Managing Electricity Transmission Network Reliability

March 2019

nationalgrid

Contents

Introduction

1.1 Purpose and Scope

The purpose of this document is to describe what National Grid Electricity Transmission (NGET) means by the term “reliability”, how we measure it, and how we can influence the reliability of our network.

This lays the groundwork for future planned consultation that will explore in detail some of the themes outlined here.

1.2 Who we are

National Grid Electricity Transmission owns and manages the England and Wales electricity transmission network transmitting high-voltage electricity from where it is produced to where it is needed throughout the country.

It broadly comprises circuits and consists of:

- Over 14,000 km of overhead line
- 600 km of underground transmission cable
- Over 300 substations

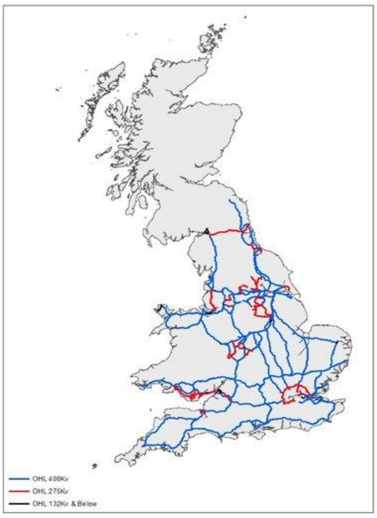
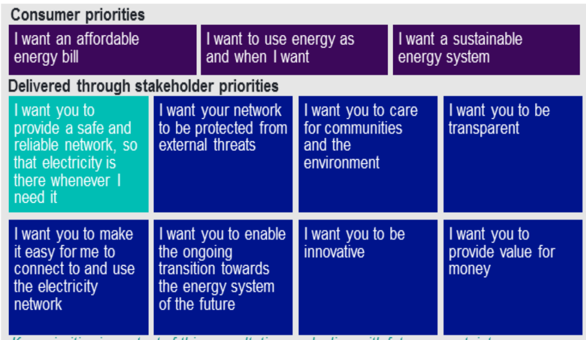


Figure 1: National Grid network map

1.3 Consumer and Stakeholder Priorities.

We are building a business plan, guided by our stakeholders, for the RIIO-T2 regulatory period which runs from 2021/22 to 2025/26[1] We will submit this to our regulator, Ofgem, later this year.
Existing consultation has revealed several key stakeholder priorities. The output of this previous consultation can be found [here.](here)



Key priorities in context of this consultation on dealing with future uncertainty

This document will focus on the priority of providing a safe and reliable network by discussing the different aspects of reliability and how they interact.

The views of our stakeholders are important to us. This document is part of an extensive programme of engagement on our future business plan.

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[1] 1 RIIO stands for Revenue = Incentives + Innovation + Outputs, and T2 is the second transmission price control under the RIIO framework.

2. What is Reliability?

The reliability of a system is essentially defined as the likelihood that the system will perform its intended function under stated conditions. The "stated conditions" define the "normal" operating parameters for the equipment (e.g. ambient temperature range, age, defined operational duty limits). NGET's network is made up of tens of thousands of pieces of equipment (assets) that must all be available to perform their duty when called upon. Some of these operate almost continuously (e.g. current carrying paths such as cables, overhead lines and transformers) whereas others are only required to operate intermittently (e.g. switchgear and reactive compensation).

To ensure that any system remains reliable in the long term its components need to be inspected, maintained, refurbished and replaced in a timely manner. However, to ensure economic operation of the electricity network the timing of these interventions needs to be optimised. This also requires balancing how much of the network can be removed from service at any one time. Any decision to undertake an intervention on equipment is based on a balance of cost, risk and performance in line with asset management best practice such as ISO 55000[2].

Resilience vs. Reliability

For the purposes of this document reliability and resilience are considered to be different but interrelated areas of consideration. National Grid has separately consulted on resilience and therefore only a cursory summary will be provided here.

National Grid defines resilience as the ability to withstand or recover from extreme events (e.g. storms, terrorist attack etc.), whereas reliability relates to the day to day management of the network and dealing with foreseeable faults and defects. Of course, the reliability of a network has an impact on its resilience and vice versa but for the purposes of this document we will focus on dealing with the natural aging and deterioration of equipment, and the consequences thereof, and strategies to mitigate the impact of this

Figure 2. Resilience vs Reliability

By current (2017/18) measures NGET's system is **99.999984%** reliable[3]. This figure may look very high but when you consider the impact of just a small percentage change in reliability as seen in Table 1 it becomes clear why reliability levels of the transmission system need to be maintained at the highest level is 99.999984% reliable[3].

