate Change Act 2008, that organisations undertaking functions of a public nature must report on how they are addressing current and future climate impacts[1]. These reports must include the current and future projected impacts of climate change on their organisation, proposals for adapting to climate change, and an assessment of the progress towards implementing the policies and proposals set out in previous reports. Such risk assessments have so far been based on subjective or qualitative judgements that draw on past experiences within an organisation and future projections of hazards taken from Met Office reports[2]. Although such qualitative assessments can provide an informative overview of the main risks, they are still subjective and open to unconscious bias that can produce misleading results. They also do not provide objective information on the change in frequency of extremes or the consequences of these changes. For example, how often customers might be affected by power outages in the future due to extreme weather and how much this change might cost an organisation in repair works if not well adapted.

A previous report within this work package (D3) identified a number of barriers that prevent electricity and gas Distribution Network Operators (DNOs) from applying a quantitative risk assessment. One of the difficulties DNOs had is with understanding and utilising outputs from climate models. Within this report, we attempt to address this concern by providing and assessing climate data from the UK Climate Projections 2018 (UKCP18) over the regions operated by the DNOs. Specifically, we provide climate model data for wind gusts, temperature and rainfall which were identified as the main variables of interest during work package D3. Furthermore, we present the projected changes for windstorms, hot spells, cold spells and wet spells over each DNO region. Ideally, we would go one step further to provide the change in faults and customer minutes lost expected due to changes in the hazards. However, we currently do not have access to all the required data to quantify the relationship between hazard and impact. Nevertheless, this analysis

[1] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/182636/report-faq-110126.pdf

[2] https://www.nationalgrid.com/electricity-transmission/document/143211/download

will help DNOs to understand the likely changes in hazards that their infrastructure might face in a warmer climate.

3. Distribution Network Operators

We assess projections of impact relevant hazards for seven electricity DNOs and four gas DNOs. The electricity DNOs are provided below and the regions they operate are provided in Figure 1:

- Electricity North West (North West England)
- Northern Ireland Energy Network (Northern Ireland)
- Northern Powergrid (North East England)
- UK power Networks (South East England)
- National Grid (South West England, South Wales, East and West Midlands)
- SP Energy Networks (Southern Scotland and Northern Wales)
- Scottish and Southern Electricity (Northern Scotland and Southern England)

Figure 1: Regions operated by Electricity DNOs[3]

[3] https://communityenergyengland.org/how-to-pages/dnos-local-energy-hubs

The gas DNOs are provided below and the regions they operate in are provided in Figure 2:

- SGN (Scotland and Southeast England)
- Wales and West Utilities (Wales and Southwest England)
- Northern Gas Networks (Northwest England)
- Cadent Gas (Northwest England, Midlands, Eastern England, London)

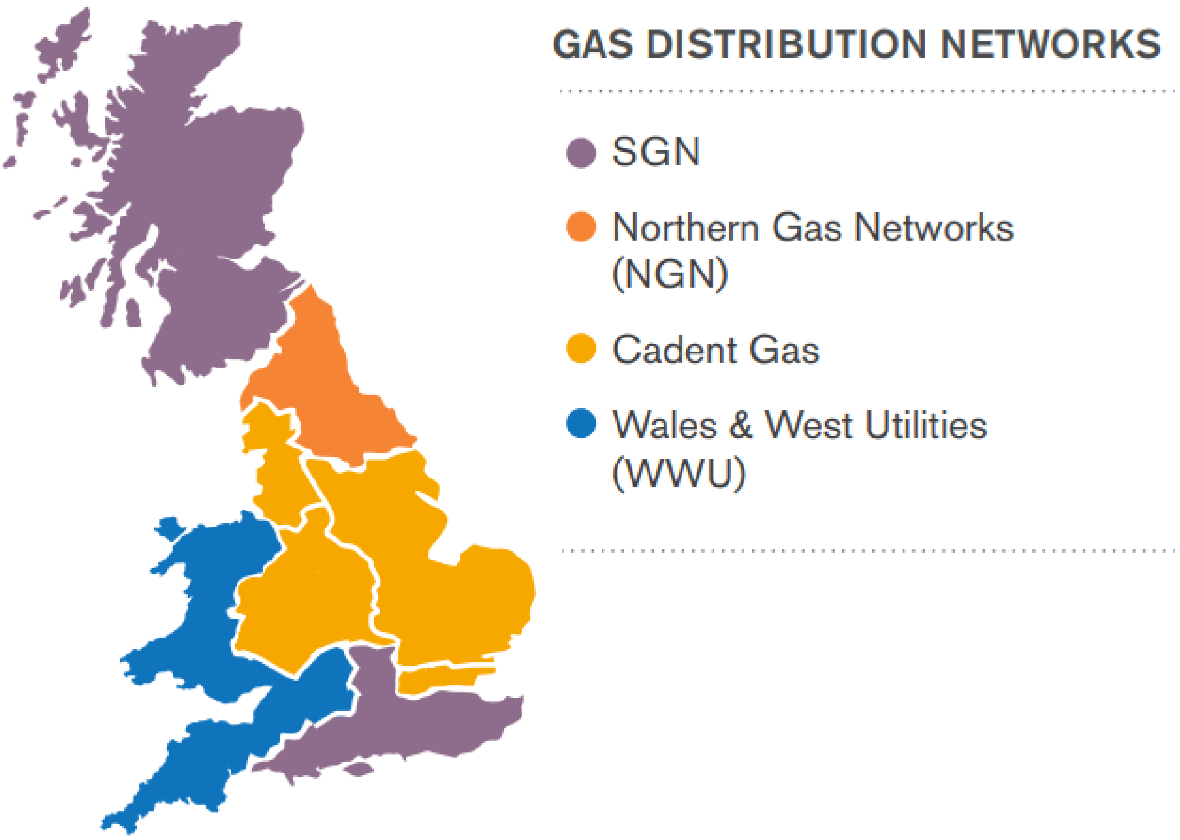

Figure 2: Regions operated by gas DNOs[4]

[4] https://www.dyballassociates.co.uk/what-is-the-energy-distribution-network-and-how-does-it-work

4. UKCP18 Climate Projections

This section describes the climate projections used in this project and why they are the most appropriate for our analysis.

UKCP18 is a set of climate projections released by the UK Met Office which include global projections at 60 km horizontal resolution (GCM), regional projections over Europe at 12 km (RCM) and a set of local 2.2 km convection-permitting model (CPM) projections over the UK. The high-resolution simulations (12 and 2.2 km) are produced by downscaling the information produced by the coarser resolution simulations. Specifically, the GCM provides information at the boundaries of the RCM to downscale to a 12 km resolution over Europe, and the RCM provides information at the boundaries of the CPM to a 2.2 km resolution. This modelling chain is required due to technical modelling reasons (i.e. computation expense restricts the resolution of the GCM and the 2.2 km simulations are only produced over the UK for the same reasons). The projections consist of 12 ensemble members. This means that the models have been run 12 times with slightly different conditions to produce 12 ways in which the climate could evolve due to natural variability and greenhouse gas emissions. For each of the 12 members, there are three time slices (TS): a control simulation (TS1: 1981-2000), and two future simulations (TS2: 2021-2040 and TS3: 2061-2080). As there are 12 members for each TS, we can combine these to have 240 years of simulated data for each time slice that are representative of climate conditions within those periods. All of the simulations have used the RCP8.5 future scenario. This is a high-emissions scenario which assumes little action to mitigate greenhouse gas emissions. It is the worst of the scenarios used for climate projections and is the only scenario that projections have been produced for. The following sections summarise the RCP8.5 scenario, what climate models are, how they produce climate projections and what they can be used for.

4.1 RCP8.5 Global Emissions Scenario

The extent to which our climate changes will depend on the quantity of greenhouse gases (GHGs) emitted globally. The more emitted, the larger the changes will be. Climate projections are produced following scenarios, called representative concentration pathways (RCP), that make assumptions about how society will develop and how much GHGs will be emitted. UKCP18 follows a high-emissions scenario, RCP8.5, in which we assume global GHG emissions will continue to increase towards the end of the 21st century and no mitigation measures are used to reduce them. The plausibility of this scenario is open to debate, future projections depend on the level greenhouse gases emitted (i.e. the higher the emissions, the larger the increases in temperature, rainfall, wind extremes), and while several policies and measures have been committed to mitigate these higher emissions, what happens in reality will depend on the societal response globally.

4.2 How Do Climate Models Work?

A climate model is a numerical model which divides the atmosphere horizontally into a number of grid boxes and vertically into a number of levels, as demonstrated by Figure 3. At each grid box on all levels, the model solves the equations of motion of the atmosphere every 60 seconds. Each 60 second interval is termed a time-step. At each time-step, grid boxes receive information from the previous time-step and from neighbouring grid boxes. In doing so, the model can represent the horizontal and vertical movement of different meteorological phenomena.

When running the model in numerical weather prediction (NWP) mode, the model simulation is updated by the most recent observations. For this reason, the data obtained from the first time-step (t + 0) of a NWP model simulation can be considered a type of pseudo-observation as it is constrained by the most recent observations. In contrast, a climate simulation is allowed to run freely for a prescribed amount of time, usually at least 20 years. During this time, the model responds to daily and seasonal variations in solar radiation which allows it to capture diurnal cycles (e.g. low temperatures at night, high in the day) and seasonal cycles (i.e. winter and summer). For future projections of climate, the model responds to gradual changes in greenhouse gas emissions, the driver of anthropogenic climate change. The rate at which greenhouse gases increase during the climate simulation is based on a scenario which makes assumptions about future societies' response to limit greenhouse gas emissions. As mentioned already, the climate simulations analysed in this report follow the RCP8.5 scenario.

The numerical model used here is the UK Met Office high-resolution convection-permitting configuration of the Unified Model over the British Isles, which is the same as that used in weather forecasting. The horizontal resolution of this model is 2.2km, meaning that the grid boxes are 2.2 km x 2.2 km in area. This is the state-of-the-art horizontal resolution for such numerical models, and this resolution is quite important for representing meteorological phenomena. For instance, a model with a 60 km horizontal resolution is unable to simulate processes that occur at smaller scales such as vertical motions that lead to intense wind gusts or heavy rainfall over localised areas.

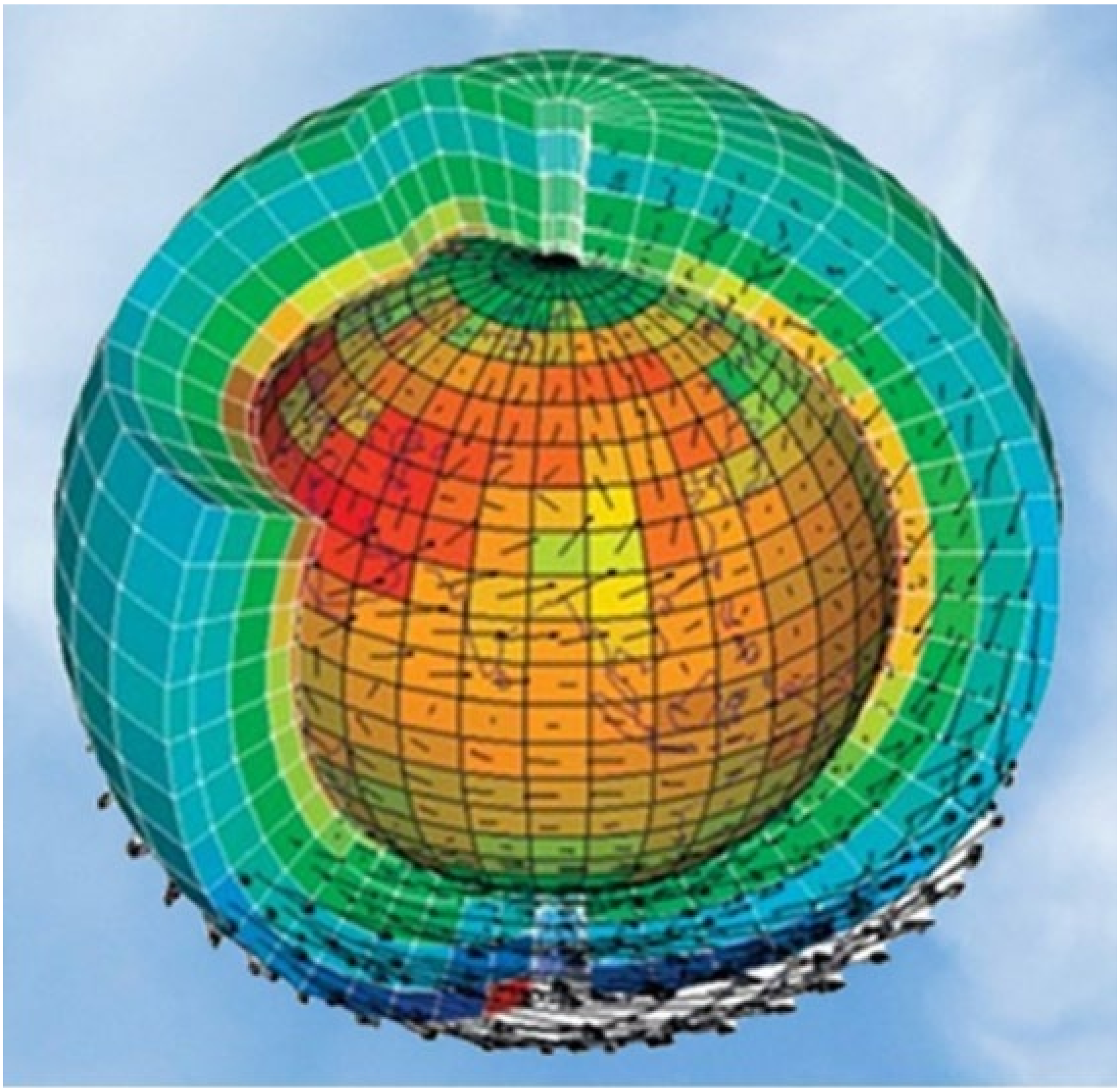

Figure 3: Anatomy of a climate model[5]

4.3 What Information Can Climate Models Provide?

A climate model is an extension of a weather forecast model, but while weather forecast models provide predictions over short timescales (days to weeks), a climate model is run over longer time spans (> 20 years) to build up a long-term record of simulated weather events from which we can obtain information such as the average temperature in a region, or the probability of temperature exceeding a high threshold. As described in section 2.1, by changing the greenhouse gas emissions in the model, we can test how these probabilities change if emissions continue to increase in the future.

