Climate Change Stress Testing

Guidance

CIWEM Chartered Institution of Water and Environmental Management

Contents

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Executive Summary

In 2019, CIWEM declared a climate change and ecological emergency[1], and committed to a number of actions which included leading the water and environmental profession to deliver resilience and adaptation, empowering its members to deliver resilient and adaptive programmes and projects and working with other organisations to collectively drive and share best practice, reflecting the latest scientific evidence and innovation. As part of this work, CIWEM's Climate Change Specialist Panel has been active in setting up workstreams to respond to the emergency and support the Institute's wider objectives.

One such workstream is this guidance document on climate change stress testing. This document aims to provide useful, non-technical guidance for organisations that could benefit from climate change stress testing. The importance of climate change stress testing as a topic is shown by the Climate Change Committee's recent report ('Key organisations failing to tackle the threat of cascading climate risks'[2]), which warned that many of the organisations providing vital energy, water, digital and transport services in the UK were struggling to take account of the climate-related risks to highly-connected infrastructure systems, and that that could lead to the 'cascade failures' if left unaddressed.

Why is this guidance needed? It is apparent from the contributions of CIWEM members and external organisations that, while there is a great deal of experience and material available on the subject of stress testing (both generally and in relation to climate change), there are some areas in which different sectors and organisations employ differing terminology and approaches. The Panel has therefore tried to strike a balance between signposting to other relevant sources when this is appropriate, and going into more detail on topics and areas that we consider to be less well covered by those other sources.

This document is structured to explore firstly the concept and definitions around stress testing, and relating it to different sectors. It then considers climate change stress testing specifically, and some of the unique aspects that make this stress testing challenging. The practical process of stress testing is then considered in a generic sense, applicable to multiple sectors and hazards, and then again specific considerations in the process of climate change stress testing are discussed. Some specific 'frequently asked questions' are covered which may be helpful to readers seeking brief answers rather than reading the whole document. Finally, several case studies are referenced to demonstrate how climate change stress testing is being approached in the infrastructure sector today.

[1] Climate and Ecological Emergency Declaration.pdf (ciwem.org)

[2] Key organisations failing to tackle threat of cascading climate risks - Climate Change Committee (theccc.org.uk)

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Introduction: Purpose and Definitions

The purpose of this document is to provide an accessible introduction to the practices of stress testing, particularly for organisations and their management who have not carried these exercises out before. The document is relevant to all sectors and climate change hazards but recognises the particular interests of CIWEM's membership by focusing on physical, rather than economic transition, risks. The document also signposts to, and discusses, relevant sector-specific guidance, such as in the utilities and financial services sectors.

Stress testing is a practice that has developed to fulfil different functions in different industries. In engineering, it is defined as "a technique to test the stability of an entity or system under adverse conditions"[3]. In the finance sector, it is typically used to describe the analytical processes that regulated entities such as banks are required to carry out, generally at the direction of a regulator or overseer such as the Bank of England, in order to manage the stability of the financial system against stressors such as low liquidity, borrower default and high unemployment[4]. The majority of literatures sources found and reviewed for this document related to this use of term in financial, rather than physical systems. However, the concept can be applied to systems in a wide range of sectors, including healthcare[5], infrastructure[6] and IT[7].

In physical systems, stress testing is intended to assist design or risk treatment processes and ensure that the system is acceptably resilient and to identify possible points of failure under specified climate scenarios. For example, building codes will state requirements for structures to be able to withstand adverse environmental conditions such as rain, snow, flooding or earthquakes. These requirements will often be derived from stress testing carried out either through computations methods or physical laboratory tests, often involving testing to destruction. Weber (2014) defines a stress test as "any analytic exercise designed to gauge how changes in variables, usually of a dramatic or "stressed" nature, affect a test subject in ways that are relevant to the subject's performance, and in particular its susceptibility to failure".

We therefore offer the following definition of stress testing, which is general enough to cover multiple sectors:

> *"Stress testing is a process for assessing the ability of a system to maintain a certain level of functionality under unfavourable conditions, and understanding the consequences if this functionality is not maintained"*

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[3] Borio *et al*, 2017
[4] Drehmann, 2008
[5] Ebi *et al*, 2018
[6] Nikolopoulos *et al*, 2018
[7] Lee *et al*, 2018

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This encapsulates the following ideas:

- There is a system of interest, with components and boundaries that can be defined and understood to some degree.
- The system has some function or purpose, so that an analyst can assess when its performance is impaired.
- A system may have been designed or have evolved to function effectively in favourable conditions, but not in unfavourable conditions. Stress testing inherently involves the consideration of extreme, rare, and/or high consequence/low probability events.

