



Identification of Appropriate Generation and System Adequacy Standards for the Internal Electricity Market

Final Report

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List of Acronyms

ACER: Agency for the Cooperation of Energy Regulators

AIT: Average Interruption Time

AS: Ancillary Services

ASIDI: Average System Interruption Duration Index

ATC: Available Transmission Capacity

CAIDI: Customer Average Interruption Duration Index

CBA: Cost-Benefit Analysis

CEER: Council of European Energy Regulators

CELID-X: Customers Experiencing Longest Interruption Durations

CEMI-X: Customers Experiencing Multiple Interruptions

CEMMI-X: Customers Experiencing Multiple Momentary Interruptions

CIGRE: International Council on Large Electric Systems

CM: Capacity Mechanism

CONE: Cost of New Entry

CVM: Contingent Valuation Method

DSM: Demand Side Management

DSOs: Distribution System Operators

EC: European Commission

EENS: Expected Energy Not Supplied

EEU: Expected Energy Unserved

EFC: Equivalent Firm Capacity

EFDO: Expected Frequency and Duration of Outages

EIR: Energy Index of Reliability

EIU: Energy Index of Unreliability

ENS: Energy Not Supplied

ENTSO-E: European Network of Transmission System Operators

EU: European Union

EUE: Expected Unserved Energy

FACTS: Flexible AC Transmission Systems

GA: Generation Adequacy

GAM: Generation Adequacy Metric

GDP: Gross Domestic Product

GT: Gas Turbine

GVA: Gross Value Added

HVDC: High Voltage Direct Current

IEAR: Interruption Energy Assessment Rate

IEM: Internal Electricity Market

LO: Line Overload

LOEE: Loss of Energy Expectation

LOI: Lack of Interconnection

LOLE: Loss of Load Expectancy

LOLP: Loss of Load Probability

LOP: Lack of Power

MAIFI: Momentary Average Interruption Frequency Index

MS: Member States

NRA: National Regulatory Authority

NTC: Net Transfer Capacity

P95: 95th Percentile

RES: Renewable Energy Resources

SAI: State Aid Inquiry

SAIDI: System Average Interruption Duration Index

SAIFI: System Average Interruption Frequency Index

SM: System Minutes

SoS: Security of Supply

SO&AF: Scenario Outlook & Adequacy Forecast

TSOs: Transmission System Operators

TYNDP: Ten-Year Network Development Plan

UCTE: Union for the Coordination of the Transmission of Electricity

VBRP: Value Based Reliability Planning

VOLL: Value of Lost Load

WTA: Willingness to Accept

WTP: Willingness to Pay

1 EXECUTIVE SUMMARY

“Security of Electricity Supply” is one of the three pillars of European Union (EU) climate and energy policy¹ in relation to the power sector. This concept has several dimensions, one of which is system adequacy, referring to the existence within a system of sufficient generation and transmission capacity to meet the load, whether under normal or unusual conditions, such as unavailability of facilities, unexpected high demand, low availability of renewable resources, etc.

The project presents the definition of adequacy and its current application in EU countries, with the aim of identifying a methodology and a shared model for adequacy evaluation, and with metrics to measure the adequacy level for the EU in its entirety

The project includes a theoretical analysis aimed at clarifying the principles of adequacy (Chapter 3), an empirical analysis for identifying current practices in the EU (Chapter 4), and a final diagnosis summarising the main topics considered in the conclusions (Chapter 5). Finally, the study’s recommendations (Chapter 6) focus on the possibility of ensuring the electricity system’s long-term adequacy whilst avoiding possible distortions in the operation of the Internal Energy Market.

The objective of the present study is to provide key inputs for the definition of a common methodology and a set of acceptable standards for the evaluation of national electricity system adequacy. Greater transparency and coordination among Member States (MS) and national policies in terms of the security of electricity supply could be highly beneficial to:

- assessing national preferences with respect to the trade-off between the social value of adequacy and the cost of providing such adequacy;
- assessing national preferences for available alternative measures to achieve the desired adequacy level (e.g. transmission vs. generation investments);
- assessing the effects of the policies of each Member State on internal security of supply (SoS), on neighbouring countries’ security levels and supply costs, and on the dynamics of the wholesale electricity market;
- Minimising the cost of ensuring adequacy in Europe by exploiting the interdependencies among interconnected national systems.

Theoretical analysis introduces main adequacy concepts

As far as Security of Electricity Supply (or its synonym, “system reliability”) is concerned, there is no common terminology adopted in the relevant literature, nor in the security of electricity supply regulation.

In order to avoid confusion, the first objective of this study is to introduce the adequacy concept and its related definition as the ability of the system to deliver electrical energy to all points of utilisation within acceptable standards, and in the amounts desired (section 3.1). Chapter 3 presents the methodologies in use for assessing adequacy and

¹ The main pillars of EU energy policy are competitiveness, sustainability and security of supply (http://ec.europa.eu/research/energy/eu/index_en.cfm?pg=policy-energy-and-climate-policy)

defines the associated metrics with regard to electricity transmission and distribution systems.

Calculation of appropriate metrics requires a suitable methodology and model. Reliability is a probabilistic concept; in fact its assessment requires the analysis of several system configurations with an associated probability of occurrence derived from variables such as:

- Random unplanned outages of generation or transmission facilities;
- Variability of a primary resource such as wind speed, solar radiation, or hydro availability;
- Demand volatility, influenced by weather, economy, and other short-term effects;
- Decisions by System Operators or generation owners such as maintenance outages or strategies for the operation of hydro plants with reservoirs.

Probabilistic methodologies present undeniable advantages over deterministic ones

The methods for calculating the adequacy metrics are categorised as deterministic and probabilistic (section 3.3). Deterministic methods are based on the analysis of a few system configurations selected as most representative of situations that can stress the system. For instance, load flow analyses, where it is assumed that certain major lines or generators may become unavailable. These methods allow the estimation of the impact of specific situations on reliability, but they cannot estimate the overall system reliability.

Probabilistic methods aim to estimate the probability of meeting the load considering that the variables that define adequacy (generation, demand, and availability of lines) are stochastic. Such methods manage high numbers of configurations, with an associated probability of occurrence derived from the underlying variables of a complex model.

Given the stochastic nature of system variables, methods that are deterministic, although frequently used, cannot allow for the calculation of metrics that reflect the actual situation of a country in relation to SoS.

Common probabilistic metrics are Loss of Load Expectancy (LOLE), Loss of Load Probability (LOLP), or Expected Energy Not Supplied (EENS).

The Monte Carlo approach is the only probabilistic method suitable for representing all of the aspects of an electricity system that may have an impact on adequacy. In fact, a Monte Carlo simulation can represent the overall power system (generation and transmission) by applying random number techniques to generate a wide range of possible states² of that system, including generation availability, wind speed, river discharges, demand, and so on. For each system state, energy not supplied (ENS) is calculated by simulating generation dispatch (or market clearing) and identifying the eventual ENS. After an appropriate sample of simulations, it becomes possible to calculate all the metrics (for instance LOLP, as the number of states with unsupplied energy divided by the total number of simulations).

A very large number of simulations is required in order to obtain an accurate estimation. Therefore, depending on the complexity of the system being analysed, further time may be necessary to compute the results.

Probabilistic metrics are able to represent the adequacy of a system

² Please note that all these states are equi-probable.

From an initially long list (section 3.4), the following metrics have been selected due to their ability to assess adequacy taking into consideration both generation and the transmission system:

- EENS: expected energy not supplied during a given time period;
- LOLP and LOLE: measuring the probability that, at some moment, available generation will be insufficient to meet the load;

Other metrics, including reserve margin, have been considered inappropriate, being unable to take into account all the relevant aspects of the interconnected electricity system, and therefore unsuitable for measuring adequacy.

In the case of the EU IEM, cross-border interconnections allow MS to support each other in the event of under-capacity; therefore, the metrics for calculation cannot ignore the cross-border dimension of electricity systems and markets. On the other hand, the limited capacity of transmission lines limits the possibility of one area (with excess generation capacity) lending support to another (with lack of capacity). Therefore, internal or cross-border congestion is an additional variable that should be included in the calculation algorithms.

EENS metrics allow the quantification of ENS and a comparison of the associated system cost with the cost of investments needed to avoid it

Metrics can be useful in providing a view of expected system reliability, or in allowing a comparison of SoS across different systems. In this sense, some metrics like LOLP and LOLE are more appropriate for analysing a given system or comparing situations among several systems. Other metrics, like EENS, allow the application of a cost-benefit analysis (CBA) to evaluate investments in transmission or generation (section 3.5).

Adequacy has an economic value; consumers prefer a reliable electricity supply and show a willingness to pay (WTP) for it. However, adequacy also has a cost, which is the provision of additional generation and transmission capacity needed to achieve an appropriate level of reliability. This suggests a trade-off between the social value of reliability and its cost. One of the requirements in addressing this trade-off is the construction of an appropriate method of measuring adequacy (i.e. an adequacy metric).

It is necessary to quantify the Value of Lost Load to obtain the economic value of adequacy

In order to put a value on reliability, a commonly employed parameter is the Value of Lost Load (VOLL), which measures the damage suffered by consumers when the supply is curtailed. In cases of productive activities (such as industrial processes engaged in the production of a good), an objective measure of the cost of interruptions, based on the loss of production or the linked benefit, is possible. In the case of domestic consumers, the VOLL is subjective and measured through the WTP in order to avoid supply curtailment. There are different methodologies for obtaining a credible estimate of the VOLL (section 3.5.2), the most accurate being based on surveys, and this calculation is crucial in estimating the social cost associated with energy not served.

Empirical analysis collects from different sources the adopted methodologies, metrics and standards used by MS to evaluate adequacy

The original approach of the empirical analysis was based on a survey addressed to EU Transmission System Operators (TSOs), but due to lack of response, a new approach was adopted. This approach consisted of the assessment of public information, TSO websites,

the Council of European Energy Regulators (CEER) Adequacy report (section 11.1), and State Aid Inquiry (SAI) data (section 11.3).

Key issues were extracted from public data and, in total, 23 countries have been covered by the analysis.

Adequacy assessment is usually performed by TSOs, but public data show this evaluation is made in few countries and is mainly limited to generation adequacy (GA)

All countries have a competent authority entitled to ensure system security and, generally, each Government mandates its TSO to take care of this activity.

The result is that a high number of countries do not perform adequacy assessments, and even if most countries do have a competent authority responsible for GA, there is no clear (or no reported) mechanism based on the GA assessment to trigger measures to ensure GA.

In general, GA alone is assessed, and both deterministic and probabilistic methods are currently in use.

Adequacy assessment depends on scenario variables, and the main uncertainty is connected to unplanned outages of generation and lines, and the availability of energy from primary sources

Probabilistic methods of simulation are used with different levels of modelling detail. In particular, the internal transmission network is rarely considered, and cross-border capacity is taken into account with simplified models lacking a detailed representation of neighbouring countries. In general, the GA factor within the EU is strong, and there is sufficient interconnection capacity; therefore, if each country evaluates GA separately, ignoring the support it could receive from other MS, there is a clear risk of obtaining a GA value much lower than the actual, which may in turn lead to the installation of capacity above socially optimal values.

The main uncertainty is connected to the availability of production sources; the consideration of intermittent renewable generation is very simplified, and in many cases this is not believed to contribute to GA. Hydropower reservoir management is not clearly mentioned although its support to adequacy could be crucial for countries with medium or high participation of hydropower in their generation mix.

Moreover, hypotheses on the evolution of generation are often based on information provided by operators or developers. This may lead to an underestimation of the generation needed, given the risk that a significant portion of announced projects are never developed, or are subject to lengthy delays.

Heterogeneous methodologies, metrics and standards are applied

A wide variety of metrics is used, but there is no specific reference to an economic value of adequacy (in particular to VOLL). Measures of this parameter are missing in most cases and, when available, the underlying methodology used to obtain such a value is neither made public nor shared among countries.

The heterogeneity of GA methodologies is a clear signal of opportunity for creating a common EU approach, including scenario assumptions consistent with those used in centralised assessment (such as the European Network of Transmission System Operators [ENTSO-E] Scenario Outlook & Adequacy Forecast [SO&AF]).

Several MS have established standards, generally in terms of LOLE targets. However, information is lacking on the criteria (if any) used to establish those standards, and a common methodology with which to set standards is also lacking.

Weakness in the current definition of metrics and standards

In several cases in the EU and other regions, it seems that metrics and standards have been set through via subjective decision, despite the evident fact that setting a standard (and the generation or transmission capacity necessary to achieve that standard) will have an economic impact on consumers. The recommendation is to set a standard that is representative of (or a reasonable proxy for) the value of the socially optimal level of reserve.

The Monte Carlo approach should be used to assess EENS with common tools and shared scenarios

Many TSOs in the EU rely on probabilistic models to carry out adequacy assessments, and the ENTSO-E itself is moving in this direction, integrating its deterministic methodology with a comprehensive and shared probabilistic approach.

The main conclusions and recommendations derived from the assessment process are listed below:

- Establish a single metric to be used in all countries, to allow comparison of the situations in each (section 5.2);
- Establish EENS as a preferred metric (section 5.2), as it alone proves appropriate for the calculation of the socially optimal levels of reserve;
- Employ a common methodology and tools (i.e. computer programmes) capable of obtaining comparable results from metric calculations, in order to ensure that quality is appropriate and that differences among country metrics are not based on differing methodologies (section 6.2);
- The proposed tool should be based on a sequential simulation model using the Monte Carlo technique in order to consider outages of generation and transmission, transmission constraints including internal transmission bottlenecks, cross-border support from neighbouring countries, renewable energy variability, operation of hydropower plants with reservoirs, maintenance of generators, and demand response (section 6.2);
- This model needs to simulate the distribution of power flow among MS and should be able to highlight possible bottlenecks in the network;
- The accuracy of the Monte Carlo models depends on the number of random samples; therefore, it will be necessary to establish a sufficient number of samples to assure the convergence of simulation results within a given bandwidth (e.g. 5%). A lower number of samples would lead to inaccuracy in the estimation of the metrics.