[5] Source: https://e-science.se/people-and-research/communities/climate-modeling/

The reliability of climate projections depends on how well a model can reproduce weather phenomena such as cyclones that produce wind and rainfall extremes, and anticyclones that produce hot spells in summer and cold spells in winter. Their reliability also depends on how well they can reproduce larger climatic features which exert a strong influence on our climate and the weather patterns we face in the UK such as the North Atlantic Oscillations (NAO), and the El Nino Southern Oscillation in the Pacific. This is tested by comparing statistics derived from a control climate of a climate model (e.g. averages, probabilities of extremes) with those derived from historical data. The global model performs well in the representation of these features and also compares well in its representation of the frequency of cyclones (that bring intense winds and precipitation) over the UK[6]; however, it tends to underestimate the frequency and persistence of 'blocking' anticyclones which are important for the representation of persistent cold extremes in winter and hot extremes in summer. We therefore have less confidence in the representation of such events as these issues are inherited by the 2.2 km model used in this analysis. However, the 2.2 km model is the state-of-the-art climate model and has been rigorously tested and updated with feedback from forecasters who assess the output on a daily basis. This model has been shown to perform well in its representation of temperature, rainfall and wind speeds and offers large improvements over previous generations of models in its representation of extreme events. This gives us confidence in its ability to be used as a tool to provide information on how extreme weather events may change in their intensity and frequency in the future in response to increasing greenhouse gas emissions[7].

While UKCP18 local represents the best UK relevant climate model projections available, it is important to note that individual events contained in climate model projections cannot be used in isolation. Each individual event should be considered as a scenario of what may happen in the future rather than something that is expected to occur. And while individual events can be useful for stress testing, they should be thought as plausible scenarios for understanding possible futures. Similarly, the timing and locations of weather events are just one possible future and real future storms may occur in different locations and at different times.

[6] Murphy, J.M., Harris, G.R., Sexton, D.M.H., Kendon, E., Bett, P., Clark, R. and Yamazaki, K., 2018. UKCP18 land projections: science report. Met Office. *Reading, UK*.

[7] Kendon, E.J., Short, C., Pope, J., Chan, S., Wilkinson, J., Tucker, S., Bett, P., Harris, G., 2021. Update to UKCP local (2.2km) projections: Science report.

4.4 Climate Data Used in the Analysis

UKCP18 data is publicly available, and the full set of available data from UKCP18 is summarised in Table 1. We employ 3-hourly wind gust data, hourly temperature data, and hourly accumulated rainfall data from the UCKP18 local simulations and produce time series of each variable for the DNO regions shown in Figure 1 and Figure 2. Producing these time series requires a number of steps and decisions to be made. Firstly, we note that the time series are generated from the raw climate model output data which is provided on a 2.2 x 2.2 km horizontal grid. For each timestep, we must extract all model grid cells that lie within a specified DNO region and calculate a measure of 3-hourly or hourly intensity for each of the variables. Specifically, we calculate the average hourly temperature and rainfall from all grid cells that overlap with the DNO region. However, for wind gusts we calculate the 98th percentile of the 3-hourly wind gusts within the region, that is, the wind gust exceeded by 2% of grid cells in the region at a given time. We choose this as measure of wind intensity for windstorms as it indicates the presence of a coherent wind feature produced by a windstorm in the region. It chosen instead of the average or maximum values as the former may filter out important features due to the highly variable nature of wind gusts in space and the latter can capture occurrences of isolated high wind gusts unrelated to windstorms, which is mostly an issue in areas such as Scotland with complex topography. No further adjustments have been applied to the data.

The data is assessed in three time slices: TS1 (1981-2000), TS2 (2021-2040), and TS3 (2061-2080). Each time slice has 12 20-year simulations providing 240 years of simulated data that is representative of the climatic conditions within a given time slice following the RCP8.5 scenario. The 240 years of simulated data for each time slice provides large event sets which allow us to robustly quantify return periods of infrequent events such as those that occur once every 20 years on average. However, there will still be large uncertainty around quantifying rare events such as a 100-year event, as this quantification would be based on the 2 largest events which may not be representative of the true 100-year event.

Table 1: Summary of available variables from the UKCP18 climate projections[8]. Note that we have only considered three of these variables in this report (wind gusts, temperature, precipitation) from the local (2.2 km) projections.

Variable at the surface (short name in CEDA catalogue)	Units	Marine	Probabilistic	*Global (60km)	Regional (12km)	Local (2.2km)	Derived
Cloud cover (clt)	%		✓	✓	✓	✓	
Precipitation (pr)	mm/day		✓	✓	✓	✓ hourly	✓*
Radiation, total downward short wave flux (rsds)	Wm^{-2}		✓				
Radiation, net long wave (rls)	Wm^{-2}		✓	✓	✓	✓	
Radiation, net short wave (rss)	Wm^{-2}		✓	✓	✓	✓	
Relative humidity (hurs)	%			✓	✓	✓	✓
Sea level pressure (psl)	hPa		✓	✓	✓	✓	
Sea water level	m	✓					
Snow: snowfall amount (prsn)	mm				✓	✓	
Snow: lying snow amount (snw)	mm				✓	✓	
Specific humidity (huss)			✓	✓	✓	✓	
Temperature, maximum (tasmax)	°C		✓	✓	✓	✓	
Temperature, Mean (tas)	°C		✓	✓	✓	✓ hourly	✓*
Temperature, minimum (tasmin)	°C		✓	✓	✓	✓	
Wind gusts (wsgmax10m)	m/s					✓ 3-hourly	
Wind speed (sfcWind)	m/s			✓	✓	✓ 3-hourly	✓
Wind speed eastwards (uas)	m/s			✓	✓	✓	✓
Wind speed northwards (vas)	m/s			✓	✓	✓	✓

[8] https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp18-guidance-data-availability-access-and-formats.pdf

5. Methods

5.1 Definition of Weather Events and their Intensity Metrics

In this section, we outline how we define windstorms, hot spells, cold spells and wet spells. We choose to assess these event types as they have been identified by DNOs as the main causes of faults in distribution networks. For each event type, we define an event intensity and assess how likely events of certain intensities are to occur in the three time slices TS1 (1981-2000), TS2 (2021-2040), and TS3 (2061-2080). The intensities are assumed to be impact relevant in that they have positive correlations with likely impacts (e.g. high wind speeds lead to more faults and longer power outages). However, there are of course issues with such an assumption, which will be discussed below alongside the description of event definitions.

5.1.1 Windstorms

Windstorms are identified as spells where 3-hourly 98th percentile wind gust exceeds 25 m s^{-1} for at least 3 consecutive 3-hourly time-steps. Events that occur within 12 hours of one another are grouped together to form a single event. The 25 m s^{-1} threshold is chosen as this is when we start to see larger impacts in terms of fault numbers and Customer Minutes Lost (CML). The threshold for 3 consecutive time-steps is applied to remove any events where the threshold is exceeded sporadically and thus may not be a windstorm. For this analysis, the severity of a windstorm is measured using the maximum 3-hourly 98th percentile wind gust produced during a windstorm. This is used as an indication of overall intensity of a windstorm across a Licence Area.

Previous research has shown a positive relationship between wind intensity and the impacts seen within electricity distribution network. However, there is considerable dispersion in this relationship in that the number faults occurring for a windstorm of given severity can vary substantially from zero faults to 300 faults, for example. Other factors likely modulate the likelihood of an asset failing at a given wind intensity, for example, trees that fall on overhead lines are more resistant to winds from a prevailing direction, uproot more easily in wet soils, and are more likely to catch wind when they are in leaf. Thus, wind intensity is only one contributing factor of wind related faults and so for an in depth understanding of current and future risk, future analyses may need to assess contributions of other factors and how these might change in the future.

5.1.2 Hot Spells

Hot spells are defined using the maximum daily temperature calculated from the hourly mean time series. Hot spells are then identified on when the daily maximum temperature exceeds 25°C for at least two days, as previous assessments (not published) show that impacts to electricity networks tend to increase above this threshold. Consecutive days that exceed 25°C are combined to form a single event. The intensity of hot spells is then defined as the maximum temperature reached during an event.

It should be noted that faults related to high temperatures are likely caused by direct heating through solar radiation. Temperature is used here as an indicator of solar radiation, given their relationship, as we do not have data for solar radiation. However, this relationship is modulated by several factors at a local scale, where impacts to assets occur, such as the topography of a locality which can provide shelter from cooling wind. In such sheltered locations, direct solar heating can lead to high temperatures that can be much higher than those in the surrounding region. These local effects will not be present within gridded datasets of observations, and it is likely that the only way to observe such effects is to have in situ observations at the point of the asset. Hence, high temperatures should only be considered as indicative of the conditions that may lead to assets failing.

5.1.3 Cold Spells

Cold spells are defined using the minimum daily temperature calculated from the hourly mean time series. Cold spells are then identified when the daily minimum temperature drops below 0°C for at least two days. Consecutive days that drop below 0°C are combined to form a single event. The intensity of cold spells is then defined as the minimum temperature reached during an event. The cold temperatures are taken to be representative of conditions in which snow and ice can occur and remain for extended periods.

5.1.4 Wet Spells (Indicator of Flooding Potential)

Flooding is a major concern for DNOs. However, we do not have time series of flooding and so we have instead defined a rainfall metric that is indicative of conditions that might lead to flooding. A wet spell is identified on a given day when the regionally averaged rainfall exceeds 1 mm. Consecutive days that exceed 1 mm are combined to form a single event. The intensity of the event is defined as the accumulated rainfall during this period. The accumulated rainfall during a wet period is chosen to represent a large-scale flooding hazard as flooding generally occurs due to persistent wet weather that causes soil moisture and river levels to gradually rise and cause flooding. However, the limitation of this metric is that it will not capture localised flooding that arises from intense convective storms on smaller spatial scales than the regions we are averaging rainfall over. Projected changes in such events across the UK can be found in a recent study[9].

5.2 Estimation of Return Periods and Uncertainties for Weather Hazards

Return periods (RPs) provide a measure of the probable frequency for an event with a specified intensity. For example, an event with a return period of 5 years is expected to occur on average once every 5 years. However, this does not mean that there are 5 years between each time such an event occurs, but that in a 100-year time period, the event has occurred at least 20 times. It is also possible that we may experience such an event twice in the same year.

RPs are estimated for each hazard in a stationary framework, this means that the probability of a specific event does not vary with time within the 20-year time period it occurs within (e.g. TS1) but can of course vary between time periods. The RPs are estimated by fitting a Generalised Pareto Distribution (GPD) to the whole 12-member ensemble in each time slice separately, giving 240 years of data for each time slice separately. The GPD is fit to the most extreme 240 events in the dataset. For example, for windstorms, we use the top 240 ranked storms according to their maximum wind gust. Focussing on only the extremes provides a more accurate estimate of the probability of an extreme event than would be achieved by including all events.

Uncertainties are estimated by applying non-parametric bootstrapping approach in which we randomly sample 1000 times, with replacement, individual years which encompass the main season for each hazard to preserve serial dependence within seasons and account for year-to-year variability in the uncertainty estimation. In each random sample, we calculate the Return Level (RL) for RPs between 1-50 years, giving 1000 estimated RLs for each RP. The expected RL for a given RP is then calculated as the median of this sample while the 95% uncertainty interval is the range between the 2.5th and 97.5th percentiles. The uncertainty interval then represents the sensitivity of the result to randomly including/excluding certain years. The 95% uncertainty interval is somewhat arbitrarily chosen; however, it is fairly typical for studies such as this.

[9] Chan, S.C., Kendon, E.J., Fowler, H.J., Youngman, B.D., Dale, M. and Short, C., 2023. New extreme rainfall projections for improved climate resilience of urban drainage systems. *Climate Services*, *30*, p.100375.

6. Results: Hazard Projections for Electricity DNOs

The projected changes for windstorms, hot spells, wet spells and cold spells are outlined for each DNO separately below. Each figure in this section presents the return period (x-axis) of events with specified intensities (y-axis) for three time slices (or time periods) (TS1: 1980-2000, TS2: 2020-2040, TS3: 2060-2080). These figures portray how extreme events are projected to change in both their intensity and frequency. To help interpretation of the figures, we describe the results in Figure 4: Northern Ireland Energy Network climate projections. Projected hazards 1-50 year return periods for three time periods. a) the maximum wind gust in a windstorm, b) the maximum temperature in a hot spell, c) the accumulated rainfall in a wet spell, and d) the minimum temperature in a cold spell. Shaded regions represent the 95% uncertainty interval of the estimated return periods.

