Review of the Climate Resilience of the Net Zero Innovation Portfolio

Deliverable G9.5: Final Report

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Key findings

This assessment gives a high-level understanding of the vulnerability/resilience of the ten technologies included in the Net Zero Innovation Portfolio (NZIP1/NZIP2) to ensure they are developed and then deployed in a way that reduces their climate vulnerability and enables the resilient delivery of the UK's net zero goals in the future. The technologies assessed include future offshore wind; power networks; hydrogen; advanced carbon capture usage and storage; energy storage and flexibility; bioenergy; direct air capture and greenhouse gas removal; building physics related technologies; ocean energy; and solar energy.

1. **Vulnerability/resilience ratings:**

On a scale from 1 = highly resilient; 2 = resilient; 3 = potentially vulnerable; 4 = vulnerable; 5 = highly vulnerable, no technology was found to be "highly vulnerable". A technology would be "highly vulnerable" if it was very or extremely climate sensitive and had major challenges to adjust/respond within existing climate limits.

- Many technologies were found to be at least "potentially vulnerable" or "vulnerable" to more than one of the climate-related hazards included in the assessment. This mainly results from medium adaptive capacity where technologies are able to adjust/respond within existing climate limits but might face major challenges beyond them.
- Flooding and storminess were identified as the two climate-related hazards to which most technologies were found to be "vulnerable". This vulnerability primarily stems from the sensitivity to infrastructure damage and a lack of adaptive capacity.

2. **Adaptation options:**

Several adaptation options were identified for each technology. Common adaptation themes were found to be regular technology maintenance, investments in infrastructure improvements and innovation, and efficiency improvements to use fewer resources.

3. **Evidence gaps and further research needs:**

The research has shown that there is overall limited evidence available regarding the vulnerability/resilience of all technologies to specific climate-related hazards.

- There is current research focused on floods and droughts (i.e. water availability and heatwaves) with relatively little evidence available for the other climate-related hazards.
- Evidence gaps remain for technologies to adapt to specific hazards, especially wind strength and wind regimes, storminess and occurrence of storm events and erosion.
- An assessment of the cascading effects between technologies in relation to different hazards and the cascading risks on individual sectors would help to understand the interlinkages of vulnerabilities/resilience between the net zero technologies assessed.

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 uses the latest scientific knowledge to inform UK climate policy and help us meet our global decarbonisation and resilience ambitions.

CS-N0W enhances the scientific understanding of climate impacts, decarbonisation, and climate action, and improves accessibility to the UK's climate data. It contributes to evidence-based climate policy in the UK and internationally, and strengthens 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)**.

Contents

Acronyms

Acronym	Definition
AC	Alternating Current
AI	Artificial Intelligence
BECCS	Bioenergy with Carbon Capture and Storage
BESS	Battery Energy Storage Systems
CCC	Climate Change Committee
CCUS	Carbon Capture, Usage and Storage
CO_2	Carbon Dioxide
CS-N0W	Climate Services for a Net Zero Resilient World
DAC	Direct Air Capture
DACCU	Direct Air Carbon Capture and Utilisation
DACCS	Direct Air Carbon Capture and Storage
DESNZ	Department for Energy Security and Net Zero

Acronym	Definition
EWR	Enhanced Water Recovery
GGR	Greenhouse Gas Removal
GSHP	Ground-Source Heat Pumps
ICT	Information and Communication Technology
IPCC	Intergovernmental Panel on Climate Change
IP rating	Ingress Protection rating
NZIP	Net Zero Innovation Portfolio
O&M	Operations and Maintenance
PCM	Phase Change Material
REA	Rapid Evidence Assessment
R&I	Research and Innovation
UK CCRA3	UK Climate Change Risk Assessment 3
WDR	Wind-Driven Rain

1. Executive summary

The aim of this work package (WPG09) was to identify vulnerabilities and areas of resilience of the specific technologies included in the Net Zero Innovation Portfolio to ensure they are developed and then deployed in a way that reduces their climate vulnerability and enables the resilient delivery of the UK's net zero goals in the future. The ten NZIP1/2 technologies: (i) Future offshore wind, (ii) Power networks, (iii) Hydrogen, (iv) Advanced carbon capture, usage and storage (CCUS), (v) Energy storage and flexibility, (vi) Bioenergy, (vii) Direct air capture (DAC) and greenhouse gas removal (GGR), (viii) Building physics related technologies such as low carbon heating/cooling for hard-to-treat buildings such as historic buildings, heat/cooling networks, heat pumps, energy efficiency measures, battery energy storage systems, energy demand management measures and building control measures, (ix) Ocean energy, and (x) Solar energy, were assessed against the following climate hazards: (a) heatwaves, (b) flooding, (c) drought, (d) wind strengths and wind regimes, (e) storminess and occurrence of storm events, (f) snow and ice, and (g) erosion.

An understanding of the vulnerability of these technologies to the climate hazards was developed as follows:

1. A systematic Rapid Evidence Assessment (REA) was carried out to identify and extract relevant evidence regarding UK climate-related hazards with regards to the ten technologies from peer-reviewed and grey literature reports (see **Annex 2**). As a 'Rapid' Evidence Assessment, the results are non-exhaustive. Instead, this step collates a summary of first-order vulnerabilities and adaptation solutions.
2. Based on the evidence assembled by the REA, a series of expert interviews and reviews were carried out to fill any gaps. Each technology was given a rating for sensitivity (low rating = insensitive to climate hazards; high rating = extremely sensitive to climate hazards); and adaptive capacity (low rating = major challenges to adjust or respond to hazards within existing or anticipated climate limits; high rating = able to adjust or respond to these current or future hazards). The combination of ratings for sensitivity and adaptive capacity gave a rating of vulnerability for each technology (1 = highly resilient; 2 = resilient; 3 = potentially vulnerable; 4 = vulnerable; 5 = highly vulnerable). The research team applied a three-tiered confidence scale to these ratings, based on the strength of evidence and level of agreement (low, medium and high confidence). As part of the assessment, adaptation options were also identified. For detailed definitions, see methods in **Annex A.1.4.**
3. Case studies were developed for four technologies: Power Networks, CCUS, Hydrogen and Buildings. These were selected based on the potential impact on the UK's net zero trajectory if a technology proves non-resilient, and the resilience of the technology itself (see **Annex 4**).

4. Evaluation criteria were developed and organised around three core adaptation concepts – Exposure, Sensitivity, and Adaptive Capacity – which provide a concise, structured approach for evaluating how climate resilience can be considered in future projects funded by NZIP (see **Section 5** and **Annex 5**).

This assessment generates a better understanding of the different climate hazards impacting the technologies and gives a high-level overview of the vulnerability and resilience of the technologies assessed. A summary of these findings can be found in Figure 1-1.

All technologies were found to be at least “potentially vulnerable” to multiple climate hazards. For vulnerable technologies, this means that these are extremely, very or climate sensitive and either have major challenges to adjust/respond within existing climate limits or are able to adjust/respond to existing climate limits but face major challenges beyond them. None of the technologies were found to be “highly vulnerable” to any climate-related hazards included in this assessment. However, ratings might vary when each technology is broken down further into sub-technologies. It should be noted that the assessment does not prioritise technologies with regards to which ones are most/least vulnerable/resilient to specific climate hazards. For specific details on each of the technologies, see **Section 3**.

According to this assessment process, the highest vulnerability scores lay within the flooding (mainly medium to high confidence) and storminess and occurrence of storm events (mainly low to high confidence) hazards. Five technologies were found to be “vulnerable” to each of these hazards. Conversely, the lowest vulnerability scores lay within the erosion (mainly low to medium confidence) and drought hazards (low to high confidence), with four-five technologies found to be at least “resilient” to these hazards. Simultaneusly, about half of the technologies were found to be at least “potentially vulnerable” to these hazards (low to high confidence) highlighting the differences in research focus of technologies on different climate hazards (see **Section 3** and **Section 4**).

Figure 1-1 Synthesis rating of vulnerability/resilience of assessed technologies with regards to climate hazards

Climate Hazard / Technology	Future offshore wind	Power networks	Hydrogen	Advanced carbon capture, usage and storage (CCUS)	Storage and flexibility	Bioenergy	Direct air capture (DAC) and greenhouse gas removal (GGR)	Buildings	Ocean energy	Solar energy
Heatwaves	2*	3**	2*	3***	3***	3***	3***	4***	2*	3***
Flooding (river, surface and coastal)	N/A	4***	2*	4**	4***	3**	4***	3**	2**	4***
Drought	N/A	2*	4**	3***	2**	3***	3***	2***	1**	3***
Wind strength and wind regimes	4***	4**	2**	1*	1*	3**	4**	3***	3**	4***
Storminess and occurrence of storm events	4***	4**	4*	2**	3***	3***	4**	3**	3*	4**
Snow and ice	3**	3**	N/A	3**	4***	2***	3**	3***	2**	4***
Erosion	2*	N/A	4*	2*	3***	1***	2**	4*	2**	4**

N/A: This hazard was not deemed relevant to this technology in both the literature and expert discussions

Formatting key for vulnerability/resilience rating:

Rating	Definition
1	highly resilient
2	resilient
3	potentially vulnerable
4	vulnerable
5	highly vulnerable

Formatting key for confidence rating:

Rating	Definition
2.50	Low*
3.00	
3.50	Medium**
4.00	
4.50	High***
5.00	

Several adaptation options were identified for each technology (see summary Table 1-1), with common themes being regular technology maintenance, investments in infrastructure improvements and innovation, and efficiency improvements to use fewer resources. Identified adaptation options for the two hazards with the highest vulnerability scores (flooding and storms), include enhanced flood defences, implementing flood tunnels or drainage systems, elevating or burying of vulnerable assets, investments in robust pipeline infrastructure and grid resilience (e.g. decentralisation), and improved planning guidelines.

Table 1-1 High-level overview of some of the identified Adaptation options for the ten technologies assessed

Technology	High-level overview of some of the identified Adaptation Option(s) for hazards that technologies were found to be at least "potentially vulnerable" to
Future offshore wind	*Wind:* Enhancing material and structural resilience in design *Wind and Storms:* Employing a systems level approach including reinforcement measures and different wind load specifications into the technology design
Power networks **(for detail, see Appendix A.4.1)**	*Flooding, Wind, Storms:* Investing in flood protection measures, decentralised and redundant systems, hardening infrastructure such as undergrounding lines or reinforcing poles
Hydrogen **(for detail, see Appendix A.4.3).**	*Drought:* Considering alternative technologies that use less water (e.g. alkaline electrolysis) *Storms:* Investing in a robust pipeline infrastructure and risk assessments ▪ *No evidence for adaptation options to erosion (vulnerable) and precipitation (potentially vulnerable)*
CCUS **(for detail, see Appendix A.4.2)**	*Flooding:* Elevating critical equipment, implementing flood tunnels *Drought, Heatwaves:* Improving technology and efficiency through wet/dry hybrid towers and solid or bio-based sorbents that do not require large amounts of water; Using heat-resistant materials, developing real-time monitoring systems ▪ *No evidence for adaptation options to storminess and occurrence of storm events (potentially vulnerable) and snow and ice (vulnerable)*
Storage & flexibility	*Flooding, Snow and ice:* Enhance infrastructure resilience (e.g. moving electronic equipment to higher elevation or into water-tight/sealed enclosures); Clearing snow around assets ▪ *No evidence for adaptation options to storminess and occurrence of storm events (potentially vulnerable) and erosion (potentially vulnerable)*
Bioenergy	*Heatwaves, Drought:* Use of drones to map soil moisture and new AI-based methods for estimating water footprint *Flooding, Wind, Storms:* Improving technology and efficiency; Enhancing crop resilience; selective breeding; implementing silviculture and forest management

DAC and GGR	*Flooding:* Elevating critical infrastructure above potential flood levels *Drought, Wind, Storms, Flooding:* Ensuring suitable land management (e.g. slope, farming practices)
Buildings **(for detail, see Appendix A.4.4)**	*Heatwaves:* Including thermal and wind flow features in urban design *Flooding:* Ensuring regular maintenance of heat pumps water seals and drainage systems *Wind, Storms:* Enhancing moisture control strategies; Robust electrical protection for battery storage systems; backup power sources ▪ *No evidence for adaptation options to erosion (vulnerable)*
Ocean energy	*Wind, Storms*: Using doppler measurement equipment to understand wave characteristics over long time periods at varying depths; Investing in technological innovations (e.g. robotics and automation)
Solar energy	*Flooding*: Perform flood risk assessment; Include soil depth in stormwater modelling; Include a weep hole/drain plug in installations *Winds, Storms, Snow and Ice:* Spreading solar plants to increase grid resilience; Installation of windshields; Anchoring of floating PV; Replacing plastic wire management systems with durable materials *Wildfire*: Ensure regular vegetation clearing or grass mowing

Overall, adaptation options were mainly found for the drought and flooding hazards but fewer were found for the climate hazards wind, storms and erosion. The different number of adaptation options across hazards found may result from most academic research up to now focusing on water availability and heat-induced risks. Many evidence gaps remain for technologies to adapt to other specific climate hazards (see **Section 3** and **Section 4**).

Overall, evidence in the academic literature was limited, which has resulted in mainly low to medium confidence levels within this assessment. The limited evidence reflects the fact that these are emerging technologies that lack a large body of evidence on performance under different conditions. Confidence levels were particularly limited by the lack of relevant evidence of technology-specific or sub-technology specific sensitivities and adaptive capacities in the academic literature. The assessment may also be influenced by the style of methodology employed in this research by combining specific technologies and climate-related hazard search terms in the REA. This approach may have missed literature associated with a given hazard and distinct elements of a technology. As a result, there may be a need to assess the specific sub-technologies and their climate-related hazards on a case-by-case basis.

While the ratings here do give a good indication of each technology's overall vulnerability levels to different climate-related hazards, the assessment does not provide a prioritisation of technologies that are most/least vulnerable/resilient to specific climate hazards and does not consider local climate hazard differences across the UK (e.g. likelihood of drought in Scotland vs. the South-East of England).

Further research would be required to generate more evidence on the sensitivity of specific technologies to climate-related hazards and their application in the UK. There are also evidence gaps around cascading effects between technologies in relation to different hazards. Another overarching evidence gap appears to be for technology improvements to withstand more extreme weather extremes (e.g. strong winds and storms). For more detailed suggestions of potential further research options, see Concluding remarks in **Section 4**.

Finally, evaluation criteria have been developed to provide a concise, structured approach for mainstreaming climate resilience in future projects supported by NZIP. Criteria around Exposure, Sensitivity and Adaptive Capacity are defined including questions that are applicable across various technology contexts, ensuring a consistent approach while accommodating the unique aspects of each project. The approach allows strengths and weaknesses in specific areas of a project across its lifecycle to be identified by DESNZ. This approach could help to identify the most cost effective and potentially resilient net zero solutions for priority development.

2. Introduction

The Net Zero Innovation Portfolio (NZIP), delivered by the Department for Energy Security & Net Zero (DESNZ), provides innovation funding for low carbon technologies and systems, to help facilitate the UK's net zero transition. While there is a growing body of evidence available regarding the ability of these technologies to support the UK's climate mitigation goals (e.g. sustainable power generation, reducing greenhouse gas emissions, sequestering and storing carbon, etc.), there is less evidence available regarding the vulnerability or resilience of these technologies to climate-related hazards. This project aims to address this evidence gap to help ensure that these technologies could be scaled up and deployed in a way that reduces their climate vulnerability and ensures the resilient delivery of our net zero goals, avoiding future mal-adapted net zero energy systems.

The introduction section in this document sets out the scope (**Section 2.1**), methodological approach (**Section 2.2**) and how to use these findings presented in the assessment (**Section 2.3**). Key findings from the vulnerability/resilience ratings review can be found in **Section 3**, and an analysis of the results and further research needs in the concluding remarks in **Section 4**. Evaluation criteria for future net zero projects can be found in **Section 5**.

Annex 1 sets out the detailed methodology, **Annex 2** provides access to the full evidence and literature extracted for this assessment, **Annex 3** provides the detailed vulnerability ratings table, **Annex 4** includes the four case studies written as part of this report, and **Annex 5** sets out the scoring for the evaluation criteria.

2.1 Scope

Following consultation with DESNZ and the CCC, the following technologies, which are included in the current NZIP1 programme and/or are planned for inclusion in the next iteration of NZIP2, were selected for inclusion in this assessment:

1. Future offshore wind
2. Power networks
3. Hydrogen
4. Advanced carbon capture, usage and storage (CCUS)
5. Energy storage and flexibility
6. Bioenergy
7. Direct air capture (DAC) and greenhouse gas removal (GGR)
8. Building related technologies
9. Ocean energy
10. Solar energy

The technologies are further defined in **Annex 1**, along with the process for selecting them.

To identify the climate-related hazards against which each technology's vulnerability and resilience was assessed, the Climate Change Committee's report: "*Delivering a reliable decarbonised power system*"[1] was used. It identified the following key climate-related hazards of relevance to the UK power system:

1. Heatwaves
2. Floods (riverine, pluvial, and coastal)
3. Droughts
4. Wind strength and wind regimes
5. Storminess and occurrence of storm events[2]
6. Snow and ice

Following consultation with DESNZ and the CCC, erosion was added to the list of climate-related hazards against which vulnerability would be assessed[3]. According to feedback received from key stakeholders, erosion had the potential to cause increasing challenges when implementing climate mitigation and energy related projects.

The geographical scope of this review is UK-wide. This review does not provide separate assessments for specific geographical regions of the UK, or any other form of spatial analysis. The analysis therefore focuses on direct and indirect effects on climate vulnerability and resilience within the UK alone and does not consider effects outside UK borders.

2.2 Methodological approach

This project has taken the following steps:

1. **Vulnerability and resilience ratings**: An assessment was conducted of the climate vulnerability and resilience of technologies in NZIP1, and technologies planned for inclusion in NZIP2. Each technology was given a rating for sensitivity[4] and adaptive capacity[5]. The combination of ratings for sensitivity and adaptive

[1] Climate Change Committee, 2023. Delivering a reliable decarbonised power system. Available at: https://www.theccc.org.uk/publication/delivering-a-reliable-decarbonised-power-system/ [last accessed 04 December 2024].