The most appropriate way to ensure that results in different countries are comparable and consistent is by use of a common model.

All the MS represented by the common model would have to share the same data, with similar levels of detail, to use the same variables subjected to the Monte Carlo simulation, and to share a common representation of cross-border and internal transmission constraints.

The probabilistic approach can be used to jointly assess generation and system adequacy

The EC's purpose, which is to obtain comparable standards for generation and system adequacy, relies on the fact that both evaluations address the ability of the system to meet the required load under the strain of various random events; therefore, investments in generation and network reinforcements can be selected on a cost-effective basis.

The optimal values of any metric should arise from CBA (or social welfare maximisation).

VOLL valuation is crucial to implementing a cost effective adequacy level

Regarding acceptable standards, it is important to underline that the relation of system cost to the VOLL value, which can be different from country to country (section 3.5.1), and the availability of different solutions for limiting EENS, can imply different levels of acceptable EENS for each country.

The VOLL calculation is complex and normally based on surveys, and it includes several factors: types of customers, duration of interruption, occurrence time and frequency.

VOLL should be calculated with a common methodology to ensure a consistent application to the EENS obtained from Monte Carlo simulations (section 6.4).

For the Internal Energy Market, price caps (if any) should be based on VOLL in order to avoid sending contrasting signals to investors about the value associated with EENS. Price caps above the VOLL may promote more capacity than is socially optimal (because prices may reach cap values in the event of EENS), while price caps below the VOLL can produce the inverse effect. In markets with good adequacy, this distortion will be negligible, as the impact of price caps on average energy prices will be low.

Heterogeneous metrics and standards increase spillage risk

As long as different metrics and standards are used to define and enforce capacity requirements to achieve adequacy, negative spill-overs of adequacy, in the shape of frequent support from one country with excess capacity to another with a deficit, may occur.

Spillage risk can be reduced by using a common model and homogeneous metrics and standards.

Responsibility and possible strategies to ensure adequacy can be different, but should be harmonised among countries

In order to achieve adequacy targets, MS rely on electricity markets or on public interventions. Network planning based on adequacy assessments can provide MS with an indication of the need to launch public interventions, as well as signals on the opportunities for investment in new generation capacity. However, the trigger for public intervention should be based on the certainty that this intervention is essential for ensuring an appropriate level of SoS.

Regarding possible public interventions, it should be noted that a lack of harmonisation in policy for incentivising investment undermines market competitiveness. Therefore, the principles applied to public interventions need to be clearly defined, transparent, non-discriminatory and verifiable.

Public intervention can be based on special incentives established to attract the investment necessary to obtain additional generation, transmission capacity or demand reduction. The identified interventions for GA are strategic reserves, last-resource tenders and capacity payments. The quantities of capacity or demand reduction to be procured through these methods should be based on achieving some pre-defined value (the standard) of a GA metric.

Assessment of investment needs should be made based on CBA, with the aim of minimising the cost of EENS ($EENS * VOLL$) plus any additional generation or transmission capacity cost (section 6.3).

2 INTRODUCTION

Internal Energy Market efficiency is influenced by national policies for the supply of electricity security, and especially by factors of transparency and coordination

The EU objective in the field of energy policy is to deliver sustainable and secure energy in the competitive European internal energy market. Internal electricity market (IEM) policies are expected to lead to the development of deep and liquid electricity markets, both long- and short-term. This can drive investment in a low-carbon electricity system that works in tandem with an emissions trading scheme, effective energy efficiency measures and targeted support for new low-carbon technologies.

Moving towards greater transparency and coordination among MS and national policies in terms of security of electricity supply could be highly beneficial in:

- assessing national preferences with respect to the trade-off between the social value of adequacy and supply cost;
- assessing national preferences for available alternative measures to achieve the desired adequacy level (e.g. transmission vs. generation investments);
- assessing the effects of the policies of each member state on: the SoS, neighbouring countries' security levels and supply costs, and the dynamics of the wholesale electricity market;
- Minimising the cost needed to ensure adequacy in Europe by exploiting the interdependencies among interconnected national systems.

Uncertainty increases investment risk

Policies to support low carbon generation have increased renewable generation production³ displacing generation from thermal sources. Owing to their low operational costs, renewables have displaced (flexible) thermal plants in the merit order. These policies, combined with the impact of the economic crisis on power demand⁴, have dramatically reduced load levels for thermal plants. Between 2008 and 2013, the average utilisation rate of thermal plants dropped from 50% to 37%. [1]

The reduction in flexible thermal generation, capable of covering renewable production fluctuation, increases the challenge of ensuring GA in electricity markets. One element of discussion is the need to ensure that new flexible resources be delivered to complement wind and solar power generation in particular. Wind and solar⁵ power generation can mean significant and sometimes sudden volatility, with fluctuations in the amount of energy being fed into the system. As with any other change in electricity supply or

³ Installed renewable generation in Europe (excluding hydropower) more than doubled between 2009 and 2013, reaching 435 TWh in 2013.

⁴ Electricity demand decreased slightly in 2013 (by 0.5% compared to 2012) and is still about 150 TWh (i.e. about 4%) below the peak reached in 2008.

[1] Linklaters, Capacity mechanisms - Reigniting Europe's energy markets, 2014

⁵ As the most popular intermittent renewable generation.

[2] European Parliament, DIRECTIVE 2009/72/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL concerning common rules for the internal market in electricity and repealing Directive 2003/54/EC, 2009.

[3] Commission Staff Working Document, Generation Adequacy in the internal electricity market - guidance on public interventions, 2013

demand, this must be balanced by the deployment of fast-acting generation, by releasing stored electricity, or by consumption response. This remains crucial to the transformation of the electricity system; it is also crucial that market incentives to invest in (or retain) system flexibility be implemented.

A closely related element of discussion is the need to ensure sufficient available capacity to meet demand at times of highest system stress, such as unplanned outages of major generation or transmission facilities. The system requires sufficient additional generation capacity to be brought on line to meet demand during these periods, however, these are the only times during which owners can produce electricity and therefore recover fixed costs. Therefore, security of electricity supply requires a solution, which in some cases is outside the market, like strategic reserves or last resort tenders.

How is it possible for MS to ensure the long-term adequacy of national electric systems?

Within this framework, some MS have launched (or are planning to adopt) special countermeasures to ensure the adequacy of national electric systems. In fact, the Electricity Directive 2009/72/EC [2] allows MS to implement special tendering procedures, or other equally transparent and non-discriminatory procedures. These procedures are to be implemented in the event that generation capacity (to be built under the normal market signals given by electricity prices and authorisation procedure) is not sufficient to ensure SoS. Another method of implementing such procedures is to introduce a capacity mechanism, which ensures a longer term stream of revenue to (selected) generators and commits consumers to pay for the capacity provided.

As public intervention to promote adequacy may entail public service obligations imposed on market participants and TSOs, “such obligations have to comply with the requirements, they have to be clearly defined, transparent, non-discriminatory, verifiable, and guarantee equality of access for electricity undertakings”[3]. Transparent and verifiable methodologies that allow the clear definition of occasions for public intervention become a key component in achieving these objectives.

Different mechanisms to safeguard SoS introduce risk of IEM distortion

The current adoption of different measures to safeguard SoS poses several risks for the IEM; the European Commission (EC) has underlined these risks in a consultative document on GA[4]. As a matter of fact, there are no agreed-upon guidelines for the implementation of measures to safeguard SoS, whether in terms of strategic reserves, tenders, capacity mechanisms or incentive schemes; no guideline has yet been developed, leaving each MS to proceed on its own.

The EC document also explores the opportunity to agree on a definition for a common European SoS safeguarding mechanism. This may help to eliminate or minimise current risks; however, implementation hurdles do arise when taking into consideration the non-aligned policies of each country. It is necessary to establish a common basis in order to evaluate the power system's ability to meet demand.

[4] European Commission, Consultation Paper on generation adequacy, capacity mechanisms and the internal, 2012.

Costs-benefit investment analysis helps to avoid IEM distortion

It is therefore expected that in order to sustain the economic efficiency of the IEM, policy decisions on “energy only market” interventions should be based on “sound” economic cost-benefit analyses.

In 2013, the ENTSO-E started the development and application of a Cost-Benefit Analysis of Grid Development Projects⁷ as part of a Ten-Year Network Development Plan (TYNDP)[5]: the cost of a new network infrastructure, or of other alternatives, is compared with the benefits gained by utilising such a system. Only projects showing a positive balance are selected.

Still, there are indicators that are not so monetised, namely the SoS specific indicator (B1), which is calculated based on Expected Energy Not Served (EENS); also, the LOLE⁸. As indicated by the ENTSO-E, EENS can only be monetised if the VOLL (section 3.5) is established, yet the lack of a uniform methodology for VOLL (or lack of definition of some VOLL) amongst MS prevents any meaningful calculation at present.

The Agency for the Cooperation of Energy Regulators’ (ACER) stated opinion on ENTSO-E guidelines [6] underscores the importance of monetising CBA indicators and the necessity of achieving a common methodology in VOLL evaluation.

Measuring the SoS level is necessary to tune effective and efficient procedures to achieve adequacy targets

“Secure Energy⁹” is one of the three pillars of EU policy in relation to the power sector. However, this is a very general term, encompassing several concepts: continuity of the service, quality of the product (voltage level, frequency, etc.), ability of the system to withstand contingencies such as sudden outages of generation or transmission, etc.

In order to obtain an operative definition of “Security of Electricity Supply”, it is first necessary to identify the different dimensions of this concept, then to define a metric that allows the measuring of these concepts in numerical terms. The existence of a metric permits the definition of targets and, consequently, those actions or investments necessary to achieve said targets. Additionally, it allows comparison of the situation to different systems.

Of course, for any metric to be useful, it should be connected (directly or indirectly) with the contribution of SoS to social welfare. Only in this case will any decision around actions or investments lead to real benefits for society.

One dimension of Security of Electricity Supply is the concept of adequacy, referring to the existence within a system of sufficient generation and transmission capacity to allow

⁷ A CBA is an analysis of the benefits associated with an investment in an electricity system (network or generation) compared to the associated cost of the investment to appreciate the profitability of a project.

⁸ The definition of these metrics will be the subject of section 3.3, but for the sake of clarity, EENS is measured in MWh and represents the ENS, while LOLE is measured in hours and represents the period of EENS occurrence.

[5] ENTSO-E, Guideline for Cost Benefit Analysis of Grid Development Projects, 2013.

[6] ACER, Opinion on the ENTSO-E Guideline for Cost Benefit Analysis of Grid Development Projects, 2014.

a load to be met under various uncertain events, including unavailability of facilities, low discharges in rivers, low wind speed¹⁰, etc.

An objective identification of the additional capacity needed to achieve the target level of adequacy allows the implementation of efficient and effective procedures to ensure adequacy in each MS.

The objective of the present study is to provide key input for the definition of a common methodology and a set of acceptable standards for the evaluation of national electric system adequacy

Based on the above, and within the context of current IEM analysis, this paper is set to provide input to the EC and its MS. The paper outlines a roadmap for the establishment of an appropriate methodology and a set of acceptable adequacy standards related to the physical phenomena that can affect the electricity supply, including expected involuntary disconnections, lack of primary resources, high demand, etc. In particular, a common methodology should be selected to identify the need for new generation capacity and to help define the criteria with which to evaluate possible incentives.

It is imperative that the cost incurred in order to reduce/mitigate the effects of generation shortages and network outages be assessed against a defined parameter appropriate to measuring the social cost on supply interruption: this should be the VOLL, which is the cost to the economy (and society) of unforeseen supply interruptions.

It is also imperative, in order to avoid any market distortion, that GA standards be comparable with those required for network outages – from the moment that both standards become capable of solving ENS, even if cost and completion time are very different.

Main phases of the study: theoretical analysis, empirical analysis, diagnosis and recommendations

To achieve these objectives, the project is divided into three phases, and the report is likewise organised into three corresponding main chapters, as detailed in the following.

1. Theoretical analysis (Chapter 3):
 - a. Classification of main concepts on adequacy and review of the terminology currently adopted (with particular reference to CEER, ACER, ENTSO-E, TSOs, CIGRE), as well as metrics definition;
 - b. Analysis of relationships between overall system adequacy and concepts and metrics of GA;
 - c. Analysis of possible relationships between metrics and their suitable applications;
 - d. Elements for assessing a CBA with particular reference to VOLL.
2. Empirical analysis (Chapter 4):
 - a. Definition of a questionnaire submitted to TSOs and MS on adequacy evaluation: including entities, methodology, hypotheses, metrics, and standards;
 - b. Survey of the GA metrics and standards implemented in MS and a review of their functional pros and cons, based on aggregated results of the research on

public data and the elaboration of the SAI data, selected and provided by the EC.

3. Diagnosis (Chapter 5):

- a. Based on the theoretical analysis and the findings of the empirical analysis, a diagnosis that identifies the cases when a metric is needed;
- b. Proposal of the criteria that the metric should fulfil, to be representative of system adequacy, as well as transparent and verifiable;
- c. Finally, methodology guidelines are drafted for the appropriate calculation of the selected metrics.