[2] ISO 55000:2014 provides an overview of asset management, its principle and terminology, and the expected benefits from adopting asset management.
[3] See National Electricity Transmission System Performance Report 2017-2018

Reliability(%)	MWh not suppliers	Equivalent houses without supply for 24 hours	Example towns/cities
99.99999	25	2938	Alcester or Tadcaster
99.99998	50	5877	Beaconsfield or Milford Haven
99.99995	125	14692	Billericay or Wilmslow
99.9999	250	29384	Harrogate or Rugby
99.9995	1248	146920	Bradford or Coventry
99.999	2496	293840	Bristol or Leeds

Table1. Indicative number of households without electricity supply for size of loss of supply event (based on 2016/17 values and assuming the average house uses 3.1MWh per year)

In order to assess how reliable a system is you need to understand what factors lead to unreliability, the interactions between these factors and how you might measure them. NGET expresses the interaction of the various aspects of network reliability through the so called "Performance Triangle" (see figure 3). This shows the relationship between loss of supply events and other network performance metrics.

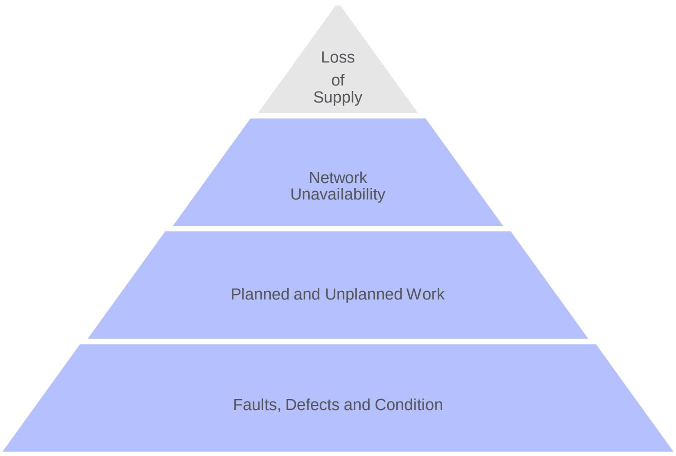


Figure 1: Performance triangle

There are a number of metrics that NGET tracks that allow for an understanding of the Performance Triangle that will be explores in Subsequent sections.

2.2 The Performance Triangle

The Performance Triangle is made up of 4 main sections:

1. Faults, Defects and Condition: This describes the general underlying state of equipment
2. Planned and unplanned work: The volume of work (maintenance[4], construction etc.) that requires access to equipment. Much of this is carefully planned long term but some short-term work will be required to resolve urgent defects and faults.
3. Network Unavailability: Maintaining and replacing equipment and connecting new supplies and customers requires parts of the network to be switched out of service, thus making it "unavailable"
4. Loss of supply: events that lead to supply being lost to customers (i.e. power cuts)

The interactions between these layers can be complex and create feedback loops:

- The risk of loss of supply events occurring increases as the network availability reduces.
- In turn network availability is reduced whenever a circuit is taken out of operation for either planned purposes or as a result of a fault.
- Planned outages are required for system construction and new user connections. They are also required for the maintenance necessary to retain a high level of system reliability.
- Faults, failures and defects have an impact on planned and unplanned work and are essential factors in understanding the total work requirements and the performance and condition of the assets that comprise the network. Hence, unreliability outages also contribute to network unavailability.

2.3 Interactions

All the elements of the Performance Triangle have interactions and feedback loops that need to be carefully considered. This can be seen, for example, by considering the need to repair defects, resulting in equipment being switched out, thus increasing network unavailability and increasing the likelihood of loss of supply events. Conversely, not taking suitable outages to resolve defects and carry out maintenance will lead to unplanned events in the future and increase the risk of loss of supply events.
It is important to understand the relationship between asset and network performance.

Increasing asset unreliability has an impact on system availability and can lead to:

[4] Our maintenance activities are defined in section 4.2

- Reassignment of network access (i.e. what equipment can be switched out), resources and physical assets
- Delays in the maintenance or asset replacement[5] programme
- In order to mitigate the impact of unreliability on the network it is important to: Understand asset condition
- Understand asset performance
- Understand future asset deterioration
- Undertake timely investment
- Prioritise and plan asset interventions

Changes to the level of interventions on assets result in a change of asset condition. If asset condition deteriorates and results in an unreliability event which needs an unplanned outage to rectify, this has an immediate impact on system availability, which restricts the ability to operate the system and may result in the cancellation of planned outages, which in turn restrict the level of maintenance and replacement activities, potentially leading to further unreliability events. An illustration of this can be seen in Figure 4.