[2] Wind strength and wind regimes refer to long-term patterns and intensities of wind, like average speeds and directions. In contrast, storminess and storm events are short-term, intense occurrences like hurricanes or thunderstorms, leading to immediate, localised damage. The key distinction is that wind regimes are ongoing and cumulative, while storms are distinct episodes/events.

[3] Erosion is a slow onset hazard, directly related to floods and droughts as well as other non-climatic (anthropogenic) drivers

[4] **Sensitivity rating:** 1 = insensitive to climate; 2 = may be sensitive to climate; 3 = climate sensitive; 4 = very climate sensitive; 5 = extremely climate sensitive.

[5] **Adaptive capacity rating:** 1 = major challendes to adjust or respond within existing climate limits; 2 = minor challendes to adjust or respond within existing climate limits; 3 = able to adjust or respond within existing climate limits but major challendes beyond them; 4 = able to adjust or respond within existing climate limits but minor challendes beyond them; 5 = able to adjust or regardless of climate.

capacity gave a rating of vulnerability[6] for each technology. The research team applied a three-tiered confidence scale to these ratings, based on the strength of evidence[7] and level of agreement[8] (low, medium and high confidence; for more detail see **Annex A.1.4**). As part of the assessment, adaptation options were also identified.

2. **Case studies:** Detailed case studies were developed for four of the innovative technologies assessed to support the development of DESNZ future Net Zero Research and Innovation Portfolio programmes. Following consultation with DESNZ and the CCC, case studies were prioritised based on how much of an impact there would be on the UK trajectory to net zero if the technology is not resilient, and on the resilience of the technology itself. Therefore, the following case studies were chosen:

   - Case study 1: Power Networks.
   - Case study 2: CCUS with a focus on CCUS infrastructure (i.e. transport and storage).
   - Case study 3: Hydrogen with a focus on transport and storage.
   - Case study 4: Buildings with a focus on heat pumps as many homes in the future will have these.

   Network infrastructure was addressed wherever possible, as it is a significant concern for DESNZ. The resilience of networks often underpins the entire technological output, such as green hydrogen's reliance on renewable energy sources for example. For the detailed case studies, see **Annex 4**.

3. **Evaluation criteria**: Evaluation criteria were developed that could be used in the assessment of future NZIP projects / programmes, to ensure that the identified vulnerabilities are factored into future NZIP funding, and for mainstreaming climate change adaptation in the NZIP projects' lifecycle to ensure their climate resilience, see **Section 5**.

The detailed methodology employed by this project is set out in **Annex 1**.

2.3 How to use these findings

As noted above, this project seeks to identify the ways in which the technologies assessed are vulnerable to climate-related hazards to better support their resilient development and

[6] **Vulnerability rating:** 1 = highly resilient; 2 = resilient; 3 = potentially vulnerable; 4 = vulnerable; 5 = highly vulnerable.

[7] **Strength of evidence:** robust evidence = evidence from at least one peer-reviewed paper; medium evidence = evidence from at least one grey literature source; limited evidence = only one expert judgement.

[8] **Level of agreement:** high = all sources agree (i.e. this could also be the case where only one source of evidence is cited given that all results were presented to expert stakeholders, who were given the opportunity to disagree with each conclusion); medium = only one source disagrees; low = multiple sources disagree.

deployment. It does *not* seek to suggest that some technologies be eliminated from consideration by the NZIP, or any other decision-making process, regarding the deployment of net zero technology due to identified vulnerabilities or due to the technology's relative vulnerability compared to other technologies.

When selecting an appropriate mix of diverse net zero technologies, a broad range of assessment criteria will need to be considered. This includes their climate vulnerability, climate mitigation potential, costs, benefits (and co-benefits) and trade-offs. These and other strategic elements will need to be considered to ensure the most efficient mix of technologies to achieve the UK's net zero goal. Attempts to directly compare technologies based on this research are therefore not recommended. Rather than seeking to exclude technologies due to potential vulnerabilities, this report seeks to first identify and then suggest actions to address vulnerabilities at an early stage. This forms part of the future technology development and as well as identify critical research and innovation project scope and funding gaps.

3. Key findings from the vulnerability/resilience ratings

All ten technologies were assessed for their vulnerability/resilience to the selected climate hazards using the methodology outlined in **Annex 1**. The ratings lie on a scale of 1 (highly resilient) – 5 (highly vulnerable) with low to high confidence ratings depending on the evidence available. For a visualisation of vulnerability/resilience ratings and confidence in these findings refer to the synthesis below in Figure 3-1.

Figure 3-1 Synthesis rating of vulnerability/resilience of assessed technologies with regards to climate hazards

Climate Hazard / Technology	Future offshore wind	Power networks	Hydrogen	Advanced carbon capture, usage and storage (CCUS)	Storage and flexibility	Bioenergy	Direct air capture (DAC) and greenhouse gas removal (GGR)	Buildings	Ocean energy	Solar energy
Heatwaves	2*	3**	2*	3***	3***	3***	3***	4***	2*	3***
Flooding (river, surface and coastal)	N/A	4***	2*	4**	4***	3**	4***	3**	2**	4***
Drought	N/A	2*	4**	3***	2**	3***	3***	2***	1**	3***
Wind strength and wind regimes	4***	4**	2**	1*	1*	3**	4**	3***	3**	4***
Storminess and occurrence of storm events	4***	4**	4*	2**	3***	3***	4**	3**	3*	4**
Snow and ice	3**	3**	N/A	3**	4***	2***	3**	3***	2**	4***
Erosion	2*	N/A	4*	2*	3***	1***	2**	4*	2**	4**

N/A: This hazard was not deemed relevant to this technology in both the literature and expert discussions

Formatting key for vulnerability/resilience rating:

Rating	Definition
1	highly resilient
2	resilient
3	potentially vulnerable
4	vulnerable
5	highly vulnerable

Formatting key for confidence rating:

Rating	Definition
2.50	Low*
3.00	
3.50	Medium**
4.00	
4.50	High***
5.00	

Overall, all technologies are expected to be affected by the assessed climate hazards, with varying degrees of vulnerabilities. Many technologies were found to be at least “potentially vulnerable” or “vulnerable” to more than one of the climate-related hazards included in the assessment. A rating of vulnerable means that a technology is extremely, very or climate sensitive and either has major challenges to adjust/respond within existing climate limits or is able to adjust/respond to existing climate limits but face major challenges beyond them. No “highly vulnerable” ratings were assigned to any of the climate hazards, across any of the technologies. This finding mainly results from technologies having medium adaptive capacity, in that they can adjust/respond within existing climate limits but might face major challenges beyond them. Another reason for the lack of highly vulnerable ratings might be that vulnerabilities were assessed across each of the technologies including sub- or chain technologies which may often be a balancing force to even out otherwise high ratings – and vice versa. For example, within solar energy, rooftop, ground-mounted and floating solar systems were considered. Assessed separately, each might potentially result in different vulnerability ratings of the technology. For further analysis, see **Section 4**. For many technologies, adaptation options will need to be included to cope with projected changes in climate hazards in the future.

Flooding and storminess were the two climate-related hazards to which most technologies were found to be “vulnerable”. This vulnerability primarily stems from the sensitivities to infrastructure damage and a lack in adaptive capacity. Power networks, storage and flexibility, DAC/GGR, solar energy (high confidence) and CCUS (all medium confidence) were identified as being vulnerable to flooding (river, surface and coastal). Future offshore wind (high confidence), power networks, DAC/GGR, solar energy (all medium confidence) and hydrogen (low confidence) were identified as being vulnerable to storminess and occurrence of storm events.

Conversely, erosion and drought were the hazards assigned with the highest number of “resilient” or “highly resilient” ratings, mainly resulting from the low-medium sensitivities and medium-high adaptive capacity ratings. Bioenergy (high confidence) was found to be highly resilient, while DAC/GGR and ocean energy (medium confidence), as well as CCUS and future offshore wind (low confidence) were found to be resilient to erosion. Ocean energy (medium confidence) was found to be highly resilient, while power networks (low confidence), storage and flexibility (medium confidence) and buildings (high confidence) were found to be resilient to drought.

The following **Sections 3.1 – 3.10** provide a high-level summary of the vulnerability/resilience reviews of each technology including a summary of potential adaptation options. For a detailed outline of each technology’s vulnerability/resilience ratings, see **Annex 3** ‘NZIP Resilience Review Ratings Workbook of Final Synthesis Ratings’; and for an analysis of the results, see ‘Concluding remarks’ in **Section 4**.

3.1 Future offshore wind

Future offshore wind was found to be **resilient to heatwaves and erosion (low confidence)**. Offshore wind power exhibits high adaptive capacity due to its inherent design and technological advancements. Power systems are equipped with robust protection mechanisms, and the industry increasingly uses data analytics and AI to proactively respond to changing conditions, including extreme heat. Furthermore, the financial and organisational capacity to address maintenance and repair needs is most often integrated into the planning phase of offshore wind projects. This, coupled with the industry's maturity, enables it to adapt effectively to various climatic challenges, including heatwaves, and maintain reliable operations.

In contrast, offshore wind was rated vulnerable to wind strength and storminess (high confidence). Extreme wind speeds can directly damage turbines, leading to operational disruptions and potential structural failures. Additionally, increased wind shear and turbulence can stress turbine components and accelerate wear and tear. Extreme weather events can also hinder maintenance efforts, prolonging downtime and increasing repair costs. Wind extremes may also lead to increased intermittency, although this is of particular concern in the context of wind and drought. As such, this can upset wind power’s contribution to the energy mix, given variable production.

While this technology is considered to be climate sensitive, it is considered to have a high adaptive capacity, with resilience measures in-built into projects to withstand extreme temperatures. **Adaptation options** such as the incorporation of material and structural resilience in design, employment of a systems-level approach and incorporating lifetime icing probability estimates into the planning phase were identified for all relevant hazards. Table 3-1 lists selected adaptation options for the climate-related hazards to which future offshore wind technology was identified to be at least “potentially vulnerable”.

Table 3-1 Adaptation options where future offshore wind was found to be at least potentially vulnerable

Climate Hazard	Adaptation Option(s)
Wind strength and wind regimes	▪ Consider variability in wind speed across different regions/areas when planning infrastructure, to smooth fluctuations in power generation ▪ Appropriate reinforcement measures/materials need to be built into the design of offshore wind infrastructure
Storminess and occurrence of storm events	▪ Different design wind load specifications should be considered for regions with and without typhoon hazards
Snow and ice	▪ Measures to reduce ice accumulation on turbine blades includes coating or heating the blades. However, it is important to note that these measures increase costs and reduce power production

	▪ It is important to integrate robust estimates of icing probability over the entire lifetime of an offshore wind project into the planning and design stage. This will help evaluate the need for and costs/benefit of icing mitigation

Overall, the evidence to assess the climate vulnerability for future offshore wind technology is mainly medium-high. Future projects must consider variability in wind speeds in different regions and implement appropriate reinforcement measures. Additionally, major research gaps identified were: a need to strengthen data collection, quality, and availability to predicting future wind regimes; to develop a better understanding of how climate change could lead to changes in migration patterns of bird and fish species; and to develop a better understanding of design measures such as anchorage of floating systems or precipitation protection options. A more detailed breakdown of the resilience and vulnerability, adaptation options and evidence gaps surrounding power networks can be found in **Annex 3.**

3.2 Power networks (see also Case study 1)

For this assessment, the scope of power networks covers electricity transmission and distribution systems, including various infrastructure elements such as overhead lines and underground cables as well as key components like transformers. The assessment also considers potential impacts on critical supply chains that support these networks. Power networks were found to be **resilient to drought (low confidence)** due to low reliance on water supply for the ongoing functionality of power networks.

However, these networks were found to be **vulnerable to a range of hazards, including flooding (low confidence), and wind strength and storminess (medium confidence).** Flooding has both direct and indirect effects to power networks. Direct damage includes water-related issues like undermined foundations, compromised structural integrity, and short-circuiting of substations and underground cables. Indirectly, flooding can trigger landslides and rockfalls, further damaging infrastructure and hindering post-flood restoration efforts. Storms can cause direct damage to generators, transmission lines, and substations through strong winds, flying debris, saltwater exposure, and lightning strikes, while extreme wind threatens overhead transmission lines, leading to conductor and pole damage. Finally, power networks were found to be vulnerable to extreme heat and heatwaves[9] (high confidence), albeit less so than flooding, wind, and storms. Additional potential hazards addressed were precipitation, sea level rise and solar storms.

[9] There is an ongoing research project under the CS-N0W programme that is exploring 'Impact of extreme heat and heatwaves on energy assets across the UK energy system' (G8). The study goes into further detail on vulnerability of and potential impact to assets within Power Networks (amongst other system functions). Findings will be available in January 2025.

While this technology is considered to be extremely climate sensitive, it is considered to have a high adaptive capacity. **Adaptation options** such as decentralised networks, undergrounding and/or reinforcing distribution and transmission lines were identified for all hazards except for precipitation, sea level rise and solar storms.

Table 3-2 lists the adaptation options for the climate-related hazards to which power networks were identified to be at least "potentially vulnerable".

Table 3-2 Adaptation options where power networks were found to be at least potentially vulnerable

Climate Hazard	Adaptation Option(s)
Flooding	▪ Flooding vulnerability must be considered in site selection and design.
Wind strength and wind regimes	▪ Hardening measures such as undergrounding transmission lines, upgrading poles and structures with stronger, more robust materials. ▪ Applying robust design principles to new transmission facilities.
Storminess and occurrence of storm events	▪ During unusual grid events, a network of distributed energy storage systems can aid restoration and re-energising of systems.
Snow and ice	▪ There are already existing standards for ice accumulation on power networks, so no further adaptation measures were identified in the literature and expert discussions.
Heatwaves	▪ To reduce the vulnerability of generation and network assets, climate impacts such as extreme heat must be considered in site selection and design. ▪ Extreme heat should factor into the maintenance and life extension of existing assets. This could include upgrading to heat resistant materials. ▪ Decentralised distribution systems should be utilised in case of power outages.[10]

Overall, power networks were identified as vulnerable to a range of climate hazards at mainly medium confidence levels. The extent of implementation of planned flood protection, the extent to which adaptive capacity exists to ensure access to water for generators that need it for operations, precipitation, and sea level rise were identified as major research gaps. A more detailed breakdown study of the resilience and vulnerability, adaptation options and evidence gaps surrounding power networks can be found in **Annex 4 A.4.1 Case study 1**.

[10] As above, this is covered in more detail in another ongoing research project under the CS-N0W programme that is exploring 'Impact of extreme heat and heatwaves on energy assets across the UK energy system' (G8). The study goes into further detail on vulnerability of and potential impact to assets within Power Networks (amongst other system functions). Findings will be available in January 2025.

3.3 Hydrogen (see also Case study 3)

Hydrogen production and distribution were found to be **resilient to heatwaves, flooding and wind strength (all with low confidence).**[11] Temperature considerations are often integrated into design and planning phases of hydrogen projects, indicating a high capacity to respond to heatwaves. Excess water associated with flooding has not been identified as an issue for hydrogen production in itself, rather, dirty and contaminated floodwaters will require additional filtration. Consideration of these factors are, however, included within existing project design. Hydrogen production is also not solely reliant on wind energy and can leverage other renewables during periods of low wind resource.

In contrast, hydrogen was found to be **vulnerable to storminess, erosion (low confidence), and drought (medium confidence)**. Droughts can significantly impact hydrogen production, because electrolysis requires substantial water resources. Storms can disrupt the import of hydrogen across sea routes as well as its transport and distribution domestically. The latter is of particular concern in the short to medium term, whilst pipelines are not fully established. Additionally, erosion can damage pipelines, leading to leaks and potential environmental risks. Precipitation was identified as an additional hazard to which hydrogen infrastructure is potentially vulnerable.

While this technology is considered to be climate sensitive, it is considered to have a medium adaptive capacity overall. While **adaptation options** were identified to heatwaves (resilient), wind and wind regimes (resilient) and flooding (resilient), no adaptation options were identified to adapt to erosion (vulnerable) and precipitation (potentially vulnerable) hazards due to lack of evidence in the literature. Table 3-3 lists adaptation options to which hydrogen was identified to be "vulnerable".

Table 3-3 Adaptation options where hydrogen was found to be at least potentially vulnerable

Climate Hazard	Adaptation Option(s)
Drought	▪ Considering alternative technologies such as alkaline electrolysis and blue hydrogen production (using less water)
Storminess and occurrence of storm events	▪ Climate-robust hydrogen transport pipeline network and storage

Overall, the evidence is limited to assess climate vulnerabilities of hydrogen technology, so areas requiring further research, such as withstanding higher temperatures, impacts of water quality on hydrogen production, and potential losses and monitoring leakages caused by storms and erosion were identified. A more detailed breakdown study of the resilience and

[11] It should be noted that hydrogen is a very broad technology so it is hard to attribute a single resilience value

vulnerability, adaptation options and evidence gaps surrounding hydrogen can be found in **Annex 4 A.4.3 Case study 3**.

3.4 Advanced carbon capture, usage, and storage (CCUS) (see also Case study 2)

CCUS was found to be **highly resilient to wind strength (low confidence), and resilient to erosion and storminess (low and medium confidence**). It should be noted that there was a lack of evidence or extensive expert knowledge to determine these resilience scores. While there is the potential for storms to impact the transport of captured CO_2 via ship, vulnerability to storms was still scored low as ship is not the only means of transport. Furthermore, it is important to recognise the potential occurrence of indirect impacts due to geohazards linked to slow onset events, such as erosion or soil moisture losses. Therefore, carbon capture plant locations should be monitored.

