Nuttall Consulting

Regulation and business strategy

Electricity Transmission Reliability Measures
Review of options and concept design

A report to AEMO

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Executive summary

Background and overview of position

The Australian Energy Market Commission (AEMC) is conducting a review of a national framework for transmission reliability. A requirement of the AEMC review is to develop a consistent approach to reporting on transmission reliability across the NEM. The Australian Energy Market Operator (AEMO) has requested that Nuttall Consulting provides advice on possible transmission reliability measures that could be reported and are suitable for capacity planning under a probabilistic planning approach.

In this report, we propose a set of measures based upon the statistical expectation of the energy demanded by customers that is not supplied at each transmission connection point. This measure is more commonly referred to in the industry as the *expected energy not supplied* (EENS) or *expected unserved energy* (EUSE). To improve the appreciation of the link between reliability and capacity planning needs, this measure could be used to report historical and forecast reliability.

This measure has a number of beneficial characteristics that should improve the efficiency of investment decisions made by TNSPs and other stakeholders:

- it provides good visibility of the reliability of supply that customers could expect from a connection to the transmission network
- it has a strong relationship to the economic value of the reliability, making it suited to meaningful comparative review and benchmarking
- it can be calculated in an objective and transparent way
- it provides good visibility of the factors that may be affecting reliability, and differences in these factors between TNSPs
- it can provide equivalent measures of reliability of transmission and distribution networks.

To improve the use of this measure, particularly the ability to make comparisons between connection points and TNSPs, the EENS measure at each connection point would be broken down into various categories, covering:

- the customer types being interrupted
- the type of outage event (e.g. line single circuit outage) causing the interruptions to supply
- the type of network limitation (e.g. thermal, voltage, stability) being alleviated by the interruptions to supply.

The EENS measure could also be supported by reporting some related measures:

- the average time between customer interruption events (or the frequency of interruptions)
- the average time of an interruption event.

All these measures could be produced by extending the processes already applied annually by AEMO to prepare the national transmission network development plan. This will require some additional effort. But the large part of this additional effort most likely will be required to prepare the initial set of measures (i.e. at start-up), in order to produce the data inputs, tools and/or models for the first time. Following this effort, subsequent measures should be able to be prepared by applying a more routine methodology that is more focused on reviewing and amending the previous inputs.

It is important to note that reporting the measures proposed here would support a probabilistic planning methodology (termed an economic approach by the AEMC). But they do not rely upon this approach being applied. Reporting these measures could still have significant benefits even if a deterministic planning approach, using redundancy standards, was applied by some TNSPs.

Measurement options considered and the rationale for the preferred

To evaluate measurement options, we have considered a number of ideal characteristics that we believe reliability measures, relevant to capacity planning, should exhibit if they are intended to improve the efficiency of the NEM:

- *visibility of the reliability of supply that customers can expect to be provided* – this requires measures at the transmission connection points that appropriately allow for the range of outage events that affect reliability, particularly the low frequency/high consequence events that normally drive capacity needs
- *suitability for benchmarking* – this requires that the measures have a strong relationship to the economic value of reliability and can be prepared from an objective and transparent process
- *incremental effort to prepare* – this requires that the measures should be as simple as possible to prepare, relying as much as possible on existing systems and processes – at the very least, the costs to prepare should not outweigh the expected economic benefits of reporting
- *visibility of the drivers of reliability* – this requires that the measures should provide an indication of the underlying issues driving unreliability
- *suitability for transmission and distribution* – this requires that the measures could be prepared for distribution networks also, and would provide a consistent measure of reliability provided by both networks.

We have evaluated a range of possible measurement options against these characteristics. These options can be considered in terms of the following groups of related measures:

- SAIDI/SAIFI/CAIDI/MAIFI, which are the measures commonly reported for distribution networks
- T-SAIDI/T-SAIFI/SARI, which are similar measures associated with transmission connection points
- asset outage measures, which are the input-measures often reported as part of transmission service incentive schemes

- expected energy not served, and associated measures, which are measures often prepared as part of a probabilistic planning assessment
- n-x compliance measures, which are measures that could be used to report the margin of compliance to a redundancy standards.

As may be expected, our evaluation found that none of the reliability measures was ideal. Measures most commonly used to report actual reliability, such as SAIDI/SAIFI/CAIDI, their transmission counterparts and asset outage measures, could provide a very volatile measure of connection point reliability and it would be difficult to alter these measures in order to prepare a less volatile statistical measure. These measures also have a relatively weak relationship to the economic value of reliability because they measure the durations of interruptions, and so, do not capture the scale of the interruption.

Measures of the margin of compliance to n-x standards are not routinely reported - although they are feasible and should be fairly easy to measure. But measures of this type would provide a very weak relationship to the reliability of supply and the economic value of this reliability. Consequently, it could be expected that the economic benefits of reporting these types of measure would be low.

On the other hand, the EENS measures are specifically designed to aid capacity planning and other decision processes. Because of this, they inherently provide a statistical measure of the reliability that customers may be provided. They can also be defined to provide a good correlation with the economic value of reliability and provide good visibility of the factors driving reliability.

Many stakeholders, however, will not be familiar with the EENS measure. And reporting actual reliability is still likely to be important for reasons other than capacity planning. Therefore, the EENS measure would most likely need to be supported by reporting other measures that are based directly upon actual interruption events. Consequently, there will be increased effect to prepare and report measures based upon EENS.

Although reporting the EENS measure with other measures of actual reliability may require additional effort, it appears to be the only measure that addresses the more critical ideal characteristics in a meaningful way, specifically providing visibility of the reliability of supply and its suitability for benchmarking. Therefore, provided the effort to prepare such a measure is reasonable (i.e. the benefits of reporting this measure will most likely outweigh the costs to prepare it) then we believe this measure should be the preferred option.

Specifying the measure and the process to calculate the measures

The EENS measure is prepared via a “simulated” approach, rather than directly from records of actual customer interruption events. Therefore, to ensure that the measures are prepared in a consistent, objective and transparent way, it will be critical that the national framework specifies the assumptions that must be used to prepare the measures. These assumptions would need to cover matter, such as:

- the outage events to be modelled
- the preparation of outage probability models

- the applicable network ratings
- assigning EENS to connection points
- customer demand assumptions
- generation dispatch assumptions
- network and generation development assumptions
- load transfers and restoration assumptions
- circumstances where the standard methodology and assumption can be changed to prepare the measures.

Various approaches could be applied to calculate EENS. In this report, we have highlighted a process that (as we noted above) is an extension of the methodology that AEMO currently applies to prepare the national transmission network development plan. This process uses the systems, software and data that TNSPs and AEMO presently use in their planning and operating roles.

The process involves undertaking network analysis familiar to TNSPs. The aim of this analysis is to identify the network conditions – allowed for by the assumptions noted above - that may result in unserved energy to customers, and then develop the relevant network equations (e.g. constraint equations) that represent this behaviour.

Following this analysis, further modelling would be undertaken – possibly using market modelling software or purpose-built spreadsheets – to perform the detailed calculation of the EENS (and other measures) based upon these equations, the various demand and generation scenarios, and the network outage probabilities.

Concluding comments and next steps

In this report we have proposed a reliability measure for transmission connection points based upon the calculation of the *expected energy not supplied*. We believe that this measure, in the form outlined, could provide greater economic benefits over other options, particularly with regard to capacity planning.

We believe that this measure can be prepared in a consistent, objective and transparent way, provided key assumptions and methodological matters are defined within the national framework. While there may some initial “start-up” effort associated with preparing this measure, we believe that the ongoing effort will be far less, and is unlikely to outweigh the potential economic benefits of reporting this measure.

To assess this measurement option further, the following matters will need more consideration:

- the best approach to prepare the measure, including the additional tasks required and an estimate of the effort to undertake these tasks – covering both start-up and ongoing tasks
- the most appropriate parties to prepare the measure and/or undertake the associated tasks
- the assumptions that should be specified within the framework
- whether other statistics of the energy not supplied at each connection point should be reported to provide a better view of the range, scale and probability of interruption events.

1 Introduction

1.1 Background and appreciation

The Australian Energy Market Commission (AEMC) is conducting a review of a national framework for transmission reliability and has published an issues paper for consultation as a first step in this review[1]. This review and the discussion in the issues paper draws upon previous work undertaken by the AEMC on the Transmission Reliability Standards Review, which was finalised in 2010.

A requirement of the AEMC review is to "develop a consistent approach to reporting on transmission reliability across the NEM, with any weightings and assumptions applied to different network elements made explicit"[2].

The issues paper states that reporting actual reliability would have some benefits, including serving as a useful accountability mechanism; and assist stakeholders, including the Australian Energy Market Operator (AEMO) and the Australian Energy regulator (AER), to identify potential over and under investments by Transmission Network Service Providers (TNSPs)[3].