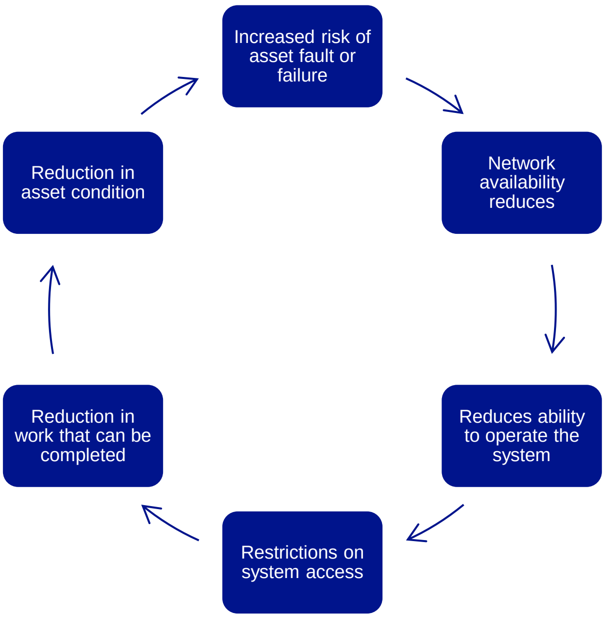


Figure 4. How poor management of influences on reliability can create a negative loop.

It is important to note that some of the interactions are subject to time lags which may be in the order of years. Not carrying out asset replacement now will not lead to immediate failure of equipment but rather will present issues in subsequent decades.

2.4 Asset Management at National Grid

NGET ensures that all assets are managed to the highest standards and takes account of best practice (e.g. the ISO 55000:2014 suite of standards).

[5] Replacement is capital investment and defined in section 4.3

Extensive use of data and analytics means that decisions regarding the stewardship of assets can be made to confidently manage the balance of cost, risk and performance. An extensive innovation programme also ensures that we can continue to develop new techniques for understanding and managing our assets, delivering value to our stakeholders.

A culture of continuous improvement, internal and external audit programmes, and international benchmarking means that we continue to deliver optimisation in the areas of maintenance and asset replacement while ensuring world class reliability.

2.5 Network Redundancy

NGET plans and operates the transmission system in accordance with the Security and Quality of Supply Standard (SQSS), which is a requirement of the Transmission Licence.

In essence, the standard determines the degree of “redundancy” (i.e. spare capacity) that must be built in to the transmission system so that the system is robust against credible equipment failures and the need to maintain the assets.

The level of “redundancy” built in to the transmission system is a between cost and security. The existing standard has delivered a high level of reliability by international standards. In operational timescales, circumstances will arise where equipment failure leads to a short-term erosion of the security standard. The most common faults that we plan and operate the system to are the loss of a single transmission circuit (such as a cable circuit), or the loss of a pair of overhead line circuits. In these circumstances, remedial action is taken as soon as possible to restore the required level of security. It is also possible that high levels of demand can be at risk to the failure of a single circuit for the time taken to reconfigure the network. This “switching time” is usually in the order of 20 minutes and the probability of a second equipment failure during this time is extremely small.

3. How do we measure Reliability?

As described above there are a number of different external and internal measures of reliability that NGET uses. The externally reported measures are described in the following sections. These measures are different but related ways of describing network and asset reliability.

3.1 Energy Not Supplied

Energy not Supplied (ENS) is perhaps the simplest and most obvious measure of network reliability as it captures loss of supply events. It is the volume of energy to customers (MWh) that is lost as a result of faults or failures on the network. Reducing ENS means minimising interruptions to supply on the electricity system. These are typically low probability but high impact events.

In terms of energy supplied, NGET's electricity transmission network is extremely reliable. Figure 1 shows NGET's transmission reliability figures as percentage of energy supplied since the start of the RIIO-T1 period[6].