The “maximum temperature in a hot spell figure” presents the RPs for hot spell intensities in the three time periods. In the 1980-2000 time period, the intensity (also called the RL in this context) associated with a RP of 20 years is around 27°C. That means that hot spells with a maximum temperature equal to or greater than 27°C occur on average once every 20 years, or around 12 times in the 240 years of simulated data used here to define the RPs in the climate representative of the 1980-2000 time period. Moving along the y-axis, we can see that the intensity (or return level) associated with a 20-year event changes to 29°C in the 2020-2040 slice and to 34°C in the 2060-2080 slice. And by moving along the y-axis, we can see that an event with an intensity of 27°C is expected to occur every 5 years in a climate representative of the 2020-2040 period and almost every year in 2060-2080.

6.1 Northern Ireland Energy Network (Northern Ireland)

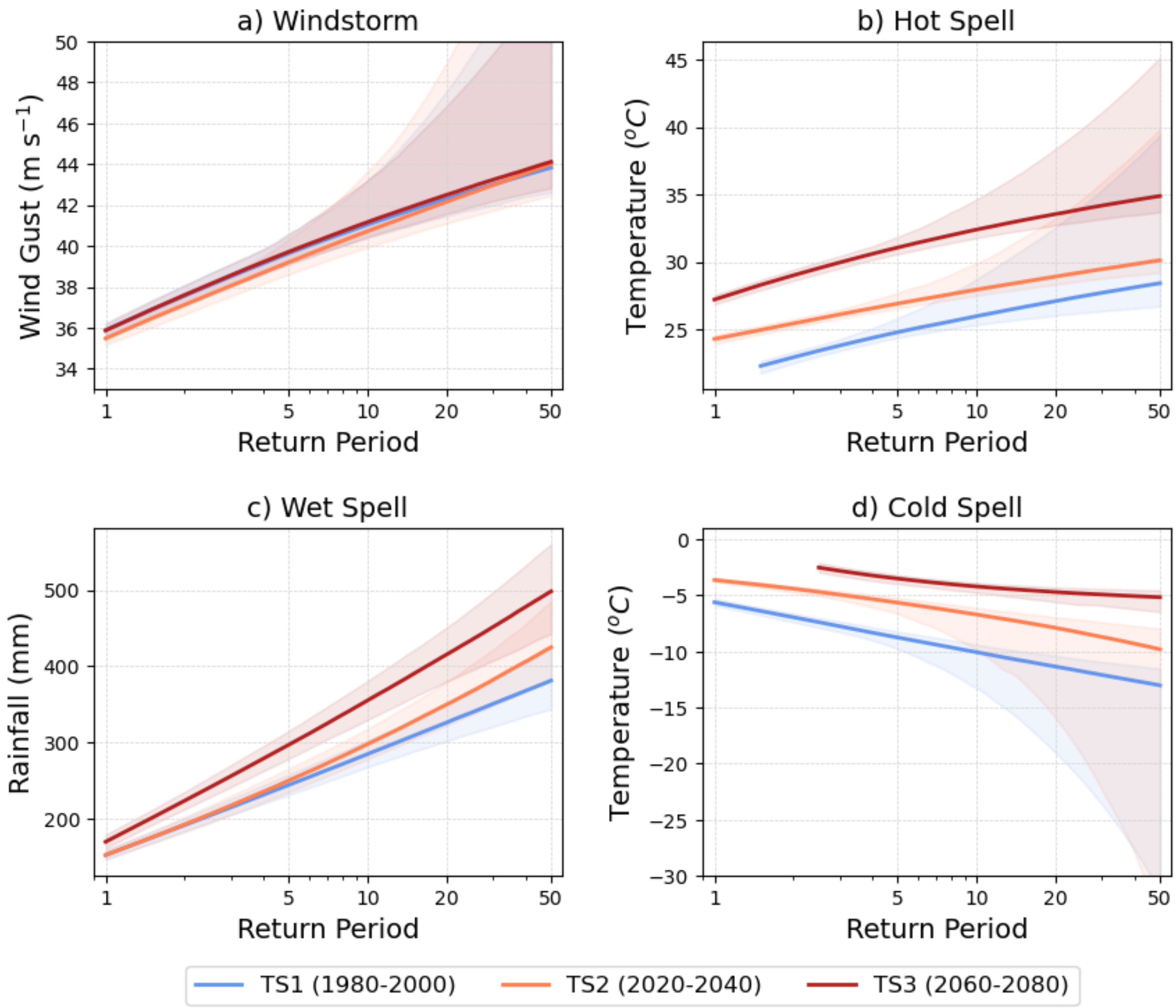

Figure 4: Northern Ireland Energy Network climate projections. Projected hazards 1-50 year return periods for three time periods. a) the maximum wind gust in a windstorm, b) the maximum temperature in a hot spell, c) the accumulated rainfall in a wet spell, and d) the minimum temperature in a cold spell. Shaded regions represent the 95% uncertainty interval of the estimated return periods.

Figure 4 depicts the projected return periods for each of the hazards in the region operated by Northern Ireland Energy Network. The projections can be summarised as follows:

- **Windstorms:** There is no discernible change in the maximum wind gusts in windstorms in this region.
- **Hot spells:** Hot spells will be warmer in the future. The maximum temperature in hot spells is projected to increase in both future periods relative to the control. This is seen at all return periods. An event that occurs every 20-years in the control is projected to occur every 7-8 years in the 2020-2040 period, and every 1-2 years in the 2060-2080 period.

- **Wet spells:** Wet spells are projected to be wetter in the 2060-2080 period. The accumulated rainfall in wet spells is projected to increase in all return periods in this period but only at extreme return levels in the 2040-2060 period. An event that occurs every 20-years in the control is projected to occur every 15 years in the 2020-2040 period, and every 6-7 years in the 2060-2080 period.
- **Cold spells:** Cold spells are projected to become warmer and less severe in the future. The minimum temperature in cold spells is projected increase at all return periods, whereby an event that occurs 10 years in the control is projected to occur once every 50 years in the 2020-2040 period and become even more infrequent by the 2060-2080 period.

6.2 Scottish and Southern Electricity (Northern Scotland)

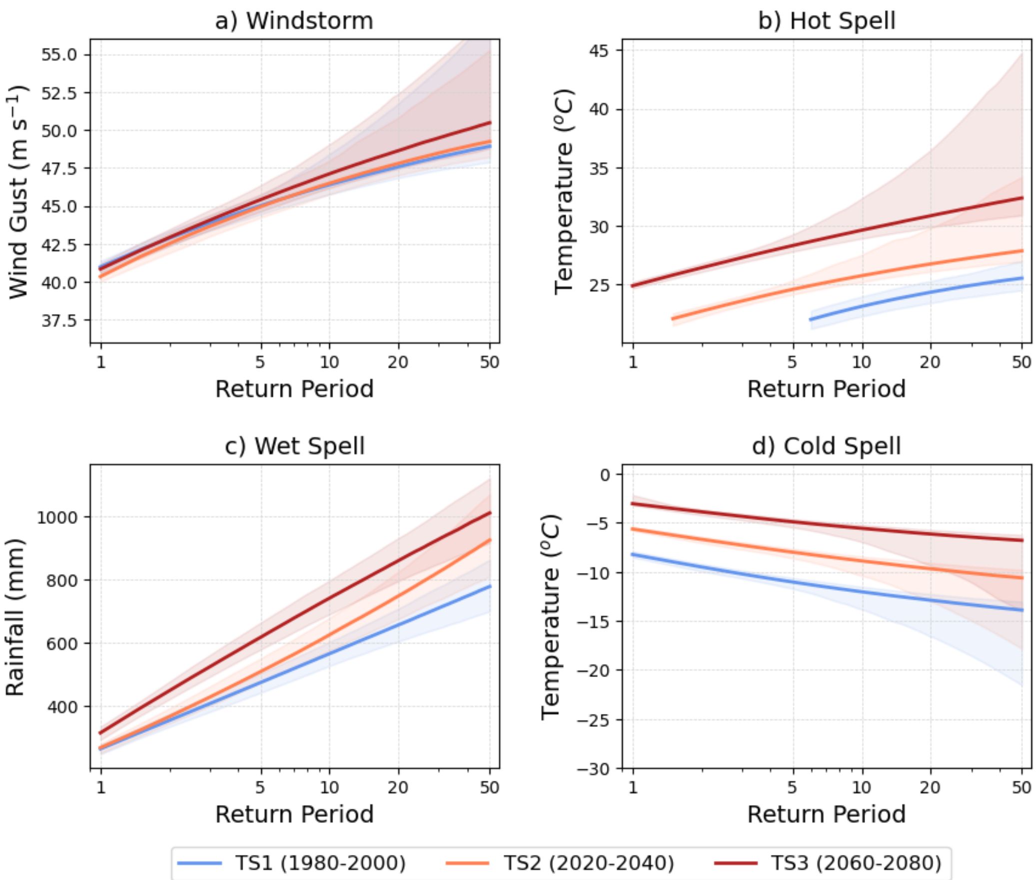

Figure 5: Scottish and Southern Electricity (Northern Scotland) climate projections. Projected hazards 1-50 year return periods for three time periods. a) the maximum wind gust in a windstorm, b) the maximum temperature in a hot spell, c) the accumulated rainfall in a wet spell, and d) the minimum temperature in a cold spell. Shaded regions represent the 95% uncertainty interval of the estimated return periods

Figure 5 depicts the projected return periods for each of the hazards in the Northern Wales region operated by SP Energy Networks. The projections can be summarised as follows:

- **Windstorms:** There is no discernible change in windstorms over this region at return periods less than 10 years. However, the maximum wind gust for more extreme windstorms is projected to increase in the 2060-2080 period, but not in the 2020-2040 period. For example, a 1 in 50 year event in the 1980-2020 period is projected to occur once every 20-30 years in the 2060-2080 period.
- **Hot spells:** Hot spells will be warmer in the future. The maximum temperature in hot spells is projected to increase in both future periods relative to the control. This is seen at all return periods. An event that occurs every 20-years in the control is projected to occur every 5 years in the 2020-2040 period, and every year in the 2060-2080 period.
- **Wet spells:** Wet spells are projected to be wetter in both 2020-2040 and 2060-2080 periods compared to the control (1980-2000). The accumulated rainfall in wet spells that occur every 20-years in the control is projected to occur every 15 years in the 2020-2040 period and every 5 years in the 2060-2080 period.
- **Cold spells:** Cold spells are projected to become warmer and less severe in the future. The minimum temperature in cold spells is projected to increase at all return periods, whereby an event that occurs 10 years in the control is projected to occur once every 50 years in the 2020-2040 period and become even more infrequent by the 2060-2080 period.

6.3 Scottish and Southern Electricity (Southern England)

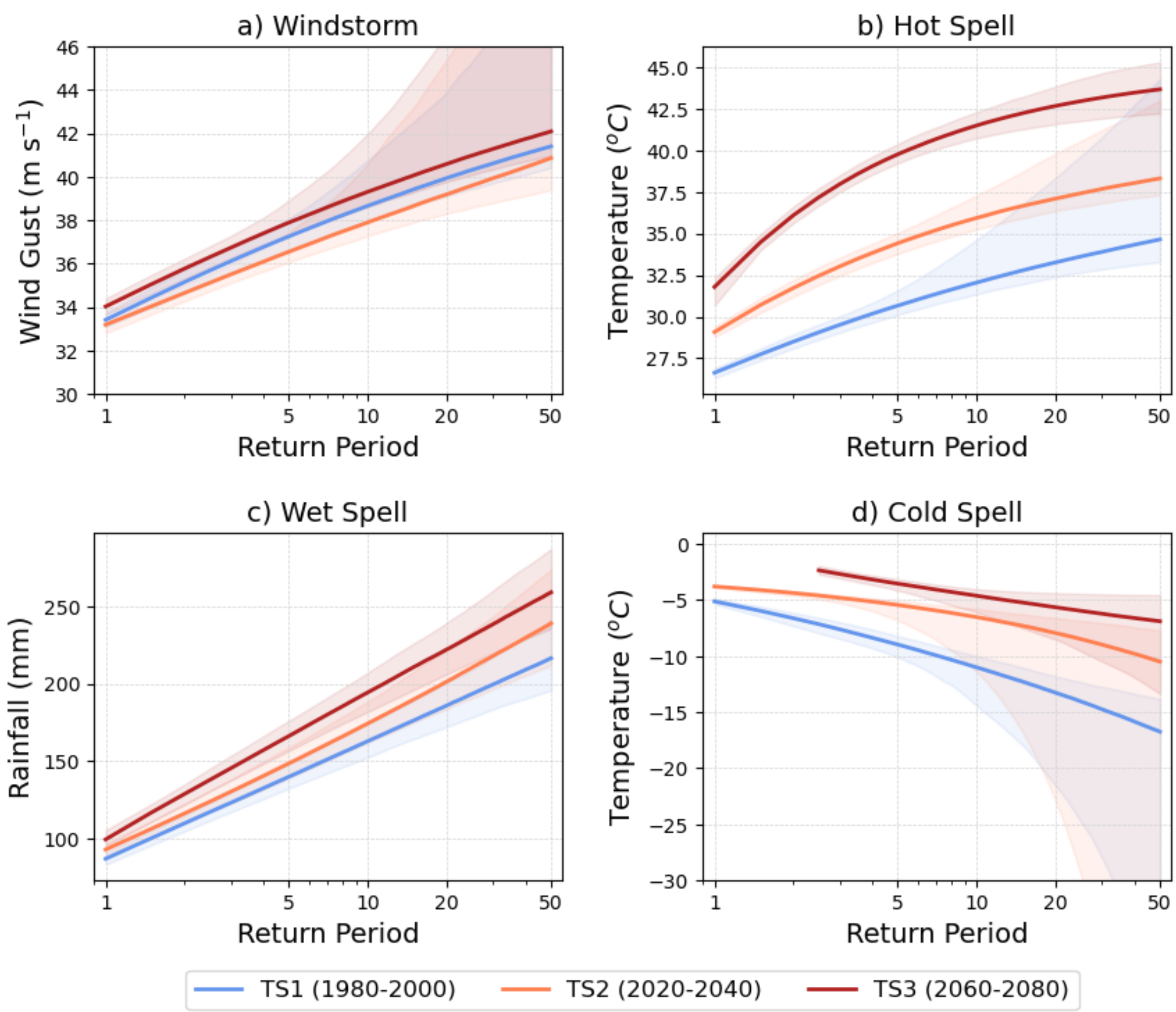

Figure 6: Scottish and Southern Electricity (Southern England) climate projections. Projected hazards 1-50 year return periods for three time periods. a) the maximum wind gust in a windstorm, b) the maximum temperature in a hot spell, c) the accumulated rainfall in a wet spell, and d) the minimum temperature in a cold spell. Shaded regions represent the 95% uncertainty interval of the estimated return periods.