However, the issues paper also notes that the AEMC considers that it is difficult in practice to devise measures that define the reliability of supply provided by a transmission network i.e. output measures[4]. It also states that the "(r)eporting would ideally need to be on a redundancy basis"[5] (i.e. with reference to n-x type of standard) in order to align with its preferred approach to setting transmission reliability standards, which is also based upon defined redundancy standards.

The Australian Energy Market Operator (AEMO) has engaged Nuttall Consulting to assist in the preparation of its submissions to the AEMC concerning the national framework review.

1.2 Terms of reference

As part of this assignment, AEMO has requested that Nuttall Consulting provides advice on possible transmission reliability measures that could be reported and are suitable for capacity planning under a probabilistic planning approach[6].

This advice should:

- define feasible measurement options

[1] AEMC, 2013, Review of the national framework for transmission reliability, Issues Paper, 28 March 2013, Sydney
[2] Ibid, pg. 2
[3] Ibid, pg. 45
[4] Ibid, pg. 45
[5] Ibid, pg. 45
[6] The probabilistic planning approach is called an economic approach in the AEMC issues paper.

- provide some evaluation of the advantages and disadvantages of these options, with regard to their suitability for measuring reliability and facilitating capacity planning and/or the appreciation of capacity planning decisions
- if possible, advise on a preferred measurement option
- explain the key assumptions required to report these measures
- explain the process required to prepare these measures on a periodic basis (e.g. annually).

At this stage, advice on the measurement assumptions and process should only be conceptual.

1.3 Definitions

The following are important definitions used in this report. Some of these definitions may not align with the usual NEM and NER definitions.

- ***customer*** is used to mean the end-consumer of electricity that is supplied from the transmission network. It may be that some relevant customers are supplied from the transmission network via a connection to an intermediate network, such as a distribution network. Importantly, its use in this report does <u>not</u> reflect all the parties with a direct connection to a transmission network if they are not end-consumers of electricity, such as DNSPs or generators.
- ***output reliability measure*** is a measure of the reliability of the supply of electricity that a customer receives from the transmission network. This is the reliability of supply that a customer could directly observe and measure.
- ***input reliability measure*** is a measure of the reliability of the transmission network, but not explicitly the reliability of supply provided by the network. This is a direct measure of the reliability of the network components that a TNSP can observe and measure.
- ***interruption*** is the total loss of supply of electricity to a customer.
- ***outage*** is the loss of ability or availability of a power system component (e.g. a transmission network component or generation unit). Of note here, an outage may not always result in an interruption.

2 Ideal characteristics of reliability measure

This section discusses the characteristics of a reliability measure (or group of measures) that we believe are important for planning the capacity of a transmission network, including ensuring stakeholder are informed on reliability in a way that is relevant to appreciating network capacity needs.

These characteristics are used in the later sections of this report, where we discuss various measurement options, and present our preferred option.

The characteristics we believe are important relate to:

- the visibility of the reliability of supply to customers
- the suitability of the measures for comparative analysis and benchmarking
- the incremental effort on TNSP or other stakeholders to prepare the measures
- the visibility of the drivers of reliability
- the suitability for providing measures of reliability for both transmission and distribution network.

2.1 Visibility of the reliability of supply to customers

A very important characteristic of measures relevant to capacity planning is that they must provide good visibility of the reliability of supply a customer should receive, and in turn, indicate the scale of investments that could be economically justified.

To ensure this, the measures should:

- *provide equivalent measures of reliability of supply at each connection point to the transmission network*

  It is important that any customer (or prospective customer) can see the reliability of supply that relates to them. This improves the certainty they can have in their reliability so they are better informed for making their own business decisions.

- *capture and properly weight the effects of low frequency / high consequence events*

  Actual reliability at a connection point over short timeframes (e.g. year on year), can be very variable, being dependant on the specific outage events that have occurred over this period. Capacity planning is often concerned with limiting the effect of outage events that may have a low frequency (e.g. less than one event per 5 years), but a high consequence if they do occur. Therefore, to make capacity-planning decisions, or appreciate the significance of a planning decision on reliability, it is important that the range of possible events and their consequences be appropriately allowed for in the measure.

- *provide different aspects of reliability that may be relevant to different customers*

  Different customers may value reliability differently. For example, some may be most concerned with the scale of the interruptions; others may be more concerned with the volume of interruptions. Alternatively, stakeholders may want to understand the range of reliability they could face, and its likelihood. Therefore, the best measures would provide different views of reliability.

2.2 Suitability of the measures for comparative analysis and benchmarking

Another very important characteristic of the measures is that they should facilitate comparative analysis and benchmarking of the reliability at a connection point over time, between connection points, and between regions.

This is critical if the introduction of the measures will add value to the NEM, driving the efficiency of the TNSPs and facilitating the types of assessments that the AER and other stakeholders need to perform.

To ensure this, the measures should:

- *reflect the economic value of reliability*

  To provide effective comparability between locations, the measures should have a very strong direct relationship to the economic value of reliability.

- *be prepared by an objective/transparent process*

  Robust benchmarking requires a good understanding of the measures being benchmarked. Therefore, the measurements must be able to be specified and calculated in such a way that subjectivity is minimised (or immaterial to the measured value), and so the measurement process can be considered to be reproducible by other parties (provided they have access to the same data).

2.3 Incremental effort to prepare the measures

The incremental effort to prepare the measures should be minimised. At the very least, the cost to prepare the measures should not outweigh the expected economic benefits of reporting the measures.

To ensure this, the measures should be:

- *as simple as feasible to prepare an "effective" measure of historical and forecast reliability*

As noted above, for capacity planning, the measures need to be appropriately weighted to allow for the range of events that could occur, particularly low frequency / high consequence outage events. Therefore, the methodology and assumptions to achieve this need to balance the complexity of the methodology against the accuracy of the measure achieved.

When assessing the incremental effort, it may be important to consider factors such as:

- the relationship of any new tasks with existing planning and operating tasks
- the relationship of any new tasks with planning and operating tasks that could be reasonably expected in the near future (this is important because most network businesses are in a process of improving their own systems associated with monitoring and analysing reliability)
- the relationship of any new tasks, with those new tasks that will be required to implement the national framework – irrespective of the measures being reported.

2.4 Visibility of the drivers of reliability

The AER or other stakeholders often need to assess the expenditure and investment needs of TNSPs in various regulatory documents, including revenue proposals, pass-through and contingent project applications, and annual planning reports. This assessment often involves the consideration of the factors driving changes to reliability. Therefore, the measures would add value to these processes if they provided some visibility of the network components and issues affecting reliability.

2.5 Suitability for transmission and distribution network

Although this review is focused on transmission, it would be preferable if reported reliability measures were consistent between transmission and distribution. This would reduce the effort of stakeholders to understand the measures, and make comparisons between sectors.

3 Defining a reliability measure

This section explains how we can define a reliability measure in a general sense. It also provides some discussion on the generic options around such a definition. This section should assist in appreciating the measurement options that are presented and evaluated in the next section.

For this report, we define reliability measures with regard to five main factors:

- the unit of measurement
- the basis of the measurement
- normalisation and indexation
- categorisation
- the calculation of the underlying measurement.

These five factors are discussed in turn in the sections below.

3.1 Unit of measurement

The unit of the measurement concerns the physical unit of quantity of the measurement.

Most output reliability measures for connection points can be viewed in terms of three different unit reference frames. Two reference frames relate to a physical measure of the demand for electricity at a connection point. The first of these can be considered an aggregate measure of the interrupted demand for electricity, which includes the following unit measurement options:

- the aggregate energy interrupted e.g. MWhr per annum
- the aggregate maximum demand interrupted e.g. MW per annum
- the total time of events requiring sustained interruptions of customer demand[7] e.g. minutes per annum
- the number of events resulting in sustained interruptions or frequency of events e.g. events per annum
- the number of events resulting in momentary[8] interruptions or frequency of events e.g. events per annum

The second of the physical reference frames is based upon measures of individual end-use customers that have or could have their supply interrupted. Unit options around this reference frame include:

[7] Note, this time would only cover the time when customer interruptions occurred, and not the time of any outage event.
[8] Momentary interruptions relate to short-duration interruption events that occur because of automatic switching arrangement, which are often used to quickly restore circuits following temporary faults.

- the total duration of sustained customer interruptions, summed across interruption events e.g. customer minutes per annum
- the total number of sustained customer interruptions, summed across interruption events e.g. customer interruptions per annum
- the total number of momentary customer interruptions, summed across interruption events e.g. customer interruptions per annum

It is important to note that for a meaningful measure at transmission connection points, the customer counts would need to reflect the actual consumers of electricity and not the intermediate DNSPs (which are effectively customers of the TNSP).