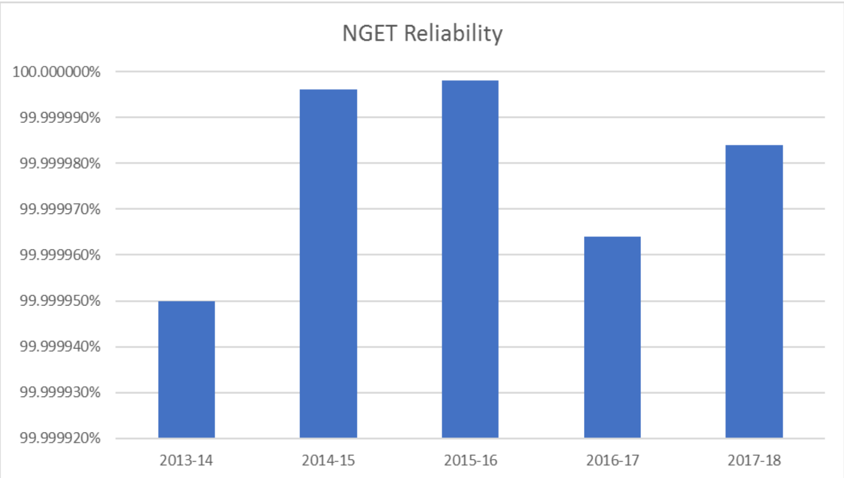


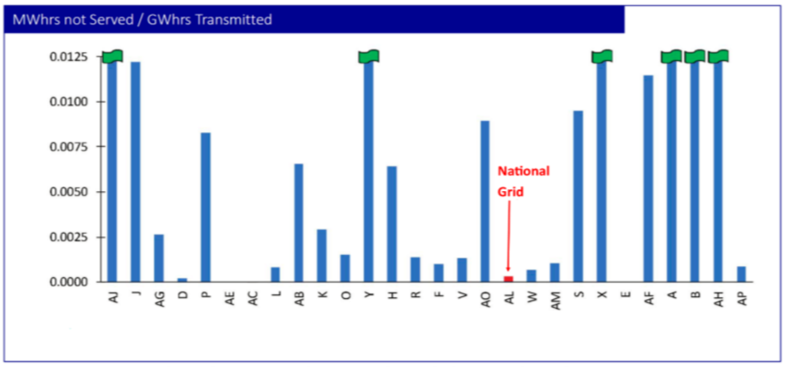
Figure 1. NGET historic reliability as defined by ENS. Note the scale starts at 99.99992%

NGET and the Scottish Transmission Owners (TOs) are incentivised to reduce ENS events through the Energy Not Supplied Incentive Scheme. It has both a reward and a penalty element where NGET will lose money for loss of supplies exceeding 316 MWh per annum (to a maximum of c.a. £48m

[6] $$Reliability\ (\%) = \left[1 - \left(\frac{Estimated\ Unsupplied\ Energy}{\text{Total energy that would have been supplied by the transmission system}}\right)\right] \times 100$$

p.a.). Conversely the company earns money (to a maximum of £3.7m) for an annual loss of supplies below 316 MWh.[7]

International comparison via benchmarking activities with similar transmission companies around the world (see Figure 2) reveals that NGET's reliability performance in recent years is among the best.



Data Source: Question 14 of KPIs tab in Practices and Question 5 of General Information tab in Performance

NA: AE,E

AJ	D	AC	Y	X	A	B	AH
0.34340	0.00021	0.00001	8.29025	0.08398	0.12674	0.03263	0.04586

Figure 2. NGET's ENS performance against 27 other (anonymised) international transmission utilities for 2016/17. Source: ITOMs Benchmarking report for 2017

Currently NGET is incentivised on ENS to achieve high levels of reliability. NGET is seeking to retain this incentive in the T2 regulatory period as we believe incentives are effective at promoting and rewarding the right behaviour. Ofgem are currently consulting on this incentive.

3.2 Network Unavailability

Network unavailability is the measure of how much of the network is switched out at any one time. Figure 3. NGET Network unavailability by month for 2017/18 shows how this is presented in the National Electricity Transmission System Performance Report.

The Network Unavailability[8] is metric is split into the following categories:

- User connections: outages required to facilitate the connection of new suppliers or customers
- System construction: Typically, asset replacement activities
- Maintenance: planned outages required for maintenance

[7] Certain exclusions do apply to the events considered under the incentive. For example events lasting three minutes or less, and events affecting for customers who have requested a lower standard of connection are not included.

[8] Network Unavailability = $\left(1 - \left(\frac{\text{The sum for all circuits of hours available}}{(\text{No.of circuits})\times(\text{No.of hours in period})}\right)\right)\times 100\%$

- Unplanned: outages relating to asset failures and defects

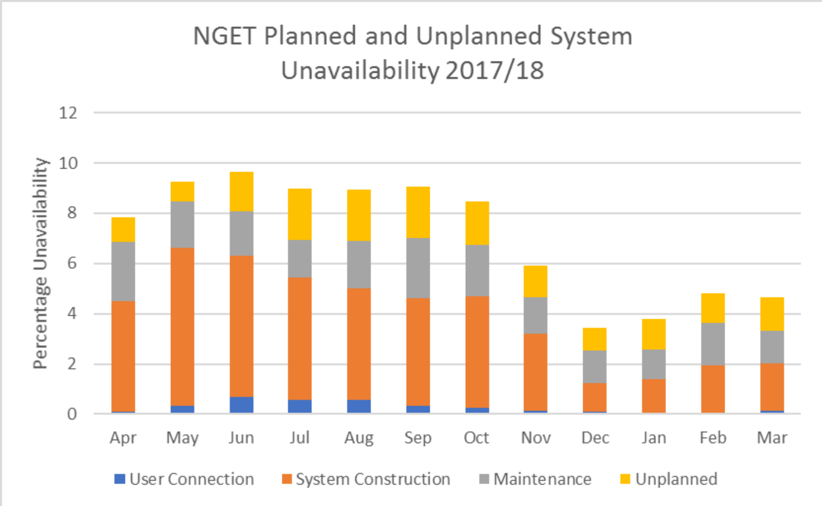


Figure 3. NGET Network unavailability by month for 2017/18

Of these the main categories that concern reliability are Maintenance and Unplanned as a subset of these categories combine to form the Average Circuit Unreliability metric which is described below.