4. Recommendations for the future, and next steps (Chapter6):

- a. Definition of an appropriate methodology and metrics to assess generation and system adequacy for the IEM, taking into consideration the experience of TSOs and the theoretical framework;
- b. Criteria to define adequate standards and VOLL methodology, to avoid negative spill-overs across Member State borders as a result of applying inappropriate generation and system adequacy standards in the IEM.

3 THEORETICAL ANALYSIS: ALTERNATIVE METHODOLOGIES TO MEASURE ADEQUACY AND RELATED METRICS

This chapter introduces the adequacy concept and related definitions (section 3.1 and 3.2), clarifies the methodologies in use for assessing adequacy (section 3.3), and defines the associated metrics (section 3.4) with regard to transmission and distribution systems.

A comparison of different metrics in terms of advantages/disadvantages and any possible relationship is performed with reference to the possible application of CBA (section 3.5). The elements for assessing a CBA, with particular reference to VOLL, are introduced.

3.1 Definition of adequacy

Security and adequacy are two facets of power system reliability

As far as Security of Electricity Supply (or its synonym, "system reliability") is concerned, there is no common terminology adopted in the relevant literature, or in the security of electricity supply directive. Yet in general, it has become standard practice to use three terms to properly establish the degree of reliability of an electric power system: reliability, security and adequacy.

In order to avoid any confusion, we shall hereby define the terminology used throughout this report, based on various benchmark studies carried out by the main regulators and institutions, as well as the feedback received.

"(System) Reliability is a general term encompassing all the measures of the ability of the system to deliver electrical energy to all points of utilization within acceptable standards and in the amounts desired"[7].

The concept of reliability embodies two main factors: system security and system adequacy. In what follows, we first define security and briefly introduce the best practices for its calculation, including the key operational parameters and solutions to achieve a secure power system. Secondly, we define system adequacy and highlight its relationship with security, discuss how to determine the optimal level of adequacy, and introduce the issue of *adequacy evaluation*.

Security is a power system's ability to withstand the risk of massive contingencies in the short term.

As explained in CIGRE' (1987):

"Security is the measure of how an electric power system can withstand sudden disturbances such as electric short circuits or unanticipated loss of system components"[7].

The concept of system security therefore deals mainly with the short-term dimension of power supply; in fact, the ENTSO-E regards it as Operational Security [8].

Best-practice approaches for the optimal calculation of system security include[5]:

[5] ENTSO-E, Guideline for Cost Benefit Analysis of Grid Development Projects, 2013.

[7] CIGRE', Power System Reliability Analysis (TB 26), CIGRE WG 03 of SC 38 (Power system analysis and techniques), 1987.

[8] ENTSO-E, Network Code on Operational Security, 2013.

- Load flow analysis
- Steady state analysis
- Voltage collapse analysis
- Dynamic stability analysis (not explicitly mentioned in the cited document).

In the calculation of system security, the status of the system is obtained considering sudden failures of network elements, loss of generation, or other types of events, depending on their probability of occurrence.

The analysis is focussed on how successfully the system is able to face the above mentioned events, *how successfully and securely it might move to another state, and how successfully it might withstand sudden disturbances like electric short circuits* [9].

The assessment of system security allows the definition of operational parameters, namely:

1. the maximum admissible flow in transmission lines, when it is lower than the thermal capacity;
2. the quantity of ancillary services (AS), namely primary, secondary, and tertiary reserves;
3. reactive power availability to control voltages in critical buses, etc.

An appropriate quantity of AS and power transmission equipment, such as tap-changing transformers, phase shifters, flexible AC transmission systems (FACTS), controllable series capacitors, switchable lines, high voltage direct current (HVDC), and so on, also plays a key role in: transferring the least-costly electrical energy from suppliers to customers; implementing optimal controls of power systems; and guaranteeing the transmission system security.

Appropriate short-term operation is considered the natural solution to maintain real-time security; the only alternative is to prevent the system from incurring a critical situation, but this requires a significant limitation in acceptable system operative conditions and can be very difficult to achieve.

In real-time operation, generation units or storing facilities of any nature, with high efficiency, fast response, shorter installation time and, eventually, environmental friendliness could flexibly meet rapid changes in the competitive electricity market; this could considerably improve the power system's ability to withstand the risk of massive contingencies.

However, the absolute security of power systems cannot be unconditionally guaranteed in a complex electricity system where unpredictable and multiple equipment failures, primary resource availability, sudden variations of RES production, and customer demand changes could cause severe impacts on power systems security. As a result, a secure power system should exhibit a high probability of residing in a secure and alert state, and of recovering rapidly from an emergency state.

Adequacy is the power system's ability to meet demand in the long term

As explained in CIGRE' (1987):

[7] CIGRE', Power System Reliability Analysis (TB 26), CIGRE WG 03 of SC 38 (Power system analysis and techniques), 1987.

[9] CIGRE', Power System Reliability Analysis (Volume 2) Composite Power System Reliability Evaluation (TB 70), Task Force 38.03.10, 1992.

"Adequacy is a measure of the ability of a bulk power system to supply the aggregate electric power and energy requirements of the customers within component ratings and voltage limits, taking into account scheduled and unscheduled outages of system components and the operating constraints imposed by operations"[7].

The ENTSO-E definition of SoS in [5] is quite similar to that of adequacy: "Security of Supply is the ability of a power system to provide an adequate and secure supply of electricity in ordinary conditions, in a specific area". The methodology for quantifying adequacy (referred to as the adequacy calculation) and corresponding metrics are described in section 3.3 and section 3.4.

Security refers to the operation of the power system; adequacy, to the planning process

While security mostly deals with the operation of a power system, adequacy is part of the planning process. In fact the concept of adequacy represents the system's ability to meet demand in the long term (which is not the case for security), taking into account the inherent uncertainty in demand and supply, the non-storability of power, and the long lead-time for capacity or network expansion.

Security and adequacy are closely related to ensuring power system reliability

In order to achieve reliability, both adequacy and security should be targeted. In particular, adequacy must be complemented with a generation mix that ensures the availability of enough generation necessary to provide AS, especially for frequency regulation.

Security and adequacy are closely related notions but are not identical. Without system security, the output of the generation resources, no matter how abundant they may be, cannot be delivered to customers. Correspondingly, a high degree of security is of little value if there are insufficient generation and transmission resources to meet customer needs.

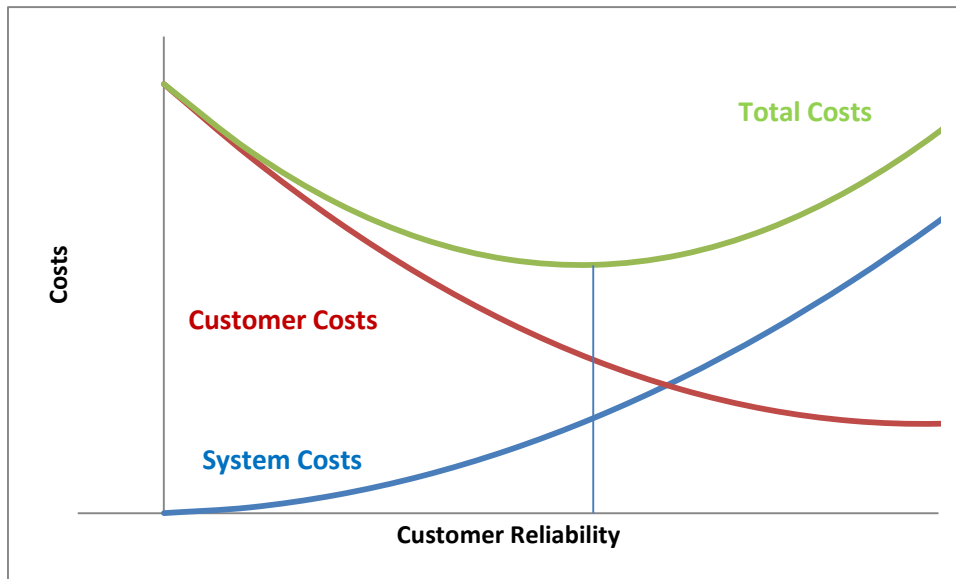
Optimal adequacy is the optimum trade-off between new investment costs and ENS costs

The optimal or desirable adequacy level should represent a balance between investments and the cost of ENS; in fact, "absolute" adequacy cannot be reached because that would require investment expenses substantially above the achievable benefits (Figure 3.1).

The evaluation of investments considering both system and consumer costs is defined as Value Based Reliability Planning (VBRP).

Investments, whether in transmission or generation, increase system costs, but the first actions selected are generally those deemed most effective to reduce ENS and consequently reduce consumers' costs; a balance may be found to ensure that new investments costing more are not higher in respect to the reduction they cause in consumer costs (ENS). Further, it is possible to identify the optimal value of reliability investments. The minimum total cost represents the economic optimum for a CBA.

[5] ENTSO-E, Guideline for Cost Benefit Analysis of Grid Development Projects, 2013.



**Figure 3.1 – Total reliability costs obtained from adding system costs (investment) and customer costs (ENS cost)
– re-drawing of a widespread representation of VBRP**

System adequacy is the sum of generation and transmission adequacy

Adequacy evaluation can refer either to generation alone, or to the transmission network, or both [10]:

- **Generation adequacy** of a power system is an assessment of the ability of the generation on the power system to match the consumption of the power system;
- **Transmission adequacy** of a power system is an assessment of the ability of a power system to manage the flow resulting from the transfer of power from generation to the consumption centre;
- **System adequacy** of a power system is a measure of the ability of a power system to supply the load in all the steady states in which the power system may exist under standard conditions. System adequacy is analysed through simultaneous consideration of GA and transmission adequacy.

It should be made clear that GA means not merely the generation sufficient to meet the load, but also reserves that can allow the system to withstand outages of major facilities, extreme dry periods, or possible shortages of fuel availability. In this sense, forward commodity market trends play a significant role in determining the system's adequacy. As a result, when looking at capacity adequacy, a key issue is to determine what factors must be accounted for when considering the ability of supply to meet demand.

GA is intended to assess the capability of the generation system to meet electricity demand, respecting national exchange limits accordingly; transmission and distribution networks (section 3.4.3) should be considered only where they constrain the ability to deliver generation MW to consumers in general.

[13] European Parliament, DIRECTIVE 2005/89/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL concerning measures to safeguard security of electricity supply and infrastructure investment, 2006.

The supply chain connecting generation with demand includes transmission and distribution networks. There can be a number of contingencies throughout the supply chain and it is important to recognise that the future SoS experienced by end-consumers depends upon the combined reliability of fuel (or other primary resource supplies), generation, transmission, and distribution.

"The first step in any adequacy evaluation is to produce the 'states of the power system' one at a time, verifying the ability of the system to supply the load power and energy"[9], where "states of the power system" signifies a combination of loads, available generators and available transmission lines.

Who is responsible for ensuring system adequacy?

In a vertically integrated utility, reliability is achieved by centralised system planning at all levels: generation, transmission and distribution (or hierarchical levels I, II and III, respectively [11]). Worldwide changes in regulation in the electric power industry, moving in the direction of open and competitive markets, has resulted in a change regarding traditional approaches to reliability.

In order to assure competitive and open access to grid capacities, the economic efficiency of the transmission network needs to be assessed in a clear and non-discriminatory way. Directives 2003/54/EC [12] and 2005/89/EC [13] (the Electricity Security of Supply Directive) make it mandatory for MS to publish every two years a System Adequacy Report with a time horizon ranging from five to fifteen years.

Public authorities are required to regularly undertake an objective fact-based assessment of the generation and system adequacy situation in their respective MS, and to incorporate new and recent developments at both the regional and EU levels.

In fact, generation and system adequacy are critical for ensuring security of electricity supplies. In order to guarantee a continuous supply of electricity to consumers, sufficient (firm¹⁵) generation capacity needs to be available, while transmission and distribution networks must be reliable when transporting generated electricity to final consumers.

However, GA can also be obtained by incentives offered by electricity markets or through public interventions. In the latter case, government agencies in charge of these decisions should have available sound criteria and corresponding information from which to launch the processes that may ensure adequacy.

TSOs (or the Electricity Policy Authority) should obtain information about generation scarcity in advance, in order to identify possible measures (investments in transmission

¹⁵ Although there is no agreed definition, firm capacity is a metric of the contribution of a generating unit to the system reliability.

[12] European Parliament, DIRECTIVE 2003/54/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL concerning common rules for the internal market in electricity and repealing Directive 96/92/EC, 2003.

[11] R. Billiton and W. Li, Reliability Assessment of Electric Power Systems Using Monte Carlo Methods, New York: Plenum Press, 1994.

[12] European Parliament, DIRECTIVE 2003/54/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL concerning common rules for the internal market in electricity and repealing Directive 96/92/EC, 2003.

[12] European Parliament, DIRECTIVE 2005/89/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL concerning measures to safeguard security of electricity supply and infrastructure investment, 2006.

assets, review of reserve allocation policy) or to provide needed information (i.e. necessity for capacity tendering) to the responsible agency and to the National Regulatory Authority (NRA).

As we witness an increase in the number of generators connected to grids operating at lower voltages (i.e. distributors), TSOs and Distribution System Operators (DSOs) need to exchange information in a way that ensures transparency and efficiency.

It is necessary that TSOs and DSOs have a methodology with which the SoS can be measured, and its acceptable levels defined. However, the levels of security should arise from an economic optimisation (investment vs. social cost of load shedding), or, if this is not possible, they should be set by the policy makers or regulator. This is relevant for TSO and DSO decisions concerning operations and investments. It is also important to have an early warning system to deal with scarcity of supply to the market.