It could also be said that stress testing “measures the resilience of systems to hypothetical adverse scenarios”. There is therefore an overlap between stress testing and scenario analysis, and stress testing may be seen as a form of scenario analysis carried out for particular purposes, although Čihák (2004) suggests that scenario analysis, sensitivity analysis and contagion analysis are all types of ‘stress tests’.

Stress testing does not only have to consider acute events (shocks vs stresses[8]), but most sources agree that stress testing focusses on extremes rather than only on typical or likely scenarios. For example, McKinsey (2017) states - “stress testing (is) a form of scenario planning focused on the tails of the distribution. Scenario planning and stress testing are methodologically identical; they differ only in the likelihood of the scenarios they consider”. Similarly, the IAA (2013) distinguish stress testing from scenario analysis and define the former as “an assessment of an extreme scenario, usually with a severe impact on the firm, reflecting the inter-relations between its significant risks”.

For reference, the IPCC (2012) defines an extreme as “the occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable”.

[8] **Mehryer *et al*, 2022**

Climate Change and Stress Testing

Climate change combines a variety of hazards and possible impacts that may affect systems of interest. In a risk management framework, these are typically expressed in terms of hazards, vulnerability and resilience (see Lavell et al, 2012; Brooks, 2003), but all these concepts are relevant to stress testing as well.

The nature of climate change means that some impacts may be very significant, but are considered to be either highly unlikely or highly uncertain. For example, the collapse of the North Atlantic meridional overturning circulation (AMOC) has been judged to have over 30% probability if greenhouse gas emissions continued unabated, but this probability reduces to 10% if global Net Zero is reached quickly (McInerney and Keller, 2008). Particular aspects of climate change that affect the choice of stress testing approach are discussed on p9.

TCFD (2017) does not specifically mention the concept of stress testing, but provides extensive recommendations in relation to scenario analysis. The guidance states "the purpose of scenario analysis is to consider and better understand how a business might perform under different future states (i.e., its resiliency/robustness)… (s)cenario analysis, therefore, evaluates a range of hypothetical outcomes by considering a variety of alternative plausible future states (scenarios) under a given set of assumptions and constraints. It does not require that any of those scenarios be extreme, although the Technical Supplement on scenario analysis[9] does mention stress testing in examples taken from the financial services and energy sectors.

Recent coverage of climate change stress testing has started to consider infrastructure systems[10] and has also received attention from the UK's Joint Committee on the National Security Strategy[11]. Again, different systems of interest (financial systems, infrastructure systems etc) have their own characteristics, participants and languages, and it seems sensible for sectors where stress testing is relatively novel to learn from more mature sectors and adopt or adapt approaches where appropriate. For example, some of the specific characteristics of infrastructure systems are:

- Costly, long-lived assets
- Often set into/integrated into landscape.
- Vulnerable to climate change and hazards arising (flood, heatwave etc).
- Need for extensive planning and funding.

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[9] www.assets.bbhub.io/company/sites/60/2020/10/FINAL-TCFD-Technical-Supplement-062917.pdf

[10] www.newstatesman.com/spotlight/energy/2021/12/uk-infrastructure-at-risk-from-cascade-failure-due-to-climate-change

[11] https://committees.parliament.uk/publications/30507/documents/175976/default/

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The fundamentals of stress testing

While stress testing can be carried out on a range of systems across financial, engineering and other sectors, a number of similar principles and steps can be identified and followed in each case.

- Tests should be conducted at an appropriate system level[12].
- Tests should be highly transparent about their assumptions, and the robustness of those assumptions. In banking, the process followed is (after Jones, Hilbers, and Slack, 2004; IMF and World Bank, 2005b):
    1. identification of specific vulnerabilities or areas of concern;
    2. construction of a scenario;
    3. mapping the outputs of the scenario into a form that is usable for an analysis and which decision-makers will understand. For example, a stress test of a bank might involve translating the scenario outputs into financial institutions' balance sheets and income statements;
    4. performing a numerical analysis,
    5. considering any second-round effects; and
    6. summarising and interpreting the results

The following generic steps are therefore suggested.

Identifying specific vulnerabilities or areas of concern

Stress tests are generally undertaken with some level of understanding of the system's vulnerabilities. These preconceptions help inform the areas of the system that are represented in more or less detail, but they should also be regularly tested themselves to prevent biases arising.

Inevitably, if certain vulnerabilities or system aspects turn out to be more or less significant following the analysis then this may mean that re-design or iteration of the stress tests is required.