3.2.1 Average Circuit Unreliability

Average Circuit Unreliability (ACU) measures the amount of network unavailability when a circuit or part of the system is switched out for the repair of unreliable assets. This can be due to a fault or failure or the need to switch the circuit out in order to resolve a defect (described in the following section).

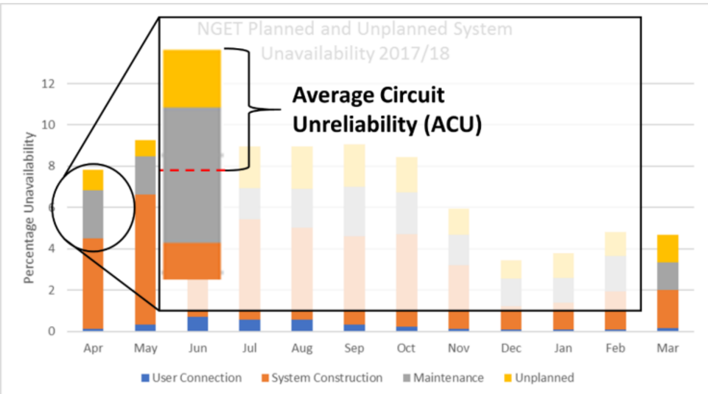


Figure 4. Average Circuit Unreliability as it relates to System Unavailability

As a transmission circuit is made up of multiple components (transformer, switchgear, overhead lines, cables etc.) if any of these components needs to be repaired, the circuit will be removed from service and the time of the repair outage will count towards this metric.

The ACU is analysed in depth to understand which assets are most contributing to network unreliability and to identify any common causes of failure or defects. It can, for example, help identify issues with a specific asset type which ensures that strategies to mitigate the impact of this unreliability can be developed. Figure 5 shows an example of the type of analysis that can be carried out using ACU. In this example, looking month by month we can see the impact of specific events and asset types on overall ACU figures, allowing for a deeper understanding of the impact that reliability outages have.

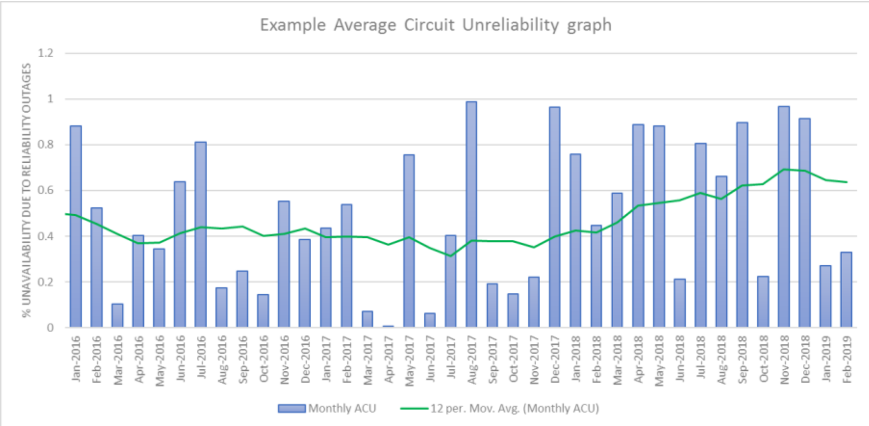


Figure 5. Example ACU tracking

ACU is not specifically reported publicly today but rather is wrapped up in more general statistics published each year describing system unavailability. However, it is a figure that is reported to, and reviewed by, Ofgem annually.

3.2.2 Assessment of ACU

Average Circuit Unreliability has been increasing over the years. This is largely due to deterioration an ageing asset base. However, it is also likely due to better detection methods (e.g. condition monitoring). Our assets are more closely inspected than ever before and as a result more defects are found and assets switched out of service in a controlled manner for repair. Despite a rise in ACU, a corresponding rise in ENS events has not seen, possibly due to the ability to remove equipment from service and repair or replace them before unplanned failures can occur.

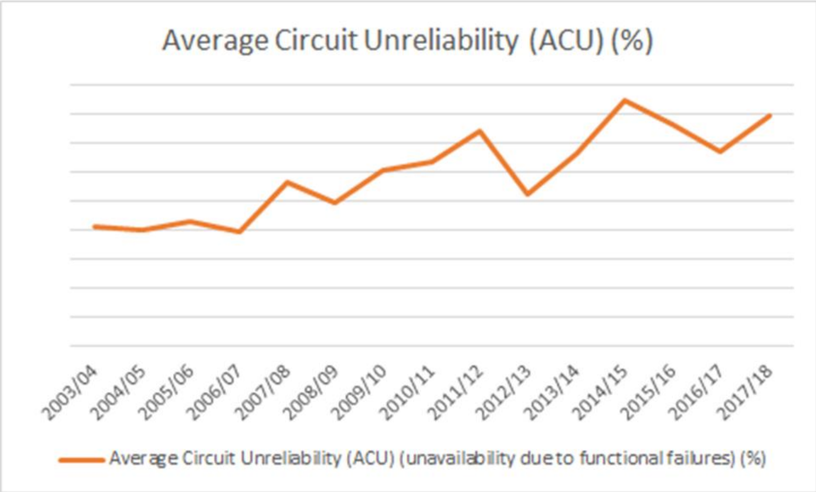


Figure 6. NGET ACU trend

This metric can be disaggregated by asset type and condition to more fully understand unreliability with particular asset classes. By monitoring the ACU, strategies can be developed to manage unreliability on the assets.