European adequacy assessment is limited to generation, while transmission adequacy evaluation is not centralised

In addition to national reports, the ENTSO-E provides a European adequacy assessment.

Within the ENTSO-E SO&AF [14] and the recently released Target Methodology for Adequacy Assessment [15], only GA is addressed, while the responsibility for evaluating transmission adequacy lies with individual countries, exploiting TSOs' knowledge of their own network management.

The approach currently implemented from the ENTSO-E is based on the definition of future scenarios, to the year 2030, where GA is verified (SO&AF, [14]); the analysis is performed on a yearly basis. Starting from these scenarios, single snapshots obtained from hourly simulations (optimal hourly dispatching of thermal units to cover residual load, considering unit costs and constraints) are analysed on an overall network model, verifying either the necessity of more reinforcements or the effects of reinforcements already planned (TYNDP, [16]). The TYNDP is published every two years; the complexity of analysing a transmission network is different from the cases of generation and national demand equivalent, and analyses here are focused only on network reinforcements, influenced by cross-border exchange limits. Internal network analyses are executed only by individual TSOs.

The process, therefore, leaves TSOs open to the possibility of identifying critical national situations that may require the implementation of additional measures, such as capacity remuneration mechanisms.

The next section discusses in detail the issue of adequacy assessment.

3.2 Adequacy assessment: preliminary concepts

The methodology for assessing a GA consists in a calculation procedure (e.g. Monte Carlo simulations), data from several sources like generators availability, wind regime, etc., and assumptions on the evolution of the system.

Depending on the adopted approach, deterministic or probabilistic (see section 3.3), different metrics for measuring a power system's adequacy can be adopted. These

[14] ENTSO-E, SCENARIO OUTLOOK AND ADEQUACY FORECAST 2014-2030, 2014.

[15] ENTSO-E, Target Methodology for Adequacy Assessment, 2014.

[16] ENTSO-E, Ten-Year Network Development Plan 2014, 2014.

metrics are defined to quantify the maturity of a system in respect to a target or standard, and are suitable for comparison among different systems or different time periods (measuring the relative developments in adequacy). For this reason, to each metric a standard value is normally associated, usually defined by the TSO, a specific government agency or an NRA, in order to establish whether the current level of adequacy is admissible.

3.3 **Methodology to assess adequacy**

Assessing adequacy in a complex electricity system subjected to market rules

The premise here is that it is not possible to obtain an electrical system characterised by "absolute" adequacy, except by considering "infinite" investments (see Figure 3.1, to clarify how investment costs can increase more than the associated benefits).

In practice, the objective is to find the best compromise between cost-effectiveness and reliability: system failures have to be accepted when the resulting drawbacks for customers remain at an acceptable level, or when there is no willingness to pay more for increasing reliability. As long as there is not a widely shared approach to measure the value of energy not served (see section 3.5), the practice of establishing the level of acceptability is defined quantitatively by reliability criteria that, historically, can be classified into two main categories: deterministic and probabilistic [7], illustrated below.

3.3.1 *Deterministic methods*

Deterministic methods: fast calculation, but does not cover all systemic contingency configurations

Deterministic models are essentially scenario-based contingency calculations. Therefore, only a small set of arbitrarily chosen conditions of the power system can be evaluated.

This kind of method generally implies reduced computation time and data management, but, as a downside, it requires a deep knowledge of the electricity system under analysis, because TSOs must identify the most significant states of the electricity system to be analysed on the basis of their experience.

With a deterministic methodology, the adequacy evaluation is based on the requirement that each outage event in the contingency set results in system performance that allows the meeting of demand by an appropriate level of frequency control reserves. These assessments are defined by selecting a discrete set of system configurations (i.e. network topology and unit commitment), a range of system operating conditions (i.e. generating unit dispatching and load distribution), a list of possible outage events (e.g. unavailability of generators or of system components such as lines or transformers), and performance evaluation criteria (i.e. values of voltage, frequency, loading of network elements inside their operating range). These operating conditions are simulated with load flow¹⁸ and dynamic stability analysis¹⁹ tools, assessing the system's performance under each simulated condition.

[7] CIGRE', Power System Reliability Analysis (TB 26), CIGRE WG 03 of SC 38 (Power system analysis and techniques), 1987.

¹⁸ A load flow analysis calculates a steady-state representation of electricity system behaviour given network topology, generation and load distributions: the results are a voltage profile and the distribution of power flow on the network.

With this approach, the definition of the study scope requires careful thought and insight because the number of possible network configurations, the range of operating conditions, and the number of conceivable outage events are very large, making exhaustive study of all combinations unreasonable. Consequently, the deterministic approach has evolved within the electrical power industry to minimise effort while providing useful results. As a result, several problems exist with this approach:

- It considers only a few discrete outcomes based on the analysis criteria, ignoring hundreds or thousands of others;
- It gives equal weight to each outcome. That is, no attempt is made to assess the likelihood of each outcome;
- Interdependence between inputs, impact of different inputs relative to the outcome, and other nuances are ignored, with the risk of oversimplifying the model and thereby reducing its accuracy;
- It is impossible to consider combinations of insufficient primary resources such as wind or water with failures in system facilities (generation and/or transmission) – a very likely event in systems with high renewable energy resource (RES) penetration.

Yet despite its drawbacks and inaccuracies, many organisations operate with this type of analysis, integrating a probabilistic model approach in order to evaluate specific cases and scenarios more accurately. As they can be undertaken quickly, deterministic approaches also remain in use, especially at the dispatching level²⁰ to assess the real-time operative security of the electricity system. For planning, meanwhile, probabilistic methodologies are normally adopted.

In what follows, two main deterministic approaches are presented:

- 1) The reserve margin method
- 2) The selected base incidents method

Although the principles of the criteria are the same across EU TSOs, standards as well as current practices for the calculation of metrics continue to differ quite significantly among TSOs (see Chapter 4 for details).

Reserve margin is the difference between available generation capacity and the load to be covered, disregarding transmission constraints

The reserve margin method is a well-known deterministic methodology, still in use in several MS, for the evaluation of GA. This criterion is based on the limit of how close the load should come to installed capacity. The reserve margin is therefore defined as the ratio of the installed or available capacity to the maximum annual load, minus one [7]. Usually, there is no focus on the role of interconnections. In the case of system dispatch,

¹⁹ A dynamic analysis represents the evolution of the electricity system over time, considering the dynamic characteristic of all system components: the results are the same as load flow but with the addition of system frequency.

²⁰ In the time horizon of dispatch, multiple failures are unlikely, so an N-m approach is appropriate.

[7] CIGRE', Power System Reliability Analysis (TB 26), CIGRE WG 03 of SC 38 (Power system analysis and techniques), 1987.

[14] ENTSO-E, SCENARIO OUTLOOK AND ADEQUACY FORECAST 2014-2030, 2014.

[14] ENTSO-E, Target Methodology for Adequacy Assessment, 2014.

this criterion of reserve margin is usually determined against limiting conditions (i.e. loss of the capacity of the largest unit used, or of a percentage of the peak load).

The consequence of ignoring transmission constraints or failures may lead to the situation where, although there is enough reserve in the system, some power system areas exhibit a lack of reserves, thus being exposed to a lower reliability level.

Figure 3.2 compares the demand at peak load with the total generation figure, reduced from the total installed figure, considering: maintenance and overhauls, outages, constraints due to severe conditions (i.e. impossibility of producing maximum power due to environmental factors), non-usable capacity at peak load (also due to contemporary factors applied to renewable production) and reserve requirements.

Peak load can also be increased to take into account severe conditions (i.e. a cold winter in a country with electrical heating), or decreased if load flexibility is an available resource (i.e. interruptible loads).

Remaining capacity is the measure of reliable capacity exceeding the severe peak load and taking into account possible load reductions.

A reserve margin approach has been adopted in the past by the Union for the Coordination of the Transmission of Electricity (UCTE) and by the ENTSO-E to establish GA [14].

Recently, the ENTSO-E has decided to move to a probabilistic analysis [15], which is more suited to managing an interconnected system characterised by relevant variations in load and high penetration of non-programmable generation.

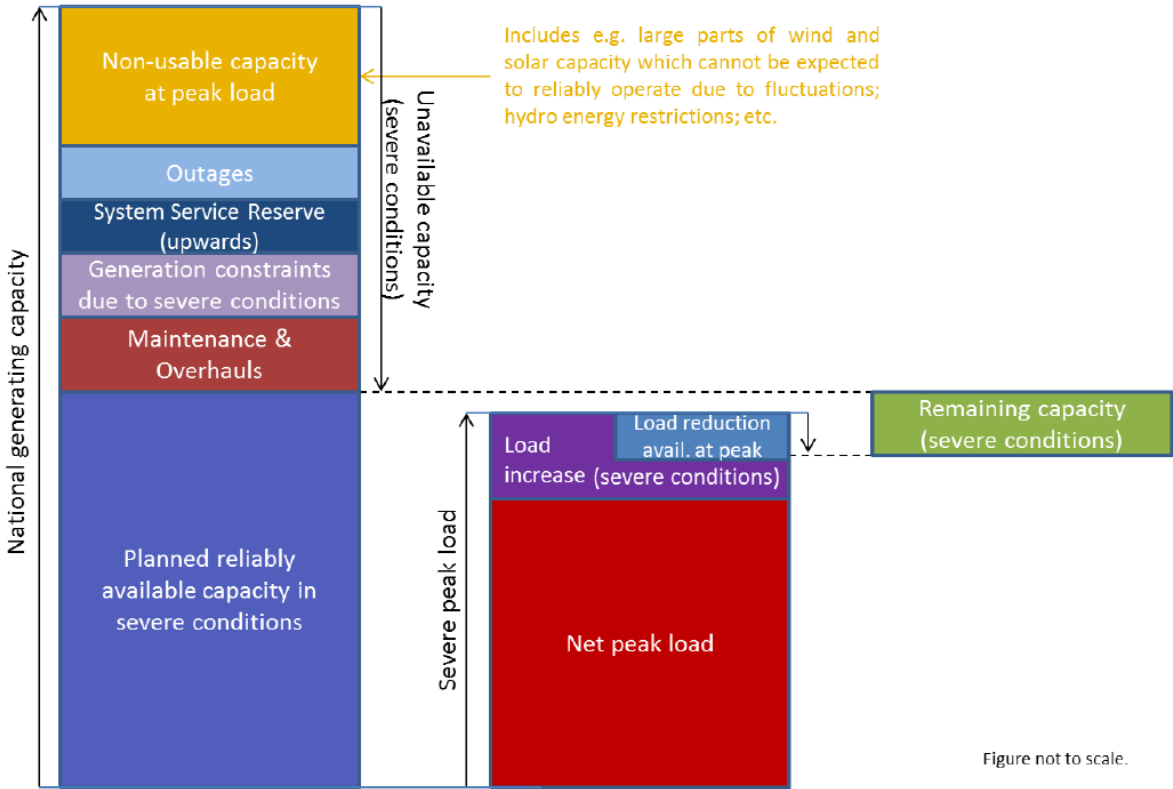


Figure not to scale.

Figure 3.2 - Graphic representation of remaining capacity

The selected base incidents method includes transmission constraints employing a deterministic simulation of a discrete set of contingency scenarios

The selected base incidents method [9] is a deterministic methodology that also takes into account the transmission grid and the related impact on system adequacy. The general procedure for the implementation of this method consists of two steps:

1. Selection of one or several base cases: these should correspond to operating conditions that are considered critical, relying on the experience of both planning and operations;
2. Subjecting each case to a series of generation and transmission incidents and examining how the system withstands the selected incidents (load flow and, when considered necessary, dynamic stability analyses).

3.3.2 Probabilistic methods

Probabilistic methods: all system configurations are derived from unavailability factors associated with each element of the system

Probabilistic criteria constitute a generalisation of the deterministic approach, since, at least in principle, all possible constraining situations are examined and, from their results, risk indices are obtained. The probabilistic approach in fact recognises the random nature of loads, RES productions, and outages of generation/transmission equipment.

Main deficiencies of the deterministic approach solved by the probabilistic method include:

- No discretion in the selection of scenarios and contingencies; the only limitation is derived from the maximum number of situations examined;
- Possibility of assigning a weight to each case under study on the basis of its probability of occurrence;
- Possibility of approaching a large interconnected system for both generation and system adequacy.

In the past, the major difficulty in probabilistic adequacy assessments involves the enormous computational effort required to analyse a huge number of system states, each characterised by its own intrinsic probability of occurrence; however, progress in computational power has overcome this problem.

Typical probabilistic simulation

A typical simulation of a probabilistic model is based on a random occurrence of facility failures, or on the availability of primary resources, from which a base dispatching of hydro/thermal units is calculated on the basis of cost minimisation criteria. A load flow analysis can follow, to highlight the effects on the network of an economic dispatching and to consider the availability of all the system's elements.

There are essentially two different types of probabilistic methods:

1. Convolution of probability functions;
2. The Monte Carlo model.

[9] CIGRE', POWER SYSTEM RELIABILITY ANALYSIS (Volume 2) Composite Power System Reliability Evaluation (TB 70), Task Force 38.03.10, 1992.

The latter is widely in use. In what follows, we briefly examine these two methods and then present the features of the probabilistic methodology for assessing adequacy at EU level, as used by the ENTSO-E.

Convolution is the joint probability of a single system's probability of outages

Convolution: the basic concept is, given the distribution probability of two variables, $f_1(x_1)$ and $f_2(x_2)$, to find the probability distribution of the sum or difference of these two variables $f_{12}(x_1 \pm x_2)$.