CCUS technologies were found to be **vulnerable to flooding, droughts, heatwaves and snow and ice (medium to high confidence)**. Vulnerabilities were identified in particular in relation to carbon steel pipelines, which can be vulnerable to damage caused by floodwaters, but also fluctuations in temperatures caused by both high and low temperatures, attributed with heatwaves and snow/ice. Finally, CCUS is highly water dependent, as it is a necessary resource needed for cooling processes

While this technology may be sensitive to climate hazards, it is considered to have a medium to high adaptive capacity overall. **Adaptation options** were identified for flood resilience and improvements to withstand extreme temperatures. No evidence for adaptation options to wind strength and wind regimes (highly resilient) and storminess and occurrence of storm events (resilient) and snow and ice (potentially vulnerable) were identified due to lack of evidence in the literature. Table 3-4 lists adaptation options to which CCUS was identified to be at least “potentially vulnerable”.

Table 3-4 Adaptation options where CCUS was found to be at least potentially vulnerable

Climate Hazard	Adaptation Option(s)
Flooding	▪ Elevating low-lying infrastructure and groundwater observations and monitoring ▪ Flood tunnels and sustainable drainage systems
Drought	▪ Wet/dry hybrid towers for water cooling in CCS power plants ▪ Solid or bio-based sorbents that do not require large amounts of water for the heating (and cooling) of liquid solvents. ▪ CO_2-enhanced water recovery (CO_2-EWR) technology
Heatwaves	▪ Use of heat-resistant materials ▪ Development of real-time temperature monitoring systems

	▪ Advanced cooling systems

Overall, the evidence for CCUS is limited, with more research needed to understand vulnerabilities across the chain of operations. A more detailed breakdown study of the resilience and vulnerability, adaptation options and evidence gaps surrounding CCUS can be found in **Annex 4 A.4.2 Case study 2**.

3.5 Storage and flexibility

The focus of the storage and flexibility analysis was on pumped hydro, compressed air, lithium-ion and flow battery technologies. Storage and flexibility technologies were found to be **resilient to wind (medium confidence) and drought (medium confidence)**. The resilience to wind is due to the durability and stability of these technologies to high winds. For drought, only pumped hydro facilities were considered sensitive and even then, they are usually designed to maintain a significant level of operation during severe droughts. Similarly, heatwaves[12] can cause a temporary ramping down of output and/or increased energy consumption due to cooling requirements. However, these technologies are generally built to be able to withstand high ambient temperatures, hence were rated as potentially vulnerable (high confidence).

Meanwhile, storage and flexibility systems were found to be **vulnerable to flooding, and snow and ice (high confidence)**. Cold temperatures can increase the viscosity of electrolytes in Lithium-ion batteries leading to lithium metal buildup at electrodes which could lead to an internal short circuit and start a fire. Additionally, water ingress caused by thawing snow and ice can damage battery components. For pumped hydro, ice formation on reservoirs can reduce water availability, limit energy generation, and cause damage to infrastructure.

While these technologies are (very) climate sensitive, they are considered to have a high adaptive capacity. Lithium-ion batteries are typically installed with a minimum level of site drainage to protect them from flooding, inside containers with a minimum ingress protection rating, and a temperature management system to ensure that a minimum internal temperature is maintained. While pumped hydro dams are typically designed to withstand the impacts of ice loads. Overall, these technologies exhibit a high level of resilience due to their high level of adaptive capacity within existing climate limits. **Adaptation options** were identified for all climate related hazards except for wind strength and wind regimes (highly resilient), storminess and occurrence of storm events (potentially vulnerable) and erosion (potentially vulnerable) due to lack of evidence in the literature. Table 3-5 lists identified

[12] There is an ongoing research project under the CS-N0W programme that is exploring 'Impact of extreme heat and heatwaves on energy assets across the UK energy system' (G8). The study goes into further detail on vulnerability of and potential impact to assets within Power Networks (amongst other system functions). Findings will be available in January 2025.

adaptation options for the climate-related hazards to which storage & flexibility technology was found to be the at least “potentially vulnerable”.

Table 3-5 Adaptation options where storage & flexibility was found to be at least potentially vulnerable

Climate Hazard	Adaptation Option(s)
Heatwaves	▪ If not already present, cooling systems can be installed/upgraded, especially for critical equipment that lack them to ensure that cooling requirements can be met efficiently.
Flooding	▪ Enhance infrastructure resilience: o Drainage systems, flood barriers, water pumps in underground areas or low-lying sections of the site to help remove floodwater o Move electronic equipment to higher elevation or into water-tight/sealed enclusures if this has not already been done
Snow and ice	▪ Regularly clearing snow around assets and vulnerable equipment

Overall, these findings have medium to high confidence levels. Storage and flexibility technologies are resilient and have existing adaptive capacity for many climate hazards but remain particularly vulnerable to hazards associated with cold weather or water ingress. A more detailed breakdown of the resilience and vulnerability, adaptation options and evidence gaps surrounding storage and flexibility can be found in **Annex 3**.

3.6 Bioenergy

The bioenergy technology analysis focused on dedicated feedstocks. Bioenergy feedstocks, particularly perennial crops like miscanthus, were generally found to be **resilient to snow and ice and erosion (high confidence)**. Most of the feedstocks have low sensitivities to frost damage and high tolerances to low temperatures. Evidence also suggests that feedstocks actively reduce the effects of erosion. A balance between high sensitivities and high adaptive capacities resulted in bioenergy being rated as **potentially vulnerable to heatwaves, drought, wind strength, and storminess hazards (high confidence), as well as the flooding (medium confidence)**. Bioenergy feedstocks possess physical adaptations such as deep and complex root systems, which contribute to an existing level of tolerance and resistance to droughts, floods and winds. This allows these crops to withstand changes in rainfall, temperature, and extreme weather events.

While this technology may be sensitive to climate hazards, it is considered to have a medium to high adaptive capacity overall. Certain sensitivities which remain are particularly regarding excessive rainfall, which can lead to flood-related issues of reduced establishment rates and impeded access to waterlogged soils during harvesting periods. Sensitivities surrounding extreme heat and drought are also key, as these hazards can lead to physical damage to crops and reductions in growth. Table 3-6 lists **adaptation options** such as improved management practices and improved species and site slection, to which bioenergy feedstocks were identified to be at least "potentially vulnerable".

Table 3-6 Adaptation options where bioenergy was found to be at least potentially vulnerable

Climate Hazard	Adaptation Option(s)
Heatwaves	▪ New AI-based methods for estimating water footprint can aid water resource management in biofuel production. ▪ Soil-less cultivation can accelerate crop growth, however, its suitability for large-scale biomass production remains limited. ▪ Irrigation during establishment may be beneficial, but water sourcing and potential greywater use should be evaluated. ▪ Improved modelling of heatwave risk is needed for informed decision-making regarding adaptation options.
Flooding	▪ Prioritise management practices that minimise soil damage. ▪ While perennial crops are relatively flood-tolerant due to their root systems, selective breeding can improve this trait.
Drought	▪ Select species with low water use to maximise water retention in the soil profile. ▪ Implement more effective irrigation and fertilisation practices. ▪ Use dynamic breeding programmes to develop crop varieties suited to specific environments. Employ advanced technologies like AI and machine learning to accelerate breeding programmes. ▪ Use drones to map soil moisture and establishment rates across individual fields to maximise planting success and optimise resource allocation. ▪ Establish mixed-species forestry stands to leverage diverse root profiles for improved water access.
Wind strength and wind regimes	▪ Use tree shelters and biodegradable guards. ▪ Implement sivcultural practices like species selection, ground preparation (avoid ploughing as this reduces root spread), thinning regimes, and shorter rotations. Diversify forest age and height structure for windfirmness.
Storminess and occurrence of storm events	▪ Adaptation options will be a combination of flood and wind hazard adaptations e.g. tree shelters/guards, silvicultural practices, ground preparation practices, species selection.

Overall, based on a relatively high amount of evidence available, bioenergy exhibits high resilience to the identified climate hazards due to the high adaptive capacity and diverse range of adaptation options for biomass feedstocks. More research will be needed to understand their long-term resilience and ability to withstand changes outside of established climate limits. A more detailed breakdown of the resilience and vulnerability, adaptation options and evidence gaps surrounding bioenergy feedstocks can be found in **Annex 3.**

3.7 Direct air capture (DAC) and greenhouse gas removal (GGR)

In this review, DAC and GGR technologies encompassed direct air carbon capture and storage (DACCS), direct air carbon capture and utilisation (DACCU), bioenergy with carbon capture and storage (BECCS), enhanced weathering and biochar. DAC and GGR was found to be **resilient to erosion (medium confidence)**, as they possess a high capacity to adapt to this risk. Biochar has itself been shown to reduce soil erosion rates. For some sub-technologies such as DACCS and DACCU, implementing erosion control measures like reinforced foundations and erosion-resistant materials can significantly reduce the impact of erosion.

However, DAC/GGR technologies were found to be **vulnerable to flooding (high confidence), wind strength (medium confidence) and storminess (medium confidence)**. Wind, storms and flooding can all lead to physical damage of infrastructure of especially DACCS and DACCU plants. Cascading effects caused by flooding are also a significant risk to CO_2 transport infrastructure, when, for example, heavy rains result in a landslide which result in a pipeline rupture, thus reducing durability of carbon storage infrastructure. Additionally, while DACCS can rely on natural gas provided that is co-captured simultaneously, DACCU plants are generally highly dependent on renewable energy resources. As a result, DACCS might be less sensitive to cascading effects from renewable energy system failures compared to DACCU.

This technology is found to be sensitive to climate and is considered to have a medium adaptive capacity overall. Especially DAC/GGR infrastructure was found to be vulnerable to climate risks. While the following projects do not specifically investigate climate risks, it should be noted that there are currently ongoing projects funded by the government (e.g. the biochar and enhanced weathering demonstrators by UKRI[13]), and that enhanced rock weathering is currently undergoing test trials in the UK[14]. **Adaptation options** to all climate-related hazards were identified except for heatwaves (potentially vulnerable). Table 3-7 lists selected adaptation options identified for the climate-related hazards to which DAC/GGR technology was found to be at least "potentially vulnerable".

[13] UKRI, 2021. UK invests over £30m in large-scale greenhouse gas removal. [pdf] Available at: https://www.ukri.org/news/uk-invests-over-30m-in-large-scale-greenhouse-gas-removal/ [Accessed 04 December 2024].

[14] Newcastle University, 2024. Study shows the crop benefits of enhanced rock weathering. [pdf] Available at: https://www.ncl.ac.uk/press/articles/latest/2024/03/enhancedrockweathering/ [Accessed 04 December 2024].

Table 3-7 Adaptation options where DAC/GGR was found to be at least potentially vulnerable

Climate Hazard	Adaptation Option(s) to DAC/GGR
Flooding	▪ Elevating critical infrastructure to above potential flood levels ▪ Ensuring that site is not in the downstream floodplain of a dam ▪ While biochar in itself has adaptation potential for flooding, land management (e.g. slope, farming practices) will need to be adapted for biochar to be successful in the long-term
Drought	▪ While biochar in itself has adaptation potential for drought, land management (e.g. slope, farming practices) will need to be adapted for biochar to be successful in the long-term
Wind strength and wind regimes	▪ Ground preparation and land management practices can enhance resilience of DAC/GGR technologies to windthrow
Storminess and occurrence of storm events	▪ Adaptation options for this hazard will be a combination of flood and wind hazard adaptations e.g. soil management, ground preparation practices, species selection
Snow and ice	▪ Species and site selection ▪ While biochar in itself has adaptation potential for drought, land management (e.g. slope, farming practices) will need to be adapted for biochar to be successful in the long-term

Overall, these findings demonstrate a high degree of vulnerability for DAC/GGR technologies with low-medium confidence. A further understanding of enhanced rock weathering and correlations between various carbon sources such as manure, compost, and biochar, and their adaptive capacities to climate change, were identified as major research gaps. A more detailed breakdown of the resilience and vulnerability, adaptation options and evidence gaps surrounding power networks can be found in **Annex 3**.

3.8 Buildings (see also Case study 4)

The analysis of building technologies primarily focused on heat pumps, advancements in insulation and energy demand management systems. Nature-based solutions[15] like green roofs, rain garden and green walls were found to be **resilient to drought (high confidence)** due to the effectiveness of various water conservation measures which can be implemented. These measures, such as reducing water consumption, rainwater harvesting, greywater

[15] Nature-based solutions were considered in the assessment due to the potential contribution to overall resilience within 'Buildings' technologies; however, nature-based solutions are not covered in DESNZ NZIP technologies. See Appendix A.1.1 for definition of technologies associated with 'Buildings' under NZIP.

systems, and blackwater recycling, significantly reduce the reliance on potable water, mitigating the impact of water scarcity during droughts.

In contrast, these technologies were found to be **vulnerable to heatwaves (high confidence) and erosion (low confidence)**. Building-related technologies including retrofitted and airtight buildings, cooling systems and solar thermal facades face challenges such as overheating and reduced efficiency in high temperatures due to several factors such as building design and insulation, and other infrastructure assets. Infrastructure assets, such as pipelines and electricity cables and water source heat pumps, often located at riverbanks, are sensitive to erosion and sediment abrasion which can impact performance over time.

This technology was found to be sensitive to climate and is considered to have a medium adaptive capacity overall. **Adaptation options** exist such as foundation reinforcement and landscape interventions, like slope stabilisation that can provide structural stability and protect buildings' foundations from soil displacement and the effects of erosion. Additionally, passive cooling strategies, including shading and reflective surfaces, and enhanced insulation combined with active cooling systems, are effective adaptive measures for managing heatwave impacts in buildings. Table 3-8 lists adaptation options to the five climate-related hazards to which building technologies were found to be at least "potentially vulnerable". No evidence for adaptation option to erosion (vulnerable) were identified due to a lack of evidence in the literature.

Table 3-8 Adaptation options where buldings related technology was found to be at least potentially vulnerable

Climate Hazard	Adaptation Option(s)
Heatwaves	▪ Reversible and ground-source heat pumps (GSHP) for adaptable cooling ▪ Designing cooling systems for higher ambient temperatures than normal practice today ▪ Accepting higher internal comfort temperatures
Flooding	▪ Elevating air source heat pumps above anticipated flood levels ▪ Additional drainage, flood barriers, and high Ingress Protection rating (IPX8 or above) for battery storage systems
Wind strength and wind regimes	▪ Enhanced moisture control strategies for historic buildings
Storminess and occurrence of storm events	▪ Proper installation and maintenance of heat pumps, with backup power sources for commercial applications ▪ Robust electrical protection and structural assessments for battery storage system
Snow and ice	▪ Freeze-thaw indicators and built-up defrost cycles for heat pumps ▪ Snow drift analysis for optimal heat pump positioning

Overall, the evidence to assess the climate vulnerability for building-related technologies is medium-high. A better understanding of passive cooling technologies, optimisation of passively designed buildings, the relationship between air tightness for air quality ventilation and ventilation for overheating, and flooding requitrements in buildings's regulations were identified as major research gaps. A more detailed breakdown study of the resilience and vulnerability, adaptation options and evidence gaps surrounding buildings can be found in **Annex 4 A.4.4 Case study 4**.

3.9 Ocean energy (wave and tidal)

The ocean energy analysis encompassed wave and tidal systems. These technologies were found to be **resilient to flooding, snow and ice, and erosion (all medium confidence), as well as heatwaves (low confidence)**. This is due to wave and tidal technologies existing further offshore, increasing their resilience to hazards such as flooding or erosion. Furthermore, while heatwaves may impact assembly processes and productivity, infrastructure such as turbine blades and subsea cables are minimally affected by high temperatures within existing climate limits. It should be noted that ocean energy substations may be more vulnerable to these climate hazards than the wave and tidal devices themselves, however, this falls under the scope of the power networks technology (**Section 3.2** and **Annex A.4.1 Case study 1**).

Wave and tidal devices were rated as **potentially vulnerable to the wind strength (medium confidence) and storminess (low confidence) hazards.** Wave and tidal devices, often positioned on or near the ocean surface, are directly exposed to the force of high waves and strong winds. Extreme weather events such as storms can lead to physical damage, operational disruptions, and increased maintenance requirements. Additionally, extreme weather can hinder maintenance operations, leading to longer downtime and reduced energy production. However, these technologies were found to have high adaptive capacities, as they are resilient and robust by nature as they are intended to withstand forces exerted by waves, tides and storm surges. Minor challenges may present themselves beyond existing climate limits, depending on the technology and location.

Adaptation options were identified for all climate-related hazards except for erosion (resilient) due to lack of evidence in the literature. Table 3-9 lists adaptation options to the two climate-related hazards to which ocean energy technoloiges were found to be at least "potentially vulnerable".

Table 3-9 Adaptation options where ocean energy was found to be at least potentially vulnerable

Climate Hazard	Adaptation Option(s)
Wind strength and wind regimes	▪ (Doppler) measurement equipment can be installed in oceans to measure wind and wave characteristics over long time periods and at varying depths to understand the effects of the local sea conditions of crashing waves/spray.

	▪ Oceanic buoys/other existing infrastructure could be used to monitor wind speeds.
Storminess and occurrence of storm events	▪ Ensure availability of advanced mooring material and technologies, robotics, and informatics for remote monitoring and efficient operational support. ▪ It is necessary for most wave devices to have a survival mode. For example, a device could be sunk to a particular depth where wave orbital motion will be reduced (e.g. related to the wavelength), or to relax the load on a turbine in an oscillating water column device. ▪ Technological innovations such as Bombora's patented mWave technology (cell modules with a unique ability to shut down in extreme storm events which limits the design loads reducing capital costs and cost of electricity), Pelamis Wave Power device with flexible joints (combined with the ability to adjust the hydraulic rams and potentially detach from the mooring which provides a level of protection against severe weather conditions), or the tidal stream device Minesto (subsea kite). ▪ Note: Prolonged periods of low wave energy provide opportunities for device maintenance. A site that is consistently energetic may be desirable from theoretical and technical resource perspectives but is undesirable from a practical resource perspective.

Overall, based on low to medium condidence, ocean energy exhibits a high-level of resilience to most hazards considered in this assessment and a high-level of adaptive capacity to deal with extreme forces. However, more research and testing may be needed to assess specific vulnerabilities related to all parts of the operational process. A more detailed breakdown of the resilience and vulnerability, adaptation options and evidence gaps surrounding power networks can be found in **Annex 3.**

3.10 Solar energy

The focus of this assessment was on rooftop, ground-mounted and floating solar systems. Though solar energy included space-based solar in the assessment scope, space-based solar is expected to be installed at geostationary orbit so is not expected to be impacted by climate hazards.