The ACU is a lagging measure of asset condition. NGET has a number of processes in place to understand the condition and performance of the assets and to plan interventions proactively.

The ACU has been reported consistently since 2002, and is a good measure of unreliability because it incorporates all unreliability related events including fault investigation and defects as well as failures. Deep dive analysis of the measure means that it can be disaggregated by equipment group and condition and this can identify issues with particular asset types. Asset management strategies can then be developed to manage such issues

4. How do we manage Risk?

4.1 Faults, Defects and Condition

Faults and failures of equipment refers to events where equipment unexpectedly fails to operate as designed and needs to be removed from service ASAP (usually immediately). An example might be a circuit breaker failing to open or close on command, or an overhead line insulator parting. A small subset of these are failures that lead to partial or complete destruction of the equipment.

Conversely defects are usually discovered by our condition monitoring and inspection programmes. Defects may require immediate outages to rectify or can be logged for future repair depending on severity.

Outages specifically caused by faults and failures or to rectify them and any defects found will count towards ACU.

Asset condition refers to the general state of equipment based on all available information and is summarised by our assessment of Network Risk.

4.1.1 Network Risk

A risk score based on Probability of Failure and Consequence of failure is calculated for each asset. By summing the risk on each asset across the system, the total network risk can be calculated.

A model has been developed with the aim that it will be used to assist in planning and prioritising the work that needs to be undertaken on high risk assets within the transmission network.

In order to ensure the longevity and performance of the network it is important to understand asset condition and the interventions needed on these assets to maintain reliability. Without effective management of activities such as maintenance, refurbishment and replacement of the assets, and understanding the related interactions between them, in time degradation of the assets would have a significant detrimental impact on the capability of the network.

Network risk is a concept that has been developed as part of the Network Output Measures Methodology for lead assets (i.e. transformers, reactors, circuit breakers, overhead lines and cables) that was developed for RIIO-T1 and has continued to develop since. Essentially network risk is a measure of the macro condition of NGET's assets and is the driver behind major capital investment (refurbishment[9] or replacement) and is ultimately how NGET's performance is measured by Ofgem.

[9] Refurbishment is capital investment and defined in section 4.3

Although not specifically created as a reliability measure it can serve that function. NGET has been tasked with achieving a target level of network risk through the RIIO-T1 regulatory period.

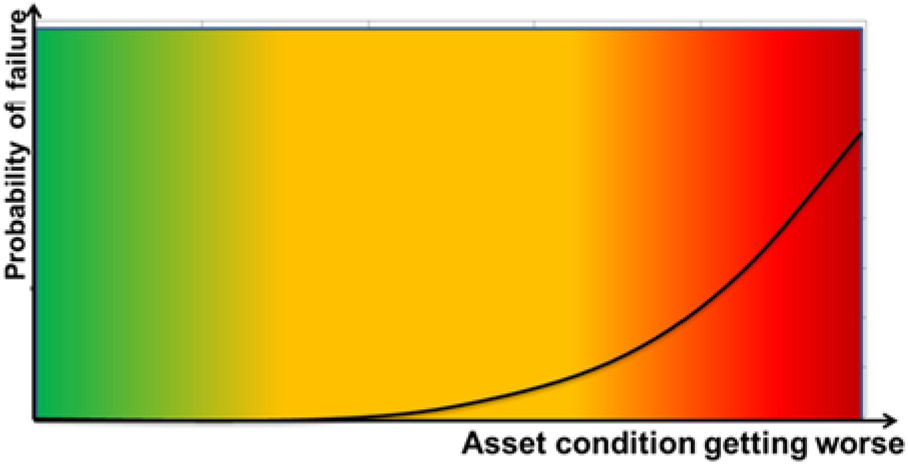


Figure 7. Curve showing how PoF might relate to asset condition

Today this approach entails detailed analysis of the various failure mechanisms that can occur on equipment, the interventions available to address these and the events resulting from them. Linking of the Probability of Failure (PoF) to asset condition is possible via relationships such as that in Figure 7. More complex curves (such as that in Figure 8) and their associated equations can then be developed and used in models.

Figure 8. How asset risk changes over time and is affected by maintenance activities and ultimately replacement

Assets have different functions and may experience a number of different failure events. Each event is assessed to understand its consequence.