[12] Cihak (2004)

Constructing a scenario

There is a significant amount of guidance available on the various climate change scenarios available, particularly the Taskforce for Climate-related Financial Disclosures (TCFD) Technical Supplement. There are also a wide range of scenarios available, such as the Network for Greening the Financial System (NGFS) scenarios[13] and the SSP's[14]. In Stress Testing, organisations will generally be interested in lower-probability, higher-impact scenarios. Further guidance is provided below in the section titled 'Specific Concepts in Climate Change Stress Testing'.

Mapping the outputs of the scenario into a form that is usable for an analysis of the system of interest

This entails:

- Representing the system of interest in the modelling environment (which could be as simple as a numerical model in an Excel spreadsheet).
- Defining the situations which constitute 'failure' – in other words, at what point does the system start to fail to meet requirements? The resilience standards referenced in p21 of the JCNSS (2022) report[15] provide useful examples in the infrastructure context.
- Determining how to measure the accuracy and usefulness of the model; for example, whether it can be compared to real-world observations ('goodness-of-fit) or if there is a validation approach that can be taken.

Performing the numerical analysis

This step involves performing any calculations that simulate the effects of input scenarios on the system of interest, and capture the results. In a Monte Carlo analysis, there will be a number of iterations of this step to build up a probabilistic output.

Considering any second-round effects

In financial stress testing it is common to consider whether there is any need to incorporate second round effects. Second round effects are when agents (organisations or individuals) make decisions in response to the outcomes of the modelled scenarios, for example by passing on price changes to other parts of the economy. In an infrastructure system, this step could include the explicit consideration of any interfaces or interdependencies with other infrastructure

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[13] www.ngfs.net/ngfs-scenarios-portal/

[14] https://iiasa.ac.at/web/home/research/researchPrograms/Energy/SSP_Scenario_Database.html

[15] https://committees.parliament.uk/publications/30507/documents/175976/default/

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systems or operators which could then be likely points of failure under a stress test if the system boundaries were expanded.

As mentioned previously, the outputs of the numerical analysis may also identify the need for refinement of the model itself (because it does not effectively represent the system of interest) or require input scenarios to be adjusted before re-modelling.

Summarising and interpreting the results

This step is important in order for stakeholders and decision-makers to be able to use the results of stress testing for risk management purposes. Results should be clearly understandable, and if additional questions are raised then the model may need to be refined or additional analysis undertaken. Decision-makers are often interested in the sensitivities of the model (which of the inputs or structural features are most important in determining the outputs) as well as the confidence there is in the outputs.

Introduction: Purpose and Definitions

Threshold effects/tipping points/feedback effects

The climate system is incredibly complex and human understanding of it is incomplete while our ability to model it is also limited. There is the potential for significant changes to occur in parts of the system, prompted by relatively minor changes in forcing variables, either because the climate system 'tips' over into a new stable state, or because runaway feedback effects take hold. Some of these situations include:

- Ocean circulation collapse
- Loss of sea ice[16]
- Land ice loss
- Permafrost thawing & methane release (including clathrate deposits), which reduce the earth's albedo and increases the greenhouse effect[17].
- Uncertainties in the role of clouds[18].

It may be necessary or desirable for organisations to consider scenarios which incorporate these more significant, but less likely, changes.

Long horizons

Climate change stress testing is carried out to longer horizons than many other types of scenario and business decision analysis. Climate change practitioners will generally consider risks out to at least a 30+ year horizon while financial stress tests are typically carried out to shorter horizons (2-5 years[19]).

Limited historical observations

While a few climate parameters can be directly recorded (such as ice core gas composition and, more recently, meteorological observations), many must be extrapolated from their own models. This lends additional uncertainty to many forecasts.

Uncertainty in market participant and policy maker action and responses

Climate change stress testing necessarily requires assumptions across the physical and social spheres eg. climate change mitigation policies and their effectiveness.

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[16] See IPCC (2019) report on cryosphere
[17] Lenton (2011)
[18] Schneider et al (2019)
[19] www.bpi.com/challenges-in-stress testing-and-climate-change/

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However, these assumptions are highly uncertain and are compounded by uncertainties in the underlying climate science and projections.

At the same time, stress testing practitioners or stakeholders, such as regulators, may demand highly granular scenarios. The conclusions being drawn from stress testing outputs should always be carefully considered to identify uncertainties that make such granularity limited in value.

How rare or extreme should the scenarios be?

Stress testing is generally understood to involve the consideration of rare or extreme events that are specifically expected to test the resilience of the system of interest. However, in some cases the scenarios recommended or required for statutory stress testing exercises (such as the three climate change scenarios covered by the Bank of England's 2019 General Insurance Stress Test[20]) do not have any probabilities accompanying them.