The third possible reference frame would be a direct representation of the economic value of interruptions to demand. Unit options here could include:

- the economic value of sustained interruptions e.g. $ per annum
- the economic value of momentary interruptions e.g. $ per annum.

In reality, these economic measures are normally calculated by first producing a physical measure and then transforming this into an economic value using a derived value of customer reliability related to those physical units (e.g. the VCR often used in the NEM, which links an energy unit of reliability to an economic value). As such, these economic measures are not discussed further in this report. Nevertheless, if some form of VCR is available, it should be a relatively trivial exercise to convert most physical measures to an economic value if that is required.

The various options in each of the physical reference frames are inter-related, and often all the measures within a specific frame can be prepared together. The set of measures in the aggregate frame provide more information on the extent and scale of reliability, particularly with regard to the maximum demand and energy interrupted. This additional information makes these aggregate measures more suited to making capacity planning decisions because they tend to have stronger relationship to the economic value of reliability. However, they provide less visibility to customers and other stakeholders of the reliability of supply – assuming most customers will not fully appreciate the significance of units of energy and demand with reference to their supply reliability.

On the other hand, the measures based upon customer counts provide more visibility to stakeholders of the reliability of supply they may receive. However, they are not as well suited to making capacity planning decisions, as they can mask the extend of reliability around the more critical peak demand times. For example, knowing only the number of minutes a customer was without supply does not indicate what their demand for electricity was during this time.

With regard to input reliability measures, the units of measurement can be considered in terms of explicit and implicit measures of reliability.

An explicit input measure concerns the physical reliability of a network asset. Consequently, measurement units are normally the number of outage events or the duration of outage events.

An implicit input measure concerns a unit of measure of some aspect of the network, which on its own does not represent the reliability of the network; however, it has some relationship with reliability. These implicit measures are often associated with measuring compliance to n-x type standards. For example, the unit of measurement for compliance against an n-x standard could simply be the number of locations compliant to the relevant standards.

3.2 The basis of the measurement

The basis of the measurement concerns the underlying approach used to make the measurement. The two broad options make use of:

- **actual event data**, whereby actual historical outage and/or customer interruption events are recorded and this information is used to prepare the measure
- **simulated events**, whereby statistics of the reliability measures are estimated, based upon some form of analysis.

Actual event data is used to provide measures of the historical reliability that customers have actually received. However, measures determined in any year – or even an average over the medium-term for transmission connection points - could result in a very variable reliability measure that is highly dependent on what events actually occurred (e.g. whether or not a low frequency/high consequence event occurred over that period). Therefore, output reliability measures based upon actual data are generally not suited to capacity planning.

The simulated approach uses contemporary engineering risk and reliability analysis techniques to model the power system, and determine the likelihood and extent of customer interruptions. In this way, various statistics of a reliability measure can be determined (e.g. the mean reliability measure that a customer should receive in any year). Consequently, these simulated measures can be made to inherently allow for low frequency/high consequence events, and so, are more suited to capacity planning and cost-benefit analysis.

That said, the simulated approach requires probabilistic models to be developed, particularly for the outage events. This can mean that input measures (e.g. the outage frequency of network components), derived from actual event data, still need to be determined. Generally, however, these input measures can be prepared at an aggregate level – and be based upon data collected over a medium to long-term period – in order that errors due to volatility can be reduced. It is also possible that industry benchmarks of these input measures can be used; however, this requires greater care to verify that they are appropriate for the TNSP's circumstances[9].

[9] For example, care is required in using published outage probabilities associated with North American networks because their major line outages can be due to issues such as snow loading, which is not appropriate for most of the NEM states.

3.3 Normalisation or indexation

Normalising (or indexing) concerns transforming the measurement unit, typically to adjust for scale. This is often important for comparing the reliability of one location against the reliability of another. For example, the maximum demand at one location could be much higher than another location. Therefore, to make a meaningful comparison of measures of interrupted demand at the two locations, we would need to adjust for the different demand levels.

This normally involves dividing the base measure by a similar measure that represents the scale. For example:

- a normalised aggregate measure of energy interrupted may be defined as the energy interrupted divided by the energy demanded e.g. given as a percentage of energy interrupted
- a normalised measure of customer minutes interrupted may be defined as the total customer minutes interrupted divided by the total number of customers e.g. minutes interrupted per customer.

It is worth noting, although such normalised measure are very useful for comparative analysis, they are not as relevant for capacity planning where the scale of the interruption is important.

3.4 Categorisation

Categorisation concerns the breakdown of the measurement into a set of similar measures to capture different aspects of reliability, and so improve the visibility or comparability of the measure. Options may include:

- customer types, which can be important where stakeholders may have different expectations of the reliability for different customer types or there may be a different economic price associated with the reliability of various customer types. Clearly, this type of categorisation may be important for capacity planning if a VCR-type parameter is available.
- event categories (e.g. contingency level or network limitation), which can be helpful to TNSPs and other stakeholders by providing visibility of the underlying factors affecting the reliability. This type of categorisation can be helpful when comparing measures between locations.

3.5 The calculation of the measurement

Calculating most measures in a repeatable way requires additional specification.

For measures based upon actual recorded event data, this typically requires the specification of which events should be included, and importantly, excluded; how normalisation should be performed; and how events should be assigned to the various categories. For example, in distribution, to reduce the volatility of the reported actual reliability, days that have an extremely high volume of interruptions may be excluded. The specification would define how such days are determined. It may also specify how the included interruption events are to be aggregated to produce the measure e.g. the sum of all events over a year or a moving average.

For measures based upon a simulated approach, the additional specification may define what statistic of the measure is being produced, and the methodology and assumptions that must be applied to prepare it. For example, a common statistic is the *expected* value, which effectively represents the estimate of the long-term mean.

4 Discussion of possible measurement options

In this section, we present various measurement options and discuss their advantages and disadvantages in light of the ideal characteristics discussed in Section 2.

Sets of reliability measures are often related, and therefore, grouped and reported together. This grouping occurs because the measures rely on similar techniques and data, and provide different views of reliability. To simplify our evaluation, we discuss the measurement options in terms of these groups.

With this in mind, the main measurement options considered here are:

- SAIDI/SAIFI/CAIDI/MAIFI
- T-SAIDI/T-SAIFI/SARI
- asset outage measures
- expected energy not served, and associated measures
- n-x compliance measures

These options are discussed in turn below.

4.1 SAIDI/SAIFI/CAIDI/MAIFI

4.1.1 Overview

This set of measures is defined as follows:

- SAIDI – system average interruption duration index (minutes per customer)

  This index represents the total duration that the average customer has sustained interruptions of supply over a defined period.

- SAIFI – system average interruption frequency index (interruptions per customer)

  This index represents the number of sustained interruptions of supply that will occur to the average customer over a defined period.

- CAIDI – customer average interruption duration index (minutes per interruption)

  This index represents the average duration of a sustained interruption of supply to customers – or the average time it takes to restore the supply to a customer after it has been interrupted.

- MAIFI – momentary average interruption frequency index (interruptions per customer)

This index represents the number of momentary interruptions of supply that will occur to the average customer over a defined period.

These measures are commonly used to report the actual reliability of distribution networks. The measures are prepared from records of the number of individual customers interrupted and the duration of the interruptions.

As can be seen from the definitions above, the measures are normalised to customer numbers. Furthermore, measures in the NEM are normally reported to four categories that specify the type of HV feeder that customers are supply from, covering:

- CBD
- Urban
- Short rural
- Long rural.

This normalisation and categorisation makes these measures suited to comparisons between DNSPs.

These measures are typically prepared based upon standardise procedures that define what events should be included or excluded. For example, IEEE 1366-2012 is a common industry guide referenced to define the approach that must be applied to prepare these measures.

It is worth noting that the IEEE 1366 guide defines a number of other similar and related measures. These other measures are not as commonly used, and therefore, we have not discussed these specific measures further here. However, the advantages and disadvantage discussed below are broadly relevant to these measures also.

4.1.2 Discussion

The SAIDI, SAIFI, CIADI, MAIFI measurement set have a number of advantages as follows.

- Visibility

  The set of measures provide good visibility of different aspects of reliability, particularly the number of interruptions and the duration of interruptions that the average customer has received. The data systems used to record interruptions could also be used to prepare other measures if needed e.g. the frequency of interruptions above and below a certain duration.

- Benchmarking

  These measures have been designed to allow for comparing *actual* reliability between DNSPs, and so inherently should facilitate intra- and inter-company benchmarking of *actual* reliability. Furthermore, the various categories are defined to facilitate a meaningful comparison between locations and networks. That is, the different categories are defined to reflect different expectations on the reliability of the associated network types. Obviously, this may need to be improved by ensuring standardised definitions across all jurisdictions, but, as noted below, this should not be too difficult.

The specification of these measures results in a reasonably objective and transparent process for recording outage events and preparing the measures. Many regulators and external parties are familiar with these processes and have conducted audits and reviews to assess the accuracy of the reported measures.