This allows, for instance:

- Given two generation units with capacities G_1 and G_2 , and the respective probabilities that the units are available (p_1 and p_2), to find the joint probability of the availability of the two generation units (i.e. the probability of the following available capacities):
 - 0: both units out $(1-p_1)(1-p_2)$
 - G_1 : unit G_2 out $(1-p_2)p_1$
 - G_2 : unit G_1 out $(1-p_1)p_2$
 - G_1+G_2 : no fault p_1p_2
- And, recursively to obtain the joint probability distribution of the entire generation available in a region.
- Given the availability of the thermal units ($G, f(G)$) and the probability of different levels of wind generation ($W, w(W)$), to calculate the probability of the total generation availability $f(G+W)$ through the convolution²² of the probability distribution functions $f()$ and $w()$.
- Given the probability distribution of total generation $f(G+W)$ and demand $h(D)$, to calculate the probability of meeting the load – i.e. the convolution of $f(.)$ and $h(.)$, obtaining the probability distribution $p(G+W-D)$.

Convolution requires additional analysis to consider maintenance outages of units and reservoir operation strategies, thus, in general, it is not a good representation of systems where transmission constraints are crucial because obtaining a composite availability of network elements and generators would be very complex.

For a more general case including both generation and transmission, it would be necessary to consider a significantly more complex simulation which involves modelling the operation of the whole system on a period-by-period basis (over a typical day or week for each season) taking into account several variables²³.

Monte Carlo models automatically analyse a wide range of possible states of the system

Monte Carlo models can represent the entire power system (generation, transmission and, in general, distribution) by applying random number techniques to simulate a wide range of possible states of the system. In particular, Monte Carlo techniques are based

²²In mathematics and, in particular, functional analysis, convolution is a mathematical operation on two functions, f and g , producing a third function that is typically viewed as a modified version of one of the original functions, giving the area overlap between the two functions as a function of the amount that one of the original functions is translated.

²³ Typical variables are: demand uncertainty (including interruptible loads and DSM), transmission capacity and outages, wind uncertainty, hydropower inflow uncertainty, reservoir storage operation, load forecast accuracy, river chain scheduling constraints, thermal start-up times, and dispatching considering costs and possible constraints.

on the idea that the decision as to whether an element will be operating or not can be determined by a uniform random number generator.

A random number is generated for each element in the simulated system, and this is subject to random unavailability. Any element whose number falls in its unavailability range is disconnected from the system for that particular simulation. This process is repeated many times to simulate different random states, as a very large number of simulations is required.

The random sampling could be extended to other factors with an associated probability such as RES production, or the dependence of load upon weather conditions.

The main drawback of a Monte Carlo simulation is that, in order to obtain reasonable accuracy in the estimation of the metric, it is necessary to perform a very high number of simulations (usually tens of thousands), because each simulation has the same importance, and only with several Monte Carlo extractions is it possible to obtain a good representation of the system. Situations with higher probability will occur more often, while rare situations can be examined, though their effect on average results will be lower.

ENTSO-E Target Methodology based on a probabilistic approach

The level of reliability of the pan-EU electricity system is assessed by the ENTSO-E through a chronological hourly simulation of the whole interconnected system in which, for every time point (hour), an optimisation procedure will try to cover the estimated load demand of each area using the generation capacity available both inside the area as well as in other areas, according to their order of merit and properly taking into account the constraints on the interconnections.

These simulations provide an estimation of the expected cross-border flows and, in addition, such modelling allows the ENTSO-E to produce an extensive range of indicators. The main indicators for adequacy assessment are: LOLE, LOLP, full load hours of generation, and RES curtailment.

Estimated marginal technology and CO₂ emissions have also been listed by stakeholders as the most interesting indicators [15]. The following paragraph discusses the main indicators for adequacy assessment.

3.4 Adequacy metrics

All metrics, independent of the kind of approach and model adopted, depend on the impossibility of feeding the load in all configurations analysed. Indeed, as already observed, "absolute" adequacy is economically unsustainable (Figure 3.1).

In this section, we first describe the most common adequacy metrics, then present their advantages and drawbacks, finally focussing on the distribution system's adequacy and on measurement of the quality of distribution service.

3.4.1 Generation and system adequacy metrics

Based on the approach adopted to assess adequacy (deterministic or probabilistic, as illustrated above), a particular TSO will normally adopt one or more metrics to describe the adequacy of their system. Following is a list of the most common metrics used, the definitions and characteristics of which are presented below:

- EENS
- LOLE

- LOLP
- 95th percentile (P95)
- Capacity margin
- Frequency and duration of expected outages
- Equivalent Firm Capacity (EFC)

Some metrics can be calculated only by using a probabilistic approach, while others can also be obtained through a deterministic approach.

It is worth observing that all the probabilistic measures are expectations – i.e. they are not deterministic values, but only the average value of a probability distribution, where the latter is a modelled approximation of reality. They provide valuable indicators of the adequacy of a system taking into account the stochastic and deterministic nature of the generation/transmission system as well as customer demand.

In what follows, we present each of the above-listed metrics and introduce the issue of comparison of adequacy levels across different countries.

EENS measures EENS on a yearly horizon

EENS²⁴ is the basis of all the metrics; it is a measure of the amount of electricity demand (in MWh in a given year) expected to be lost when demand exceeds the available generation [7].

It is possible to divide this energy into primary causes:

- Lack of Power (LOP) –there is no sufficient generation capacity in the electrical system considered (this concerns GA).
- Lack of Interconnection (LOI) – generation or system adequacy depending on the identified solution; generation capacity is available in an area different from that where energy is required, and network constraints prevent supply from reaching the load. For GA, only cross-border exchange capabilities or internal limiting sections are normally taken into consideration, while for system adequacy, the detailed representation of the network also includes interconnection branches whose overload is classified as 'lack of interconnection'.
- Line Overload (LO) – relevant to system adequacy, network element overloads make it impossible to feed a load (i.e. higher load than generation in an area of the network characterised by poor meshing).
- Network splitting or isolated node – relevant to system adequacy, the unavailability of one or more network elements jeopardises the electrical system, making it impossible to feed the load of a single node or a portion of the network; the managing of such situations may depend on islanding policy adopted by a single TSO.

Demand side management (DSM) policies should be taken into consideration in the evaluation of ENS because there is a difference between 'authorised' and 'unauthorised' interruptions to demand. In fact, the former is associated with demand side contracts

²⁴Also known as Expected Unserved Energy (EUE) or Loss of Energy Expectation (LOEE).

[7] CIGRE', POWER SYSTEM RELIABILITY ANALYSIS (TB 26), CIGRE WG 03 of SC 38 (Power system analysis and techniques), 1987.

[15] ENTSO-E, Target Methodology for Adequacy Assessment, 2014.

(CIGRE Working Group, WG C1.27, is currently working on this argument) or with direct participation of the load to a dispatching market; it may be counterproductive to include in the adequacy evaluation the first figure from the moment that it can generate a double counting of costs.

Starting from the determination of EENS, it is possible to quantify several additional metrics normally used by TSOs to assess the adequacy of their generation and transmission systems:

- Energy index of reliability (EIR) and energy index of unreliability (EIU) are equal to normalisation of EENS obtained dividing by the total energy demanded; this ensures that systems large and small can be compared on an equal basis and the evolution of the load in a system can be tracked.
- System Minutes (SM) is obtained from EENS, normalised by peak demand.

EENS can be calculated both from a deterministic or probabilistic method, but in the former case, an entire year of simulation is needed.

LOLE represents the yearly hours with EENS occurrence

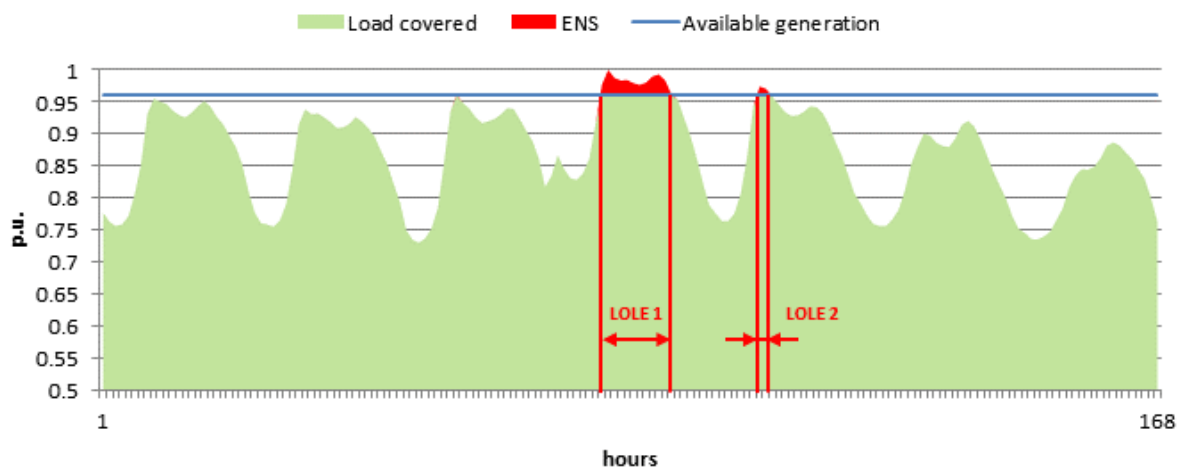


Figure 3.3 - Graphic representation of ENS and LOLE in a sample week of the year

LOLP corresponds to the probability of EENS occurrence at load peak

LOLP represents probability that the load will exceed the available generation [17]; this is often limited to the ability to meet annual, weekly peak load (referring to Figure 3.3, supposing the week presented is the only one exhibiting EENS in the given year, LOLP calculated on weekly peak load is equal to a probability of 1/52).

The same division by primary causes adopted for LOLE can also be applied to LOLP.

As with LOLE, this index defines the likelihood of encountering trouble, but not the severity.

This metric can be calculated only with a probabilistic methodology.

P95 is the LOLE calculated in a critical scenario

P95 represents the number of hours during a very cold winter²⁵ (once every 20 years) during which the load cannot be covered by all means available. It is equal to LOLE, but calculated in a critical scenario[18].

This index is adopted by different TSOs such as Elia, Tennet, and Statnett.

Capacity margin represents the average excess (or scarcity) of available generation capacity over peak demand

Capacity margin is the average excess of *available generation capacity over peak demand*, expressed in percentage terms. Available generation capacity takes into account the contribution of installed capacity at peak demand by adjusting it to the appropriate availability (de-rating) factors, which take into account the fact that plants are sometimes unavailable due to outages[19]. This figure can be calculated without any probabilistic simulation, as it is based only on average unavailability, through a quantitative approach. Figure 3.4 is a graphic example of the relationship between the de-rated capacity margin and the probability of lost load occurring [20]. The figure represents margin variability all across the year, while the de-rated margin is only an average figure: this limitation is evident if the margin shows a large variation in respect to the average, in which case periods with negative margins can occur.

In particular, the UK Department of Energy & Climate Change underlines how de-rated margin is an appropriate indicator at times when intermittent generation is not significant and the proportion of each type of generation in the fleet is roughly constant year-on-year (it is therefore not expected that the de-rated capacity margin will remain a good metric of SoS).

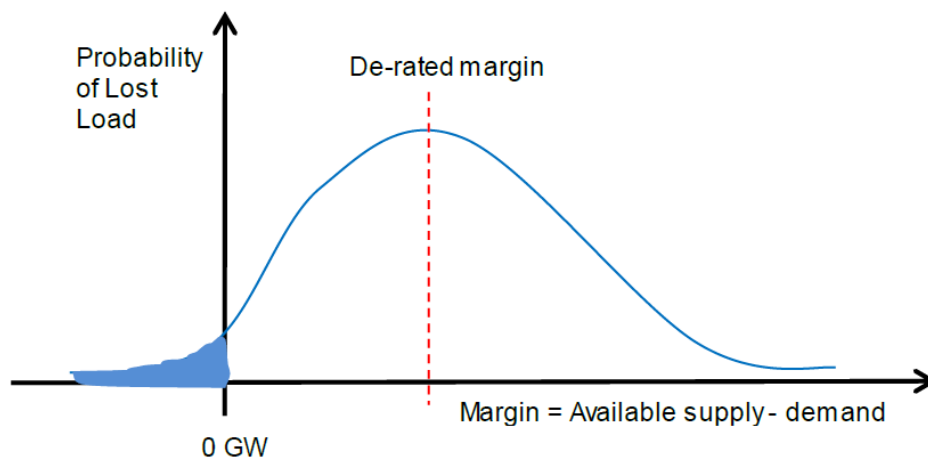


Figure 3.4 – Example of margin variation over the year with respect to de-rated margin

²⁵ For some systems, the summer period has become the most critical in recent years due to the evolution of scenario drivers, i.e. sectorial demand peak and average availability of the different generation sources, including intermittent renewables.

[16] CIGRE', METHODS AND TECHNIQUES FOR RELIABILITY ASSESSMENT OF INTERCONNECTED SYSTEMS (TB 129), Task Force 38.03.11, 1998.

[18] Pentilateral Energy Forum Support Group 2, Generation Adequacy Assessment, 2015.

Frequency and duration of expected outages gives a measure of the impact of electricity disconnections on customers

Frequency and duration of expected outages is an illustration of the results of the probabilistic risk measures in terms of tangible impacts for electricity customers. This is based on decisions around how the electricity system would operate at a time when supply does not meet demand, and on the order and size of mitigation actions taken by the System Operator. It is therefore not as accurate as the LOLE or EENS, but it allows an overview of the probability of experiencing controlled disconnections of customers [19].