Solar energy was found to be **vulnerable to flooding, wind strength, snow and ice (high confidence), storminess and erosion (medium confidence).** Flooding can damage electrical components and accelerate the degradation of floating solar systems. Flooding can also lead to soil erosion, which destabilises the foundations of solar. However, solar plants typically have adaptive capacity by installing their electrical equipment above predicted flood levels. Meanwhile, although solar systems are designed to withstand high wind speeds to an extent and moderate wind speeds can help dissipate heat and improve performance, extreme wind events can lead to significant physical damage and production losses. Water intrusion from storm events or snowmelt can cause water damage, deteriorate materials, and lead to electrical failures. However, electrical equipment is typically housed in enclosures with a minimum level of ingress protection.

Solar energy was rated as potentially vulnerable to heatwaves and drought (high confidence). High temperatures can reduce the efficiency of solar panels, particularly for crystalline silicon technologies. Additionally, dust accumulation (e.g. from drought or wildfire) on panels can decrease output and increase the risk of overheating. For floating solar panels, fluctuating water levels due to drought can lead to structural damage. However, design considerations, such as mounting to maximise air flow and regular cleaning, can mitigate these impacts. While heatwaves and drought may reduce solar energy production, these systems are generally designed to operate within these conditions, demonstrating a high adaptive capacity.

Additional hazards that were identified in the assessment were humidity (potentially vulnerable, medium confidence), wildfire (vulnerable, medium confidence) and changes to the atmosphere (no vulnerability assessment possible due to lack of evidence).

This technology was found to be very sensitive to climate and is considered to have a low to medium adaptive capacity overall. A comparativle detailed list of **adaptation options** were identified for all climate-related hazards except to atmospheric changes due to a lack in the literature. Table 3-10 only summarises adaptation options for the climate-related hazards where solar energy was found to be “vulnerable”. The reason that comparatively more adaptation options were identified might be because there was more literature available to the technology and climate-related hazards.

Table 3-10 Adaptation options where solar was found to be at least vulnerable

Climate Hazard	Adaptation Option(s)
Flooding	▪ Perform a flood risk assessment to identify the expected maximum flood level and raise electrical components, waterproofing electrical enclosures. Installing electrical equipment on elevated pads will reduce the likelihood of water damage ▪ A weep hole or drain plug in an electrical enclosure will allow water ingress to drain out ▪ Include soil depth (rooting depth) in stormwater modelling and design or installing vegetated ground cover to facilitate infiltration around arrays
Wind strength and wind regimes	▪ Integrating solar panels with buildings can serve as tuned mass dampers, providing additional seismic mitigation and vibration control ▪ Spreading solar plants, rather than having a single point of connection, can help to minimise the impacts of weather, increasing grid resilience ▪ Rooftop PVs should not be fully ballasted due to turbulent winds flowing over parapets. Adding bracing or torque fasteners could be advantageous to better secure panels

	▪ Considering wind tested design recommendations to include wind speed, vertical height and natural frequency of arrays to improve resilience; considering vortex shedding and reviewing other design components such as dynamic loading as well as worst case scenarios ▪ Windshields can be installed behind the perimeter of panels to prevent strong winds blowing into the back of them. Floating PV can be weighted to reduced flipping over from high winds ▪ Redesigning PV systems with high tilts in high wind regions is critical to ensure their resilience. Applying a tracking system with high wind mode to change the tilt during high wind conditions and reduce the amount of wind loading along the array ▪ Panels with thicker glass and thin frames are more prone to sustain high winds
Storminess and occurrence of storm events	▪ Anchoring of floating solar PV may reduce movement during high storm events
Snow and ice	▪ Avoid use of plastic wire ties and ensure wire connections are under modules or otherwise protected from where icicles will form ▪ Use wire management options that will hold under additional weight from snow
Erosion	▪ Pollinator plantings are a very effective method to reduce soil erosion and scouring ▪ Continual O&M must be conducted to ensure that the site is not experiencing any soil erosion and scouring vulnerabilities
Wildfire	▪ Regular vegetation clearing or grass mowing that do not cause disruption or damage to equipment

Overall, based on medium to high confidence ratings, these findings demonstrate a high degree of vulnerability for solar energy technologies due to the wide range of different kinds of solar energy and its applications in different locations and landscapes. A more detailed breakdown of the resilience and vulnerability, adaptation options and evidence gaps surrounding power networks can be found in **Annex 3**.

4. Concluding remarks

This project has assessed the climate vulnerability and resilience of technologies in NZIP1, and technologies planned for potential inclusion in NZIP2. These technologies include future offshore wind, power networks, hydrogen, advanced carbon capture, usage and storage (CCUS), energy storage and flexibility, bioenergy, direct air capture (DAC) and greenhouse gas removal (GGR), building related technologies, ocean energy, and solar energy.

Additionally, four case studies (power networks, CCUS, hydrogen, buildings) were developed (**Annex 4**). Following a Rapid Evidence Assessment (REA) literature review of the technologies against the UK-relevant climate-related hazards heatwaves, flooding (river, surface, and coastal), drought, wind strength and wind regimes, storminess and occurrence of storm events, snow and ice, and erosion, expert interviews were carried out, and sensitivity and adaptive capacity ratings were determined. For the technologies future offshore wind (**Section 3.1**), power networks (**Section 3.2**), hydrogen (**Section 3.3**) and solar energy (**Section 3.10**), additional climate hazards such as sea level rise, precipitation or humidity were also identified. Based on the existing evidence, which is overall limited, all ten technologies were assessed for their vulnerability/resilience to the climate hazards on a scale of 1 (highly resilient) – 5 (highly vulnerable) with low to high confidence ratings indicating the strength of evidence that was available to determine these ratings (see Methods **Annex 1**).

All technologies were found to be at least “potentially vulnerable” or “vulnerable” to more than one of the climate-related hazards included in the assessment. A rating of vulnerable means that a technology is extremely, very or climate sensitive and either has major challenges to adjust/respond within existing climate limits or are able to adjust/respond to existing climate limits but face major challenges beyond them. None of the technologies were found to be “highly vulnerable” to any climate-related hazards included in this assessment. This finding mainly results from technologies’ medium-high adaptive capacity, meaning they are able to adjust/respond within existing climate limits but might face major challenges beyond these limits. Another reason for the lack of highly vulnerable ratings might be that vulnerabilities were assessed across each of the technologies including sub- or chain technologies. For example, solar energy considered rooftop, ground-mounted and floating solar systems; power networks covered different distribution systems including infrastructure elements and components such as transformers; or storage and flexibility considered pumped hydro, compressed air and different battery technologies – which when assessed separately, might potentially result in different vulnerability ratings of the technologies as the technologies rely on a series of inputs and associated infrastructures to fulfil their primary purpose of net-negative emissions. As another example, the DAC/GGR technology includes DACCS, DACCU, BECCS, enhanced weathering and biochar, which are described here as chain or sub-technologies. The inclusion of these sub-technologies might also lead to variation in future ratings because within a given technology, sub-technologies may often be a balancing force to even out otherwise high ratings – and vice versa. For instance, although DAC/GGR was identified as resilient to erosion, this rating was driven primarily by the effects of well-managed BECCS technologies and biochar. It is suggested that the impact of chain technology and its differentiation is only captured to some extent in the overall ratings and should be considered for future climate vulnerability assessments.

The research has shown that there is overall limited evidence available regarding the vulnerability/resilience of all technologies to climate-related hazards. This limitation is reflected in the low confidence ratings, where often, only one expert or one expert and one source of grey literature was available to provide relevant evidence. As a result, there remains a considerable degree of uncertainty in ratings (for example, offshore wind to erosion; hydrogen to wind strength, and power networks to drought).

Particularly the lack of technology-specific evidence of sensitivities and adaptive capacities in the academic literature informed the confidence levels in the assessment. For example, while confidence for vulnerability of hydrogen to drought is medium, confidence for vulnerability of hydrogen to storminess and occurrence of storm events, and erosion is low as limited evidence exists. The identified lack of technology-specific evidence of sensitivities and adaptive capacities in the academic literature may be caused by a generally greater research focus on the relationship between drought and hydrogen production, as compared to other climate hazards. Likewise, it may also be influenced by the methodology employed in this research, in which specific technologies and climate-related hazard search terms were combined in the REA. This approach may have missed literature associated with a given hazard and distinct elements of a technology and its sub-technologies. As a result, there may be a need to assess the technologies and their climate-related hazards on a case-by-case basis.

For each of the technologies assessed, several adaptation options were identified, with solar having a more advanced list due to more available literature. Across technologies, common themes are regular technology maintenance, investments in infrastructure improvements and innovation, and efficiency improvements to use fewer resources. Adaptation options were mainly found for the drought and flooding hazards but less for the climate hazards wind strength and wind regimes, storminess and occurrence of storm events, and erosion. This reflects the lack of evidence of adaptation options specifically for each technology with regards to the climate hazards wind and storms, and highlights a current research focus on the climate hazards heatwaves and water availability (i.e. drought and flooding). For the two climate-related hazards to which most technologies were found to be vulnerable, flooding and storminess, identified adaptation options include: enhanced flood defences, implementing flood tunnels or drainage systems, elevating or burying of vulnerable assets, investments in robust pipeline infrastructure and grid resilience (e.g. decentralisation), and improved planning guidelines.

Three more remarks could be considered for this assessment:

- The assessment does not prioritise technologies with regards to which ones are most/least vulnerable/resilient to specific climate hazards and does not consider local climate hazard differences across the UK (e.g. likelihood of drought in Scotland vs. the South-East of England).

- There is a clear need for targeted research on the vulnerability/resilience of net zero technologies to fill existing evidence gaps and to inform future R&I project requirements and scope to ensure a high confidence of ratings and therefore long-term system performance.
- An assessment of the cascading effects between technologies in relation to different hazards and the cascading risks on individual sectors would help to understand the interlinkages of vulnerabilities/resilience between the net zero technologies assessed.

The combination of the remaining degree of uncertainty and variation across technology-ratings does not diminish the key findings of this research, however, rather, serve as a reminder of the importance of acknowledging uncertainty where present.

Overall, this assessment generated a better understanding of the different climate hazards impacting the ten technologies and gives a good indication of each technology's vulnerability and resilience to climate-related hazards (see **Section 3**, **Annex 3**). Further evidence and research in this area would improve understanding of climate hazard impacts on net zero technologies and their deployment, and help ensure the resilient delivery of the UK's net zero goals.

For the assessment of future NZIP projects / programmes, to ensure that the identified vulnerabilities are factored into future NZIP funding, and to encourage projects to implement adaptation measures, **Section 5** outlines a set of evaluation criteria that could be considered to evaluate their vulnerability/resilience. These criteria can support the NZIP, delivered by DESNZ, to provide funding for low carbon technologies and systems.

5. Evaluation criteria to mainstream climate resilience in NZIP technologies

This report has highted vulnerabilities of NZIP technologies to climate hazards. As DESNZ deploys funding to roll out these technologies, it should consider these vulnerabilities as part of funding decisions. To support DESNZ with this effort, criteria series of evaluation criteria have been developed to provide a concise, structured approach for evaluating how climate vulnerability and resilience could be considered in future projects funded by NZIP. These have not been applied in the assessment here but were developed as a framework for potential future use.

The evaluation criteria are organised around three core adaptation concepts – Exposure, Sensitivity, and Adaptive Capacity – which provide a concise, structured approach for evaluating how climate resilience could be considered in future projects funded by NZIP. Each category includes questions that are applicable across various technology contexts, ensuring a consistent approach while accommodating the unique aspects of each project.

The evaluation criteria are informed by guidelines produced by the World Bank's 'Resilience Rating System: A Methodology for Building and Tracking Resilience to Climate Change'[16], the European Commission's 'Technical guidance on the climate proofing of infrastructure in the period 2021-2027'[17] and the UK National Infrastructure Commission's 'Resilience Standards and Outcomes: A Summary of Principles and Standards for Economic Infrastructure Resilience'[18].

Unlike the World Bank's approach in the aforementioned report, scoring is not done as an 'overall grade' for project resilience. Instead, scoring is focused on specific aspects pertaining to Exposure, Sensitivity and Adaptative Capacity. This approach allows for strengths and weaknesses in specific areas of a project to be identified instead of producing one high-level, aggregate rating. Nevertheless, an aggregate score for each project could be derived if DESNZ is seeking one indicator of the extent to which a project addresses climate resilience. A 1-5 five-point scale response is used for each question to indicate the extent to which the project has addressed this aspect:

1. **Not at all** – No evidence of this aspect being addressed.
2. **Minimal** – Limited or partially addressed, with significant gaps remaining in addressing this aspect.
3. **Moderate** – Some evidence it is addressed, but key elements are incomplete or underdeveloped.
4. **Substantial** – Largely addressed, though minor enhancements may still be required.
5. **Fully Addressed** – Complete and comprehensively addressed, with all necessary measures implemented to address this aspect effectively.

Specific scoring considerations for each question are outlined in **Annex 5**. Whilst it is not expected that the evaluator will be an expert for the technological aspects of each project, with these criteria questions, they are seeking to see the extent to which the project has addressed these climate adaptation aspects.

When applying these criteria, it is important to consider the different project life cycle stages (design, construction, operation and decommissioning) where specific climate concerns would be identified, so eventual adaptation measures and/or practices would be suggested.

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[16] World Bank, 2021. Resilience Rating System: A Methodology for Building and Tracking Resilience to Climate Change. [pdf] https://documents.worldbank.org/en/publication/documents-reports/documentdetail/860801611264556929/resilience-rating-system-a-methodology-for-building-and-tracking-resilience-to-climate-change [Accessed 15 November 2024].

[17] European Commission, 2021. Technical guidance on the climate proofing of infrastructure in the period 2021-2027. [pdf] https://climate.ec.europa.eu/document/download/abd8d140-1808-4bc5-86ed-4cbb9352fd5c_en [Accessed 15 November 2024].

[18] National Infrastructure Commission, 2019. Resilience Standards and Outcomes: A Summary of Principles and Standards for Economic Infrastructure Resilience. [pdf] Available at: https://nic.org.uk/app/uploads/NIC-Resilience-Standards-Report-Final-190924.pdf [Accessed 15 November 2024].

It is also relevant to consider the whole value chain of the project to identify any potential direct/indirect climate impacts that may challenge the successful development of the entire project concept.

Evaluation criteria questions for each adaptation category are presented below:

Exposure

Location

- To what extent has the project assessed its location's exposure to specific climate hazards such as floods, droughts, or extreme heat?

Hazard intensity

- To what extent has the project identified and accounted for the range and intensity of climate hazards it may face now and in the future?

Sensitivity

Resource dependency

- To what extent has the project addressed its dependency on resources impacted by climate such as water, energy, or raw materials?

Performance impact

- To what extent has the project evaluated how climate could affect its performance?

Maladaptation[19] risk

- To what extent does the project avoid creating future vulnerabilities or maladaptation risks?

Adaptive Capacity

Adaptive management

[19] Maladaptation defined by the IPCC as 'actions that may lead to increased risk of adverse climate-related outcomes, including via increased greenhouse gas, emissions, increased or shifted vulnerability to climate change, more inequitable outcomes, or diminished welfare, now or in the future. Most often, maladaptation is an unintended consequence.' Source: IPCC, 2022. Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change – Summary for Policymakers. [pdf] Available at: https://www.ipcc.ch/report/ar6/wg2/downloads/outreach/IPCC_AR6_WGII_IntroductionWGII.pdf [Accessed 15 November 2024].

- To what extent is the project designed to evolve and adapt to future climate conditions or new climate information?

Recovery planning

- To what extent does the project include recovery strategies to ensure continuity of services during disruptions?

Governance structures

- To what extent does the project have internal governance structures that support its long-term resilience and adaptation goals?

Learning mechanisms

- To what extent does the project include mechanisms for ongoing monitoring, evaluation, and learning (MEL) in response to changing climate risks?

6. Annexes

Annex 1: Methodology

A.1.1 Identifying and agreeing NZIP technologies to assess

NZIP1 includes the following technologies:

1. Future offshore wind
2. Nuclear advanced modular reactors (supported through the aligned Advanced Nuclear Fund)
3. Energy storage and flexibility
4. Bioenergy
5. Hydrogen
6. Homes
7. Direct air capture and greenhouse gas removal (GGR)
8. Advanced carbon capture, usage and storage (CCUS)
9. Industrial fuel switching
10. Disruptive technologies

Initial discussions with the Project Steering Group confirmed that some technologies that are either likely to be important components of NZIP2, or will be relied on to achieve NZIP2 and future programmes on the path to net zero, are missing from this list. These included solar (particularly space-based solar and floating solar) and ocean energy (tidal and wave). In contrast, there was less interest in focusing on nuclear and industrial fuel switching, due to the greater existing understanding of the vulnerability/resilience of these technologies. Overall, the Project Steering Group selected the technologies that would be included in this review based on the overarching aim of "maintaining pathways to net zero until the preferred / most viable options become clearer." The following technologies were therefore included in this review:

1. **Future offshore wind, encompassing:**
    a. Electricity generation derived from offshore wind capacity, utilising both fixed and floating systems using offshore wind capacity. These include but are not limited to consideration of innovations and implementation of new structural elements including lightweighting components and composite materials;
    b. Impacts and resilience of respective critical supply chains particularly in relation to connectivity between offshore generation and onshore networks.