- Effort

  These measures are an accepted approach to reporting actual reliability in all NEM states and many other places internationally. Therefore, DNSPs already have systems and processes in place to record and prepare reports. Also, regulators and stakeholders are familiar with these systems and reports.

  There are some variations in definitions between jurisdictions but it should not be too difficult to standardise these. This may require some modifications to some definitions and processes, but it is unlikely that these modifications would require any major (and costly) changes to internal recording systems. It is worth noting however that it may be difficult to recalculate historical reliability to the redefined measure.

These measures however have a number of disadvantages, particularly associated with capacity planning.

- Low frequency / high consequence event

  The main problem with these measures as currently defined is that they do not provide a robust measure of the potential effect on reliability of events that are of more concern for many capacity-planning decisions i.e. the low frequency / high consequence events. That is, the reported measures of actual reliability are directly affected by the occurrence or otherwise of actual events over the measurement period.

  They do have a defined processes to allow for "major event days", but this is based upon a statistical measurement of the days with very poor reliability – normally due to major storms resulting in wide spread outages across the network. This process does not attempt to adjust the measure to provide a long-term average or other statistical measure, allowing for all probable events, which is more relevant for capacity planning.

  Averaging across a number of years could be applied to smooth the volatility in any year. However, given the very low frequency nature of some important transmission events (i.e. less than 1 in 10 year event), it is unlikely that such an averaging approach could provide a reasonable measure of the statistical mean at a connection point.

- Effort to prepare

Although the effort to prepare measures of actual reliability may be low, due to the point above, it may require significantly more effort to prepare statistical measures of historical reliability or produce forecasts of these reliability measures.

The measures may be extrapolated and adjusted to provide an indication of reliability in the future, relative to current reliability. But, important for this review, forecasts of these measures are not explicitly and routinely determined through typical capacity planning processes. Therefore, to do this would require the methodology and assumptions associated with forecasting to be defined through the framework.

This methodology would need to allow for the low frequency / high consequence events discussed above for reporting measures of both historical and forecast reliability. Important to our considerations here, the likely approach to achieve this would involve first preparing a forecast using an energy measure – such as EENS discussed below – and then transforming this to the SAIDI/SAIFI/etc. measures for reporting purposes.

- Benchmarking

  Although we noted above that these measures have been defined to enable comparisons of reliability, they do not provide a robust indication of the economic value of the measure.

  This is due to the customer focus of the measure. Because of this, the specific types of customer that have been interrupted or the amount of interrupted demand is not known. Consequently, the equivalent number of minutes not supplied for say urban customers for two DNSPs may have different economic values.

  This limitation could be corrected for, but this would require a methodology to be defined and may require alterations to existing systems and processes used to record customer interruptions. For example, as well as the duration of the interruption, which is currently recorded, the customer demand or energy interrupted would also need to be estimated and recorded.

- Provides visibility of drivers of reliability

  The measures do not provide significant insight into what may be driving reliability or changes to reliability. In some respects, this is due to them being output measures.

  That said, the internal systems used to record interruptions, normally also record the cause of the interruption, and so, input measure could be defined around this data.

- Suitability for transmission and connection points

  Although the measures are used for distribution presently, at least in principle, the measures could be used for transmission connection points also. However, as TNSPs do not report these measures, their systems are not set up to record the relevant data. Importantly, the measures should reflect the end-use consumers, whereas, to a TNSP, the DNSP or its connection point is seen as a customer. Therefore, to use these measures for transmission, there may need to be some interaction between DNSP and TNSP to refer TNSP outages to the individual customers interrupted.

Importantly, the comments above on low frequency / high consequence will be far more relevant to transmission, where most outages of circuits (or even multiple outages at times) will not result in a customer interruption. As such, the definition of "major event days" may not be so useful for TNSPs.

4.2 T-SAIDI/T-SAIFI/SARI

4.2.1 Overview

This set of measures is similar to set above. However, these measures are aimed at transmission connection points. The measures are defined as follows:

- T-SAIDI – transmission system average interruption duration index (minutes)

  This index represents the total duration that the supply to a connection point would be interrupted over a defined period.

- T-SAIFI – transmission system average interruption frequency index (interruptions)

  This index represents the number of sustained interruptions of supply to a connection point over a defined period.

- SARI – system average restoration index (minutes per interruption)

  This index represents the average duration of sustained interruptions of supply to a connection point – or the average time it takes to restore the supply to a connection point after it has been interrupted.

These output measures can be used to report the actual reliability of transmission connection points. The measures are prepared from records of the number of interruptions to supply and the duration of individual interruptions. As can be seen from the definitions above, the measures are based around a unit of time.

These measures are commonly referred to in literature[10], but are not routinely used in the NEM. As far as we are aware, there is not an accepted standardised definition of how these measures should be prepared, and we have seen some variation in the literature.

It is also worth noting that the measures as commonly defined assume that supply is totally interrupted to the connection point. However, often only a portion of the downstream supply is interrupted due to an upstream transmission network limitation. Therefore, a connection point may effectively lose only part of its supplied demand rather than all of it. Consequently, for the discussion below, we have assumed that the measures of time are weighted to reflect such partial interruptions of the supplies from a connection point.

[10] For example, W Li, Probabilistic Transmission System Planning, IEEE press, 172-173, 2011

4.2.2 Discussion

Given the similarities to the distribution measures, the T-SAIDI, T-SAIFI, SARI measurement set has similar advantages and disadvantages. However, there are some differences. Its advantages are:

- Suitability for transmission and connection points

  The measures have been designed with transmission networks in mind and so do not rely on the need for end-use customer information.

- Visibility of reliability

  The set of measures provide good visibility of different aspects of reliability, particularly the number of interruptions and the duration. As with the distribution measures, the data systems used to record interruptions could also be used to prepare other measures if needed e.g. the frequency of interruptions above and below a certain duration.

- Effort

  Preparing the measures of actual reliability should be routine, relying on systems and records already maintained by TNSPs. Some interaction with DNSPs may be required where partial loss of customer supplies occurred, particularly if this was initiated by the DNSP's load shedding equipment.

- Benchmarking

  Like the distribution measures, preparing measures of actual reliability would be undertaken in a fairly objective and reviewable way, as it should rely largely upon the manipulation of recorded data. If required, the recording of this data and the associated calculations should be able to be audited in a similar way that regulatory audits are conducted for the distribution measures.

These measures however have a number of disadvantages, particularly associated with capacity planning.

- Low frequency / high consequence event

  As with the distribution measures, they do not provide a robust measure of the potential effect on reliability of the events that are of most concern for many capacity planning decisions i.e. the low frequency / high consequence events.

- Effort to prepare

  Although the effort to prepare measures of actual reliability may be low, due to the point above, it may require significantly more effort to prepare statistical measures of historical reliability or produce forecasts of these reliability measures.

  As with the distribution measures, these measures could be extrapolated and adjusted to provide an indication of reliability in the future, relative to existing reliability. This would require the methodology and assumptions associated with forecasting to be defined within the framework. Moreover, this methodology would need to allow for the low frequency / high consequence events for both reporting measures of historical and forecast reliability. The likely approach to achieve this would involve first preparing a forecast using an energy measure – such as EENS discussed below – and then transforming this to the T-SAIDI/T-SAIFI/SARI measures for reporting purposes.

- Benchmarking

  Although we noted above that measures of actual reliability could be prepared in an objective way, as with the distribution measures, they do not provide a robust indication of the economic value of reliability for similar reasons.

- Provides visibility of drivers of reliability

  The measures do not provide significant insight into what may be driving reliability or changes to reliability. In some respects, this is due to them being output measures.

  That said, the internal systems used to record interruptions normally also record the cause of the interruption, so input measure could be defined around this data.

4.3 Asset outage measures

4.3.1 Overview

Transmission asset outage measures are defined as follows:

- the number of outages over a period e.g. outages per annum
- the duration of an outage e.g. minutes per outage
- the availability (or unavailability), which is a combined measure representing the total duration over a period that the network asset is available (or unavailable) e.g. minutes per annum or simply a percentage.

These input measures are presently used in the NEM to report the actual reliability of transmission network, and are often used to defined service incentive scheme measures and targets. The measures are prepared from records of actual circuit outages, but may not necessarily relate to interruptions of supply.

These measures are typically categorised in a number of ways to improve the visibility of the significance of the outage and the comparability between TNSPs. The categories may include:

- the asset type - normally only overhead lines, underground cables and transformers are defined, but this could include the nominal voltage of these assets also
- the time of the outages, such as outages occurring during on-peak, off-peak, and shoulder times
- the criticality of the circuit, with respect to the role the circuit plays in the bulk transfer of power through the system.