EFC corresponds to renewable capacity able to maintain the same LOLE for the system

An adequacy calculation can also be used to compare different system configurations, often in relation to its evolution. In particular, EFC represents the quantity of firm capacity, always available, that can be replaced by a certain volume of wind generation (a similar approach can also be extended to other intermittent renewable sources) to give the same level of SoS, as measured by LOLE. This measure is often used to calculate the average contribution of wind power to the de-rated margin. It varies with the proportion of wind power in the system, taking into account its geographical distribution [19].

The comparison of adequacy levels in different systems depends on the metrics adopted and the consistency of the underlying assumptions

It can be difficult to compare the adequacy levels of different countries because, in general, they can adopt different metrics to quantify adequacy. Furthermore, even when the same metric is adopted, the different sizes and compositions of electricity systems should not be neglected in order to obtain an effective comparison.

Regarding model application, it is worth recalling the importance of underlying hypotheses in order to yield comparable results; for the electricity system in particular we should recall, among others: time discretisation, variability of load depending on the weather, the random nature of non-dispatchable generation, interconnection modelling, reserve estimation, voluntary or price-driven demand side response, and security margins in the network.

These aspects will be addressed in detail in sections 3.6 and 4.2, while the next section discusses the pros and cons of the different metrics defined above.

3.4.2 Advantages and disadvantages of different metrics

Regarding the advantages and disadvantages in the use of different metrics and the possibility of identifying relationships among them, it is clear from the definitions given above that the considered metrics are different ways to characterise the EENS in a system (based on its duration, probability, frequency of occurrence).

The basic relationship among these metrics suggests that it should be possible, starting from EENS calculation, to indifferently obtain any one of these metrics using a common methodology and underlying hypotheses.

[19] Office of Gas and Electricity Markets UK, Electricity Capacity Assessment Report, 2013.

[20] Department of Energy & Climate Change, Reliability Standard Methodology, 2013.

LOLE is one of the most adopted metrics because of its simplicity; however, as already pointed out, it does not provide any information about the severity of the problem (i.e. a blackout affecting the entire electricity system or minor load curtailments due to the impossibility of covering high peak loads can, in fact, present the same number of hours of LOLE).

Furthermore, the quantification of EENS appears to be the most direct way to obtain a monetisation of interruption costs (see 3.5) in order to compare possible investments toward reaching adequacy targets. Table 3.1 summarises the main advantages and disadvantages for each metric.

Table 3.1 – Main advantages and disadvantages of different adequacy metrics

Metric	Advantages	Disadvantages
EENS	Quantification of ENS: possibility of monetising interruption costs to be used in CBA approach.	It is not possible to directly compare electricity systems of different dimensions. This limitation can be overcome with a normalisation of EENS, obtained by dividing by the total energy requested.
LOLE	Simple definition of the likelihood of encountering problems.	The severity of problems is not quantified. Only homogeneous systems should be compared. It can depend on decisions regarding electricity system operation in critical conditions.
LOLP	Simple definition of the likelihood of encountering problems. Possibility of comparing electricity systems of different size.	The severity and duration of the problem are not quantified.
P95	Simple definition of the likelihood of encountering problems.	The severity of the problem is not quantified. Difficulty in drawing a comparison for different countries due to their peculiarities in the definition of severe operating conditions.
Capacity margin	Simplified quantitative approach, no simulation needed.	An appropriate indicator at times where intermittent generation is not significant and the proportion of each type of generation in the fleet is roughly constant year-on-year.
Frequency and duration of expected outages	Illustration of the results of the probabilistic risk measures in terms of tangible impacts for electricity customers.	Not as accurate as the LOLE and EENS. It can depend on decisions regarding electricity system operation in critical conditions.

3.4.3 Assessment of distribution network adequacy

Transmission and distribution networks present structural differences

The overall problem of distribution network²⁷ adequacy evaluation can become very complex in most systems as it involves all the electrical system levels, starting at generating stations and terminating at the individual consumer's load points.

In addition, transmission and distribution networks are operated and owned by different players, TSOs and DSOs respectively.

Furthermore, transmission and distribution networks present not only voltage but also structural differences: the former is meshed and normally consists of long overhead lines while the latter is more extended, in terms of total km of lines or cables. The distribution network is generally operated with a radial configuration²⁸ to reach all the users in the proximity of a substation, with possible alternative re-closure paths (i.e. in the event of a fault it is possible to connect part or all of the load to another substation; a meshed distribution network is normally managed in a radial way, to better control power flows); and with shorter branches often realised with underground cables, in order to reach customers where overhead lines are not possible (i.e. city centres).

For these reasons, distribution is usually analysed as a separate entity [11], even if the increasing presence of generation, especially renewable, at the distribution level should be considered by the TSOs within generation and system adequacy assessment; toward this aim, the definition of data exchange processes among TSOs and DSOs on present and provisional scenarios of generation and load is therefore strictly necessary [21].

The substantial differences between the two networks also result in different requirements and, as a consequence, different adequacy constraints, as illustrated below.

The quality of distribution service is measured with respect to the supply continuity to the end user

Distribution performance is monitored through indicators, presented in Table 3.2; the quality of service standards are imposed from single NRAs and, unlike transmission level, the introduction of new generation cannot be generally considered an alternative to network reinforcement investments. DSOs are normally obliged to accept all connection requests, from consumers or generators (which can be required to partially cover connection costs), on the basis of a non-discriminatory approach. Network strengthening is therefore the only practical way to fulfil these requests, also thanks to lower cost and environmental impact with respect to transmission reinforcements.

Reward/penalty schemes can also be applied by NRAs to quality-of-service target fulfilment from DSOs, and this is another difference with respect to transmission

²⁷Electrical systems are constituted from different levels of voltage (transmission-level voltages are usually considered to be 110 kV and above) in order to minimise the losses associated with the transfer of electrical power, proportional to the product of voltage and current. Losses depend only on current, and in particular from its square, so that higher voltages allow the transmission of power over long distances, reducing losses.

²⁸ Meshed distribution networks are used, in this case the techniques are conceptually the same as those used for transmission.

[11] R. Billinton and W. Li, Reliability Assessment of Electric Power Systems Using Monte Carlo Methods, New York: Plenum Press, 1994.

[21] CEER, Assessment of electricity generation adequacy in European countries, 2014.

networks, where the attention is more focussed on general system parameters and where the meshing of the network intrinsically warrants better quality standards.

The quality of distribution service is monitored by NRAs through ex-post indicators

A secure supply of electricity can only be possible in the presence of a robust, reliable and resilient grid. Network users expect a high continuity of supply at an affordable price. The fewer the interruptions, and the shorter these interruptions are, the better the continuity is from the viewpoint of the network user. Therefore, one of the roles of DSOs is to optimise the continuity performance of their distribution and/or transmission network in a cost-effective manner. The role of regulators in setting the quality of service standards is to ensure that this optimisation is carried out by distributors in a suitable way, taking into account the users' expectations and their WTP.

There is a wide range of overall quality indicators [22] in use (considering the quality as perceived by an end user, which is not related to the origin of an interruption).

Table 3.2- Distribution indicator descriptions

Quality indicators	Description
SAIDI	<i>System Average Interruption Duration Index</i> represents the sum of customer-sustained outage minutes per year divided by the total customers served.
SAIFI	<i>System Average Interruption Frequency Index</i> represents the number of customer interruptions divided by the total customers served.
CAIDI	<i>Customer Average Interruption Duration Index</i> , for the group of customers that actually experienced one or more interruptions, and how long (on average) those interruptions lasted. The figure represents the total number of customer interruption durations divided by the total number of customers interrupted.
CEMI-X	<i>Customers Experiencing Multiple Interruptions</i> is a measure of the percentage of customers who experienced X interruptions. CEMI-3 is the percentage of customers who had three or more interruptions.
CELID-X	<i>Customers Experiencing Longest Interruption Durations</i> . CELID-8 is the percentage of customers who experienced outages exceeding 8 hours.
MAIFI	<i>Momentary Average Interruption Frequency Index</i> represents the system-wide average number of momentary outages per year and is the number of momentary customer interruptions divided by the total customers served. A momentary interruption is typically defined as any interruption that is less than the definition of a sustained outage.
CEMMI-X	<i>Customers Experiencing Multiple Momentary Interruptions</i> is a measure of the percentage of customers who experience X momentary interruptions.
ASIDI	<i>Average System Interruption Duration Index</i> measures the average interruption duration as a function of the installed load in the system as opposed to the number of customers.

[22] CEER, Benchmarking Report 5.2 on the Continuity of Electricity Supply, 2015.

Quality indicators	Description
AIT	<i>Average Interruption Time</i> is the measure for the amount of time the supply is interrupted. This indicator measures the total number of minutes that the power supply is interrupted during the year.

All the above indices are normally calculated ex-post based on measurements of actual supply interruptions, since they are used by regulators to control the performance of distribution companies. Therefore, the available methodologies are aimed at the ex-post measurement of these indicators, rather than at forecasts.

In order to forecast indicators of quality of service to the end user, it would be possible to separately analyse the generation and transmission systems on the one hand, and the distribution system on the other. This approach is only possible assuming that a lack of power supply from the transmission side will inevitably lead to end user service interruptions; in fact, studying generation and transmission distribution would be represented only as an equivalent.

Table 3.3 – Indices for quantifying long interruptions used in different countries

Country	Index	Weighting
AUSTRIA	SAIDI, SAIFI, ASIDI, ASIFI, CAIDI, (CML, ENS)	By the power affected. By transformer stations affected; improvement of quality of data for weighting by number of customers is ongoing.
BULGARIA	SAIDI, SAIFI	By the number of customers.
CYPRUS	SAIDI, SAIFI, per cause, per voltage, percentage indicators, lost MVAs per cause, affected consumers, faults per type, faults per location, faults per substation/feeder, average time for supply restoration, time interval for supply restoration.	By the power affected.
CZECH REPUBLIC	Distribution: SAIFI, SAIDI, CAIDI Transmission: ENS, average duration of one interruption per year (sum of duration divided by number of interruptions).	DSO - by the number of customers, TSO - by the power affected.
DENMARK	SAIDI, SAIFI, ENS	By type of interruption and number of customers.
ESTONIA	SAIDI, SAIFI, CAIDI, total annual interruption time for each customer.	By the number of customers.
FINLAND	DSOs: in 1-70 kV: T-SAIDI and T-SAIFI, < 1 kV: amount of interruptions. TSO and regional network operators: In 400 kV, 220 kV and 110 kV: duration of interruptions and amount of interruptions at connection points.	Weighted by the annual energy consumption.
FRANCE	Transmission: AIT, SAIFI and ENS Distribution: SAIFI, SAIDI and "Percentage of customers with insufficient quality of supply" (the definition of a "customer with insufficient quality of supply" depends on the location) There are several versions of each of these indicators, depending on the type of disconnection (planned/unplanned), the voltage level, the cause (exceptional event included or not) ...	Depends on the indicator.
GERMANY	SAIDI (LV), ASIDI (MV), SAIFI	LV: number of customers; MV: rated apparent power of the affected power transformer.
GREAT BRITAIN	The two main indicators are Customer Interruptions and Customer Minutes Lost.	By the number of customers.
GREECE	SAIDI, SAIFI	By the number of customers.
HUNGARY	Distribution level: the indicators used in IEEE Std. 1366-2003: SAIDI, SAIFI, CAIDI for both planned and unplanned interruptions. Transmission level: AIT ENS/ES (outage rate) and unavailability of transmission lines.	By the number of customers.
IRELAND	CML & CI	For distribution, the CIs and CMLs are reported on an average customer basis. For transmission, the system minutes lost indicator is related to the power affected.
ITALY	For transmission: ENS, ENW, AIT, SAIFI. For distribution: SAIDI, SAIFI.	For distribution: by the number of customers affected. For transmission: number indicators refer to transmission users.
LITHUANIA	TSO - ENS, AIT DSO - SAIDI, SAIFI	By the number of customers. ENS, AIT - interrupted power.
LUXEMBOURG	More detailed regulations came into force on 20 May 2011. Final set of indicators will be determined after first data evaluation.	