2. **Power networks, encompassing:**
    a. Electricity distribution networks including but not restricted to overhead lines, such as conductor sag, underground cables and pipes as well as key infrastructure components, incorporating transformers;
    b. Potential impacts on respective critical supply chains.
3. **Hydrogen, encompassing:**
    a. Hydrogen use, including but not restricted to lower cost, more efficient hydrogen gas turbines, co-location of production, storage, and usage;
    b. Development of alternative, large-scale hydrogen storage solutions that are quicker to deploy and likely to be more widely deployable than salt caverns (including lined rock caverns);
    c. Development of fast-cycling salt cavern storage capability;
    d. Potential impacts on respective critical supply chains.
4. **Advanced carbon capture, usage and storage (CCUS), encompassing:**
    a. A range of carbon capture technologies applied to industrial sites in the industrial, waste and power sectors. These carbon capture technologies may be coupled with a range of storage options, such as geological storage (carbon capture & storage) or be utilised in industrial processes to create products, such as materials, chemicals or fuels (carbon capture & utilisation). 'Advanced' CCUS, may refer to new methods of carbon capture that are yet to be deployed on commercial scales, beyond the amine solvent-based capture systems that are currently the most technologically ready capture technology available.
5. **Energy storage & flexibility, encompassing:**
    a. Systems enabling a smart and flexible energy system, including but not restricted to development of alternative large-scale, long duration energy storage solutions; including but not restricted to development of system operation capability (including systems and data);
    b. Potential impacts on respective critical supply chains.
6. **Bioenergy, encompassing:**
    a. Common pathways for bioenergy (for example, combustion and biogas), in addition to dedicated feedstocks, such as miscanthus or short rotation forestry. We do not capture evidence on the full range of feedstocks, such as agricultural residues or food waste. Similarly, we address biochar under 'direct air capture and greenhouse gas removal’ (T7).[20]

7. **Direct air capture (DAC) and greenhouse gas removal (GGR), encompassing:**
    a. Methods that receive policy support in the UK context, or methods that are currently practiced within voluntary carbon markets: DACCS, BECCS, enhanced weathering and biochar.[21]
8. **Buildings/homes, encompassing:**
    a. Development of low carbon heating/cooling for hard-to-treat buildings;
    b. Reducing the total cost of switching from gas boilers to heat pumps (various types);
    c. Reducing the cost and operating challenges of heat/cooling networks through, for example, the positioning or protection of equipment to minimise exposure to extreme weather, or the (retro)fitting of roof/wall/floor insulation;

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[20] Bioenergy is a source of energy from the organic material that makes up plants, known as biomass. Biomass contains carbon absorbed by plants through photosynthesis. Bioenergy is principally used to refer to the combustion of biomass to produce energy, where the carbon released during combustion returns to the atmosphere, making bioenergy a near zero-emission fuel. For example, biomass combusted to produce process heat or electricity as already practiced at industrial sites across the UK.
Bioenergy may also refer to pathways that convert biomass into another energy carrier without combustion, such as biomass gasification, which can be used to produce syngas, which can then be transformed into hydrogen or a range of biofuels, such as biojet fuel. Biomethane can similarly be produced through anaerobic digestion or gasification of biomass. Pyrolysis may also be used to produce hydrogen and biochar.
A range of feedstocks may be used including dedicated energy crops, such as miscanthus or short rotation forestry, alongside biogenic wastes such as agricultural residues, food wastes, farm waste and sewage. As a result of the range of feedstocks, bioenergy may be produced at a range of sites, including industrial or energy from waste sites, in the case of combustion, but also landfills and wastewater treatment plants. Similarly, if coupled with carbon capture and storage (CCS), bioenergy pathways may produce negative emissions, constituting a method of greenhouse gas removal whilst producing energy (or BECCS). In many pathways, bioenergy is combined with CCS to produce both hydrogen, biochar, or other products. UK climate policy will increasingly require the application of CCS, as noted in the 2023 Biomass Strategy. After deliberation amongst the Project Steering Group, it was decided that BECCS was best addressed separately under T8, 'DAC and GGR'.

[21] Direct air capture refers to the capture of atmospheric CO_2 via solid or liquid sorbents. The captured CO_2 is then permanently stored, for example, in geological storage, or utilised, for example, in the manufacturing of synthetic fuels, such as kerosene and methanol. If utilised in short-duration storage DAC is a method of carbon capture and utilisation (or 'DACCU'), as the captured CO_2 is returned to the atmosphere. If permanently stored, DAC may be referred to as a method of greenhouse gas removal (or 'DACCS', direct air carbon capture and storage). We propose to capture within the evidence review both the storage and utilisation of CO_2 with respect to DAC.
Greenhouse gas removal is a term used more exclusively in the UK policy context, as an umbrella term to refer to a range of methods of removing and permanently storing, principally CO_2, from the atmosphere. This includes DACCS alongside enhanced weathering, biochar, and bioenergy with carbon capture and storage (BECCS). BECCS in the UK context refers a range of pathways that capture biomass, biogenic waste or biogas into another energy carrier, such as power, heat, fuels, hydrogen or methane. This may therefore overlap with, for example, advanced CCUS applications in the waste sector, if co-combusting biogenic wastes, or biomass gasification if used in conjunction with carbon capture and storage. The CCC (and DESNZ) definition of GGR includes, in addition to the methods mentioned, wood in construction, biomass burial, carbon-negative cements, and ocean-based removal methods (such as ocean alkalinity enhancement). The UK tends to use the term "engineered carbon dioxide removal" to describe principally DACCS & BECCS.

d. Energy efficiency measures, demand management measures and building control measures.

9. Ocean energy, encompassing:

a. All relevant ocean energy methods inlcuding but not restricted to tidal and wave energy systems.

10. Solar energy, encompassing:

b. Traditional solar technologies including but not restricted to rooftop, ground-mounted and floating solar.

A.1.2 Climate-related hazard selection and geographic scope

To identify the climate-related hazards against which the vulnerability/resilience of these technologies was assessed, the research team looked to the Climate Change Committee's report: "Delivering a reliable decarbonised power system", which identified the following key climate-related hazards of relevance to the UK power system:

1. Heatwaves
2. Flooding (river, surface, and coastal)
3. Drought
4. Wind strength and wind regimes
5. Storminess and occurrence of storm events[22]
6. Snow and ice

In discussions with the Project Steering Group, we agreed to add erosion to the list of climate-related hazards against which vulnerability would be assessed.

The geographical scope of this review was agreed to be UK-wide. This review does not provide separate assessments for specific geographical regions of the UK, or any other form of spatial analysis. The analysis therefore focuses on direct and indirect effects on climate vulnerability and resilience in the UK and does not explore trans-boundary effects.

A.1.3 Rapid Evidence Assessment

This project assessed the climate vulnerability/resilience of each selected technology to the climate-related hazards listed in the preceding section. The assessment used the Rapid Evidence Assessment (REA) methodology,[23] searching for and identifying evidence

[22] Wind strength and wind regimes refer to long-term patterns and intensities of wind, like average speeds and directions. In contrast, storminess and storm events are short-term, intense occurrences like hurricanes or thunderstorms, leading to immediate, localised damage. The key distinction is that wind regimes are ongoing and cumulative, while storms are distinct episodes/events.

[23] See Collins, A., Coughlin, D., Miller, J. and Kirk, S. (2014) The Production of Quick Scoping Reviews and Rapid Evidence Assessments: A How to Guide, Joint Water Evidence Group, Defra. Smithers, R.J. (2015) SPLiCE Phase 1: A methodology for Rapid Evidence Assessments. Report for Defra.

encompassing both components of climate vulnerability: sensitivity and adaptive capacity. This assessment was based on the definitions of terms contained in the IPCC's Sixth Assessment Report (AR6: WGII Glossary). This ensures comparability with similar assessments conducted within the UK and internationally. Sensitivity and adaptive capacity are defined by the IPCC as follows:

Sensitivity: The degree to which a system or species is affected, either adversely or beneficially, by climate variability or change. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range, or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea level rise).

Adaptive capacity: The ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities or to respond to consequences.

The REA identified evidence regarding each technology's sensitivity/adaptive capacity to each climate-related hazard. This began with a search of the available academic literature but was supplemented by grey literature[24] searches. In accordance with the REA methodology, one person was assigned to review the literature for each technology. A QA check was done of random 10% of papers per technology to check if the correct and relevant information was extracted from the literature. The results of this literature review are captured in an evidence extraction Excel workbook, attached as **Annex 2**.

As the NZIP technologies are cutting-edge, there may not be sufficient literature available even on completion of each of these steps. To fill gaps where relevant information on the vulnerability/resilience of these technologies had not yet been published, and to validate the findings of the review of academic and grey literature, we conducted interviews with expert stakeholders to further build the evidence base. This step was particularly important regarding adaptive capacity, which is rarely captured in the literature and often needs to be assessed via interviews with expert stakeholders.

We conducted interviews with expert stakeholders to test the findings of the REA. This included experts in these technologies within Ricardo and Tyndall, in DESNZ and other government departments, and external experts working in the industry. These experts helped to address gaps in the evidence base, while also bringing their practical insights and experience from the use of these technologies into the evidence base. Their additions are

[24] This included the online publication repositories of the DESNZ, Defra, CCC, the Scottish Government, the Northern Ireland Assembly Department of Agriculture, Environment and Rural Affairs (DAERA), and the Welsh Government, among other sources. The platform from which each source of grey literature was identified is recorded in the evidence extraction spreadsheet, attached as **Annex 2**.

reflected in the narrative descriptions that accompany the ratings of sensitivity and adaptive capacity for each technology – this process is set out in the next section (**Section A.1.4**).

A.1.4 Vulnerability / resilience rating

The climate vulnerability/resilience of each technology has been assessed by rating the sensitivity and adaptive capacity of each technology to each climate-related hazard using the following matrices and definitions for each rating:

Definitions for rating climate sensitivities:

Sensitivity rating	Definition of ratings	
1	**Low**	Insensitive to climate
2	**Low-medium**	May be sensitive to climate
3	**Medium**	Climate sensitive
4	**Medium-high**	Very climate sensitive
5	**High**	Extremely climate sensitive

Definitions for rating adaptive capacities:

Adaptive capacity rating	Definition of ratings	
1	**Low**	Major challenges to adjust or respond within existing climate limits
2	**Low-medium**	Minor challenges to adjust or respond within existing climate limits
3	**Medium**	Able to adjust or respond within existing climate limits but major challenges beyond them
4	**Medium-high**	Able to adjust or respond within existing climate limits but minor challenges beyond them
5	**High**	Able to adjust or respond regardless of climate

Definitions for vulnerability ratings:

Vulnerability rating	Definition of ratings
1	Highly resilient
2	Resilient
3	Potentially vulnerable
4	Vulnerable
5	Highly vulnerable

Vulnerability matrix:

Adaptive capacity	5	1	2	2	3	3
	4	2	2	3	3	4
	3	2	3	3	4	4
	2	3	3	4	4	5
	1	3	4	4	5	5
Vulnerability		1	2	3	4	5
		Sensitivity				

The assessment is recorded in an Excel workbook attached as **Annex 3**. For each rating, a series of columns was completed, including:

1. Qualitative description of sensitivity / adaptive capacity to support the rating, by reference to the evidence assessed.
2. Confidence in each rating – based on strength of evidence and level of agreement (discussed further below).

3. Caveats.

4. Evidence gaps and further research needs.

Confidence has been rated in line with the IPCC AR5 and AR6 methodology by considering:

1. Number of studies and **strength** of their evidence:[25]

    a. 3 indicates robust evidence: relevant evidence from at least one peer-reviewed source.

    b. 2 indicates medium evidence: no relevant peer-reviewed literature, relevant evidence from at least one grey literature source.

    c. 1 indicates limited evidence: no relevant peer-reviewed or grey literature, only expert judgment.

2. Level of **agreement** between sources of evidence:

    a. high (3): all sources agree[26] (i.e. full agreement; no disagreement in literature or expert discussions found)

    b. medium (2): only one source disagrees (i.e. some agreement; one disagreement between experts and literature)

    c. low (1): multiple sources disagree (i.e. no agreement – relevant peer-reviewed or grey literature and experts contradict each other)

These dimensions were combined using a matrix to give an overall confidence rating on a scale[27] from 1 (low) to 5 (high) for each of the ratings as follows.

[25] While this number of evidence sources may not be considered "robust/medium/limited" in all contexts, it is important to bear in mind the context of this research. There is less literature available on the resilience of these cutting-edge net zero technologies due to the relatively short time during which they have been studied and implemented. These confidence ratings are therefore meant to be realistic to the state of the literature on these technologies, and to provide an indication of relative confidence in findings across the different technologies.

[26] Where only one source of evidence is cited, this was considered to be "all" sources agreeing. This is because all results were presented to expert stakeholders, who were given the opportunity to disagree with each conclusion. Where they did not disagree with the source cited, this has been considered as agreement for the purposes of understanding the extent to which consensus exists around the point of evidence relied upon.

[27] A low confidence rating includes any number between 2.5 and 3.0; a medium confidence rating includes any numbers between 3.5 and 4.0; a high confidence rating includes any numbers between 4.5 and 5.

<table>
<tr><td rowspan="3">Agreement</td><td>High agreement = 3</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td>Medium agreement = 2</td><td>2</td><td>3</td><td>4</td></tr>
<tr><td>Low agreement = 1</td><td>1</td><td>2</td><td>3</td></tr>
<tr><td colspan="2" rowspan="2">Confidence</td><td>Limited evidence = 1</td><td>Moderate evidence = 2</td><td>Robust evidence = 3</td></tr>
<tr><td colspan="3">Strength of evidence</td></tr>
</table>

For ease of review, the vulnerability/resilience ratings, alongside the confidence in these ratings, for each technology for each climate-related hazard was combined in a colour-coded synthesis sheet in the workbook attached as **Annex 3**.

As part of the assessment, adaptation options were also identified.

Annex 2: Rapid Evidence Assessment – Evidence Extraction Workbook

Please see the attached Excel workbook which contains the results of the evidence extraction process outlined in the methodology above.

Annex 3: NZIP Resilience Review Ratings Workbook

Please see the attached Excel workbook which contains the results of the vulnerability/resilience rating process outlined in the methodology above.

Annex 4: Case studies

The following case studies contain references to key documents throughout. These are included as footnotes, or by using a reference code system Tx-y, where Tx refers to the technology (T2: power networks, T3: Hydrogen, T4: CCUS, T8: Building) , and y refers to the reference number. A full list of coded references for each technology can be found in the ‘Evidence extraction excel workbook’ in **Annex 2**.

A.4.1 Case study 1: Power Networks

A.4.1.1 Description of technology

Power networks are essential infrastructure systems that facilitate transmission and distribution of electricity[28]. These networks are structured across different phases of the electricity supply chain – generation, transmission, and distribution – each addressing specific technical and operational needs. This structure ensures electricity is reliably and safely delivered to end-users, from large industries to residential consumers.

The transmission network carries high-voltage electricity across long distances from power plants to substations. Key components here include high-voltage transmission lines (often overhead) and transformers that, for example, step up the voltage produced by generators. Higher voltages reduce electricity losses over long distances, making bulk electricity transport to populated regions more efficient. As such, high-voltage direct current (HVDC) systems are increasingly used in the transmission network due to their efficiency for long-distance and underground routes; they also help reduce line losses compared to traditional Alternating Current (AC) transmission[29].

Distribution networks operate at lower voltages and deliver electricity from substations to end users. Distribution systems include transformers, cables, and overhead lines. Here, transformers step down the voltage from transmission levels to safer, more usable levels for residential and commercial consumers. These distribution transformers are often found on poles or in ground-level enclosures near buildings, where they make power accessible for local consumption.

As the climate changes, power networks face increasing vulnerabilities[30]. For example, rising temperatures reduce the efficiency of overhead transmission lines[31] and transformers, while more frequent and severe storms or flooding events can damage substations and underground cables. Flooding can have lasting impacts, especially on substations where sensitive electrical equipment is exposed to water. The aging of existing infrastructure poses additional challenges. Upgraded networks can integrate renewable sources more efficiently, support a balanced grid, and improve overall system reliability – essential steps in the transition towards net zero.

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[28] National Grid, 2022. https://www.nationalgrid.com/stories/energy-explained/electricity-transmission-vs-electricity-distribution.
[29] GGI Insights, 2024. https://www.graygroupintl.com/blog/energy-infrastructure.
[30] IEA, 2020. https://www.iea.org/reports/power-systems-in-transition.
[31] There is an ongoing research project under the CS-N0W programme that is exploring ‘Impact of extreme heat and heatwaves on energy assets across the UK energy system’. The study goes into further detail on vulnerability of and potential impact to assets within power networks (amongst other system functions). Findings will be available in January 2025.

As a result, it is essential for utilities to actively consider investments in upgrades, both to support the energy transition and enhance climate resilience. These advancements can reduce the likelihood of outages during extreme weather events and protect critical services such as healthcare and transportation, which rely heavily on uninterrupted power supply.

A.4.1.2 Key vulnerabilities

Power networks were found to be vulnerable to five out of the seven identified climate hazards, including flooding, wind strength, storminess, snow and ice, and heatwaves, as highlighted in Table 6-1.

Table 6-1 Vulnerability rating of power networks

Climate Hazard	Level of Vulnerability/Resilience (Rating)	Confidence (Rating)
Flooding	Vulnerable (4) – extremely climate sensitive, medium-high adaptive capacity	High
Wind strength and wind regimes	Vulnerable (4) – very climate sensitive, medium adaptive capacity	Medium
Storminess and occurrence of storm events	Vulnerable (4) – very climate sensitive, medium adaptive capacity	Medium
Snow and ice	Potentially vulnerable (3) – climate sensitive, medium-high adaptive capacity	Medium
Heatwaves	Potentially vulnerable (3) – very climate sensitive, high adaptive capacity	Medium

Flooding: Power networks were identified to be most vulnerable to the impacts of flooding, driven by the sensitivity of power network infrastructure to flooding both directly and indirectly. Prolonged exposure to water can physically damage equipment, for instance by undermining transformer and tower foundations and compromising their structural integrity (T2-20). Similarly, substations and underground cables are also sensitive to water damage caused by flooding, which can ultimately lead to short-circuiting (T2-20, 14, 15, 18). In addition to this, power network infrastructure was found to be equally sensitive, and therefore vulnerable, to the indirect effects of flooding, for instance, the physical damage caused by rockfalls and landslides that often result from flooding (T2-20). Similarly, flooding can also hamper response and restoration efforts in the aftermath of faults caused by flood effects.