4.3.2 Discussion

These measures have some advantages:

- Effort

  Preparing the measures of actual reliability should be fairly routine, relying on systems and records already maintained by TNSPs.

- Benchmarking

  Preparing measures of actual reliability would be undertaken in a fairly objective and reviewable way, as it should rely largely upon the manipulation of recorded data.

- Provides visibility of drivers of reliability

  As the measures are input measures, they can provide some insight into what specific matters may be driving unreliability or changes to reliability. Although, given some of the disadvantage highlighted below with regard to the visibility of these measures provide of output reliability, some care is required here.

- Suited to distribution and transmission

  These input measures are equally suited to transmission and distribution networks (although, there will be limited comparability between them in terms of the output reliability).

These measures however have a number of disadvantages, particularly associated with capacity planning.

- Suitability for transmission and connection points

  As the measures are input measures, it can be difficult to relate these to specific connections points, particularly in circumstances where customer demand was not interrupted.

- Low frequency / high consequence event

  The measures of actual reliability do not provide a robust measure of the potential effect on reliability of the events that are of most concern for many capacity-planning decisions i.e. the low frequency / high consequence events.

- Views of reliability

  As the measures are input measures, they provide a very weak measure of the reliability of supply. For example, a system designed with a very high level of redundancy can have very poor asset reliability, but still have very good supply reliability.

- Effort to prepare

  Although the effort to prepare measures of actual reliability may be low, more effort would be required to prepare statistical measures of historical reliability or produce forecasts of these reliability measures. This generally requires statistical analysis of longer time-series of outage data, and assumptions on how this may be extrapolated into the future.

- Benchmarking

  Although we noted above that measures of actual reliability could be prepared in an objective way, because of the disadvantages noted above, the measure is a very poor representation of the economic value of reliability.

4.4 Expected energy not served and associated measures

4.4.1 Overview

In jurisdictions using probabilistic planning, most notably Victoria, the most common reliability measure used and reported is an energy-based measure, known as the expected energy not supplied (EENS)[11].

Based upon the definitions used in this report, this measure can be considered to be a simulated measure that represents the *mean* energy that will not be supplied to customers, over a defined period, allowing for the effects of events that could occur over that period. The events that may be considered always include unplanned network outages, but may also cover other uncertainties such as customer demand levels, generation outages, and systems developments.

At any location on the network where the EENS is estimated, this energy measure can be transformed into a measure of the economic value using the value of customer reliability (VCR) for that location.

It is worth noting that this is an absolute measure relevant to any location. Therefore, it is not normalised for comparative purposes. However, similar to the SAIDI, SAIFI, CAIDI, etc. set of measures, there are a number of other measures related to EENS that can be also calculated and reported to provide other views of reliability, both absolute and normalised. The most relevant of these other measures are as follows:

- Loss of load probability (percentage per annum) – The probability that the network will be in a state requiring the interruption of the supply to some customers. This can be viewed as a normalised measure of the EENS.
- Expected duration of load curtailment (hours per year) - The total length of time that the network will be in a state requiring the supply to customers to be interrupted. This is effectively the loss of load probability transformed into a time dimension.
- Expected frequency of customer interruption events (events leading to customer interruption per annum) – The average number of times the system will transition to a state requiring the supply to customers to be interrupted. It is worth noting

[11] The measure is sometimes also referred to as the expected unserved energy (USE), particularly by in Victoria.

that this is the frequency of events leading to customer interruptions, rather than the frequency of individual customer interruptions.

- Average duration of load curtailment (hours per event) - The average time that a customer interruption event will last, where such an event results in the supply to customers being interrupted. This measure is equivalent to the expected duration divided by the expected frequency of load curtailment events.

It is important to note that there is not a standardised specification and methodology associated with calculating these measures. Nonetheless, various accepted techniques can be applied to prepare them. These techniques range from simple approaches, suitable for simple radial supply arrangements, to more complex modelling, suitable for more highly meshed and generation-dependant situations.

It is also worth noting that, although *expected* measures (i.e. long-term averages) are the common statistic calculated, the approaches should be able to be adapted to produce other statistics that provide greater insight into the probable distribution of energy not supplied. For example, provided appropriate outage models are prepared, it should be possible to produce measures representing percentiles or confidence limits of the energy not supplied.

4.4.2 Discussion

As these measures are specifically designed to aid capacity planning decisions they have a number of advantaged with respect to the ideal characteristics.

- Suitability for transmission and connection points

  EENS measures are normally calculated for network limitations and specific projects, not connection points. Nonetheless, it should be simple to define the rules that should be applied to allocate EENS to each connection points.

- Low frequency / high consequence events

  These measures inherently provide statistics that should appropriately weight the likelihood and consequence of the range of outage events that could affect the transmission network.

  Obviously, the accuracy of the measure is related to the accuracy of the outage models used to prepare these measures. However, statistical analysis may well be able to provide some bound on this accuracy.

- Visibility of reliability

  The set of measures provide good visibility of different aspects of reliability, particularly the scale of the interruptions, the number of interruptions and the duration.

  The methods used to prepare this set of measures could also be used to prepare other measures if needed.

- Benchmarking

These measures have been prepared to facilitate the economic analysis of network needs. As such, they provide a very strong link to the economic value of reliability. Furthermore, noting the point above on the ability to produce other measures, it should be possible to define EENS in a range of categories, which in turn should facilitate a benchmarking exercises. Such categories could cover:

- customer types
- outage event types
- contingency levels
- constraining network limitations.

Finally, the preparation of the measures should be able to be performed in a reasonably objective and transparent way, provided the methodology and assumptions are specified within the national framework.

- Provides visibility of drivers of reliability

  As the output measures make use of certain input measures, which can also be reported, the set of measures together can provide some insight into what specific matters may be driving unreliability or changes to reliability.

- Suited to distribution and transmission

  Measures of EENS are equally suited to quantifying the reliability of supplies from transmission and distribution networks. Moreover, they provide an equivalent measure of reliability for both networks.

These measures however have some disadvantages over other measures, mainly related to the effort to prepare.

- Effort to prepare

  It is not clear whether preparing the set of expected measures would be a significantly greater effort than preparing alternative measures of actual reliability. The expected measures require careful modelling and calculations, whereas the actual measures require careful event logging and then data extractions and cleansing.

  Nonetheless, there may be some argument that actual reliability can be measured without the need for also producing a "simulated" measure that allows for low frequency/high consequence events. However, it is far less likely that stakeholders would find it acceptable to produce only a simulated measure without also reporting actual reliability in some way.

  Therefore, reporting to these types of measures will most likely require a material increase in effort to introduce and annually prepare the complete suite of simulated measures in addition to the effort required to report actual measures.

  This will most likely require the initial development of standard tools or models to prepare the "simulated" measures, and then the annual population and review of these models. That said, the actual incremental effort may be able to be minimised by the careful design of standardised models and assumptions. As such, the cost of this increased effort may well be much lower than the overall benefits of reporting these measures.

4.5 N-x compliance measures

4.5.1 Overview

The AEMC issues paper indicated the AEMC's preference for a set of n-x type standards within the national framework and reporting performance against these standards. Reliability measures specifically related to such standards are not normally routinely specified and reported. Although, annual planning reports often provide some informal measurement of compliance to relevant standards.

Simple implicit input measures that can be used to report levels of compliance to such standards would include:

- a simple binary measure at the connection points indicating whether the maximum demand was within a certain range of compliance e.g. whether the maximum demand was within 95% of the trigger point demand level
- an alternative to this would be to report the margin of compliance in terms of the percentage of maximum demand from the trigger point.

Both measurements would need to be made with reference to the precise definition of the n-x standards within the framework.

4.5.2 Discussion

Measures of this type have some advantages.

- Effort

  Preparing the measures of actual and forecast reliability should be fairly routine, relying on systems and records already maintained by TNSPs and largely required for their annual planning process.

- Benchmarking

  Provided the standards are well defined through the framework, the measures should be able to be preparing in a reasonably objective way.

- Suited to distribution and transmission

  These input measures are equally suited to transmission and distribution networks (although, there will be limited comparability between them in terms of the output reliability).

These measures however have a number of disadvantages, particularly associated with the visibility of the reliability and the economic significance of the measure.

- Low frequency / high consequence event

  Although the setting of the standard may have some relevance to low frequency/high consequence events, the measure does not provide any weight to this.

- Views of reliability

  As the measures are input measures, they provide a very weak measure of the reliability of supply. The relevance of the relationship to the measure relates more to the setting of the standards and the assignment of connection points to the standard.

- Benchmarking

  Although we noted above that the measures can be prepared in an objective way, because of the disadvantages noted above, the measure will most likely be a very poor representation of the economic value of reliability.

- Provides visibility of drivers of reliability

  Although the standards provide some indication of redundancy (and possibly other design requirements), the measures themselves do not provide significant insight into what may be driving unreliability or changes to reliability other than differences in demand levels.