Figure 6 depicts the projected return periods for each of the hazards in the Northern Wales region operated by SP Energy Networks. The projections can be summarised as follows:

- **Windstorms:** There is no discernible change in windstorms over this region. Although the maximum wind gust increases at all return periods in the 2060-2080 period compared to the 1980-2000 period, the near future period (2040-2060) sees a reduction in the maximum wind speed relative to the control period. This indicates the strong influence of natural variability in windstorms, though it is possible that a warmer climate contributes to the higher windstorm severities seen in the 2060-2080 period.

- **Hot spells:** Hot spells will be warmer in the future. The maximum temperature in hot spells is projected to increase in both future periods relative to the control. This is seen at all return periods. An event that occurs every 20-years in the control is projected to occur every 3-4 years in the 2020-2040 period, and every 1-2 in the 2060-2080 period.
- **Wet spells:** Wet spells are projected to be wetter in both 2020-2040 and 2060-2080 periods compared to the control (1980-2000). The accumulated rainfall in wet spells that occur every 20-years in the control is projected to occur every 15 years in the 2020-2040 period and every 6-7 years in the 2060-2080 period.
- **Cold spells:** Cold spells are projected to become warmer and less severe in the future. The minimum temperature in cold spells is projected to increase at all return periods, whereby an event that occurs 10 years in the control is projected to occur once every 50 years in the 2020-2040 period and become even more infrequent by the 2060-2080 period.

6.4 SP Energy Networks (Southern Scotland)

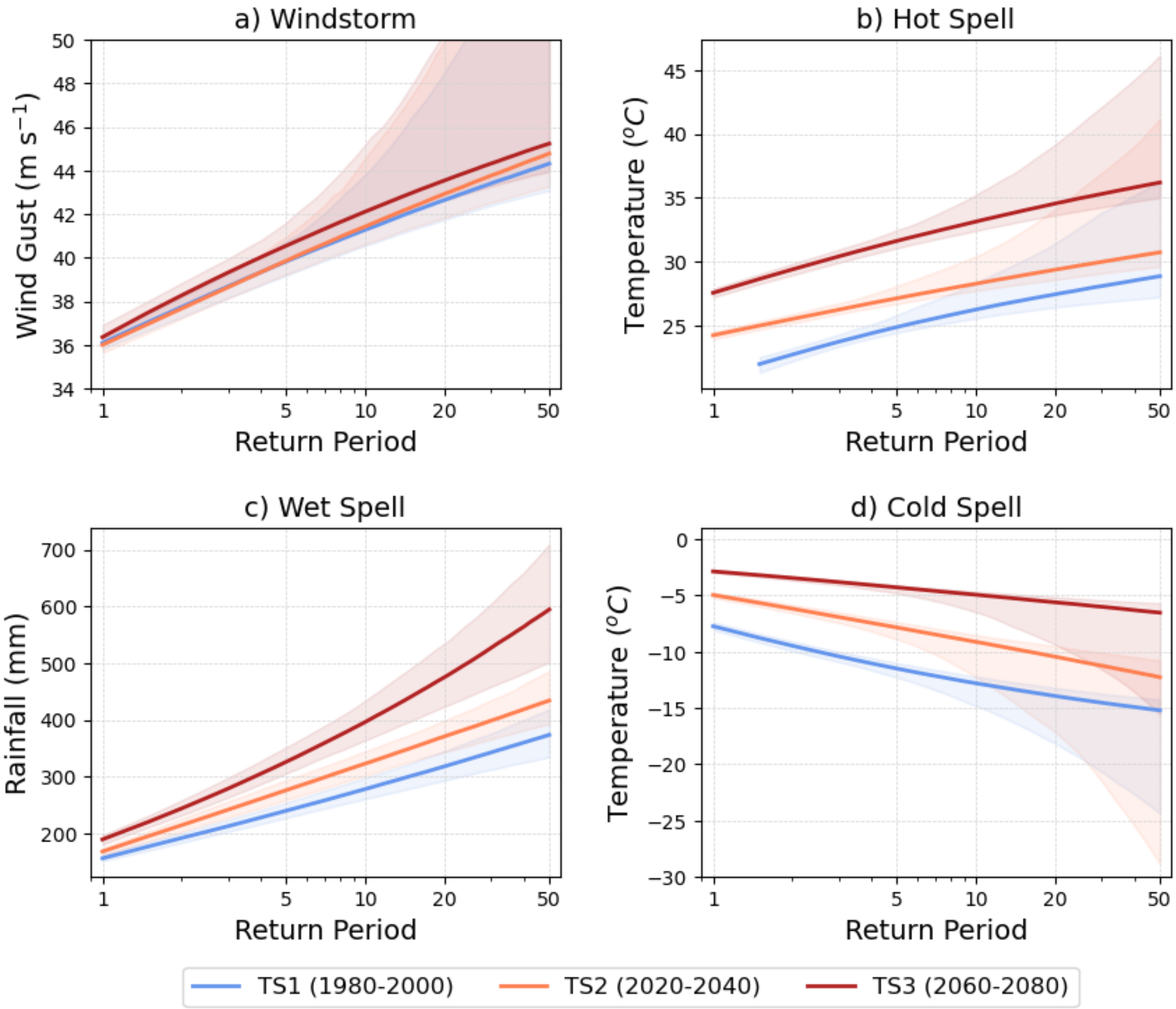

Figure 7: SP Energy Networks (Southern Scotland) climate projections. Projected hazards 1-50 year return periods for three time periods. a) the maximum wind gust in a windstorm, b) the maximum temperature in a hot spell, c) the accumulated rainfall in a wet spell, and d) the minimum temperature in a cold spell. Shaded regions represent the 95% uncertainty interval of the estimated return periods.

Figure 7 depicts the projected return periods for each of the hazards in the Southern Scotland region operated by SP Energy Networks. The projections can be summarised as follows:

- **Windstorms:** Windstorms are projected to have a minor increase in their intensity in the 2060-2080 period where the maximum wind gust in windstorms is projected to increase relative to the control period (1980-2000). For example, an event occurring every 10 years in the control is projected to occur every 6-7 years in the 2060-2080 period. Little change is found in 2020-2040 period compared to the control.

- **Hot spells:** Hot spells will be warmer in the future. The maximum temperature in hot spells is projected to increase in both future periods relative to the control. This is seen at all return periods. An event that occurs every 20-years in the control is projected to occur every 6-7 years in the 2020-2040 period, and every 1-2 years in the 2060-2080 period.
- **Wet spells:** Wet spells are projected to be wetter in both 2020-2040 and 2060-2080 periods compared to the control (1980-2000). The accumulated rainfall in wet spells that occur every 20-years in the control is projected to occur every 10 years in the 2020-2040 period and every 5 years in the 2060-2080 period.
- **Cold spells:** Cold spells are projected to become warmer and less severe in the future. The minimum temperature in cold spells is projected to increase at all return periods, whereby an event that occurs 10 years in the control is projected to occur once every 50 years in the 2020-2040 period and become even more infrequent by the 2060-2080 period.

6.5 SP Energy Networks (Northern Wales)

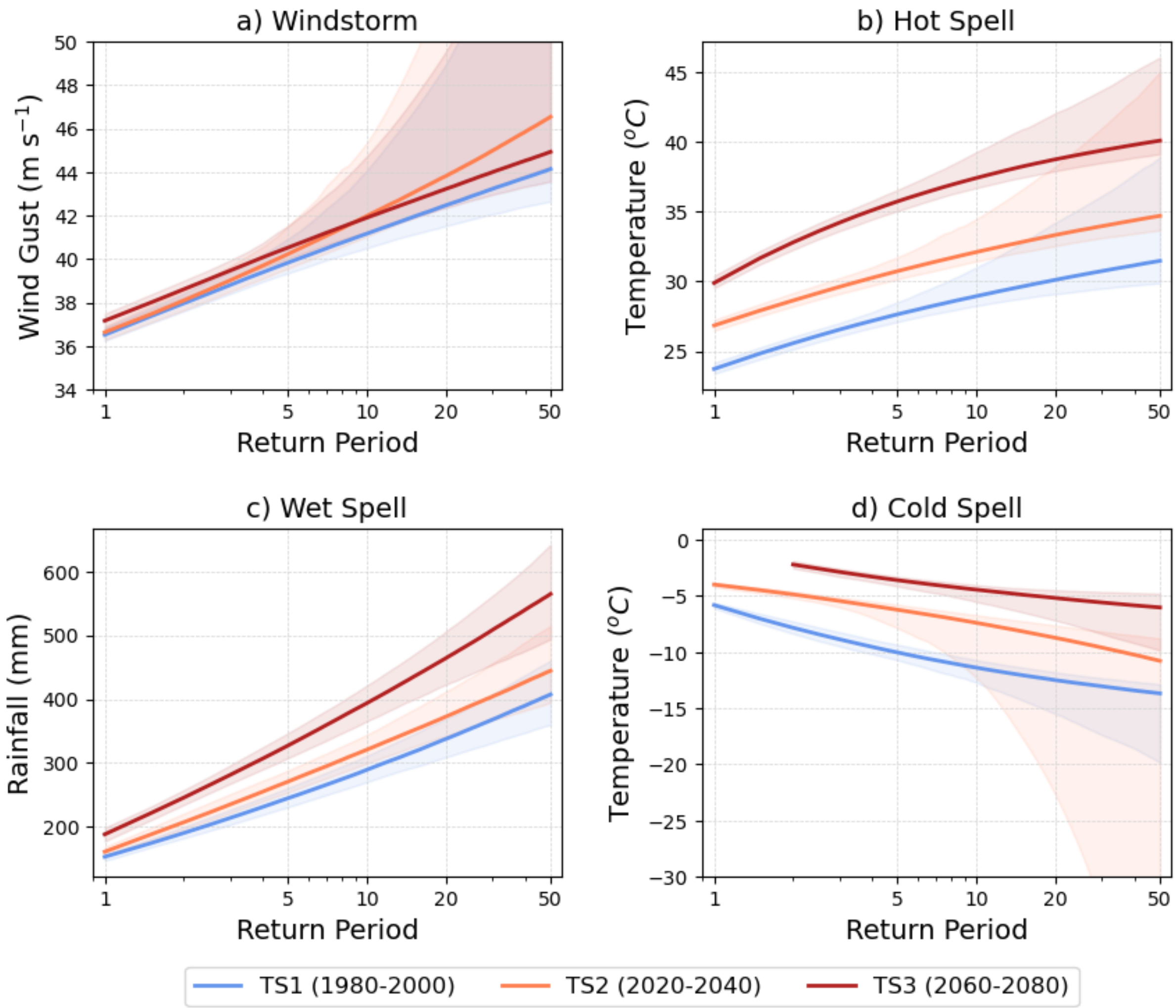

Figure 8: SP Energy Networks (Northern Wales) climate projections. Projected hazards 1-50 year return periods for three time periods. a) the maximum wind gust in a windstorm, b) the maximum temperature in a hot spell, c) the accumulated rainfall in a wet spell, and d) the minimum temperature in a cold spell. Shaded regions represent the 95% uncertainty interval of the estimated return periods.

Figure 8 depicts the projected return periods for each of the hazards in the Northern Wales region operated by SP Energy Networks. The projections can be summarised as follows:

- **Windstorms:** Windstorms are projected to have a minor increase in their intensity in the 2060-2080 period where the maximum wind gust in windstorms is projected to increase relative to the control period (1980-2000). For example, an event occurring every 10 years in the control is projected to occur every 6-7 years in the 2060-2080 period. Similar changes are found in the 2020-2040 period for a 10-year event though even higher changes are seen for a 50-year event which is projected to occur every 20 years in the 2020-2040 period though only every 30 years in the 2060-2080 period. This result indicates the strong influence of natural variability as well as the potential for very damaging windstorms in the near future.

- **Hot spells:** Hot spells will be warmer in the future. The maximum temperature in hot spells is projected to increase in both future periods relative to the control. This is seen at all return periods. An event that occurs every 20-years in the control is projected to occur every 4-5 years in the 2020-2040 period, and every year in the 2060-2080 period.
- **Wet spells:** Wet spells are projected to be wetter in both 2020-2040 and 2060-2080 periods compared to the control (1980-2000). The accumulated rainfall in wet spells that occur every 20-years in the control is projected to occur every 15 years in the 2020-2040 period and every 5 years in the 2060-2080 period.
- **Cold spells:** Cold spells are projected to become warmer and less severe in the future. The minimum temperature in cold spells is projected to increase at all return periods, whereby an event that occurs 10 years in the control is projected to occur once every 50 years in the 2020-2040 period and become even more infrequent by the 2060-2080 period.