Despite this sensitivity to flooding, investments are increasingly being made to bolster power networks' resilience through enhanced flood protection. Regulators are routinely investing in flood protection and resilience upgrades such as flood detection sensors to minimise water damage at critical sites such as major substations. With flood protection considerations built into the design and planning of power networks, infrastructure in high-risk zones is increasingly able to respond to flood risk (T2-27).

Wind strength and wind regimes: Extreme winds can cause physical damage to substations and overhead lines, which makes power networks sensitive to the climate-hazard wind strength and wind regimes (T2-18, 52). High wind strength can damage power line infrastructure, particularly due to trees that may fall over bringing down poles tor towers, or cause short circuit conditions, which in turn increases the risk of power outages (Ricardo experts). Power networks' direct sensitivity can further be amplified by indirect sensitivity, as fallen trees, debris and broken poles can leave roads obstructed, hindering emergency response and restoration (T2-52).

To mitigate these risks, power network operators have implemented tree management programs, proactively trimming and removing vegetation near power lines to reduce the likelihood of wind-related damage. This preventative approach helps to improve network resilience against high wind events, minimising potential disruptions and damage (Ricardo experts).

Storminess and occurrence of storm events: Storms can bring strong winds, flying debris, and saltwater exposure that can physically damage equipment (T2-20, T2-8). Overhead transmission lines and transformers face elevated risks from storm conditions, as high winds and falling trees frequently cause short circuits, faults, and power outages (T2-25, 34). Likewise, lightning strikes during storms may also induce overvoltages, posing a fire risk to cables and transformer towers (T2-1). Storms also carry the potential for landslides and flooding, which can further damage substations, transmission poles, transformers, and cables. To this end, substations in coastal areas are particularly sensitive to storm surges and ensuing coastal erosion, which increases the likelihood of service disruptions (T2-20). Notably, prolonged exposure to wet environments can corrode equipment and reduce infrastructure lifespans (T2-20). Furthermore, storm-induced damage to information and communication technology (ICT) indirectly impacts power networks, given their reliance on ICT infrastructure for operations (DESNZ experts).

To address storm-related risks, power networks include design features to withstand wind, lightning, and storm surges. However, while storms are accounted for in current network planning, the anticipated increase in storm severity and frequency due to climate change suggests that network designs will require updating to ensure resilience under more intense conditions (DESNZ experts).

Snow and ice: Power networks are also sensitive to physical damage caused by snowfall and ice accumulation (T2-20), albeit less so. Heavy snow or ice can weigh down overhead lines, making them more susceptible to strong winds, which can cause "galloping" – a phenomenon where the lines move erratically, causing short supply interruptions such as flickering lights (T2-52). Additionally, icing during cold weather can significantly reduce the capacity of power lines, further compromising the efficiency of networks (T2-25, T2-34). However, it is important to consider that cold weather can drive increased demand for electricity, leading to higher current flow in the cables, which may counteract some icing effects by generating additional heat (DESNZ experts).

To address these challenges, existing standards for ice accumulation on power lines are actively applied, ensuring that infrastructure can withstand typical ice loads (DESNZ experts). This proactive approach aims to maintain operational efficiency and reduce the risks associated with snow and ice impacts on the power network.

Heatwaves: Power networks are sensitive to extreme heat and heatwaves through three primary channels; physical damage to power lines, reduced transmission efficiency, and potential impacts on critical supply chains that underpin the transmission and distribution of power. Higher temperatures can damage power lines primarily by accelerated degradation and increased sagging (T2-24, 25). Heat-induced material fatigue can weaken the structural integrity of these materials, increasing the likelihood of faults and reducing the overall lifespan of the power line infrastructure. Sagging is also a greater concern for overhead lines, which have less structural support than buried cables and are directly exposed to ambient temperature changes. Higher temperatures likewise reduce the efficiency of power distribution, by impacting transmission capacity of power lines (T2-27), and also increase electrical resistance in conductors, reducing transmission efficiency. This results in higher energy losses, as more of the transmitted electricity is dissipated as heat rather than reaching end-users (T2-17). Increased sagging due to higher temperatures increases efficiency losses in power lines. Heatwaves can also impact power networks by reducing the efficiency of photovoltaic (PV) power generation (T2-4) and by limiting thermoelectric power generation due to warmer water temperatures that reduce cooling efficiency (T2-17). Additionally, extreme heat can intensify the urban heat island effect in densely populated areas (T2-7) leading to higher infrastructure costs and greater risk of power supply outages. As such, these challenges can further strain critical supply chains linked to transmission and distribution infrastructure.

Despite an inherent sensitivity to extreme heat, power networks do possess certain components which afford them the ability to adapt. Protection and monitoring technologies such as thermal protection relays, overhead line monitoring and dynamic line rating (DLR) enhances their ability to adapt and respond to heatwaves (Ricardo experts). Notably, the shift towards data-driven and predictive planning has further enhanced power networks' adaptive capacity. AI is increasingly utilized to enhance forecasting and planning capabilities for heat-related challenges. Furthermore, "digital twins" allow utilities to simulate network resilience scenarios and improve adaptability (Ricardo experts, DESNZ experts).

A.4.1.3 Key areas of resilience

The only climate hazard, out of the seven assessed, that power networks were found to be resilient to was drought, see Table 6-2.

Table 6-2 Resilience ratings for power networks

Climate Hazard	Level of Vulnerability/Resilience (Rating)	Confidence (Rating)
Drought	Resilient (2) – may be sensitive to climate, high adaptive capacity	Low

Power networks were found to be resilient to drought conditions because water scarcity poses less risk to power transmission and distribution equipment. Rather, it is of greater concern for power generation equipment, where limited water availability can lead to overheating and operational failures, directly affecting power output and system reliability. By contrast, water availability is not an acute concern for power networks themselves, which can operate reliably even under drought conditions (Ricardo experts).

A.4.1.4 Potential adaptation options

This study shows that despite vulnerabilities to the identified climate hazards, there is potential to enhance the resilience of power networks through the application of targeted adaptation measures outlined in Table 6-3.

Table 6-3 Adaptation options for power networks

Climate Hazard	Adaptation Option(s)
Flooding	▪ Site selection and design
Wind strength and wind regimes	▪ Hardening measures ▪ Applying robust design principles to new transmission facilities
Storminess and occurrence of storm events	▪ Network of distributed energy storage systems can aid restoration and re-energising of systems
Snow and ice	▪ Apply existing standards for ice accumulation on power networks
Heatwaves	▪ Site selection and design ▪ Maintenance and life extension of existing assets. This could include upgrading to heat resistant materials.

	▪ Decentralised distribution systems should be utilised to reduce risk of power outages.

Flooding: To manage flooding risks, power networks can enhance resilience through strategic site selection and robust design standards. Facilities should be constructed in locations less prone to flooding, and those in vulnerable areas should employ flood-resistant designs. Integrating flood vulnerability mitigation measures into regulatory frameworks and project approval processes ensures these considerations are standard in all future infrastructure. These adjustments protect the network from flood-induced damages and reduce service interruptions during extreme weather events.

Wind strength and wind regimes: Power networks exposed to high winds can benefit from hardening measures, including undergrounding transmission lines, and upgrading structural elements. Stronger materials and reinforced poles can enhance resilience against severe wind. These upgrades can reduce the likelihood of line damage or collapse, particularly in high-wind areas. In locations where constructing new transmission facilities is essential, applying these robust design principles ensures long-term stability and minimises disruption during wind events.

Storminess and occurrence of storm events: During severe storm events, the implementation of distributed energy storage systems can support grid resilience. These systems allow the network to operate in an "islanded" mode, independent of the main grid, and can release stored energy in a coordinated fashion to maintain power delivery. This distributed storage network assists in the rapid restoration and re-energising of power systems after disruptions, minimising the impact on customers and enabling faster recovery from storm-induced outages.

Snow and ice: Current standards for ice accumulation on power networks are considered sufficient to manage the effects of snow and ice. Since these standards already address accumulation impacts, no additional adaptation measures were identified. Regular monitoring and maintenance of these standards will ensure continued resilience to ice-related vulnerabilities.

Heatwaves[32]: Adaptation to heatwave vulnerability requires incorporating heat resilience into guidelines, regulations, and project approval processes. Site selection, design, and maintenance should consider extreme temperatures, as well as other associated risks like flooding and water scarcity, to extend the life and effectiveness of network assets. This could include upgrading systems to heat resistant materials. Decentralised distribution systems are also critical during extreme heat events, as they allow localised management and

[32] There is an ongoing research project under the CS-N0W programme that is exploring 'Impact of extreme heat and heatwaves on energy assets across the UK energy system' (G8). The study goes into further detail on vulnerability of and potential impact to assets within Power Networks (amongst other system functions). Findings will be available in January 2025.

quicker response to power outages. These measures ensure that power networks remain functional, minimise disruptions during extreme heat and protect system outputs under future climate conditions.

A.4.1.5 Evidence gaps

In assessing the vulnerability and resilience of power networks, this study has identified several areas in need of further research. Addressing these evidence gaps can enhance our understanding of the vulnerability/resilience of power networks to climate hazards and facilitate the application of targeted adaptation measures to counteract vulnerability. The following lists the evidence gaps identified for the power network technology:

- **Heatwaves:** To enhance resilience against heatwaves, there is a need for innovation in overhead alternating current (AC) cable technology. High-temperature, low-sag conductors could reduce some of the negative impacts that may result during periods of extreme heat. Research and development in this area would provide solutions to manage the stress placed on traditional conductors in hot weather, improving network reliability under higher temperatures.
- **Flooding:** Further research is needed to assess the implementation and effectiveness of planned flood protection measures for power networks. Understanding the degree of implementation and learning from the impacts of these measures will help improve flood resilience across the sector and establish best practices for flood mitigation in vulnerable areas.
- **Storminess and occurrence of storm events**: The UK CCRA3 also highlights a broader "adaptation shortfall" that extends to storm and wave events, especially given the increasing reliance on offshore wind. Further investigation is needed into the risks these storm events pose to offshore infrastructure and the ways in which offshore energy assets can be better protected against storm surge, waves, and extreme winds.
- **Snow and ice:** For snow and ice hazards, research is needed to determine how increased demand for power in cold weather, which generates heat in the cables, might offset icing on power lines. By examining this balance, the sector can better understand the real impact of snow and ice accumulation on power lines during winter months and optimise strategies to prevent power losses during extreme cold.

A.4.2 Case study 2: CCUS

A.4.2.1 Description of technology

Carbon capture, usage, and storage (CCUS) refers to a range of methods and technologies developed to remove CO_2 from point sources such as power generation and industrial facilities. The captured CO_2 in this process is then either utilised for other industrial uses or stored in a safe and permanent place. There are different kinds of storage options coupled with the use of these technologies:

- *Geological Storage (Carbon Capture & Storage):* This methodology involves the transport of captured carbon, via road, rail, ship, or pipeline, and storage in underground geological formations, such as under the seabed[33].
- *Other Storage and utilisation options:* Captured carbon can also be used to create products. There are a variety of pathways for the utilization of carbon dioxide, such as by processing with chemicals, fuels, or sequestration in construction materials[34]. It can also be used and then emitted again, for instance through chemical conversion used to make synthetic fuels[35].

CCUS technologies can support the phase out of fossil-based energy production, such as gas power plants by reducing CO_2 emissions released to the atmosphere at the source. Additionally, in the UK, CCUS can facilitate the growth of low-carbon hydrogen production. CCUS is therefore seen as a crucial technology in the mitigation of CO_2 emissions[36]. It is thought to be an instrumental player in facilitating economic development while supporting decarbonisation pathways.

A.4.2.2 Key vulnerabilities

CCUS technology was identified as vulnerable to half of the climate hazards assessed: flooding, heatwaves, drought, and snow and ice. There is a medium to high confidence rating on the identified vulnerabilities, based on literature available and discussions with experts, as shown in Table 6-4.

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[33] NOAA, 2022. https://www.noaa.gov/carbon-capture-and-storage-in-sub-seabed-geological-formations.

[34] Hepburn, C., Adlen, E., Beddington, J., Carter, E.A., Fuss, S., Mac Dowell, N., Minx, J.C., Smith, P. and Williams, C.K., 2019. The technological and economic prospects for CO2 utilization and removal. *Nature*, *575* (7781), pp.87-97.

[35] CCUS Hub, 2024. https://ccushub.ogci.com/ccus-basics/understanding-ccus/.

[36] IPCC, 2022*: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926

Table 6-4 Vulnerability rating of CCUS

Climate Hazard	Level of Vulnerability/Resilience (Rating)	Confidence (Rating)
Flooding	Vulnerable (4) – extremely climate sensitive, medium adaptive capacity	Medium
Heatwaves	Potentially vulnerable (3) – very climate sensitive, medium-high adaptive capacity	Medium-High
Drought	Potentially vulnerable (3) – climate sensitive, medium-high adaptive capacity	High
Snow and ice	Potentially vulnerable (3) – may be sensitive to climate, low-medium adaptive capacity	Medium

Flooding: Flooding was identified as the hazard that CCUS is most vulnerable to. Firstly, flooding was found to pose a risk to pipelines, such as those used for natural gas. CCUS pipelines can experience similar vulnerabilities. There are several causes for this; flooding can cause additional pressure to be placed on pipelines due to the change in weight and density of the soil, leading to bending and shifting which could lead to ruptures over time. Additionally, floodwaters could cause the unearthing of pipelines, which leaves them exposed to water, environmental stressors, and surrounding debris, which can lead to the corrosion of the outer surface, weakening the material. These risks are observed across a range of underground pipelines, such as those used for natural gas and CO_2 pipelines (T4-28). Heavy rains and flooding can also result in events such as landslides, which have previously caused a CO_2 pipeline to rupture due to excessive pressure placed on the pipeline weld (T4-27). There are some major industrial hubs that are connected via pipeline in the UK, such as the Grangemouth pipeline that connects Scotland to mainland Europe. It is therefore crucial to consider how these pipelines can be made resilient to hazards such as flooding.

Secondly, floods can present a risk to other CCUS infrastructure, outside of pipelines. For instance, CCUS facilities, particularly in low-lying areas if flooding levels are outside of current thresholds, could be damaged by floodwaters, causing damage or reduced efficiency, and the potential release of captured carbon (T4-21). These infrastructures could include CCUS infrastructure located near ports, such as the hydrogen super-hub in the Port of Southampton, a new scheme which will incorporate CCUS technologies[37]. Flooding may

[37] UK Government, 2024. https://www.great.gov.uk/international/investment/sectors/carbon-capture-usage-and-storage/.

also increase the instability of excavation sites for carbon storage due to the presence of additional groundwater changing the stability of the soil (T4-21).

Heatwaves: Extreme temperatures can disrupt the integrity and efficiency of CCUS systems by degrading materials or decreasing cooling efficiencies for example (T4-21; T4-20). While absorber columns are designed to withstand high temperatures, other parts of the CCUS chain, such as pipelines may be more vulnerable. Heatwaves can cause variations in the surrounding soil temperature, which can be transferred to the pipeline structure. Temperature changes within the pipe can cause changes in pressure and volume of the captured carbon inside, increasing the fragility of the pipe infrastructure (Ricardo expert). While CCUS technologies are able to withstand temperatures within the existing climate limits, challenges remain beyond them, especially in the case of repeated exposure to extreme temperatures.

Drought: CCUS is a water resource-intensive technology. Restrictions on water resources may occur in the future, particularly during periods of drought where limitations on industrial water usage may be put in place. Water is required for cooling processes at the power-plant level and is also an integral part of the carbon capture processes. Therefore, periods of drought can cause operational challenges, such as halting carbon absorption and increasing costs (T4-1, T4-12).

Snow and Ice: CCUS technologies may also be vulnerable to snow and ice due to the low temperatures. This particularly affects the integrity of the transportation pipelines which can be particularly vulnerable due to the risk of low temperatures causing cracks in the pipes, tanks and vessels involved in the transportation of captured CO_2 (T4-23). This could also cause the release of captured carbon, rendering the technology ineffective. CCUS technologies are able to respond within existing climate limits, but major challenges remain beyond them.

A.1.4.1 Key areas of resilience

CCUS technology was found to be resilient to half of the climate hazards assessed: erosion, storminess and occurrence of storm events, and wind strength and wind regimes. However, confidence in the strength of resilience is low due to the literature available currently, see Table 6-5.

Table 6-5 Resilience rating of CCUS

Climate Hazard	Level of Vulnerability/Resilience (Rating)	Confidence (Rating)
Erosion	Resilient (2) – low-medium sensitivity, medium-high adaptive capacity	Low

Storminess and occurrence of storm events	Resilient (2) – low-medium sensitivity, medium-high adaptive capacity	Medium
Wind strength and wind regimes	Very Resilient (1) – low sensitivity, high adaptive capacity	Low

Erosion: There is little research done on the possible effects of erosion on CCUS technologies, with the confidence rating for this technology being classified as low. However, erosion can undermine the foundations of CCUS infrastructure, leading to structural instability of capture technologies, particularly for facilities in coastal or riverine areas (Ricardo experts). It is therefore important to monitor for the possible effects of erosion at capture and storage sites overtime.

Storminess and occurrence of storm events: Few vulnerabilities were identified for this hazard. This is largely due to pipelines being protected from the effects of inclement weather by being underground. Some sensitivity could be experienced during the transportation of CO_2 in various modes of transportation, either through road, rail, or ship, as transportation can be vulnerable to disruptions caused by storms and extreme weather events. Transport via ship is considered to be particularly vulnerable to these disruptions, especially when no other mode of transport is available, however as ship transport is not likely to be the main means of CO_2 transport in the UK, this was marked as low sensitivity.

Wind strength and wind regimes: Little evidence was found to describe the climate risk of CCUS to high winds. This is likely due to neither the capture nor storage technologies of CCUS being exposed to the effects of high winds. However, this underlies a high uncertainty reflected in the low confidence rating which is supported by only one expert judgment. Further research should be considered in the future.

A.1.4.2 Potential adaptation options

This study has identified several ways that CCUS technologies can build and maintain resilience in the future. Adaptation options were identified for heatwaves, droughts, and flooding, three of the hazards that CCUS was found to be at least potentially vulnerable to. No other adaptation options were identified for the other hazards. See a summary in Table 6-6 and below.