4.6 Summary

A summary of the advantages and disadvantages of each measurement option is provide in Table 1 below.

Table 1 Summary of advantages and disadvantages of the measurement options

Option		visibility of reliability	suitability for benchmarking	incremental effort	visibility of drivers	suitability from T&D
SAIDI/SAIFI/CAIDI /MAIFI	advantages	good visibility of actual reliability at each connection point, provide different aspects of reliability	suitable for benchmarking actual reliability, industry familiarity with systems and processes used to prepare measures, actual measures use objective/transparent process	systems already in place to prepare measures of actual reliability		
	disadvantages	do not provide robust measure of low frequency/high consequence events, difficult to adapt to provide this measure	weak measure of economic value of reliability	greater effort to prepare statistical measures that allow for low frequency/high consequence events	limited insight into drivers of reliability	customer focus of measure is more suited to distribution, interaction between DNSPs and TNSPs will be necessary, more variability of actual reliability for transmission
T-SAIDI/T-SAIFI/SARI	advantages	good visibility of actual reliability at each connection point, provide different aspects of reliability	suitable for benchmarking actual reliability, actual measures use objective/transparent process	measures of actual reliability will use systems and records already maintained by TNSPs/DNSPs		
	disadvantages	do not provide robust measure of low frequency/high consequence events, difficult to adapt to provide this measure	weak measure of economic value of reliability	greater effort to prepare statistical measures that allow for low frequency/high consequence events	limited insight into drivers of reliability	
Asset outage measures	advantages		actual measures use objective/transparent process to prepare	systems already in place to prepare measures of actual reliability	good visibility of driver of reliability	suited to distribution and transmission measures (although, limited comparability between measures)
	disadvantages	do not provide measure of reliability of supply, not suited to measures at a connection point, do not provide robust measure of low frequency/high consequence events	very weak measure of economic value of reliability	greater effort to prepare statistical measures that allow for low frequency/high consequence events		

Option		visibility of reliability	suitability for benchmarking	incremental effort	visibility of drivers	suitability from T&D
Expected energy not served, and associated measures	advantages	good visibility of reliability at each connection point, provide statistical representation of low frequency/high consequence events, provide different aspects of reliability	very strong measure of economic value of reliability, can be prepared from objective/transparent processes, can provide visibility of factors underlying reliability that may allow better comparisons between TNSPs		good visibility of drivers	suited to distribution and transmission measures
	disadvantages			likely that measures of EENS will need to be supported by other measures of actual reliability, and therefore, additional effort requited to prepare the EENS measures		
N-x compliance measures	advantages		provided appropriately specified, the measures should result from an objective/transparent process	low effort largely relying on existing data and processes already applied by TNSPs as part of their annual planning requirements		suited to distribution and transmission measures (although, limited comparability between measures)
	disadvantages	weak visibility of reliability at connection point, do not explicitly provide robust measure of low frequency/high consequence events	very weak measure of economic value of reliability		limited insight into drivers of reliability	

5 Preferred measurement option

5.1 Rationale for preferred option

In Section 2 we presented some ideal characteristics that reliability measures would need to have if they were to facilitate capacity planning or the appreciation of capacity planning decisions. Of most note here was the requirement to provide visibility at connection points of the “effective” reliability that customers could receive, particularly with regard to the types of low-frequency/high-consequence event that tend to drive capacity needs. Another important characteristic was the requirement for the measures to be suitable for comparative analysis and benchmarking studies, and in particular the need for the measures to reflect the economic value of reliability.

In Section 4 we discussed a range of measurement options and evaluated them against the ideal characteristics. This evaluation indicated that none of the typical reliability measures were ideal.

The output measures most commonly used to report actual reliability, such as SAIDI/SAIFI/CAIDI and their transmission counterparts, would most likely provide a volatile measure of connection point reliability. They are also not suited to altering in order to provide a less volatile, statistical measure. Furthermore, they have a relatively weak relationship to the economic value of reliability, as they do not capture the scale of the interruption.

The asset reliability measures that are also commonly used, particularly within transmission service incentive schemes, are also not ideal. Owing to their input-reliability focus, they provide poor visibility of the reliability of supply, and most likely would be too volatile at a connection point. They also have a very weak relationship with the economic value of the reliability.

Measures of the margin of compliance to n-x standards are not routinely reported - although they are feasible and should be fairly easy to measure. However, this type of measure would provide a very weak relationship to the reliability of supply and the economic value of reliability. Consequently, it could be expected that the economic benefits of reporting these types of measure would be low.

On the other hand, measures such as EENS are specifically designed to aid capacity planning (and other operational and planning processes). As such, they inherently provide a measure of the “effective” reliability, both historical and forecast. They can also be defined to provide a good correlation with the economic value of reliability and they provide good visibility of the factors driving reliability.

Many stakeholders, however, will not be familiar with this measure. For reasons other than capacity planning, reporting actual reliability is still likely to be important. Therefore, reporting reliability based upon EENS-type measures would most likely need to be supported by reporting other measures that are based directly upon actual interruption events. Consequently, there will be increased effect to prepare and report measures based upon EENS.

Additionally, they may be some concern that reporting EENS on its own - even supported by actual measures – may mask the range of interruption events and their likelihood. Given EENS is a long-term average, the reported annual figure can be much lower than the interrupted energy of the typical outage event that produces it. Therefore, there is a possibility that stakeholder could misunderstand the reliability risks they face with regard to the scale of event that may occur. This may mean that an EENS measure would need to be supported by other related measures that help describe the range of interruption events that could occur.

Although the EENS measure has the drawback noted above, it appears to be the only measure that addressed the more critical ideal characteristics in a meaningful way. Therefore, provided the effort to prepare such a measure is reasonable (i.e. the benefits of reporting these measures will most likely outweigh the costs to prepare them) then we believe this would be the preferred option, supported by other measures of actual reliability.

5.2 Overview of preferred option – the EENS measure

The main reliability measure reported would be the *expectation* of the reliability of supply at each connection point. This would be termed:

- the *expected energy not served (EENS)*, and reflect the average, long-term, MWhr per annum of customer demand for electricity that is not supplied downstream of the connection point, due to a transmission network limitation.

This measure would be prepared via a "simulated" approach, and not from records of actual outage events and customer interruptions. However, certain inputs to the calculations may be based upon actual records, such as asset outage events.

The measure would be used to report historical and forecast reliability to ensure that stakeholders are aware of the current reliability at each connection point and how this reliability may change over the planning horizon.

The EENS measure at each connection point would need to be broken down into various categories to:

- aid in the visibility of reliability customer receive (or could receive)
- provide some visibility of the range of interruption events
- indicate what is driving unreliability
- provide comparative indicators to n-x standards.

The categories would most likely need to be:

- the customer type interrupted (e.g. by VCR categories)

- the contingency (outage) events, covering:
  - asset type (e.g. transformers, lines, etc.)
  - contingency level (e.g. normal, n-1, n-2, etc.)
  - pre and post contingent load shedding
- the network limit (e.g. thermal, steady state voltage, voltage stability, transient stability, etc.).

To provide greater visibility of the probability and extent of interruption events, the EENS measures would also be supported by reporting other measures. These additional measures would cover:

- the average time between customer interruption events (or frequency of interruptions)
- the average time of an interruption event.

These other measures are prepared inherently in the EENS calculation process, and so there should not be a materially greater effort to provide these.

Reporting EENS as an absolute measure provides visibility of reliability levels and the scale of investments that may be justified at connection points, which is important for making capacity-planning decisions. But it is not a suitable measure for comparative analysis and benchmarking as it is affected by the scale of demand at each connection point. For these purposes, this measure will need to be normalised to adjust for scale. Therefore, the related measure for comparative purposes would be:

- the loss of load probability (LOLP) – calculated as EENS at the connection point divided by the total energy delivered at the connection point.

Similar to the EENS measure, LOLP measure would be provided in the categories noted above.

5.3 Other considerations

Some consideration could also be given to providing other statistics of the energy not served. A range of statistics could provide a more formal representation of the range of reliability at each connection point. For example, the standard deviation of energy not served or confidence limits of energy not served could be provided in addition to the expected value. However, these other measures may require more complex probability models and increase the effort to prepare the set of measures.

At this stage, we have not included these options in the preferred measures. However, further consideration could be given to the feasibility of preparing these measures, as they would provide a more robust view of possible reliability outcomes at each connection point.

Furthermore, as noted above, the EENS-based measures would need to be supported by also reporting other measures that reflect the shorter-term actual reliability at each connection point.