6.6 Electricity North West (Northwest England)

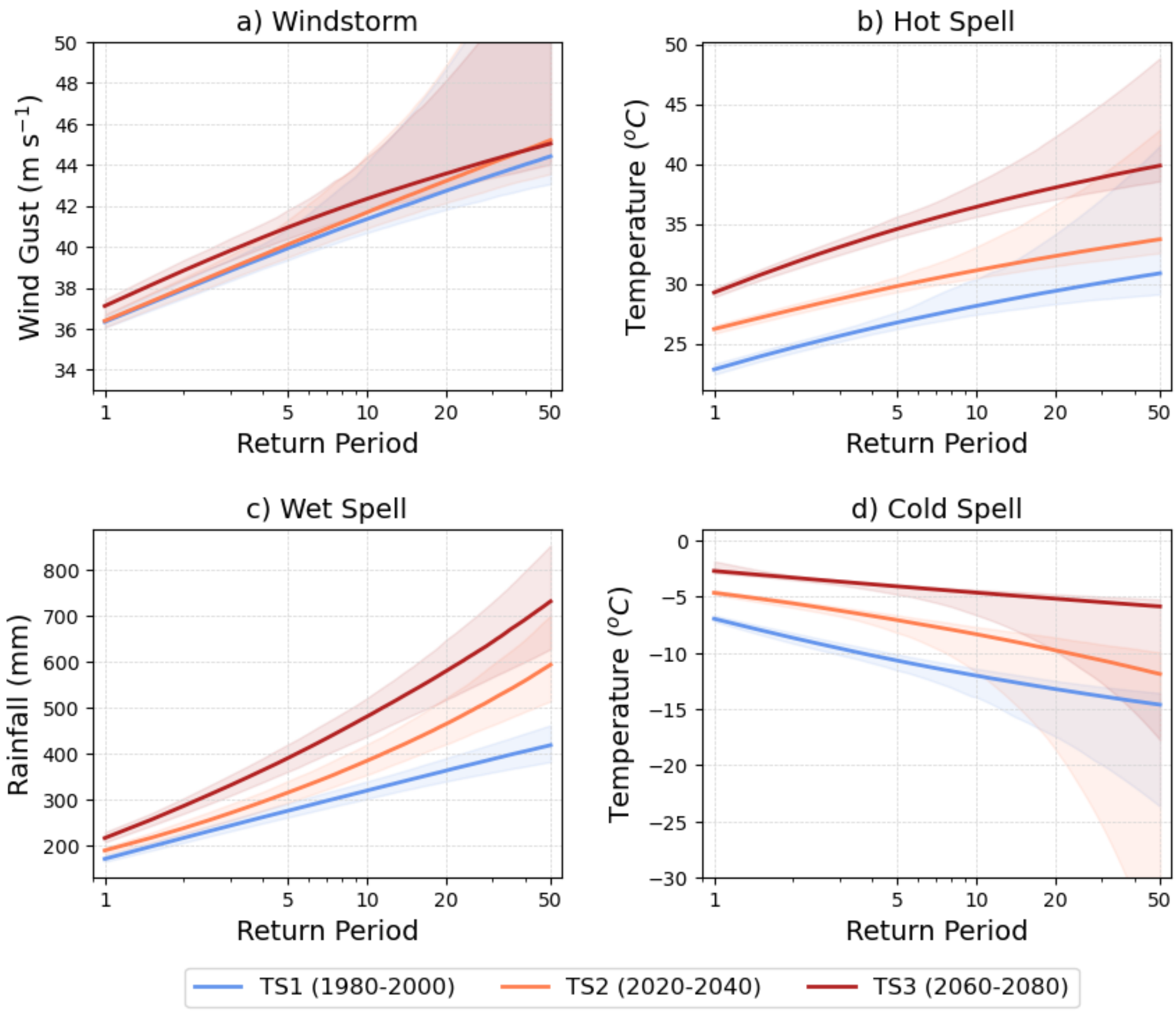

Figure 9: Electricity North West climate projections. Projected hazards 1-50 year return periods for three time periods.. a) the maximum wind gust in a windstorm, b) the maximum temperature in a hot spell, c) the accumulated rainfall in a wet spell, and d) the minimum temperature in a cold spell. Shaded regions represent the 95% uncertainty interval of the estimated return periods.

Figure 9 depicts the projected return periods for each of the hazards in the region operated by Electricity North West. The projections can be summarised as follows:

- **Windstorms:** Windstorms are projected to be more intense in the 2060-2080 period where the maximum wind gust in windstorms is projected to increase relative to the control period (1980-2000). For example, an event occurring every 10 years in the control is projected to occur every 6-7 years in the 2060-2080 period. Little change is found in 2020-2040 period except at very high return periods where a 50-year event is projected to occur every 20-30 years in both future periods.

- **Hot spells:** Hot spells will be warmer in the future. The maximum temperature in hot spells is projected to increase in both future periods relative to the control. This is seen at all return periods. An event that occurs every 20-years in the control is projected to occur every 5 years in the 2020-2040 period, and every 1-2 years in the 2060-2080 period.
- **Wet spells:** Wet spells are projected to be wetter in the future. The accumulated rainfall in wet spells is projected to increase in at all return periods in both future periods relative to the control. An event that occurs every 20-years in the control is projected to occur every 8 years in the 2020-2040 period, and every 4 years in the 2060-2080 period.
- **Cold spells:** Cold spells are projected to become warmer and less severe in the future. The minimum temperature in cold spells is projected increase at all return periods, whereby an event that occurs 10 years in the control is projected to occur once every 50 years in the 2020-2040 period and become even more infrequent by the 2060-2080 period.

6.7 Northern Powergrid (Northwest England)

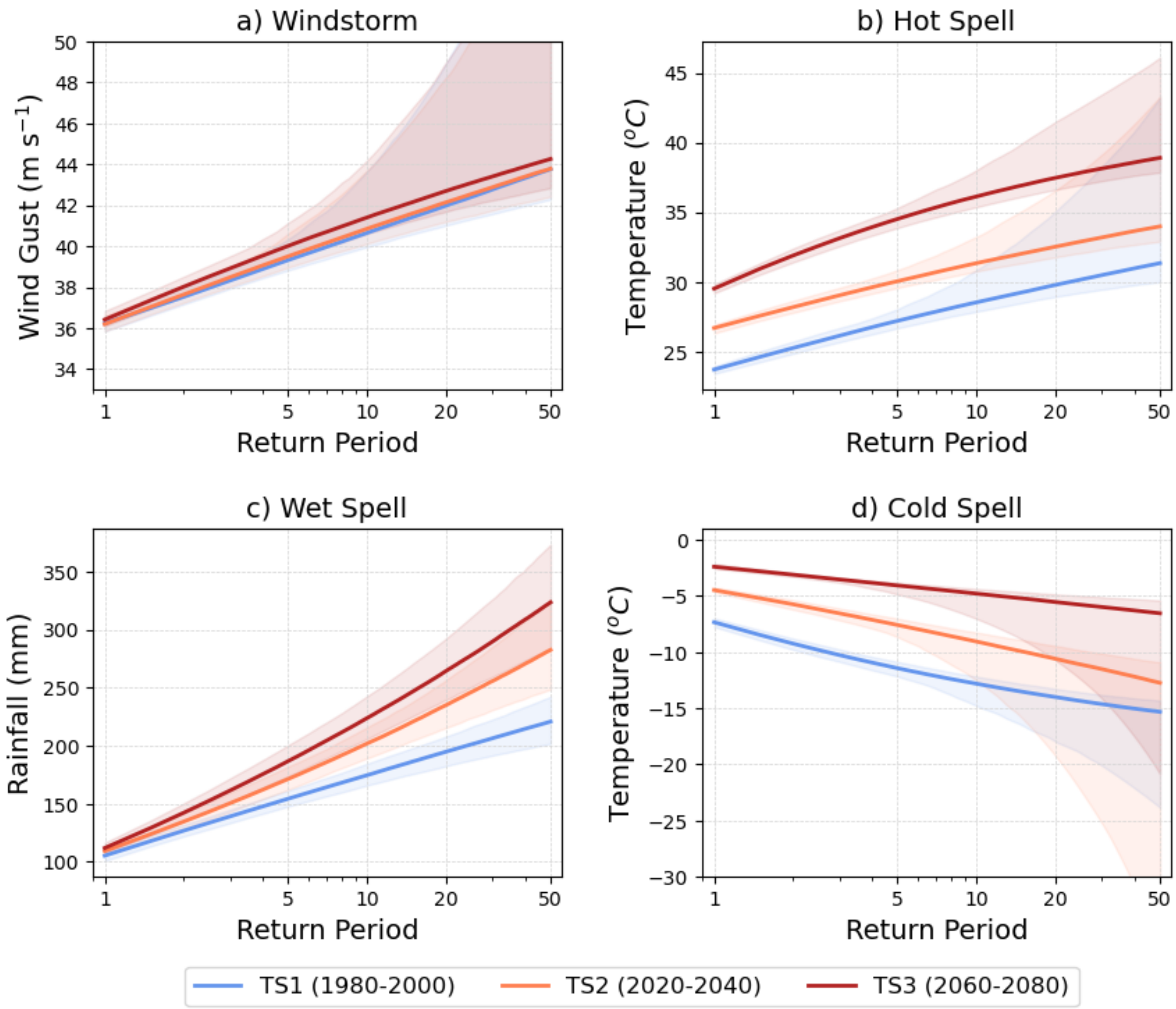

Figure 10: Northern Powergrid climate projections. Projected hazards 1-50 year return periods for three time periods. a) the maximum wind gust in a windstorm, b) the maximum temperature in a hot spell, c) the accumulated rainfall in a wet spell, and d) the minimum temperature in a cold spell. Shaded regions represent the 95% uncertainty interval of the estimated return periods.

Figure 10 depicts the projected return periods for each of the hazards in the region operated by Northern Powergrid. The projections can be summarised as follows:

- **Windstorms:** Windstorms are projected to have a minor increase in their intensity in the 2060-2080 period where the maximum wind gust in windstorms is projected to increase relative to the control period (1980-2000). For example, an event occurring every 10 years in the control is projected to occur every 8 years in the 2060-2080 period. Little change is found in 2020-2040 period compared to the control.

- **Hot spells:** Hot spells will be warmer in the future. The maximum temperature in hot spells is projected to increase in both future periods relative to the control. This is seen at all return periods. An event that occurs every 20-years in the control is projected to occur every 5 years in the 2020-2040 period, and every 1-2 years in the 2060-2080 period.
- **Wet spells:** Extremely wet spells are projected to be wetter in both future periods and become more frequent. The accumulated rainfall in wet spells is projected to increase at most return periods, though the largest increases are found the more extreme events. An event that occurs every 20-years in the control is projected to occur every 10 years in the 2020-2040 period, and every 6-7 years in the 2060-2080 period.
- **Cold spells:** Cold spells are projected to become warmer and less severe in the future. The minimum temperature in cold spells is projected increase at all return periods, whereby an event that occurs 10 years in the control is projected to occur once every 50 years in the 2020-2040 period and become even more infrequent by the 2060-2080 period.

6.8 National Grid (Southwest, South Wales, East and West Midlands)

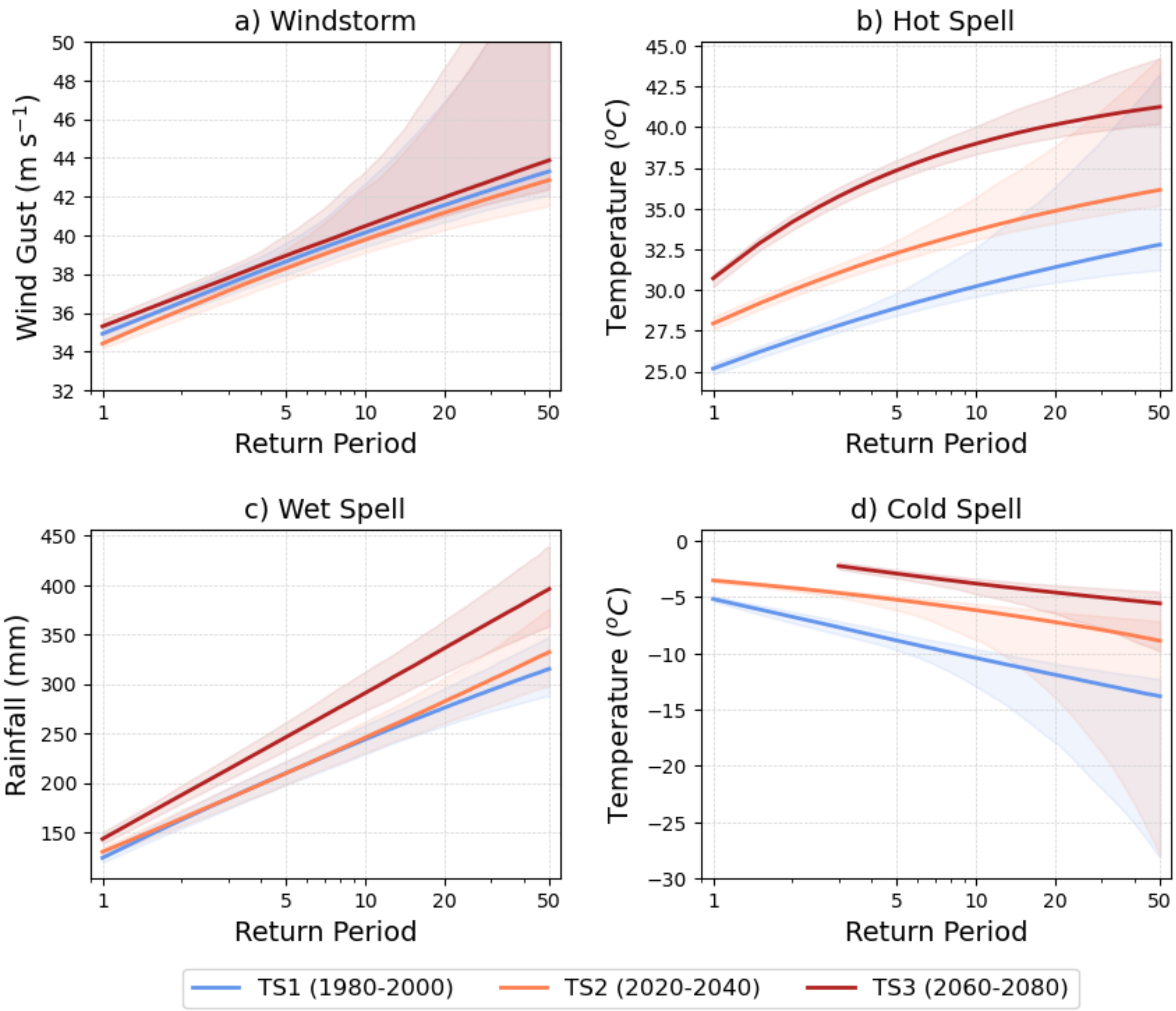

Figure 11: National Grid climate projections. Projected hazards 1-50 year return periods for three time periods. a) the maximum wind gust in a windstorm, b) the maximum temperature in a hot spell, c) the accumulated rainfall in a wet spell, and d) the minimum temperature in a cold spell. Shaded regions represent the 95% uncertainty interval of the estimated return periods.