Table 6-6 Identified adaptation options for CCUS

Climate Hazard	Adaptation Option(s)
Flooding	▪ Elevating low-lying infrastructure and groundwater observations and monitoring ▪ Flood tunnels and sustainable drainage systems

Drought	▪ Wet/dry hybrid towers for water cooling in CCS power plants ▪ Solid or bio-based sorbents that do not require large amounts of water for the heating (and cooling) of liquid solvents. ▪ CO_2-enhanced water recovery (CO_2-EWR) technology
Heatwaves	▪ Use of heat-resistant materials ▪ Development of real-time temperature monitoring systems ▪ Advanced cooling systems

Flooding: For CCUS technologies, flooding can be difficult to adapt to, especially in low-lying or coastal areas where there is an increased risk of groundwater flooding (Ricardo experts). The adaptive capacity of CCUS to flooding is considered medium. Elevating critical infrastructure above potential flood levels and ensuring the capture plant is not in the downstream floodplain are some adaptation options protecting CCUS infrastructure from floodwaters. Groundwater observations and monitoring should also be carried out throughout build sites, as well as risk assessments (T4-21).

Another strategy that can alleviate some of the risk and damage caused by floods, particularly to underground pipelines, is the development of flood tunnels (T4-28). Underground flood tunnels can redirect excess flood and stormwaters away from the surface and original basin. However, the development of flood tunnels is restricted by geographical features such as rock type, density and groundwater and it can be a very lengthy construction project. Alternative strategies could include sustainable drainage systems that collect and temporarily store excess storm water and then slowly release it into the stormwater system. Mitigating the damage and impact of floodwaters can protect CCUS infrastructure and pipelines from floodwater damage.

Drought: CCUS technology will need to enhance water recovery and reduce water usage to adapt to drought. Water-efficient technologies such as wet/dry hybrid towers can reduce water usage for water cooling in CCS power plants (T4-1). Solid or bio-based sorbents are also alternative options for the absorption process. Unlike liquid solvents, they do not require large amounts of water. Solid sorbents present themselves as a viable alternative to existing absorption technologies, however, large-scale operational technologies are still under-developed (T4-29). Furthermore, but proposed mainly in areas of high aridity and as co-location of coal CCS, advanced CCUS systems can also enhance water recovery through CO_2-EWR technology, which extracts water from deep saline aquifers. These technologies both store CO_2 and provide an alternative water source by injecting CO_2 into deep saline layers while displacing liquid mineral or deep-water resources. These technologies already exist in the oil and gas extraction industry, demonstrating their commercial viability (T4-12).

Heatwaves: Integrating the use of heat-resistant materials to the construction of CCUS infrastructure and integrating real-time monitoring systems to detect and respond to temperature fluctuations will make CCUS infrastructure more resilient to sudden high-temperatures (T4-20). Additionally, the development of cooling systems, particularly surrounding capture technologies, will help to maintain operational efficiency during heatwaves (T4-12).

A.4.2.3 Evidence gaps

Due to limited literature assessing the vulnerability and resilience of CCUS technologies to climate hazards the confidence levels of the vulnerability ratings are low. More research is necessary to understand the climate-related vulnerabilities of CCUS technologies overall. Particularly, it will be necessary to understand how climate hazards may impact different parts of the CCUS operational chain, from capture technologies, transport to storage. Additionally, more research is required to understand the different capture technologies (e.g., membranes, absorption, adsorption) as they may have different vulnerabilities to climate hazards. Finally, further consideration will be required to understand what the impact of climate hazards will be on the utilisation options that result in permanent storage, and the potential risk of captured CO_2 to be re-released.

For the climate hazards considered in this study, the following evidence gaps should be considered:

- **Heatwaves:** Further research is necessary to understand the extent to which high temperatures can impact the phase change CO_2 via pipelines.
- **Drought:** Lack of comprehensive studies addressing CCUS' impact on water resources.
- **Erosion:** A better understanding of how ground conditions and potential for compressive ground stability hazards, ground obstructions and groundwater may impact the building of CCUS CO_2 transport pipelines and storage sites.

A.4.3 Case study 3: Hydrogen

A.4.3.1 Description of technology

Low carbon hydrogen is a versatile energy carrier and can be used to power thermal, electrical, and chemical applications. The two main production pathways for low carbon hydrogen are reforming of natural gas combined with CCUS ('blue hydrogen') and electrolysis of water using renewable electricity ('green hydrogen'). Low carbon hydrogen is a key feedstock to many (hydrogen derivative) sustainable fuels such as low carbon ammonia, methanol and sustainable aviation fuels (SAF). The majority of current hydrogen production is from steam methane reforming of natural gas ('grey hydrogen'). For blue hydrogen production, CCUS technologies are used to capture and store the carbon dioxide released during the production processes. In this climate resilience review, hydrogen use considers technologies across the value chain of production, transmission, storage, and power generation. This includes more efficient hydrogen gas turbines, large-scale underground hydrogen storage solutions and potential impacts on respective critical supply chains[38]; etc. All climate hazards were assessed here, with snow and ice considered not applicable.

Although this work looks at each technology separately, it is important to recognise that hydrogen interacts significantly with the rest of the energy system – therefore requiring consideration of its interconnectedness with the system as a whole. It is important to recognise that the adverse impacts from climate hazards on electricity generation assets, gas assets, alternative technologies, and power networks may negatively impact hydrogen production (DESNZ experts).

Sensitivity to hazards such as rain, heat and cold are usually already considered in the planning/design stage of hydrogen (in the same way as ammonia and LNG) projects as well as production infrastructure facilities accordingly (Ricardo experts). The sensitivity to hazards associated with hydrogen transmission by pipeline would be very similar to those of other pipeline power networks (i.e. gas and heat) and CO_2 pipelines from CCUS.

A.4.3.2 Key vulnerabilities

Hydrogen technology is vulnerable to three of the climate hazards assessed: drought, storminess and occurrence of storm events, and erosion. However, confidence in the strength of vulnerability is low to medium due to lack of literature currently available as well as some disagreement in expert discussions, see Table 6-7.

Table 6-7 Vulnerability rating of hydrogen

Climate Hazard	Level of Vulnerability/Resilience (Rating)	Confidence (Rating)
Drought	Vulnerable (4) – very climate sensitive, low-medium adaptive capacity	Medium
Storminess and occurrence of storm events	Vulnerable (4) – climate sensitive, low-medium adaptive capacity	Low
Erosion	Vulnerable (4) – climate sensitive, low-medium adaptive capacity	Low
Precipitation	Potentially vulnerable (3) – climate sensitive, medium-high adaptive capacity	Low

[38] It should be noted that supply chains were not specifically covered in the REA. The main points here around supply chains result from the expert discussions.

Drought: All hydrogen production pathways require adequate access to water[39]. Production capacity, therefore, may be impacted during periods of drought and in regions of high water stress. Low carbon hydrogen projects located in such areas are thus increasingly exposed to water shocks and the tightening of local water use regulations (T3-23; 24). The inability to obtain abstraction licences, for example, can halt hydrogen production because the issuance of these licences is dependent on the amount of water available. As such, producers may encounter difficulties in obtaining the required permits and permission during periods of drought and in regions experiencing water stress (DESNZ experts). All of the currently conceptualised gigawatt-scale green (and blue) hydrogen projects rely on desalination plants and will therefore be resilient to water shortages. However, the majority of currently planned green hydrogen projects planned in the UK, including both smaller as well as large-scale projects (e.g. Kintore), depend on inland water resources. Consequently these projects are particularly sensitive to drought (Ricardo experts). The dependence on inland water resources suggests that there is low-medium adaptive capacity for hydrogen technology to respond drought.

Drought also reduces the storage capacity of hydrogen. For hydrogen storage in salt caverns, for example, certain water saturation (minimum 10%) in the porous rock is crucial because the formation water is the region where microbes grow (T3-16).

Storminess and occurrence of storm events: Storms may impact hydrogen import, transport, and demand (even if only in the short/medium term)[40]. Currently, in the UK hydrogen is transported through tube trailers, making transport very climate sensitive (DESNZ experts). However, in the long-term, given the scale of hydrogen that will need to be transported, it is expected that a pipeline infrastructure will be developed[41] to enhance efficiency of transport. This suggests that in the short to medium term (up to ~2035 - 2040), in the absence of the adaptive capacity that a pipeline backbone would afford, storms are a major climate hazard to hydrogen transport, as they can cause road closures, disruptions, and divert traffic (EMEC, Ricardo experts).

For the UK's energy mix to become carbon net zero, it is expected that hydrogen will be transported domestically, as well as being imported from outside the UK. Imports increase the sensitivity of hydrogen to climate hazards. The sensitivity of hydrogen to climate hazards is mitigated by the existing climate adaptive capacity of shipping, ensuring a level of resilience for hydrogen transport across the Atlantic or by other sea routes. Prevalance of storms could, however, negatively impact hydrogen supply though these routes (Ricardo experts).

[39] Hart et al., 2024 – CS-N0W report 'Water Availability for Hydrogen Production'
[40] Note that one expert disagreed about the sensitivity of hydrogen transport to storms given that reliance on tube trailers is unlikely and not sustainable in the long-term. Reliance on pipelines is more likely which suggests that hydrogen transport may not be sensitive to storms in this way.
[41] Reference: https://www.nationalgas.com/future-energy/hydrogen/project-union

Storms can also impact hydrogen demand. Increased turbulent weather may increase the number of days with reduced solar energy capacity, therefore requiring larger solar plants or non-renewable energy resources for hydrogen production and more storage to meet hydrogen demand.

Erosion: Erosion can physically damage hydrogen pipelines and cause leakages. Pipelines that are exposed to erosion of riverbeds would be vulnerable to washout. Washout often occurs with natural gas pipelines, and can thus be expected for hydrogen pipelines (Ofgem experts). Physical damage to pipelines may cause leakages, however, at present, there is no robust mechanism for leakage monitoring (DESNZ experts). The climate sensitivity of hydrogen infrastructure to erosion and the lack of monitoring indicate that it is likely to be challenging to adapt/respond to erosion.

Precipitation: Precipitation was identified as a potential additional hazard to hydrogen infrastructure (low confidence in the rating). Precipitation can physically damage pipelines by accelerating degradation. Such challenges (e.g. wet environments) are commonly accounted for in the design/planning stage of projects (Ricardo experts) suggesting that hydrogen infrastructure will only face minor challenges to adjust/respond to climate challenges related to precipitation in the future.

A.4.3.3 Key areas of resilience

Hydrogen technology is resilient to half of the climate hazards assessed: heatwaves, flooding, wind strength and wind regimes. However, confidence in the strength of resilience is low due to the literature available currently and some disagreement in expert discussions, see Table 6-8.

Table 6-8 Resilience rating of hydrogen

Climate Hazard	Level of Vulnerability/Resilience (Rating)	Confidence (Rating)
Heatwaves	Resilient (2) – may be sensitive to climate, medium-high adaptive capacity	Low
Flooding (river, surface and coastal)	Resilient (2) – may be sensitive to climate, medium-high adaptive capacity	Low
Wind strength and wind regimes	Resilient (2) – may be sensitive to climate, high adaptive capacity	Low

Heatwaves: Heatwaves have a marginal impact on hydrogen storage capacity and production efficiencies. Hydrogen feedstocks (i.e. renewable energy sources), which impact hydrogen production given the interconnectedness of hydrogen with the overall energy system, are more sensitive to heat and are less able to respond to climate challenges.

Simultaneously, experts agree that higher temperatures are likely to decrease the amount of available storage only marginally (Ricardo experts, EMEC). Higher operating temperatures can marginally improve the efficiency of water electrolysis, though negatively impact on the overall plant thermal management and require greater cooling to avoid exceeding design temperatures and/or overheating. This ultimately leads to the need for greater cooling load, that is, higher water/air requirements for cooling. Note that water cooling is likely to be used for very large-scale plants and that the water used may be seawater. Smaller plants would most likely use closed-cycle-air-cooled cooling systems, and these would be more susceptible to heatwaves as the differential temperatures between the plant operation temperature and air temperature would be less, likely resulting in a reduction in overall plant efficiency (Ricardo experts).

Flooding (river, surface, coastal)[42]: Water used in the production of hydrogen requires water quality levels of almost deionized water quality[43]. Operational costs are kept comparatively lower, the cleaner the abstracted water from the environment. Flooding can negatively impact water quality, content, and flow rate of water that is used to produce green hydrogen (Ricardo experts). While the extent to which water quality issues resulting from flooding would impact hydrogen production are largely unclear, minor challenges to adjust/respond to especially river and surface flooding might exist. For example, dirty, silty or contaminated river water will require additional filtration and filtering, which needs to be (and is usually) factored into the design of projects reliant on river water (Ricardo experts). It should also be noted that hydrogen production through electrolysis will unlikely be dependent on surface water in the UK. Therefore, potential impacts on the quality, content and flow rate of water are unlikely to be an issue. Because large scale hydrogen production will likely rely heavily on seawater as opposed to inland freshwater resources, the sector has inherent adaptive capacity to deal with the effects of river and surface flooding (EMEC). However, specifically if constructed on floodplains, coastal flooding might cause physical damage to hydrogen plants infrastructure (like all critical infrastructure) (Ricardo experts). As the sensitivities of hydrogen technology can be mitigated by avoiding building infrastructure on floodplains, for example, the technology is able to adjust/respond to flooding, indicating resilience.

Wind strength and wind regimes: Renewable energy resources such as wind and solar are often used to generate green hydrogen. Hydrogen technologies and infrastructure can therefore be vulnerable to changes in wind and sunlight (heat) (T3-10). If a mix of renewable

[42] Note that one expert disagreed on how hydrogen production is unlikely to rely on inland water resources (and that river and surface flooding are therefore not an issue), noting that the largest green hydrogen production plant planned in the UK (Kintore) is planning to source its water from the River Don. However, very large (GW scale) blue hydrogen production plants will likely source their water from the sea via a desalination plant, potentially making them vulnerable to coastal flooding.
[43] Hart et al., 2024 – CS-N0W report 'Water Availability for Hydrogen Production'

energy sources are used to supply hydrogen plants, hydrogen technology will be better able to respond to changes in one form of supply.

A.4.3.4 Potential adaptation options

The climate resilience review for hydrogen has identified various adaptation options to address specific vulnerabilities to climate hazards, including drought and storminess.

Some adaptation options were identified for the hazards to which hydrogen is resilient (heatwaves, flooding, wind strength and wind regimes). No adaptation options were identified for erosion and precipitation, to which hydrogen is at least potentially vulnerable . A summary of the adaptation options is given inTable Table 6-9.

Table 6-9 Identified adaptation options for hydrogen

Climate Hazard	Adaptation Option(s)
Drought	▪ Alkaline electrolysis ▪ Blue hydrogen production (using less water)
Storminess and occurrence of storm events	▪ Climate-robust hydrogen transport pipeline network and storage

Drought: Alternative technologies for hydrogen production offer promising solutions to water-related concerns. Utilising production technologies that require less water such as alkaline electrolysis is beneficial to sustainably address water scarcity challenges. These technologies can help meet future demand for hydrogen, while reducing freshwater withdrawal and consumption to levels even below those seen today (T3-24). Alkaline electrolysis also requires water, albeit slightly less than other production pathways. For these, it is unlikely that water would be used for cooling, it is more likely that air would be used (EMEC). These plants are typically much smaller and are often located nearby renewable energy sites (Ricardo experts, EMEC). Grey and future blue hydrogen production plants are much larger in size. For these plants, hydrogen production processes, sea water will have to be used due to the size of the plants. For these, the amount of water is only a concern in terms of the concentrated brine that is returned to the sea (environmental concern) (Ricardo experts).

Storminess and occurrence of storm events: As discussed previously, hydrogen imports and/or exports to the UK through sea routes and the following transport on land using tube trailers within the UK are likely to take place for many years. In the long-term, pipelines wil likely be used, given that reliance on tube trailers for hydrogen transport is not sustainable and given the scale of hydrogen that will need to be transported. It should be ensured that hydrogen transport through pipelines is resilient to storms. Thus, investing in a robust pipeline infrastructure for hydrogen storage and transport is necessary to help adapt to vulnerabilities caused by storms (EMEC).

Flooding: Hydrogen projects that are planning to use river water can adapt to the poor water quality caused by flooding, by designing the filtration/water processing systems based on the 'dirty' floodwater quality rather than 'typical' river standards (Ricardo experts).

A.4.3.5 Evidence gaps

The vulnerability rating of hydrogen technology to climate hazards is overall based on low confidence levels due to limited literature assessing climate change impacts other than water availability / drought on hydrogen production. The vulnerability assessment highlights that there are other additional climate-related vulnerabilities on hydrogen production and transport that should be considered in the future. The following evidence gaps were identified:

- **Heatwaves:** Are hydrogen power plants already being built to withstand higher temperatures? What is (or will be) most likely to be used for cooling – water or air?
- **Drought:** If hydrogen production through electrolysis is sensitive to drought, what other methods of production can be utilised at scale?
- **Flooding:** To what extent does negatively impacted water quality affect the production of hydrogen? Are potential losses only marginal?
- **Storminess and occurrence of storm events:** Storms and erosion may lead to leakages. There is currently a lack of evidence about technologies that can be used to monitor leaks (DESNZ experts).

A.4.4 Case study 4: Buildings

A.4.4.1 Description of technology

Buildings play a central role in the UK's net zero ambitions and climate adaptation strategies, given they are responsible for around 30% of national emissions[44]. This case study focuses on the design features of buildings and building-related technologies and their resilience to several climate hazards. These include low carbon heating/cooling for hard-to-treat buildings, heat/cooling networks, heat pumps, energy efficiency measures, battery energy storage systems, energy demand management measures and building control measures. Following discussion with DESNZ, the primary technology assessed in this case study is heat pumps as many homes in the future will have these.

[44] UK Government, 2021. Heat and building straregy. https://www.gov.uk/government/publications/heat-and-buildings-strategy/heat-and-building-strategy-accessible-webpage.