The four consequence elements considered are:

1. Environmental: reflects the different environmental impacts for each event
2. Safety: reflects the different safety impacts to the public and personnel for each event
3. Financial: reflects the business cost of the intervention, such as repair or replacement, needed to address the asset failure event
4. System: reflects the impact on the network, given an asset failure event

Full detail on risk calculations and the impact on Network Output Measures can be found here on the Ofgem website.

4.2 Maintenance activities

There are several different types of activities that can be carried out under the banner of "maintenance". These are:

- Routine inspections
- Condition monitoring
- Intrusive maintenance

The maintenance regime that NGET employs is designed to ensure an acceptable level of reliability balanced against cost and risk and is currently largely time interval based but also employs elements of duty and condition.

4.2.1 Routine Inspections

To support the maintenance regime Site Routine Inspections are undertaken. These inspections are scheduled at regular intervals (Weekly, Monthly, Quarterly) and dependant on the time of year include pre-winter and spring time inspections. The inspections cover a whole range of checks such as checks to oil levels, gas pressures, test running of compressors, checks to confirm heaters are working and general visual checks of the equipment for signs of external damage.

As NGET employ such a thorough maintenance regime supported by non-intrusive tools and regular inspections inevitably defects will be discovered; particularly given the age range of the asset base.

4.2.2 Condition Monitoring

In addition to routine inspections we carry out regular Condition Monitoring checks of the main substation plant using non-intrusive tools such as Thermal Imaging, Radio Frequency Interference (RFI) monitoring and Dissolved Gas Analysis (DGA).

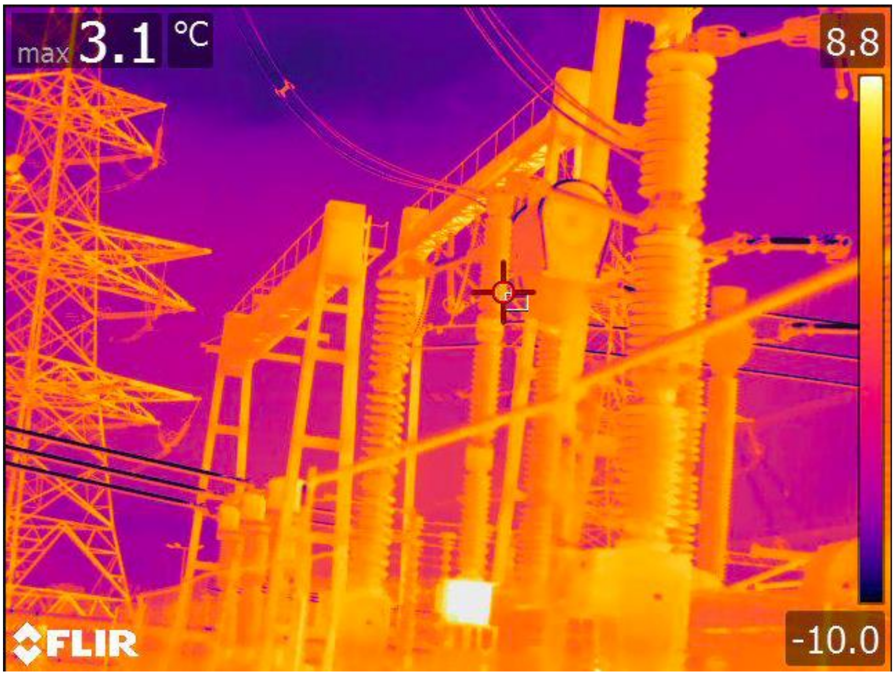


Figure 9. Condition Monitoring of substation assets via non-intrusive thermal imaging

4.2.3 Intrusive maintenance

Maintenance activities that require the equipment to be switched out and made dead are regularly undertaken. For many asset types the time intervals between maintenance has been extended over time as knowledge has increased to ensure we continually strive for the optimum cost/risk/reliability balance. Extensions to maintenance frequencies have also been made possible by the better use of data and the improvement in the use and understanding of the condition monitoring mentioned above.

4.2.4 Defects

During any of the 3 activities outlined above defects can be identified. Most defects found on inspection during maintenance will be rectified during the maintenance outage. On rare occasions, found on inspection defects may lead to an extension of the planned outage window in order to fully remedy the issue before the equipment can be safely returned to operational service.

Defects found via routine inspection or detected via the use of non-intrusive tools will be dealt with and prioritised dependant on their urgency. On some occasions, due to the severity and operational / safety implications, it may be necessary for the affected equipment to be removed from service immediately to expedite repairs or it may be acceptable to wait until the next maintenance opportunity.

Should a defect be identified associated with an asset which for operational reasons is difficult to release immediately the equipment will be closely monitored and/or measures put in place to protect personnel in the event of a failure. The measures will be utilised for a short time to allow a controlled release from service and to prevent other System constraints or disruption of the maintenance or construction programme.