Figure 11 depicts the projected return periods for each of the hazards in the region operated by National Grid. The projections can be summarised as follows:

- **Windstorms:** There is no discernible change in windstorms over this region. However, within the region, increases are found over the South West and South Wales which are averaged out when including them with the midlands. These results are not shown here.
- **Hot spells:** Hot spells will be warmer in the future. The maximum temperature in hot spells is projected to increase in both future periods relative to the control. This is seen at all return

periods. An event that occurs every 20-years in the control is projected to occur every 4-5 years in the 2020-2040 period, and every 1-2 years in the 2060-2080 period.

- **Wet spells:** Wet spells are projected to be wetter in the 2060-2080 period, but no change is found in the 2020-2040 period compared to the control (1980-2000). The accumulated rainfall in wet spells is projected to increase at all return periods in the 2060-2080 period and an event that occurs every 20-years in the control is projected to occur every 8 years in the 2060-2080 period.
- **Cold spells:** Cold spells are projected to become warmer and less severe in the future. The minimum temperature in cold spells is projected increase at all return periods, whereby an event that occurs 10 years in the control is projected to occur once every 50 years in the 2020-2040 period and become even more infrequent by the 2060-2080 period.

6.9 UK Power Networks (Southeast England)

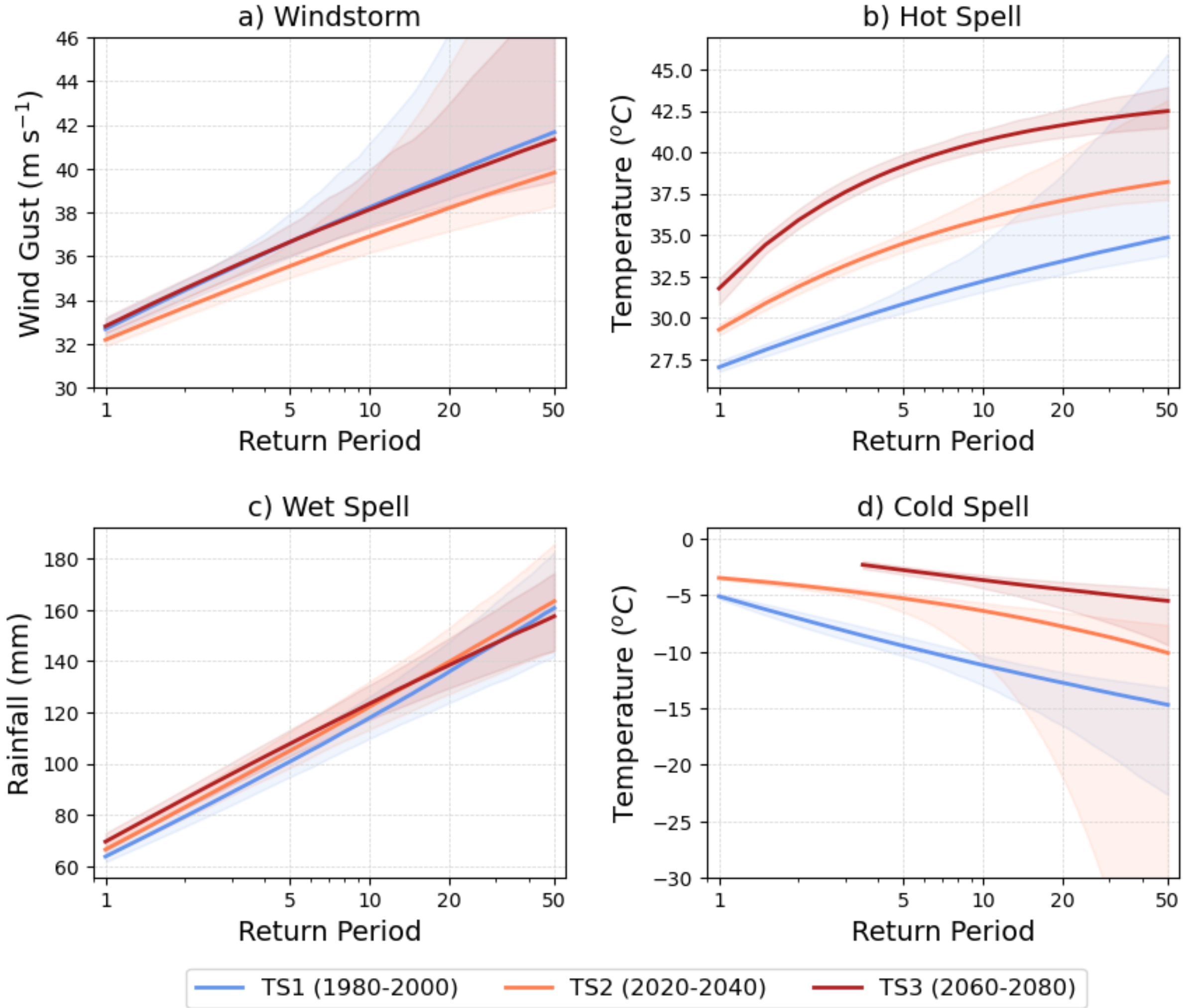

Figure 12: UK Power Networks climate projections. Projected hazards 1-50 year return periods for three time periods. a) the maximum wind gust in a windstorm, b) the maximum temperature in a hot spell, c) the accumulated rainfall in a wet spell, and d) the minimum temperature in a cold spell. Shaded regions represent the 95% uncertainty interval of the estimated return periods.

Figure 12 depicts the projected return periods for each of the hazards in the region operated by UK Power Networks. The projections can be summarised as follows:

- **Windstorms:** There is no discernible change in the maximum wind gusts in windstorms in this region. However, the maximum wind gust in windstorms is slightly reduced in the 2020-2040 period compared to the control indicating a strong natural variability in wind-related risk over the coming 60 years.

- **Hot spells:** Hot spells will be warmer in the future. The maximum temperature in hot spells is projected to increase in both future periods relative to the control. This is seen at all return periods. An event that occurs every 20-years in the control is projected to occur every 3 years in the 2020-2040 period, and every year in the 2060-2080 period.
- **Wet spells:** There is no large change in the accumulated rainfall during wet spells.
- **Cold spells:** Cold spells are projected to become warmer and less severe in the future. The minimum temperature in cold spells is projected increase at all return periods, whereby an event that occurs 10 years in the control is projected to occur once every 50 years in the 2020-2040 period and become even more infrequent by the 2060-2080 period.

7. Results: Hazard Projections for Gas DNOs

The projected changes for windstorms, hot spells, wet spells and cold spells are outlined for each gas distribution network operators separately below.

7.1 SGN (Scotland region)

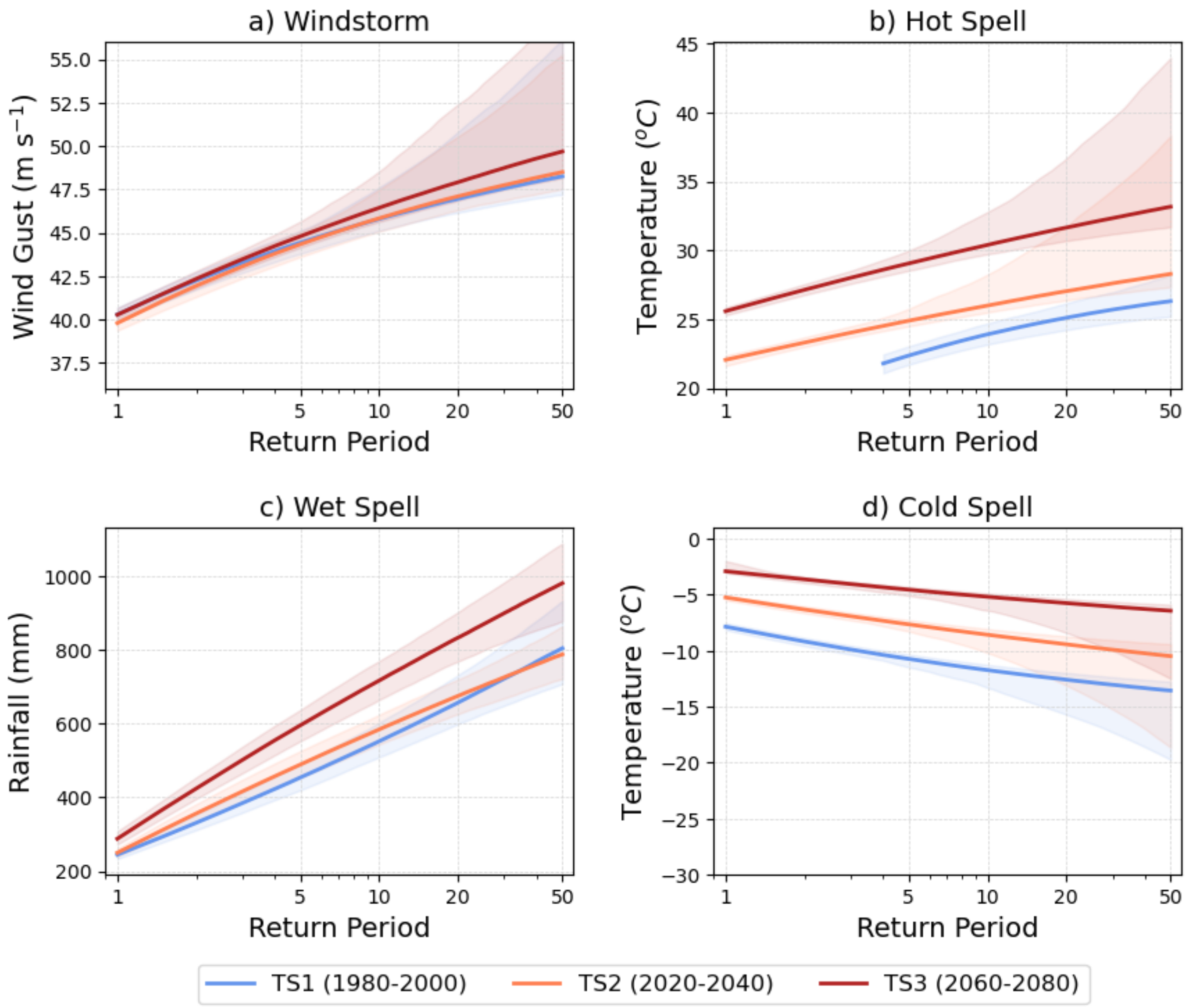

Figure 13: SGN (Scotland) climate projections. Projected hazards 1-50 year return periods for three time periods. a) the maximum wind gust in a windstorm, b) the maximum temperature in a hot spell, c) the accumulated rainfall in a wet spell, and d) the minimum temperature in a cold spell. Shaded regions represent the 95% uncertainty interval of the estimated return periods.

Figure 13 depicts the projected return periods for each of the hazards in the Scotland region operated by SGN. The projections can be summarised as follows:

- **Windstorms:** Windstorms with return periods below 10 years show no change in windstorms over this region. However, more extreme windstorms are projected to be more frequent in the future period (2060-2080). For instance, a 50-year event in the control period (1980-2000) is projected to occur every 20-30 years in the 2060-2080 period. No change is found in the 2020-2040 period.
- **Hot spells:** Hot spells will be warmer in the future. The maximum temperature in hot spells is projected to increase in both future periods relative to the control. This is seen at all return periods. An event that occurs every 20-years in the control is projected to occur every 5 years in the 2020-2040 period, and every year in the 2060-2080 period.
- **Wet spells:** Wet spells are projected to be wetter in 2060-2080 period compared to the control (1980-2000), though little change is found in the 2020-2040 period. The accumulated rainfall in wet spells that occur every 20-years in the control is projected to occur every 7-8 years in the 2060-2080 period.
- **Cold spells:** Cold spells are projected to become warmer and less severe in the future. The minimum temperature in cold spells is projected to increase at all return periods, whereby an event that occurs 10 years in the control is projected to occur once every 50 years in the 2020-2040 period and become even more infrequent by the 2060-2080 period.