Heat pumps are low-carbon systems that provide heating and cooling by transferring heat between the building and the external environment. This process, which can work in reverse to offer cooling during warmer periods, is crucial for reducing dependency on fossil-fuel-based heating. Three main types of heat pumps – air source, ground source, and water source – are used depending on the building context and surrounding environmental features. Air source heat pumps are the most widely applicable due to the relatively easier access to air. Ground source heat pumps, while offering greater efficiency for buildings with both cooling and heating demands, require land area and expensive boreholes, limiting their feasibility in dense urban areas. Water source heat pumps, though less common, can provide efficient heating and cooling in specific locations with suitable water access.

In addition to heat pumps, insulation technologies, including wall, roof, and floor insulation, are key components in enhancing a building's energy efficiency. By improving the thermal performance of buildings, insulation helps maintain indoor temperatures within a safe and comfortable range, reducing the need for excessive heating or cooling.

In the following sections, key vulnerabilities, areas of resilience and potential adaptation options for buildings and buildings-related technology are summarised. The evidence is clustered by climate hazard and specific details on heat pumps are provided according to the available information retrieved.

A.4.4.2 Key vulnerabilities

Buildings and related technologies, including heat pumps, exhibit varying degrees of vulnerability to several climate hazards: heatwaves, flooding, wind strength, storms, snow and ice, and erosion. The term 'buildings and related technologies' includes a variety of components that present different vulnerabilities. While buildings themselves may not be directly vulnerable to heatwaves, their occupants are if the systems, such as cooling and ventilation, are not adequately designed for prolonged high temperatures. Similarly, heat pumps may not be inherently vulnerable to heatwaves if selected for appropriate operating conditions; however, performance may vary depending on installation and maintenance practices. These distinctions highlight the need for more detailed assessments to address specific vulnerabilities within individual technologies and their interactions with buildings and users.

Table 6-10 summarises these vulnerabilities along with confidence ratings based on available evidence.

Table 6-10 Vulnerability rating of buildings

Climate Hazard	Level of Vulnerability/Resilience (Rating)	Confidence (Rating)
Heatwaves	Vulnerable (4) – very climate sensitive, medium adaptive capacity	High

Flooding	Potentially vulnerable (3) – climate sensitive, medium adaptive capacity	Medium
Wind strength and wind regimes	Potentially vulnerable (3) – climate sensitive, medium adaptive capacity	High
Storminess and occurrence of storm events	Potentially vulnerable (3) – climate sensitive, medium adaptive capacity	Medium High
Snow and ice	Potentially vulnerable (3) – climate sensitive, medium-high adaptive capacity	High
Erosion	Vulnerable (4) – climate sensitive, low adaptive capacity	Low

Heatwaves: Building internal environment comfort was found to be very sensitive to heatwaves, as extreme temperatures increase cooling demands and reduce the efficiency of many cooling systems, including heat pumps. Air-source heat pumps in cooling mode (i.e. chillers), lose efficiency as air temperatures rise, resulting in reduced output capacity and increased energy consumption. Prolonged high temperatures place a continuous demand on these systems, raising the likelihood of malfunctions (T8-21).

Evidence collected shows that well-insulated buildings with carefully designed ventilation perform better in maintaining indoor temperatures than those relying on air infiltration alone. Insulated and airtight buildings with adequate mechanical ventilation and cooling maintain internal temperatures in heatwaves better than naturally-ventilated buildings. However, a large proportion of buildings, and residential buildings in particular, are naturally ventilated and therefore at risk of overheating during heatwaves (Ricardo expert). Especially in retrofitted historic buildings critical factors in determining overheating risk are surface-to-volume ratio, shading and air exchange ratio. The adaptive capacity of building-related technologies to heatwaves is medium (3/5). Passive design techniques have limited impact under extreme temperatures (T8-7). Improved fabric performance, including insulation and airtightness, when paired with an active cooling system, will be a common means to mitigate rising temperatures at the cost of increased energy consumption (Ricardo expert).

Flooding: Buildings were found to be moderately sensitive to flooding, particularly due to the vulnerability of electrically powered systems. Flooding can cause significant power outages, which disrupt essential building operations, as all heating and cooling systems depend on electricity, either as the primary energy source or for auxiliary components (Ricardo expert). Heat pumps located outdoors at ground level are susceptible to inundation (T8-19). Evidence from flooding events in England illustrates the extensive impact, with infrastructure damage having led to power cuts that disrupted service for over 2 million customers (T8-19). Heat pumps and battery storage systems located at ground level are especially prone to flood damage, as water exposure can damage components and cause system shutdowns (T8-37). Higher-than-normal levels of humidity or water exposure that can adversely affect the system's components in winter months can further exacerbate these risks (T8-38). The adaptive capacity of building-related technologies to flooding is medium (3/5). This rating reflects that vulnerabilities can be mitigated by locating heat pumps and batteries in elevated locations, following flood hazard assessments, and periodically reviewing defences (T8-38, Ricardo expert).

Wind strength and wind regimes: Buildings were found to be moderately sensitive to winds and wind-driven rain (WDR) specifically. Building fabric exposed to WDR faces surface erosion, which leads to weaker construction and long-term durability decline (T8-4). Timber is particularly vulnerable, as WDR-induced moisture leads to swelling and shrinking, resulting in cracks and potential structural degradation. Additionally, moisture penetration from WDR can foster mould growth inside buildings and promote algae on exterior surfaces (T8-40). Poor ventilation in external wall cavities can exacerbate these issues by trapping moisture (T8-28). Building technologies placed outdoor, including air-source heat pumps, solar panels, wind turbines, and ventilation systems, are also susceptible to physical damage from high winds. Such systems face increased risk of impact from falling trees or debris (T8-37, T8-38, Ricardo expert). The adaptive capacity of buildings-related technologies to wind strength and wind regime is medium (3/5). Battery energy storage systems benefit from physical protection indoors, while green roofs[45], drainage systems in wall cavities, and wind barriers can manage moisture intrusion and reduce wind impact (T8-28).

Storminess and occurrence of storm events: Buildings and related outdoor technologies, including heat pumps, show medium vulnerability to this hazard. Storms often lead to power outages, which disrupt the operation of heat pumps and battery systems, affecting their heating, cooling, and storage capabilities (T8-31). Heating systems including heat pumps are vulnerable to lightning strikes and electrical surges, which can damage electrical components and compromise functionality, and face physical damage from hailstones. Energy storage systems face similar risks (T8-38). The adaptive capacity of buildings-related technologies to storminess and storm events is medium (3/5). Surge protectors and lightning protection systems provide options for heat pumps and battery storage protection but do not entirely eliminate storm risks.

Snow and Ice: Buildings, particularly retrofitted historic structures, were found to be moderately vulnerable to snow and ice due to the impacts of freeze-thaw cycles, which can cause structural deterioration. The addition of internal insulation in retrofitted historic

[45] Nature-based solutions were considered in the assessment due to the potential contribution to overall resilience within 'Buildings' technologies; however, nature-based solutions are not covered in DESNZ NZIP technologies. See Appendix A.1.1 for definition of technologies associated with 'Buildings' under NZIP.

buildings lowers outer wall temperatures, making them more susceptible to frequent and intense freeze-thaw cycles, which heightens the risk of frost-related damage (T8-4). Air-source heat pumps are also sensitive to prolonged low temperatures and high humidity, as ice buildup on the heat exchange coil necessitates the activation of the defrost cycles. In poorly designed systems, snow accumulation can obstruct airflow through the fan, further impacting the heat pump's efficiency (T8-29). The adaptive capacity of buildings-related technologies to snow and ice is medium (3/5). Defrost cycles in heat pumps effectively clear frost buildup, resuming heating within minutes, though they reduce overall efficiency (T8-29).

Erosion: Buildings and associated technologies were found to be sensitive to erosion, especially those located near water sources or buried underground. Water-source heat pumps positioned along riverbanks or sea walls are at risk from erosion and sediment abrasion, which may degrade performance over time (Ricardo expert). District heating systems are increasingly exposed to erosion hazards due to the potential for pipe wear from water flow, corrosion-erosion interactions, and ground erosion, which can expose, and damage buried pipelines (government stakeholder). Additionally, building decarbonisation technologies reliant on underground power infrastructure, such as pipelines and electricity cables, are indirectly sensitive to erosion impacts on these supporting assets (T8-19). The adaptive capacity of buildings-related technologies to erosion is currently limited, as specific adaptation options for erosion remain underdeveloped, and existing measures primarily address infrastructure, not building systems directly.

A.4.4.3 Key areas of resilience

Building technologies, particularly heat pumps, exhibit resilience to drought. Table 6-11 summarises the drought vulnerability of buildings along with its confidence rating based on available evidence.

Table 6-11 Resilience rating of buildings

Climate Hazard	Level of Vulnerability/Resilience (Rating)	Confidence (Rating)
Drought	Resilient (2) – low-medium sensitivity, medium-high adaptive capacity	High

Drought: Buildings and related technologies demonstrate resilience to drought, with an overall low to medium sensitivity rating (2/5). While urban greening and water-based features, such as fountains and water walls, rely on water availability and may lose effectiveness during prolonged droughts, these impacts are limited in scope. Evaporative cooling systems may also suffer at a time when cooling is in high demand, but these are not common in the UK building sector. Subsidence affecting building foundations is similarly a localised concern, mainly influenced by soil type and extended dry periods, rather than posing a widespread risk. The adaptive capacity of building-related technologies to drought is rated medium-high (4/5), as effective water conservation measures mitigate water scarcity. Common strategies include reducing water consumption, implementing rainwater harvesting, and using greywater and blackwater recycling systems in both residential and commercial settings (T8-7, T8-41, T8-42, T8-44, Ricardo expert).

A.4.4.4 Potential adaptation options

The climate resilience review for buildings has identified various adaptation options to address specific vulnerabilities to climate hazards, including heatwaves, flooding, wind strength, storminess, and snow and ice. Table 6-12 below summarises the identified adaptation options.

Table 6-12 Identified adaptation options for buildings

Climate Hazard	Adaptation Option(s)
Heatwaves	▪ Reversible and ground-source heat pumps (GSHP) for adaptable cooling ▪ Designing cooling systems for higher ambient temperatures than normal practice today ▪ Accepting higher internal comfort temperatures
Flooding	▪ Elevating air source heat pumps above anticipated flood levels ▪ Additional drainage, flood barriers, and high Ingress Protection rating (IPX8 or above) for battery storage systems
Wind strength and wind regimes	▪ Enhanced moisture control strategies for historic buildings
Storminess and occurrence of storm events	▪ Proper installation and maintenance of heat pumps, with backup power sources for commercial applications ▪ Robust electrical protection and structural assessments for battery storage system
Snow and ice	▪ Freeze-thaw indicators and built-up defrost cycles for heat pumps ▪ Snow drift analysis for optimal heat pump positioning

Heatwaves: Urban design strategies incorporate thermal and wind flow considerations to reduce cooling loads, particularly in urban heat island-prone areas. Effective shading, such as external shutters on south- and west-facing windows, mitigates solar heat gain (T8-3, T8-18).[46] Reversible heat pumps and ground-source heat pumps (GSHP) offer adaptable and

[46] See also CS-N0W projects D4 and G10 on Heating and cooling needs of the UK housing stock (D4) and Heat vulnerability and adaptation options – a Manchester case study (G10)

efficient cooling options, with projects in Coimbra and the UK demonstrating successful GSHP applications (T8-21, T8-40, T8-42). Additionally, battery energy storage systems (BESS) require robust cooling systems, temperature monitoring, and wildfire risk mitigation during heatwaves to ensure functionality (T8-38).

Flooding: For flood-prone areas, regular maintenance of heat pumps is critical to ensure water seals and drainage systems are effective (T8-22). Battery storage systems can be adapted by installing additional drainage, flood barriers, and using equipment with a high IP rating (IPX8 or above) to protect against water ingress. Proper ventilation also helps keep moisture levels low in storage systems (T8-38).

Wind strength and wind regimes: Buildings, particularly historic ones, benefit from enhanced moisture control strategies to handle wind-driven rain, such as using cavity trays in exposed locations to prevent water penetration (T8-4). Securing heat pumps with wind barriers or enclosures reduces exposure to high winds (T8-37). For battery systems, regular site safety assessments, wind barriers, and securing structures against wind damage are essential, as well as considering local geographical features for potential hazards (T8-38).

Storminess and occurrence of storm events: Proper installation and regular maintenance of heat pumps help prevent storm damage, and backup power sources are recommended for commercial applications to ensure continuous operation during power outages (T8-31). Battery energy storage systems require robust electrical protection, regular maintenance, and structural assessments to enhance resilience to storms (T8-38).

Snow and ice: Adaptation options for snow and ice include the use of freeze-thaw indicators on heat pumps and built-in defrost cycles to manage frost buildup. Heat pumps also require positioning and orientation assessments, such as snow drift analysis, to minimize exposure to freezing (T8-29). Solar thermal facades benefit from additional insulation, enhancing energy efficiency during colder months (T8-2).

A.4.4.5 Evidence gaps

The resilience and vulnerability assessment for building technologies, particularly heat pumps, has identified several key areas where evidence is limited. Addressing these gaps would enhance understanding of how buildings and associated technologies can better adapt to climate hazards. The following research questions outline the primary evidence gaps:

Heatwaves:

- How will future climate conditions affect the UK's passively-cooled buildings compared to the expected comfort design conditions at the time at which they were designed?
- How can the balance between air-tightness for reduced heat losses and ventilation for overheating be optimised? Specifically, what standards for air quality ventilation

align with requirements to prevent overheating, particularly in naturally ventilated homes?

- Are there effective regulatory strategies that integrate cooling and air quality considerations to ensure adequate ventilation without compromising indoor thermal comfort?

Flooding:

- What specific flooding resilience measures should be incorporated into building regulations and planning conditions to improve adaptive capacity for both new constructions and retrofits? How can these measures be tailored to account for regional flood risks and varying building typologies?

Erosion:

- What is the current adaptive capacity of building technologies to resist erosion, particularly in coastal and sloped areas? What are effective adaptation options that could be standardised to prevent erosion-related structural vulnerabilities?

Annex 5: Scoring for evaluation criteria

Exposure

Location

To what extent has the project assessed its location's exposure to specific climate hazards such as floods, droughts, or extreme heat?

1: No evidence of assessing location-specific climate hazards.
2: Minimal mention of hazards, no detailed location-specific analysis.
3: Identifies major hazards but lacks comprehensive mapping or projections.
4: Detailed analysis of current hazards with partial future projections.
5: Comprehensive, scenario-based hazard assessment with detailed future projections.

Hazard Intensity

To what extent has the project identified and accounted for the range and intensity of climate hazards it may face now and in the future?

1: No identification of hazard types or intensities.
2: Limited reference to hazard types, no quantitative analysis.
3: Identifies key hazards with basic qualitative analysis.
4: Detailed assessment of current and some future hazard intensities.
5: Comprehensive hazard typology and intensity analysis.

Sensitivity

Resource dependency

To what extent has the project addressed its dependency on resources impacted by climate such as water, energy, or raw materials?

1: No analysis of resource dependency.
2: Minimal reference to resource dependency, no mitigation measures.
3: Identifies key dependencies with basic mitigation strategies.
4: Strong analysis of dependencies with robust mitigation plans.
5: Comprehensive strategy addressing current and future resource dependencies with monitoring systems.

Performance impact

To what extent has the project evaluated how climate hazards like extreme heat or heavy rainfall could affect its performance?

1: No consideration of performance under climate hazards.

2: Minimal reference to climate performance impacts.
3: Basic assessment of performance impacts, focusing on current conditions.
4: Strong assessment of performance impacts, with some future considerations.
5: Comprehensive analysis of performance under multiple climate scenarios.

Maladaptation risk

To what extent does the project avoid creating future vulnerabilities or maladaptation risks?

1: No consideration of maladaptation risks.
2: Minimal mention of potential maladaptation risks.
3: Basic recognition of maladaptation risks.
4: Strong consideration of risks, with robust plans to prevent maladaptation.
5: Comprehensive integration of maladaptation prevention into project design and implementation.

Adaptive Capacity

Adaptive management

To what extent is the project designed to evolve and adapt to future climate conditions or new climate information?

1: No flexibility; project is unresponsive to future changes.
2: Minimal flexibility, with limited mechanisms for updates.
3: Moderate flexibility for addressing short- to medium-term changes.
4: Strong flexibility, addressing long-term risks and incorporating regular updates.
5: Fully flexible, with built-in mechanisms for adaptive pathways and long-term scenario planning.

Recovery planning

To what extent does the project include recovery strategies to ensure continuity of services during disruptions?

1: No mention of recovery planning or service continuity.
2: Acknowledges recovery but lacks specific measures or details.
3: Some recovery measures are outlined, but they are incomplete or lack cimplementation pathways.
4: Well-documented strategy with clear actions and responsibilities but missing advanced features like scenario testing.
5: Comprehensive recovery strategy fully integrated into project design with scenario testing and continuous improvement mechanisms.

Governance structure

To what extent does the project have institutional and governance structures that support its long-term resilience and adaptation goals?

1: No institutional or governance structures in place; no oversight for resilience measures.
2: Basic structures exist but lack clear roles, authority, or alignment with resilience goals.
3: Moderate support; governance structures are present but not fully aligned with long-term adaptation needs.
4: Strong governance support; roles and responsibilities are well-defined, with partial integration into broader adaptation frameworks.
5: Comprehensive and integrated structures fully support long-term resilience goals.

Learning mechanisms

To what extent does the project include mechanisms for ongoing monitoring, evaluation, and learning (MEL) in response to changing climate risks?

1: No monitoring, evaluation, or learning mechanisms in place.
2: Basic monitoring systems exist, but with limited scope and no mechanisms for learning.
3: Moderate MEL mechanisms; some monitoring is present, with limited processes for feedback and learning.
4: Robust MEL systems; regular monitoring and some learningprocesses are in place.
5: Comprehensive MEL framework; fully integrated with continuous feedback loops and mechanisms for learning and adjusting to climate risks.

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