Country	Index	Weighting
THE NETHERLANDS	SAIDI, SAIFI and CAIDI.	By the number of customers.
NORWAY	With reference to end users (all voltage levels): SAIDI, SAIFI, CAIDI, CTAIDI, CAIFI, interrupted power per incident and ENS. With reference to reporting points (i.e. distribution transformer or a customer connected above 1 kV): Number and durations.	By the number of customers.
POLAND	Distribution level according to the IEEE Std. 1366-2003: SAIDI, SAIFI. Transmission level: ENS, AIT and according to the IEEE Std. 1366-2003 SAIDI, SAIFI.	By the number of customers.
PORTUGAL	Transmission: ENS, AIT, SAIFI, SAIDI, SARI Distribution: END, AIT (TIEPI), SAIFI MV, SAIFI LV, SAIDI MV, SAIDI LV	SAIFI and SAIDI: weighted by delivered points (transmission and MV) and by number of customers (LV); TIE (Distribution - TIEPI) and END (distribution): weighted by installed power; ENS (transmission): estimated; TIE (transmission): ENS energy supplied.
ROMANIA	DSO: SAIFI, SAIDI; ENS and AIT at 110 kV level; TSO: ENS and AIT for the whole country.	At 110 kV (max distribution level) and TSO (220-750KV) use ENS and AIT; at 110 kV also SAIFI and SAIDI.
SLOVAK REPUBLIC	Average time of interruption (220 or 400 kV).	Average number of interruptions per 1 transformer on voltage level 220 - 400 kV.
SLOVENIA	Distribution: - SAIDI, SAIFI, CAIDI, CAIFI Transmission: - SAIDI, SAIFI (implicitly ENS, AIT, AIF, AID)	By the number of customers TSO: for calculation of SAIDI, SAIFI, MAIFI, weighted by the number of "users" of the transmission grid: there are 3 types of transmission users: 1) HV transformation stations (counted each as 1 user, independent of number and size of transformers installed); 2) HV final consumer (large industrial customers): and 3) producers connected to transmission grid.
SPAIN	In distribution: TIEPI, NIEPI, 80% of TIEPI and 80% of NIEPI at area I level or individual level. In transmission: ENS, AIT and facility available percentage.	By the power affected.
SWEDEN	(iv) Until now, SAIDI and SAIFI for DSOs. From 2010, interruptions data at customer level is available. This allows publication of: e.g. NIS-tagged information, supplied energy, maximal supplied power, etc. at a large range of customer levels. System level indicators such as interrupted power, ENS, ASIDI, ASIFI, SAIDI, SAIFI, customer experiencing multiple interruptions (CEMI), confidence interval reflecting best and worst served customers at arbitrary level, etc. can also be calculated.	By the number of customers and/or supplied energy.

Table 3.3, sourced from [23], reports the reliability indicators adopted by some European countries, accounting for major events. As a reference point, in the United States of America (the U.S.), each customer is likely to encounter roughly over 2 hours of interruption (on average) and is likely to face about 1.5 interruptions. These numbers are comparably larger than their European counterparts, such as Denmark where each customer on average faces about 24 minutes of interruption with the chance of 0.5 outages. Similarly, each customer in Germany faces an average outage of 23 minutes as the country claims to have the most reliable power grid in Europe. The average number of outages that a customer faces is highest in Spain and Italy (2.2 times). The length of interruptions that each customer is likely to face is also highest in Spain, with 104 minutes on average. Likewise, the UK customer faces a relatively lengthy interruption of about 90 minutes per outage on average.

Additional details on single countries and main interruptions are included in [24], [25], [26].

3.5 **Cost-benefit analysis for system reliability**

Reliability as an economic value is linked to the impact of the supply interruption on the end user

One way of dealing with the economic quantification of the quality of electricity supply is through the assessment of the economic impacts of the lack of reliability. The cost of supply interruptions is related to the external consequences (economic losses) incurred by consumers when an electricity shortage occurs. The damage, in turn, depends strongly both on the characteristics of the interruptions and on how different consumer categories make use of electricity. Impacts are classified as indirect or direct economic or social:

- **Direct economic** impacts are those resulting directly from supply interruptions.
- **Direct social** impacts include lack of transportation, loss of leisure time, uncomfortable building temperatures, personal injury or fear.
- **Indirect** impacts usually arise as consequences not necessarily related to electricity supply interruptions and may be difficult to categorise as social or economic (for instance, looting during an extended blackout).

As far as the power system is concerned (illustrated in sections 3.3 and 3.4), well-established methods and tools are available for the assessment of continuity of supply indices. Their utilisation provides TSOs with system adequacy indices (such as EENS), which are of a technical nature and are therefore suitable for developing investment decision processes based on "reliability criteria".

Indices to quantify reliability as an economic value underlie investment decision

[22] CEER, 5th Benchmarking Report on Electricity Quality of Supply, 2011.

[24] SESAME - Securing the European Electricity Supply against Malicious and accidental threats, ASSESSMENT OF SECURITY OF ELECTRICITY SUPPLY (SES) INDICATORS IN EUROPE, 2014.

[25] SESAME - Securing the European Electricity Supply against Malicious and accidental threats, System Specification of Decision Support System, 2012.

[26] SESAME - Securing the European Electricity Supply against Malicious and accidental threats, Analysis of Historic Outages, 2011.

These indices, however, do not directly enable decision-makers to develop “value based” planning procedures where reliability (or unreliability) levels of the concerned power system can be quantitatively expressed through economic indicators. Usable cost parameters for the assessment of the economic value of reliability of supply, or of economic losses due to interruptions, must be expressed in terms of €/interruption, €/kW of peak load, €/kWh of annual energy consumed, or €/kWh of ENS [27].

Three indices are most frequently used and referenced in [28]: Interruption Energy Assessment Rate (IEAR), VOLL, and WTP.

- IEAR is a system-wide interruption cost index. It is expressed in €/kWh and, therefore, in association with the adequacy index EENS (per year), it provides an estimation of the expected annual economic damage incurred on average by customers due to interruptions.
- VOLL, the prevailing meaning of which in the literature corresponds to the estimated total damage caused by interruptions divided by the amount of electricity not delivered in a given time period (usually a year). This is conceptually equivalent to IEAR and so can be used to assess the damage suffered by the system due to interruptions of supply. VOLL is also defined as the value (€/kWh) an average consumer puts on an unsupplied kWh of energy, rather than the cost of an unsupplied kWh, or as the customer’s WTP to avoid an additional period without power.
- WTP represents the customers’ willingness to pay to improve their continuity of supply, by decreasing the frequency and/or the duration of interruptions and by avoiding specific types of incidents – e.g. those lasting more than a pre-defined upper limit. WTP may be expressed as €/kWh of consumed energy if it represents the propensity of customers to pay for an increase in their electricity bills in order to have a given quality improvement.

VOLL is the most widely used index and referred to by the ENTSO-E in [5].

3.5.1 Value of Lost Load

VOLL measures the cost of energy unserved to consumers

To monetise the effect of reducing lost load during contingency periods the VOLL can be used. VOLL is indeed “a measure of the cost of ENS (the energy that would have been supplied if there had been no outage) to consumers”[5].

VOLL can be extremely different from country to country

However, in the EU only certain MS have a validated reference VOLL, and there is no overall European reference VOLL.

[27] CIGRE Task Force 38.06.01, “Methods to consider customer interruption costs in power system analysis”, August 2001.

[28] SECURE: Security of Energy Considering its Uncertainty, Risk and Economic implications, DELIVERABLE No 5.6.3: Costs of electricity interruptions, 2009.

As explained by the ENTSO-E in [5], an obstacle in the use of VOLL to monetise the reduction of EENS associated to network reinforcements resides in the intrinsic difficulties of obtaining a VOLL value on a Union-wide basis, based on the same factors.

VOLL values can be extremely different from country to country; for example, as illustrated in Table 3.4[29], mentioned by the ENTSO-E in [5].

Table 3.4 -VOLL estimation in year 2030

VOLL in US\$(2007)/kWh Entire economy (all consumer sectors)	Maximum range	90% confidence limit range
Developed countries	4 ÷ 40	5 ÷ 25
Developing countries	1 ÷ 10	2 ÷ 5

The ENTSO-E has detailed the European situation in Annex 4 of [5]:

- VOLL reflects the mean value of an outage per kWh (long interruptions) or kW (voltage dips, short interruptions), appropriately weighted to yield a composite value for the overall sector or nation considered.

VOLL results differ from one country to another (Table 3.5), essentially because of differences in the sectorial composition of electricity consumption (share of industry, tertiary sector etc.), the level of dependency on electricity in the economy, and seasonality (which can inject more or less volatility into demand).

- The different methodologies for measuring VOLL adopted from individual MS contributes to VOLL heterogeneity.

It is also important to underline that TSOs can evaluate the adequacy of their systems in order to monitor them or to take actions; in the latter case, VOLL values could be used for a CBA of investments as summarised in the *used in planning* column of Table 3.5.

[5] ENTSO-E, Guideline for Cost Benefit Analysis of Grid Development Projects, 2013.

[29] University of Bath, European project CASES - “WP5 Report (1) on National and EU level estimates of energy supply externalities”, 2006.

Table 3.5 - VOLL current values in Europe

Country	VOLL (€/kWh)	Date	Used in planning	Method/reference	Ref .
Austria (Econtrol)	WTP: Industry 13.2, Households 5.3 Direct worth: Households 73.5 Industry: 203.93	2009	No	R&D for incentive regulation, surveys using both WTP and Direct Worth	[30]
France (RTE)	26. Sectorial values for large/small industry, service sector, infrastructures, households, agriculture available	2011	Yes (mean value)	CEER: surveys for transmission planning using WTP, Direct Worth and case studies	[31]
Great Britain	19.75	2012	No	Incentive regulation, initial value proposed by Ofgem	[32]
Ireland	Households: 68 Industry: 8 Mean: 40	2005	No	R&D, production function approach	[33]
Italy (AEEG)	10.8 (Households) 21.6 (Business) Up to €40/kWh for Transmission [23]	2003	No	Surveys for incentive regulation, using both WTP and Direct Worth (SINTEF)	[34] [23]
Netherlands (Tennet)	Households: 16.4 Industry: 6.0 Mean: 8.6	2003	No	R&D, production function approach	[35]
Norway (NVE)	Industry: 10,4 Service sector: 15.4 Agriculture: 2.2 Public sector: 2 Large industry: 2.1	2008	Yes (sectorial values)	Surveys for incentive regulation, using both WTP and Direct Worth (SINTEF)	[36] [37]
Portugal (ERSE)	1.5	2011	Yes (mean value)	Portuguese Tariff Code	[38]
Spain	6.35	2008	No	R&D, production function approach	[39]
Sweden	Households: 0.2 Agriculture: 0.9 Public sector: 26.6 Service sector: 19.8 Industry: 7.1	2006	No	R&D, WTP, conjoint analysis	[40]

[23] CEER, 5th Benchmarking Report on Electricity Quality of Supply, 2011.

[30] M. Bliem, Economic Valuation of Electrical Service Reliability in Austria – A Choice Experiment Approach, IHSK, 2009.

[31] RTE, Quelle valeur attribuer à la qualité de l'électricité ?, 2011.

[32] Reckon, Desktop review and analysis of information on Value of Lost Load for RIIO-ED1 and associated work, May 2012.

[33] Sustainable Energy Ireland, Security of Supply in Ireland, 2007.

[34] L. L. SCHIAVO and A. BERTAZZI, The use of customer outage cost surveys in policy decision-making: the Italian experience in regulating quality of electricity supply.

[35] Nooij, Koopmans, Bijvoet, The value of security of supply, SEO, 2005.

[36] KILE-satser, FASIT, 2011.

[37] G. Kjölle, Customer Costs Related to Interruptions and Voltage Problems: Methodology and Results, (SINTEF) IEEE TRANSACTIONS ON POWER SYSTEMS, 2008.

[37] ERSE, PARÂMETROS DE REGULAÇÃO PARA O PERÍODO 2012 A 2014, 2011.

[38] P. Linares and L. Rey, The costs of electricity interruptions in Spain. Are we sending the right signals?, Alcoa Foundation, 2012.

[39] Carlsson, F. & Martinsson, Peter e Elforsk, Kostnader av elavbrott: En studie av svenska elkunder (rapport nr 06:15), 2006.

Factors affecting VOLL depend on the impact of interruption on consumer activity

The main factors affecting the VOLL have been investigated in [29]:

- Types of customers. These can be the manufacturing sector, the tertiary sector, agriculture, and households. These categories, however, can be further divided. Companies can be disaggregated by industrial sector, regions, size, etc. Households can be disaggregated by income, region, size, etc. The degree of disaggregation undertaken will of course depend on data availability about the differences in the use of electricity and the value associated with these activities.
- The perceived reliability level. This parameter will influence the degree to which customers prepare for the loss of power and how they value the lost load. For instance, high frequency of interruptions lowers the VOLL, while long interruption durations usually increase it. Various preventive measures can be undertaken by customers to avoid costs of outages so that a lower perceived reliability level may lead to lower measured VOLL. Here it should be noted that lower perceived reliability is likely to have negative long-term effects on welfare, since certain investment, production and activity will not be undertaken unless reliability is sufficiently high.
- The time interruptions. For households it is much more of a nuisance to lose power during leisure time than during working hours. The opposite is true for businesses, for example in the service sector, where costs will primarily occur during hours of production.
- The duration of an interruption. For some sectors, the cost is highly non-linear as a function of duration. Sometimes costs per unit of time fall with the length of an interruption (at least for relatively short time intervals). In other cases, however, the opposite may occur, such as if production material or equipment is damaged after a certain time without electricity supply. Taking this to the extreme, for very lengthy interruptions in an unreliable system, the VOLL can be settled at the cost of auto-generation.
- Pre-notification of a power interruption. This gives consumers the opportunity to prepare for the loss of power. Such interruptions are therefore usually assumed to carry lower costs than those that occur without advance warning. This assumption is, however, not always supported by the results of household surveys.

Influence of adequacy criteria on VOLL value

When the standards are arbitrary, the VOLL values are implicitly defined by the adequacy standard, but in this case, it represents the marginal cost of achieving the standard, instead of the actual cost for consumers.

For instance, an adequacy requirement of a minimum reserve percentage or quantity implicitly defines the VOLL as the cost of providing an additional MW of reserve.

Adequacy standards are necessary if the reliability level of the system is not directly obtained from a CBA on the investments necessary to improve system adequacy. If a CBA methodology is adopted, adequacy standards remain an important indicator of the reliability of the system, but their achievement is subject to economic criteria.

3.5.2 Methodologies for VOLL calculations

Methodologies for VOLL assessment may adopt empirical or analytical approaches

The main methodologies for VOLL assessment are summarised in Table 3.6 with their advantages and drawbacks (see [41], [42], [43], [44],[29], [45]).