7.2 SGN (Southeast England)

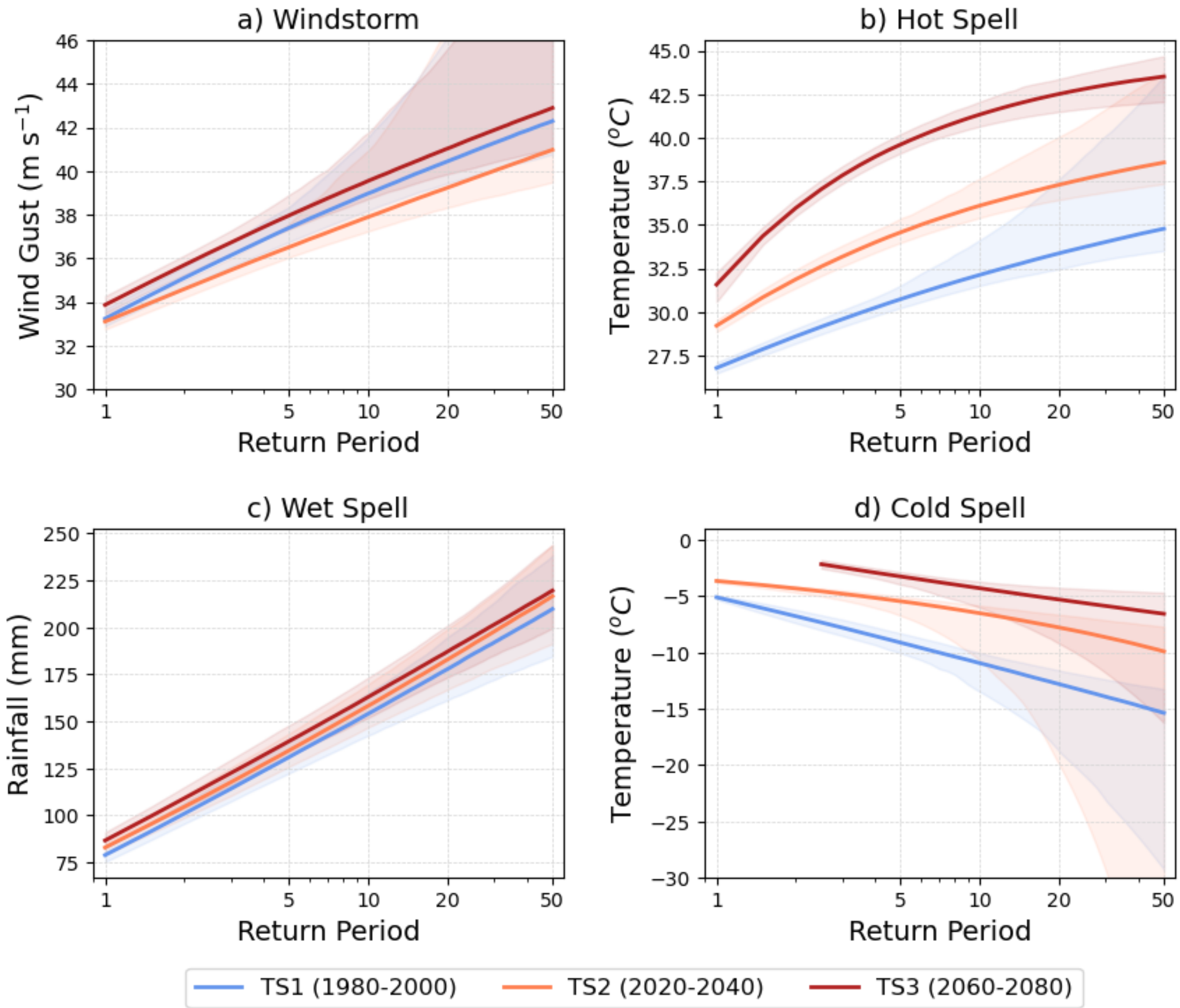

Figure 14: SGN (Southeast England) climate projections. Projected hazards 1-50 year return periods for three time periods. a) the maximum wind gust in a windstorm, b) the maximum temperature in a hot spell, c) the accumulated rainfall in a wet spell, and d) the minimum temperature in a cold spell. Shaded regions represent the 95% uncertainty interval of the estimated return periods.

Figure 14 depicts the projected return periods for each of the hazards in the Southeast England region operated by SGN. The projections can be summarised as follows:

- **Windstorms:** There is no discernible change in windstorms over this region. Although the maximum wind gust increases at all return periods in the 2060-2080 period compared to the 1980-2000 period, the near future period (2040-2060) sees a reduction in the maximum wind speed relative to the control period. This indicates the strong influence of natural variability in windstorms, though it is possible that a warmer climate contributes to the higher windstorm severities seen in the 2060-2080 period.

- **Hot spells:** Hot spells will be warmer in the future. The maximum temperature in hot spells is projected to increase in both future periods relative to the control. This is seen at all return periods. An event that occurs every 20-years in the control is projected to occur every 3-4 years in the 2020-2040 period, and every 1-2 in the 2060-2080 period.
- **Wet spells:** Little change is found for wet spells.
- **Cold spells:** Cold spells are projected to become warmer and less severe in the future. The minimum temperature in cold spells is projected to increase at all return periods, whereby an event that occurs 10 years in the control is projected to occur once every 50 years in the 2020-2040 period and become even more infrequent by the 2060-2080 period.

7.3 Wales and West Utilities (Wales and South West England)

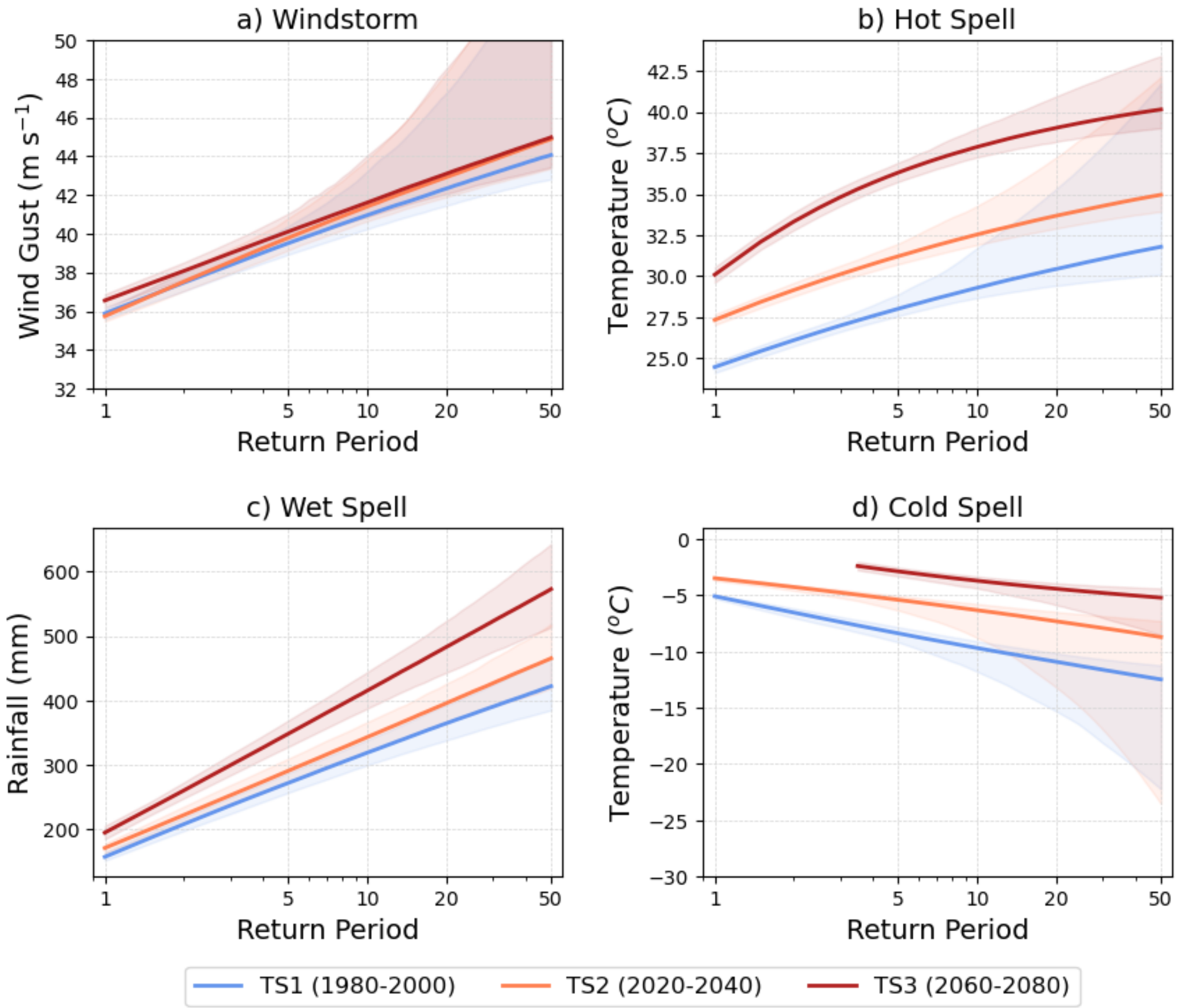

Figure 15: Wales and West Utilities climate projections. Projected hazards 1-50 year return periods for three time periods. a) the maximum wind gust in a windstorm, b) the maximum temperature in a hot spell, c) the accumulated rainfall in a wet spell, and d) the minimum temperature in a cold spell. Shaded regions represent the 95% uncertainty interval of the estimated return periods.

Figure 15 depicts the projected return periods for each of the hazards in region operated by Wales and West Utilities. The projections can be summarised as follows:

- **Windstorms:** The maximum wind gust within windstorms is projected to increase in both future periods. The largest increases are seen for the more extreme events. For instance, a 50-year event in the control period is projected to occur every 30 years in both the 2020-2040 and 2060-2080 periods. More modest increases are found for events of lower return periods.

- **Hot spells:** Hot spells will be warmer in the future. The maximum temperature in hot spells is projected to increase in both future periods relative to the control. This is seen at all return periods. An event that occurs every 20-years in the control is projected to occur every 3-4 years in the 2020-2040 period, and every 1-2 in the 2060-2080 period.
- **Wet spells:** Wet spells are projected to be wetter in both the 2020-2040 and 2060-2080 periods compared to the control (1980-2000. The accumulated rainfall in wet spells that occur every 20-years in the control is projected to occur every 15 years in the 2020-2040 period and every 6-7 years in the 2060-2080 period.
- **Cold spells:** Cold spells are projected to become warmer and less severe in the future. The minimum temperature in cold spells is projected to increase at all return periods, whereby an event that occurs 10 years in the control is projected to occur once every 50 years in the 2020-2040 period and become even more infrequent by the 2060-2080 period.

7.4 Northern Gas Networks (North and Northeast England)

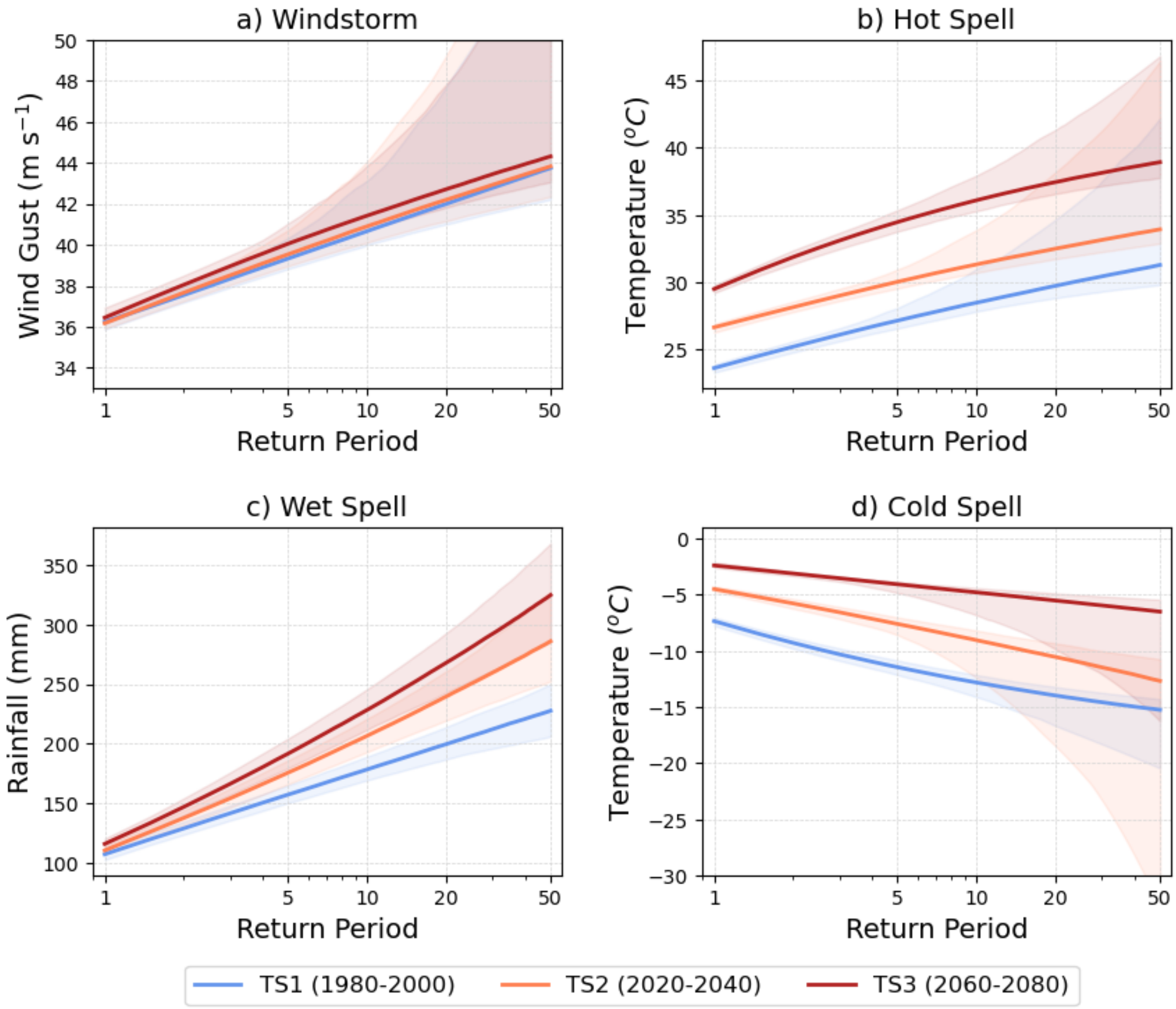

Figure 16: Northern Gas Networks climate projections. Projected hazards 1-50 year return periods for three time periods. a) the maximum wind gust in a windstorm, b) the maximum temperature in a hot spell, c) the accumulated rainfall in a wet spell, and d) the minimum temperature in a cold spell. Shaded regions represent the 95% uncertainty interval of the estimated return periods.