This disparity is recognised in the literature[21], and we therefore suggest that organisations undertaken climate stress testing should consider including more severe but unlikely scenarios. Eg IPPC's 'very unlikely' (0-10%) 'extremely unlikely' (0-5%) or 'exceptionally unlikely' (0-1%) statuses.

Notably, public guidance already states that "any safety critical elements of proposed infrastructure (e.g. parts of nuclear power stations) should be assessed against the high impact, low probability scenarios of climate change"[22].

Incorporating managerial responses

Stress testing approaches must consider how the systems and component entities modelled may respond to possible scenarios to the time horizon of interest. It may not be realistic to assume a completely passive response by individuals, organisations or other system agents over a 30+ year timescale – instead, these entities are likely to respond to new information as it becomes available year by year and adapt their strategies accordingly.

However, there can be particular reasons for assuming no intervention during the test period. For example, regulators may require banks to assume a fixed balance sheet.

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[20] https://www.bankofengland.co.uk/-/media/boe/files/prudential-regulation/letter/2019/general-insurance-stress test-2019-scenario-specification-guidelines-and-instructions.pdf

[21] For example, Mearns *et al* (2001) p759 and Weitzman (2011)

[22] HMG (2011)

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Choice of system level

In the financial system, regulators are particularly concerned with the potential for widespread borrower default (a subset of counterparty risk better known as credit risk). This risk of default can be driven by asset prices or the financial health of a borrower or borrowers, and stress testing is widely deployed to assess the risks of defaults propagating throughout a financial system, with resultant loss of confidence and contagion. The concept of failures propagating through a complex system is also familiar in the infrastructure sector, where examples can readily be found of interconnected systems which rely on one another. For example, many infrastructure assets rely on electricity supplies, telecommunications networks and transport access for their continued functioning. Considering infrastructure systems at an appropriate level is therefore important both for stress testing and resilience work, but also for decision-making more generally[23].

[23] Hall et al (2013); Young and Hall (2015)

Frequently Asked Questions

What is Stress Testing and how does it relate to Scenario Analysis?

Stress Testing is a specific type of Scenario Analysis. It looks at certain future scenarios which are particularly likely to cause a system to fail, while Scenario Analysis looks at a broader range of scenarios which may be high-stress, low-stress or business as usual.

How should adverse scenarios be selected?

Adverse scenarios should be sufficiently distinct to one another (this may require creation of separate models).

One specific challenge arises when the adverse scenarios being considered have never been observed before in the system of interest, or a similar system (see 'Threshold effects/tipping points/feedback effects', above).

Who can carry out Stress Testing, and what tools and resources do they need?

Stress Testing often requires the input of multiple teams, and depends on the system of interest. Often there is a model-builder or analyst, who constructs the main model or models that simulate the conditions of stress and the response of the system, but they will often not be an authority on the system of interest and will have to elicit information from subject matter experts in order to build the model. If the system is an engineered asset, subject matter engineers will typically be design engineers, reliability engineers and those with specific expertise in safety and Failure Modes and Effects Analysis (FMEA). If the testing organisation is interested in the financial implications, it is likely that a finance team will be involved.

Tools and resources required will vary widely depending on the system of interest and the scale and complexity of modelling being undertaken. In some cases, an Excel model or linked models may be all that is required. This can be augmented by Scenario Analysis tools such as the @Risk Excel Add-In. In other cases, more complex models implemented in different programming package and languages such as MATLAB or Python may be used. For examples, see here - https://www.mathworks.com/discovery/climate-stress testing.html. However, the principles are the same.

In any case, the stress tester should be aware of the different models and implicit or explicit assumptions that underlie the inputs to their model, and ensure that their model is robust to these.

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Case studies

These sources include case studies of stress testing carried out by relevant organisations. The tests have been carried out using a wide range of techniques and input scenarios, and have not therefore been chosen to represent any particular best practice.

Sector guidance	Does this guidance cover procedures relevant to stress testing?
Wastewater resilience measurement (sewer flooding)	Yes
Power Transmission and Distribution - National Grid Adaptation Report and TCFD Disclosure	Yes, +2°C and +4°C scenarios are considered. Interdependencies with other infrastructure operators are considered to some extent.
Railways - Network Rail Weather Resilience and Climate Change Adaptation (WRCCA) Plan	Yes - P21 – "the purpose of this evaluation was to determine the gaps in current asset designs, standards and controls that would result in significant disruption to the network as a result of adverse and extreme weather." This assessment considers RCP 8.5 at 90th percentile, and also considers 'cascade risks' and system interdependencies Asset risks in the 'major' category increasing from 4% in 2019 to 11% by 2080 (see Fig 5-6)
Flood Defence – Environment Agency ARP	Yes, but it considers only +2°C and +4°C scenarios

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