We have not focused on this need in this report. Nonetheless, this would probably require the reporting of the following:

- output measures for each connection point, using the T-SAIDI/T-SAIFI/SARI group of measures (or even the SAIDI/SAIFI/CAIDI measures, if it is feasible for the DNSP to provide the required customer information); reporting these would aid stakeholders in appreciating the relationship of the EENS-based measures to actual historical reliability
- input measures, using the existing asset-based outage measure; this would provide some backward compatibility to existing service reporting and aid in the visibility of drivers of reliability.

Further work would be required to specify how these other measures would need to be calculated and categorised. This matter is not discussed further in this report.

6 EENS measurement specification

The previous section explained that the preferred option would be based around measures of expected energy not served (EENS) at each connection point. This measure must be prepared from a “simulated” approach, which requiring technical analysis and modelling of the transmission network.

To ensure the measures are produced consistently between TNSPs and in an objective way, it will be critical that the national framework specifies the assumptions that must be used to prepare the measures.

This section discusses these assumptions, indicated the main matters that will need to be addressed.

6.1 Standard methodology and assumptions

Preparing the EENS measure in the format discussed in Section 5 will require the following matters to be specified within the national framework:

- the outage events to be modelled
- the preparation of outage probability models
- the applicable network ratings
- assigning EENS to connection points
- customer demand assumptions
- generation dispatch assumptions
- network and generation development assumptions
- load transfers and restoration assumptions
- circumstances where the standard methodology and assumption can be changed for preparing the measures.

These matters are discussed in turn below.

6.1.1 modelled outage events

To ensure that all TNSPs allow for the same outage events, it will be important that the range of events that should be modelled is specified. This specification will need to define the following:

- The **assets** that can be assumed to be out of service. This will need to cover, at least, overhead lines, underground cables, transformers, generators. Thought may also need to be given to whether other more extreme outage events should be allowed for, such as a bus bar outages or circuit breaker failures.

- The **failure type** of the assets that will be allowed for. For example, often only major failures of transformers are modelled where a replacement would be required resulting in an extended outage. However, thought may need to be given to whether more minor failures should be modelled, where the outage would be shorter but the probability of the event would be higher.
- The **contingency levels**, in terms of the number of coincident outages that must be allowed for. Obviously single outages will need to be allowed for. However, some thought may need to be given to how double outages or levels above should be modelled. The higher the contingency level then the greater the extent of technical analysis required, but the lower the probability of the event occurring.

6.1.2 preparation of outage probability models

The asset outage probabilities and outage durations are essential inputs to calculating the EENS measure. Ideally, these should be based upon historical records of outage events. To ensure all TNSPs approach the preparation of these parameters consistently, it will be important that the approach to recording events and analysing events is defined.

It may well be that these records and calculations will need to be periodically reviewed by the standard setter to ensure that they have been prepared correctly, prior to their use for preparing the measures.

6.1.3 network ratings

The rating of individual network assets (e.g. the thermal rating of an overhead line) can be a critical parameters when determining how much customer demand cannot be supplied. However, different TNSPs define ratings in different ways, particularly with regard to the ratings applicable for operating and planning purposes.

To ensure a consistent measure of EENS is provided for all TNSPs, the ratings that must be assumed and how they must be calculated may need to be defined. This should not assume the asset is operated differently from how it is, but should ensure the appropriate operating rating is assumed for the relevant circumstances.

6.1.4 assigning EENS to connection points

The typical method used to calculate EENS is focused on estimating the amount of EENS, not which connection points this occurs at. Assigning EENS to the appropriate connection points will be far more important for preparing these measures. Therefore, the approach to assigning EENS will need to be specified.

We understand that presently AEMO estimate this based upon the connection point with the highest sensitivity of demand level to the relevant network constraint. In simple situations, this may be acceptable. However, for more complex situations (e.g. where multiple constraints associated with a specific contingency affect multiple connection points with varying degrees of sensitivity) some form of optimisation may be required that minimises the total amount of unserved energy across all the relevant connection points.

6.1.5 customer demand assumptions

The customer demand at each connection point is an important input for calculating the EENS. The peak demand in any year is related to the extremeness of the weather that year. Therefore, multiple demand scenarios can be assessed to allow for the probability of these demand outcomes on the level of EENS.

To ensure consistency between TNSPs, the framework will need to specify the following:

- the customer demand scenarios to model – this will most likely cover what probability of exceedence (PoE) of the maximum demand should be used. To align with existing demand forecasts prepared by TNSPs, the calculation may need to allow for three scenarios: the 90%, 50% and 10% PoE maximum demand forecasts. This should provide a reasonable spread of the likely range of maximum demands that could occur and the relationship of EENS to these demand levels. It could also allow for various economic growth scenarios. It is worth noting that calculating the measure for the preceding year would require the actual peak demand for that year to be "weather corrected" to the equivalent PoE.
- The probability for each demand scenario – assuming more than one demand scenario is used, the specification will need to define how the probability for each scenario should be calculated. For example, would they be assumed equally likely or is some other probability more appropriate.
- The annual demand profile (e.g. hour-by-hour demand level) – the demand profile is required to determine how much energy is at risk of being shed at any point in time. Therefore, the specification will need to define how this profile should be prepared. This may require the TNSP to use an actual profile from the recent past that most closely reflects the relevant PoE scenario. This profile would then be scaled in a defined way to reflect the relevant maximum demand.

6.1.6 generation dispatch assumptions

For transmission, the amount of unserved energy to customers often will be related to specific generation dispatch patterns. Therefore, generations scenarios may need to be prepared that match the defined demand scenarios.

To achieve this, the specification will need to define the technique and assumptions to prepare these scenarios. This will most likely require some form of market simulation in order to determine relevant economic dispatch patterns. In addition, multiple dispatch scenarios may need to be prepared for each demand scenario to allow for the probability of generation outages.

Therefore, the specification may need to cover factors such as:

- the form of modelling to use
- generator price assumptions
- generator availability and forced outage rates

- the range or number of generation scenarios to use for each demand scenario.

6.1.7 network and generation development assumptions

Where forecasts of the EENS measures are required over the planning horizon, assumptions concerning the network (including interconnectors) and generation developments that should be allowed for will need to be defined.

Importantly, for generation developments, this may need to define:

- what committed, planned or proposed developments can be allowed for
- what should be assumed in circumstances where future generation may fall below defined minimum reserve levels.

This may require additional scenarios to be defined to allow for the uncertainty around these developments.

6.1.8 load transfers and restoration assumptions

In addition to re-dispatching generation, the actual level of unserved energy is dependent on what network rearrangements are made (pre- or post-contingency) to transfer load to reduce constraints or maintain a secure state. Furthermore, emergency procedures may be used to restore supplies in times much shorter than the usual repair times associated with major failures.

Therefore, the allowed switching and restoration arrangements may need to be defined to ensure all TNSPs consistently model the same operational approaches that are available to them in reality.

For example, this may specify that the following must be allowed for:

- any automatic control schemes that allow post contingent load shedding
- any network rearrangements that are typically applied in particular circumstances to allow post-contingent shedding e.g. radialising parts of network at time of peak demand, if the security criteria would be violated otherwise
- the allowance for emergency contingency plans if these have been specifically developed for the specific modelled contingencies e.g. if a spare transformer has been purchase to enable a fast replacement of a failed transformer then this should be allowed for.

6.1.9 circumstances where the standard methodology and assumption can be changed

There may be particular circumstances where deviating from the specification will improve the accuracy of the measure. The framework may need to define under what circumstances this can occur, what process the TNSP must follow to do this, and what information must be reported to stakeholders when this has occurred.

7 Measurement process

In this section, we provide an overview of the process the TNSPs could apply annually to prepare the EENS measures in the format discussed in Section 5.2.

7.1 Overview of measurement process

As discussed in Section 4.4, there is not a standardised methodology for preparing EENS, and various approaches can be used that are suited to certain circumstances. Broadly, however, most approaches involved the following steps:

1. **Prepare analysis inputs**, including demand/generation scenarios and event probabilities
2. **Identify the critical network conditions** (e.g. the outages, network limitations, generation and demand patterns) that may result in unserved customer demand under the various standard assumptions
3. **Develop the network relationships** associated with these conditions (e.g. the sensitivity of unserved demand to variations in demand and generation levels)
4. **Undertake time-sequential modelling** (e.g. an hour-by-hour simulation), using the network relationships, to determine the amount of unserved energy associated with the various demand and generation scenarios
5. **Undertake a probabilistic analysis**, using the various outage and scenario probabilities, to calculate the EENS.

The tasks involved in each of these steps and the associated incremental effort is discussed in more detail in the sections that follows.

7.1.1 Preparing inputs

The main inputs to the annual measurement process are as follows:

- network and generation outage probabilities
- VCRs for each connection point
- generation availability and dispatch scenarios
- customer demand scenarios.

Although preparing outage probabilities and VCRs for each connection point will be significant tasks, they will be necessary whether the economic or economic-redundancy planning approach is adopted. Therefore, the need for these inputs in order to prepare the EENS measures should not result a significant amount of additional effort.