Figure 16 depicts the projected return periods for each of the hazards in the region operated by Northern Gas Networks. The projections can be summarised as follows:

- **Windstorms:** Windstorms are projected to have a minor increase in their intensity in the 2060-2080 period where the maximum wind gust in windstorms is projected to increase relative to the control period (1980-2000). For example, an event occurring every 10 years in the control is projected to occur every 8 years in the 2060-2080 period. Little change is found in 2020-2040 period compared to the control.

- **Hot spells:** Hot spells will be warmer in the future. The maximum temperature in hot spells is projected to increase in both future periods relative to the control. This is seen at all return periods. An event that occurs every 20-years in the control is projected to occur every 5 years in the 2020-2040 period, and every 1-2 years in the 2060-2080 period.
- **Wet spells:** Extremely wet spells are projected to be wetter in both future periods and become more frequent. The accumulated rainfall in wet spells is projected to increase at most return periods, though the largest increases are found the more extreme events. An event that occurs every 20-years in the control is projected to occur every 8 years in the 2020-2040 period, and every 6 years in the 2060-2080 period.
- **Cold spells:** Cold spells are projected to become warmer and less severe in the future. The minimum temperature in cold spells is projected increase at all return periods, whereby an event that occurs 10 years in the control is projected to occur once every 50 years in the 2020-2040 period and become even more infrequent by the 2060-2080 period.

7.5 Cadent Gas (Northwest England, Midlands, Eastern England, London)

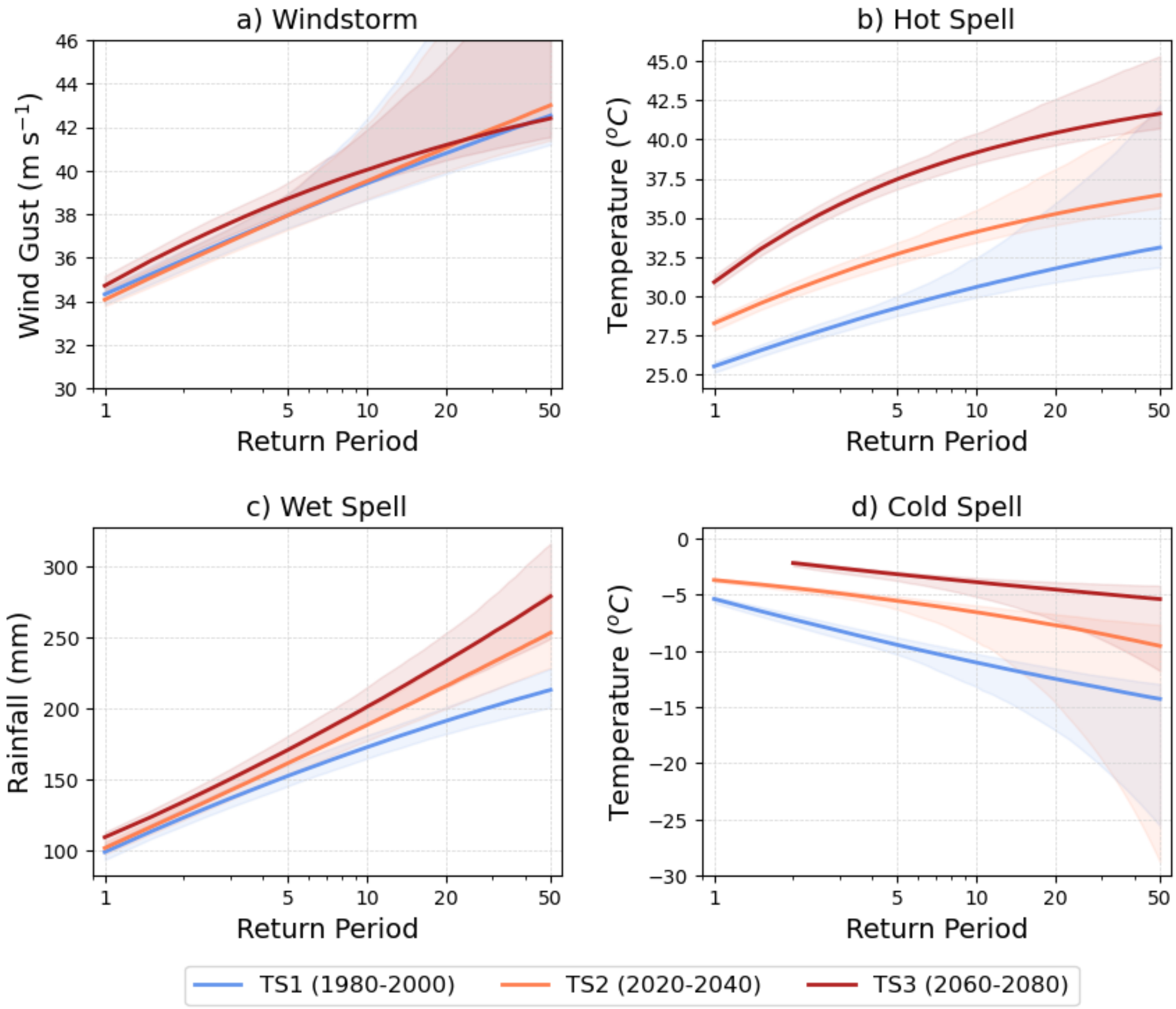

Figure 17: Cadent gas climate projections. Projected hazards 1-50 year return periods for three time periods. a) the maximum wind gust in a windstorm, b) the maximum temperature in a hot spell, c) the accumulated rainfall in a wet spell, and d) the minimum temperature in a cold spell. Shaded regions represent the 95% uncertainty interval of the estimated return periods.

Figure 17 depicts the projected return periods for each of the hazards in the region operated by Cadent Gas. The projections can be summarised as follows:

- **Windstorms:** Windstorms are projected to have a minor increase in their intensity in the 2060-2080 period where the maximum wind gust in windstorms is projected to increase relative to the control period (1980-2000). For example, an event occurring every 10 years in the control is projected to occur every 8 years in the 2060-2080 period. Little change is found in 2020-2040 period compared to the control.

- **Hot spells:** Hot spells will be warmer in the future. The maximum temperature in hot spells is projected to increase in both future periods relative to the control. This is seen at all return periods. An event that occurs every 20-years in the control is projected to occur every 5 years in the 2020-2040 period, and every 1-2 years in the 2060-2080 period.
- **Wet spells:** Extremely wet spells are projected to be wetter in both future periods and become more frequent. The accumulated rainfall in wet spells is projected to increase at most return periods, though the largest increases are found the more extreme events. An event that occurs every 20-years in the control is projected to occur every 10 years in the 2020-2040 period, and every 6-7 years in the 2060-2080 period.
- **Cold spells:** Cold spells are projected to become warmer and less severe in the future. The minimum temperature in cold spells is projected increase at all return periods, whereby an event that occurs 10 years in the control is projected to occur once every 50 years in the 2020-2040 period and become even more infrequent by the 2060-2080 period.

8. Conclusions

In this report, we have presented projections for four hazards: windstorms, hot spells, cold spells and wet spells. These projections have been assessed over regions operated by 7 electricity DNOs and 4 gas DNOs. The projections are derived from a set of very high-resolution climate simulations that offer the most realistic representation of weather extremes such as rainfall and wind gusts. The climate projections assessed here follow the RCP8.5 scenario which is a high-emissions scenario in which we assume global greenhouse gas emissions continue to increase towards the end of the 21st century and no mitigation measures are used to reduce them.

The results can be summarised as follows:

- Extreme windstorms are likely to increase in frequency and intensity over the UK as a whole. Within individual regions operated by DNOs, the projections are less certain, partly due to random variability regarding exactly where is worst affected by individual storms; however, we expect regions in the north and west of the UK will be worst affected by changes in windstorms, particularly exposed coastal regions.
- Extremely hot temperatures are very likely to increase in their intensity and frequency in the future in all regions of the UK (we have high confidence in this as it is consistent with historical

trends). As a result, projections indicate that all regions will experience high temperatures more frequently in the future, with a 1 in 20 year events occurring, on average, every 3 to 5 years for the TS2 (2021-2040) time slice and occurring on average every 1 to 2 years for the TS3 (2061-2080) time slice.

- Extremely cold temperatures are likely to decrease in their intensity and frequency in the future, following historical trends. As a result, all regions are likely to experience cold temperature less frequently in the future.
- Wet spells with large rainfall accumulations are very likely to increase in intensity and frequency in the future. We also expect wetter winters and more short duration (1-hour) intense rainfall events, although we have not shown this specifically in this report. However, we note that the magnitude of increase varies across different regions, likely linked to variations in the tracks of cyclones and their frequency.

The climate projections assessed here include a control (1981-2000), near future (2021-2040) and far future (2061-2080) period. Projections for the time periods in between (2001-2020, 2041-2060) are now also available meaning that there are 100-year long simulations available. However, their inclusion was not within the scope of this work as they were not available at the beginning of the project. Inferences about projections within the 2041-2060 period are difficult as the rate of global warming, and changes in hazards, depends on multiple variables. However, we can at least say with some confidence that the risk of windstorms will be largely influenced by natural variations of our climate and so their risk will not decrease. In contrast, it is likely that the risk due to high temperatures and rainfall extremes will increase.

In terms of what these results mean for DNOs; faults related to extreme winds, high temperatures and rainfall will likely increase across the UK. However, there is more uncertainty for windstorms in terms of where the risk of impacts will increase. Conversely, faults occurring due to cold weather will likely decrease as our climate warms.

However, DNOs should note that this analysis only provides a simple overview of the changes in these event intensities, and that impacts within these events are uncertain as they are both nonlinear and are likely to have multiple contributing factors. For example, wind forces are proportional to the square of the wind speed, so a doubling of wind speed increases the wind force 4-fold (although the relationship between this and damage is more complex). Similarly, trees falling on overhead lines during windstorms are more easily uprooted in wet soils and may be less resistant to winds that come from non-prevailing direction. As soils will likely become wetter in future winters due to increased rainfall, wind-related risk to infrastructure may increase even without any change in wind intensity. Similarly, intense hot spells can put a strain on electricity distribution networks by decreasing the capacity of transmission through overhead lines, if more people use air conditioning in the future, demand may be increased to levels that cannot be met resulting in power outages or service reductions. DNOs are best placed to understand the potential consequences of these projected changes, while quantifying the contribution of such additional factors will help improve predictions and provide information to assessments of future risk such as that done here, in terms of the variables that should be assessed (e.g. wind speed, direction, soil moisture).

Furthermore, we note that this report does not assess all hazards that are relevant to DNOs such as drought, flash flooding arising from short-duration rainfall extremes or coastal flooding that may be influenced by sea level rise and the changing frequency of storms. However, there are published research on projected changes in such hazards that DNOs may wish to draw information from[10,11,12,13].

Finally, climate projections depend on the greenhouse gas emissions scenario used. Thus, what happens in reality will also depend on how society responds globally and by how much we reduce greenhouse gas emissions. The higher the emissions in a scenario, the larger the increase in variables such as temperature, rainfall and wind extremes. The projections assessed here follow the RCP8.5 scenario which assumes no mitigation or reduction in greenhouse gas emissions. A more optimistic scenario in which emissions are reduced compared to RCP8.5 would produce smaller projected increases in these hazards. Projections for alternative emissions scenarios are not available for UKCP18 due to the high computational costs of running high-resolution simulations. However, there are alternative methods of conveying future climate risk without using different emissions scenarios. For example, using coarser resolution climate models for generating future projections under different emissions scenarios, the latest report from the Intergovernmental Panel on Climate Change[14] assess the likelihood of a certain degree of global warming occurring (e.g. 2°C warmer than preindustrial conditions) and quantify projected changes in hazards at different levels of global warming (e.g. how do heat waves change in a period that is 2°C warmer than preindustrial conditions?). Using the updated 100-year high-resolution climate simulations,

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[10] https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/ukcp18_local_update_report_2021.pdf
[11] https://www.sciencedirect.com/science/article/pii/S2212096320300553#f0030
[12] https://www.sciencedirect.com/science/article/pii/S2405880723000365
[13] https://www.science.org/doi/10.1126/sciadv.aaw5531
[14] https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_SPM.pdf

that are now available for UKCP18, one could also quantify the change in risk per degree of warming and incorporate IPCC information to gauge the likelihood of that level of warming.

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