4.3 Capital Investment

Where an asset is approaching the end of its life and the onset of failure cannot reasonably be prevented significant investment is usually required to replace or refurbish it. This is prioritised via the assessment of network risk outlined previously using a combination of the probability of failure and the consequence. In addition, the optimisation of system access, resources, and other considerations will mean that replacement work for individual assets can be delayed or brought forward within acceptable margins.

Every asset has an underlying set of failure modes that ultimately decide the lifetime it can expect to see. These cannot be addressed by maintenance activities so intervention falls into one of the following options:

- Refurbishment
- Replacement
- Disposal (an Opex investment) to remove the end-of-life failure risk entirely

To understand the risk around end of life failure, NGET routinely reviews the health of its asset population and forecasts how this is expected to change over time. This gives a measure of the changing probability that an asset may fail. To arrive at a risk value, the probability and a value of the consequences of events that may arise from asset failure are also understood.

Deriving a health measure for an asset (and therefore its probability of failure) is a function of the 'work' that the asset has been subject to and its response to that work over time. This requires multiple data inputs that can be grouped in the following categories. Examples of the specific data inputs are provided in but are not exhaustive.

Work not done/Energy Input/Exposure		Asset Response/Vulnerability		
Environment/Exposure	Operational Exposure	Condition Assessment	Performance	Asset Inventory Data
Corrosion Wind Induced Motion	Thermal Loading Short Circuit Current No. Of Switching Operations	Oil Analysis Thermography Partial Discharge Power Factor Visual	No. of severity of condition related defects Faults – automatic disconnections from the system due to defects and failures Failures – assets in a state requiring immediate replacement	Manufacturer Variant Installation date at location Age

Table 2. Example data inputs to asset health assessments.

The consequences of the events that may arise from end of life failure modes have some safety, system, environment and financial consequence. The type of asset (e.g. oil filled) and its location in physical space (e.g. urban) and on the system, are variables that affect these values.

A measure of asset risk of failure *today* is only a part of the understanding required to manage this over time. To derive the volumes requiring an intervention, a forecast of how the asset health is expected to deteriorate is needed. Each asset's health measure is a point on a deterioration 'curve'. This is a graphical function describing the change in probability of failure over time, to the point at which an asset is expected to be in a 'state requiring intervention'.

The ability to forecast growth in risk over time, enables management of the population to a desired risk objective. Simply, this translates into a volume of interventions required over a defined period. This is the foundation of the capital investment plan, with understanding the impact of each asset or group of assets on the total risk of failure across the network.

4.3.1 Refurbishment

Asset refurbishment is possible for certain asset classes and usually involves stripping down and rebuilding the asset back to an acceptable standard for reinstallation.

The decision to refurbish instead of replace follows careful consideration of a number of criteria. For refurbishment to be a technically feasible and cost-effective alternative:

- The population size must be sufficiently large: the costs associated with developing the technical content of a refurbishment procedure, and the set-up costs of a dedicated facility to undertake the work, mean that it is difficult to make refurbishment of small populations cost-effective.

- The ongoing lifetime cost of supporting a refurbished asset family must be considered: it may be more cost-effective to replace highly complex units that require frequent intervention. A net present cost analysis is undertaken to assess this factor.

- Continuing spares support must be considered: whilst some spares can be re-engineered without significant risk, this is not appropriate for performance-critical components. If such components are unavailable (or not available cost-effectively), refurbishment is unlikely to be a realistic option.

- Adequate technical expertise must be available: both to develop and deliver the refurbishment and to support the refurbished population to its end of life. Large populations facilitate the retention of expertise much more easily than small populations.

- The condition and deterioration mechanisms of the asset type must be well understood: there must be effective mitigation and rectification measures available to address these such that the intended life extension is achieved.

4.3.2 Replacement

The need to replace equipment is assessed within the parameters set by the Network Output Measures methodology for lead assets. Essentially this prioritises the replacement of the poorest condition, highest consequence of failure assets. As the understanding of failure mechanisms and asset degradation have advanced the need to replace many types of equipment has been delayed with assets typically being in excess of 50 years old (compared with a design life of 40 years) on replacement. For non-lead assets, similar processes of assessing their health and developing strategies are applied.

Replacement of equipment is typically planned over timescales of 10+ years. This is due to the long lead times associated with the both planning the work and procuring the replacement equipment.

5.Conclusion

Establishing metrics and measures for reliability is complex and the interactions between the various factors is non-trivial, particularly due to the potentially extensive time lags between changes. This document has sought to set the scene for how NGET monitors, measures and manages reliability and the levers that are available for influencing this.

Subsequent consultation will explore some of the areas in this document in more detail and this will be driven by your feedback on the areas that you would like to know more about.

National Grid plc
National Grid House,
Warwick Technology Park,
Gallows Hill, Warwick.
CV34 6DA United Kingdom
Registered in England and Wales
No. 4031152

nationalgrid.com