Additional effort will be required however to annually prepare the generation and demand scenarios, which are required for the time-sequential modelling stage.

For the demand scenarios, demand traces (e.g. hour-by-hour demand over the measurement period) for each connection point will need to be prepared each year. Various traces will need to be prepared to represent the various maximum demand scenarios, defined within the standard assumptions. Similarly, generation availability and dispatch scenarios, suitable for the time-sequential modelling, will need to be prepared that match the set of demand scenarios.

Preparing suitable demand traces will most likely involve the extraction and processing of historical demand traces. In this way, historical traces are determined that best reflect the relevant maximum demand conditions defined in the standard assumptions. These historical traces are then scaled to represent the current or forecast demand traces for each demand scenario. Generation traces for these demand scenarios can then be prepared using market modelling software.

With regard to the incremental effort, it is worth noting that much of the analysis and review associated with determining the appropriate historical demand traces will be necessary even if the economic-redundancy approach is adopted because they will be required to undertake the periodic review of the redundancy standards. Therefore, the actual incremental effort due specifically to the introduction of this EENS measure may not be as significant as suggested above.

7.1.2 Identify the critical network condition

The first analysis stage involves studying the network in order to identify if customer demand may need to be shed for the standard assumptions and under what circumstances this may occur.

This type of analysis involves conducting a set of “screening” power flow contingency studies, based upon the set of contingencies defined by the standard assumptions. These screening studies tend to focus only on the worst-case demand levels and most onerous generation patterns in order to identify the specific network limitations that may be violated such that customer demand would need to be shed to alleviate them – as opposed to other operator actions.

The purpose of these initial studies is to identify the specific network limitations that need to be analysed further in the following stages.

We would expect that these network studies are not significantly different from the existing analysis that TNSPs have to do annually in order to undertake their annual planning and reporting obligations, and for operational planning purposes (e.g. to review or prepare contingency plans, and review or prepare constraint equations). Also, much of this analysis should be able to be largely automated by the use of the contingency analysis tools and scripting languages available in commercial power system software.

Nonetheless, although we would expect that most TNSP would already routinely conduct 1st order contingency studies (i.e. N-1 conditions) as part of their annual planning process, higher order contingencies (e.g. N-2) may not be routinely assessed. Therefore, depending on what contingencies are specified, additional screening studies may need to be performed above those that TNSPs presently undertake. Importantly, if 2nd order or above contingencies are required then the number of studies will increase significantly. Power system software can easily automate these higher order studies, such that thousands of individual cases can be assessed in minutes. However, because these higher order contingencies will stress the network far more significantly than the N-1 cases, it is far more likely that violations will be found and additional manual analysis – outside of the automated routines - will be required to assess these violations.

That said, we would expect that operating and planning personnel experienced with the networks would be aware of the most critical contingency conditions, certainly up to N-1-1 and N-2 situations. As such, even if there are a significant number of violations for these higher order contingencies, it should be feasible to group them so that the critical conditions can be defined.

Also, once this analysis has been performed to prepare the initial set of measures, we would expect that the effort to prepare subsequent measures would reduce significantly. For example, the effort to prepare subsequent measure would largely involving reviewing the contingencies results and determining the far fewer cases where conditions had changed significantly from the previous analysis.

7.1.3 Develop the network relationships

The second analysis stage involves determining the relationship of variables, such as connection point demand and generation dispatch, with the violation of the critical network limitations identified in the stage above.

This involves performing additional network studies to develop these relationships. The set of relationships should be similar in form to the "constraint equations" presently used in the NEM dispatch engine and other market modelling software. As such, the analysis required here should be similar to the existing analysis that TNSPs and AEMO already perform when reviewing or preparing constraint equations for operational and planning purposes.

That said, as the focus here is on connection point EENS measures (rather than regional measures) there may be some additional effort to ensure appropriate relationships are formed at this level. Furthermore, as noted above, if higher order contingencies are included in the standard assumptions then a large number of additional relationships may need to be determined. However, similar to the point made above, although this may result in significant additional effort to prepare the initial set of measures, the effort required for subsequent measures should be far less.

7.1.4 Undertake time-sequential modelling

The third analysis stage takes the network relationships (e.g. constraint equations) developed above and the complementing demand and generation scenario traces. Using these inputs, time-sequential modelling (e.g. hour-by-hour analysis) of the unserved energy at each connection point can be calculated to cover all combinations of possible outcomes, including:

- the demand scenarios

- the generation scenarios associated with each demand scenarios
- the critical contingencies and associated network limitations.

Ideally, the outputs of this analysis would provide the total annual pre- and post-contingent energy at risk at each connection point, associated with:

- the relevant demand and generation scenario
- the relevant network outage event
- the type of network limitation (e.g. thermal, voltage, voltage stability, etc.).

This stage should be similar to the time-sequential modelling that AEMO performs to undertake its national planning task. However, as EENS measures at each connection point are required (rather than a regional measure), the modelling is likely to be more involved. For TNSPs, however, this task may be relatively new.

It may be that spreadsheets could be used to undertake this analysis. However, the analysis can also be performed using market modelling software, similar to the tools AEMO currently uses for its time-sequential modelling. It is worth noting that the market modelling software approach may mean that the generation dispatch traces can be prepared inherently in the time sequential modelling – rather than a separate task.

Whatever tool is adopted to undertake this analysis, we would expect that this analysis should be fairly routine. That is, the effort would largely involve populating the model with the various inputs. The actual time-sequential modelling would be relatively automated.

7.1.5 Probabilistic analysis

This final stage involves aggregating the outputs from the time-sequential modelling (i.e. connection point unserved energy) via the various event probabilities in order to calculate the total EENS reliability measures for each connection point in the form discussed in Section 5.2.

There are various approaches that could be applied to undertake this analysis, which depend upon how the time-sequential modelling is performed. For example, it may be feasible to set up a Monte Carlo type of analysis directly within the time-sequential modelling to allow for the outage events and various demand scenarios. In these circumstances, the measures would be calculated inherently through the time-sequential modelling.

Whatever the approach adopted, this stage will be new to all TNSPs. However, as with the stage above, it should be similar in principle to analysis that AEMO performs to calculate regional EENS levels as part of its national planning task.

This stage may require some initial training and/or model development in order to prepare the initial measures. But we would also expect this stage to be fairly routine when preparing subsequent measures, largely involving data input into whatever tools are being used to perform the probabilistic analysis.

7.2 Summary and conclusions

In this section, we have described an example process that could be applied to prepare the EENS measures in the format defined in Section 5.

This process is largely an extension of the methodology already applied annually by AEMO to prepare the national transmission network development plan (NTNDP). It also makes use of many of the systems and tasks that TNSPs and AEMO already have to perform to undertake their normal planning and operating tasks.

Preparing the measure by this process *will* require additional effort on the part of TNSPs or AEMO however.

This additional effort will be required to develop the set of network constraint equations suitable for calculating EENS at a connection point level (rather than the regional level). Depending on the range of network outages that must be allowed for in the measure, there may be additional effort to identify and prepare additional constraint equations for conditions that are not presently modelled.

Furthermore, for most TNSPs that do not already routinely calculate EENS on their network or the associated energy at risk, there will also be the additional and new effort associated with undertaking the time-sequential modelling and probabilistic analysis associated with preparing these measures.

It is important to note however that much of this additional effort will be required to prepare the initial set of measures i.e. start-up effort. Following this, the preparation of subsequent measures should be relatively routine. For example:

- After the initial set of network constraint are identified and modelled, subsequent analysis will involve more of a review task to confirm previous constraints are still valid. As such, it is likely that a much smaller number of additional constraint equations will need to be developed each subsequent year.
- Additional effort may be required to train TNSP staff in the tools and theory behind the time-sequential modelling and probabilistic analysis. Additional effort may also be required to prepare the models associated with these tasks. However, once this has been performed, actually undertaking the modelling and analysis should be fairly routine, mainly involving data entry.

It is also worth noting that other approaches could be used to prepare the measures that could reduce the effort further. Most notably, most commercially-available power system software used in the transmission industry has reliability and optimal power flow modules. These modules allow reliability measures, such as connection point EENS, to be calculated. These modules have the potential to combine the network analysis, time-sequential modelling, and probabilistic analysis steps into a single and largely automated task. This approach ultimately could be the simplest provided the appropriate data inputs and models can be developed.

Finally, it is also worth noting that, because much of the analysis is very similar to the tasks AEMO already performs to achieve its system/market operator and national planner roles, consideration needs to be given to whether AEMO should be tasked with preparing these measures for all regions. The TNSPs would only be responsible for providing relevant data to AEMO, reviewing the assumptions, and reviewing AEMO's analysis. This could result in the least effort across the industry and ensure a more consistent approach to the analysis between regions.