Methods based on direct surveys with consumers can lead to discrepancies

Revealed preferences:

Stated choice surveys estimate VOLL based on costs inferred from choices consumers say they will make under future hypothetical outages. Two possible approaches are described. The first is the so-called Contingent Valuation Method (CVM), according to which customers are asked to estimate their costs or losses due to supply interruptions of various durations and frequencies at different times of the day and year. Alternatively, consumers have to directly indicate how much money they are ready to pay for more reliability, indicating their explicit WTP, or how much money they want to receive in order to accept a lower reliability of supply, indicating their explicit willingness to accept (WTA). The second approach is the so-called Conjoint Analysis, where consumers have to show their preferences with regard to both reliability and electricity prices by indirectly providing a ranking among various combinations of those two factors.

A positive aspect of the stated choice is its bottom-up approach that elicits individual customer preferences, providing a high degree of objectivity. It is ideal for customers who have never experienced an outage, whereas the revealed preferences approach is more relevant to customers who are more experienced with outages and can reliably report the costs and impacts of such. Also, a stated choice survey obviates the need for customers to report direct costs through the price-to-outage trade-off questions, which survey specialists generally believe enables more accurate reporting of VOLL for residential customers. A customer may not know their direct costs but can be capable of accurately judging the opportunity cost of losing service and therefore stating their (monetary) utility for maintaining service continuity. Finally, the timing and duration of outages can be incorporated directly and implicitly in the survey and post-survey regression analysis with the revealed preferences approach.

However, certain respondents, especially in the residential sector, may not provide reliable answers to questions about damage, WTP, WTA and price-to-outage trade-offs, because they rarely have to make such decisions. To control the inexperience of respondents, surveys should include at the outset a question on whether the respondent has experienced an outage before, and if so, to what extent. Responding to such questions rationally is especially challenging for respondents in regions with high

[28] University of Bath, European project CASES - “WP5 Report (1) on National and EU level estimates of energy supply externalities”, 2006.

[41] R. Billinton, G. Tollefson and G. Wacker, Assessment of electric service reliability worth, International Journal of Electrical Power & Energy Systems, 1993.

[42] V. Ajodhia, Regulating Beyond Price - Integrated Price-Quality Regulation for Electricity Distribution Networks, 2006.

[43] M. d. Nooij, C. Koopmans and C. Bijvoet, The value of supply security. The costs of power interruptions: Economic input for damage reduction and investment in networks, Energy Economics, 2007.

[44] A. Sanghvi, Economic costs of Electricity supply interruptions: US and foreign experience, Energy Economics, 1982.

[45] London Economics International LLC, Value Of Lost Load Literature Review And Macroeconomic Analysis Prepared For ERCOT, 2013.

reliability and low frequency of outages. In addition, residential respondents' valuation of the drop in electricity prices is subjective, and may be incorrectly valued if the respondents treat the trade-off questions with scepticism, leading to biased results. Another drawback of the stated choice method lies in the fact that consumers, when asked to provide their evaluation through a questionnaire, generally know that policy makers may use their answers, and therefore they often respond strategically. As a result, WTP values are often equal to zero or much smaller than WTA values.

Analytical methods –assessment strictly depends on the assumption

Proxy methods

This approach estimates VOLL by estimating the value of loss of production (for non-residential customers) and/or the value loss of leisure time (for residential customers). To explain this better, proxy or indirect analytical methods allow one to evaluate interruption costs by inference from indices or variables that are closely related to the direct cost induced by power supply interruption, such as electricity supply rates, Gross Domestic Product (GDP), wage rates, etc. In this context, in the industrial or tertiary sectors, the costs of lost production may be quantified explicitly.

The proxy method, on the other hand, determines preferences as those of the average customer.

An old and well known proxy approach implies taking the ratio of GDP to the total energy consumption (€/kWh) as an estimate of the unit Cost of Unsupplied Energy, or, conversely, of the Value of Service Reliability for the whole national power system.

This estimate constitutes a poor approach, as it ignores the fact that non-supplied energy occurs normally during peak hours but production can be transferred to times with supply. Furthermore, the cost of an unexpected interruption with previous notification may produce high cost because of the loss of products in process.

A similar approach has been used for applications to different customer categories by considering detailed and specific supplementary data such as sales, employees and value-added data. The quantification of costs may not be trivial for households, because these do not produce market goods. In any case, it is possible to relate power interruptions to lost leisure time. Indeed, electricity supply interruptions mean less free time and loss of leisure can be expressed in terms of the wage rate. Thus, supply interruptions can be quantified indirectly, since the free time lost can be monetised by multiplying the number and length of interruptions by the prevailing wage rate.

This method has several drawbacks: it cannot estimate the subjective costs per person, which is probably the highest; for industries it assumes a linear relationship between production and energy consumption, neglecting the fact that for announced interruptions industries can move production to times with supply; furthermore it does not consider the costs of damages to equipment and production in process.

The main advantages of proxy methods are that they are quite easy to apply, they use readily available data and, consequently, they are practically inexpensive to implement. A frequent criticism of proxy methods concerns the fact that most of them are based on limiting and sometimes unrealistic assumptions. Moreover, there can be data inconsistencies between the numerator (GDP or gross value added [GVA]) and the denominator (consumption) because different agencies typically collect these data. For the non-residential sector, this approach assumes that all sectors' business activities cease simultaneously, and does not always consider real world factors, such as:

1. Staggered³⁶ outages, which can disrupt business and non-business activities as much as if these outages were combined into one continuous outage. If unaccounted for, this can lead to underestimations of VOLL;
2. Supply chain linkages between sectors, i.e. the “knock-on” effect of stopping one sector’s production and consequently another sector’s production, which, if unaccounted for, can again lead to underestimations of VOLL;
3. The possibility of engaging in productive, albeit limited, business activities during an outage, for example in an emergency, grocery stores in communities experiencing an outage during the daytime can still sell goods that do not require refrigeration and have long shelf lives, such as canned food. If unaccounted for this will lead to an overestimation of VOLL;
4. The possibility of recovered production post-outage to compensate for lost production during the outage. If unaccounted for, this will lead to an overestimation of VOLL.

For the residential sector, valuing time is difficult. Some leisure activities require electricity, such as surfing the web, and it is difficult to put a monetary value on such activities when they are done purely for personal enjoyment. The electricity bill approach will not recognise the value of such leisure activities. Other household activities do not require electricity, (e.g. reading a book), so it can be argued that a residential VOLL (e.g. using aggregate wages to consumption ratios) may be overestimated. Furthermore, assigning a cost to financially intangible activities such as leisure or sleep can lead to arbitrary and biased VOLL estimates. As mentioned, the underlying theory in the residential sector estimate is to find the equilibrium price at which the value of a marginal hour of leisure equals the value of a marginal hour of labour. In an unplanned outage, the hour is not marginal but random. In this case, estimating VOLL based on the value of a marginal hour may lead to underestimation. Though generally easy to obtain, not all macroeconomic data are available and, in such a case, a survey or other outreach methods would be required, increasing study time and expenditure. Finally, in the various methods for estimating VOLL using production functions, there is no consideration of timing and duration of outages.

A case study approach may be used to determine the VOLL that occurred during blackouts. This option analyses an actual outage event with predefined parameters, such as outage timing, duration and geographic location. So the case study approach consists of collecting as much information and data as possible immediately after the occurrence of a large-scale power supply interruption. Through these data, the costs of both generation and network outages can be quantified, directly or indirectly, and indices like €/kWh not supplied or €/kW lost during the interruption can be assessed for the whole area concerned as well as for different consumer categories, depending on the detail and accuracy of the study. Each type of interruption impact may be associated with the economic value of that category and all cost contributions are added together to obtain an aggregated value for the total interruption costs. Case studies may involve the consideration and listing of the different effects of a supply interruption in all fields of human activity.

This approach has the benefit of using actual, and generally reliable, data. Also, because the outage event is not hypothetical, the sample period is set. Therefore, it is easier to identify potential factors (or explanatory variables if conducting statistical analysis) and

³⁶ Brief and frequent outages.

to incorporate them into the VOLL calculation. This saves research time and resources. Another merit of this approach is that the interruption cost values relate to consumer experiences of actual interruptions rather than to hypothetical scenarios. Moreover, consumers make available much detailed information regarding the different factors that influence the costs of supply interruptions.

However, even though the outage is actual and not hypothetical, detailed firm-specific data may not be available and the VOLL is not directly observable. Since it is based on a single event, it is most likely not representative of other types of outages.

Another main drawback of the approach is that the number of case studies and the relevant data sets are very small, compared to the total number of interruptions affecting electricity supply during power system operation. Therefore, interruption cost indices obtained from a few case studies can never be fully representative of interruptions or of their consequences in general. Moreover, case studies are often more expensive than proxy studies and revealed preference studies based on analyses of the costs of back-up power deployment.

Table 3.6 – Summary of VOLL Estimation Methodologies [45]

Approach	Description	Strength	Weakness
Revealed preference (market behaviour)	Use of surveys to determine expenditures that customers incur to ensure reliable generation (i.e. back-up generators and interruptible contracts) to estimate VOLL	- Uses actual customer data that is generally reliable	- Only relevant if customers actually invest in back-up generation - Limited consideration for duration and/or timing of outages - Difficult for residential customers to quantify expenses
Stated choice (contingent valuation and conjoint analysis)	Use of surveys and interviews to infer a customer's willingness-to-pay, willingness-to-accept and trade-off preferences	- More directly incorporates customer preferences - Includes some indirect costs - Considers duration and/or timing of outages	- Experiment and survey design is time-consuming and effort intensive - Need to manage for potential biases - Residential customers may give unreliable answers due to lack of experience
Proxy method (macroeconomic)	Uses macroeconomic data and other observable expenditures to estimate VOLL (e.g. GDP/electricity consumption)	- Few variables - Easy to obtain data - GDP reasonable proxy for business VOLL	- Does not consider linkages between sectors or productive activities - Proxies for cost of residential outages may be arbitrary or biased - Costly to gather data - Available case studies may not be representative of other outages/jurisdictions
Case study	Examines actual outages to determine VOLL	- Uses actual, generally reliable data	

3.5.3 Empirical studies on VOLL estimation

At present, several empirical studies exist that have attempted to establish VOLL estimates for specific power markets, both at system-wide and customer level. The main studies are summarised in the table below [45], as they provide a range of VOLL estimates (expressed in \$/MWh) that may be considered as relative benchmarks against which to compare potential future VOLL estimates for other power markets.

[45] London Economics International LLC, Value Of Lost Load Literature Review And Macroeconomic Analysis Prepared For ERCOT, 2013.

[43] LONDON ECONOMICS INTERNATIONAL LLC, VALUE OF LOST LOAD LITERATURE REVIEW AND MACROECONOMIC ANALYSIS PREPARED FOR ERCOT, 2013.

Table 3.7 - VOLL estimates worldwide

Market	Methodology	Details	System-wide VOLL	Residential VOLL	Large commercial and industrial VOLL	Small commercial and industrial VOLL
United States	Multiple surveys	Median VOLL	-	107	8239	17013
United States (Southwest)	Multiple surveys	Median VOLL	-	0	8774	35417
United States (MISO)	Multiple survey/Proxy-macro methods	Median VOLL	-	1735	29299	42256
					Commercial VOLL	Industrial VOLL
United States (Northeast)	Proxy methods	Mean VOLL for a 5- to 10-hour power outage	9283-13925	-	-	-
Austria	Combination of revealed preference and stated choice surveys	Mean VOLL for a 12-hour power outage	-	1544	7329	
New Zealand	Combination of revealed preference and stated choice	Mean load-weighted VOLL for an 8-hour power outage	41269	11341	77687	30874
Australia	Survey	Mean duration-weighted VOLL for different outage durations	45708	-	-	-
Australia (Victoria)	Combination of revealed preference and stated choice	Mean duration-weighted VOLL for different outage durations	44438	4142	28622	10457
Ireland (2007)	Proxy methods	Mean VOLL for an 8-hour power outage	16265	-	-	-
Ireland (2010)	Combination of survey and proxy methods (production function approach)	Mean VOLL	9538	17976	10272	3302

For the Netherlands, a difference between day and night VOLL values is presented, as reported in the following table from [46].

Table 3.8: Netherlands, costs of a 1-hour power outage, no advance notice, millions of Euros, 2001³⁹

	On average	During the day	At night	Sunday, during the day
Nationwide		156	98	81
Randstad		72	38	33
Rest of the country		84	59	48
All households		37	85	64
Individual household (euro) ⁴⁰		5	12	9
All businesses	121			
Agriculture	1			
Energy companies	3			
Industrial sector	10			
Construction	10			
Transport	5			
Services	69			
Government	24			

Comparison among VOLL estimates begins from the comparison of the scenario fundamentals

Any comparison between different VOLL estimates should take into account not only any heterogeneity in the methodological approach to the estimation problem, but also the level of comparability between the power markets underlying the VOLL estimation in terms of economic and demographic features, electricity consumption patterns, and market design.

In fact, a highly rural region will likely have a long, linear transmission system that extends across the region with a fairly low customer density. This kind of environment

³⁹Source: SEO (2003), table 4.1, table 5.1 and page 45.

⁴⁰Source is SEO (2004, p. 134).

[46] C. N. B. f. E. P. Analysis, Capacity to spare? A cost-benefit approach to optimal spare capacity in electricity production, 2004.

requires a different infrastructure and investment profile and is likely to have a different consumption profile. Moreover, electricity consumption patterns, as indicated by the system size (consumption and peak demand), as well as by peak periods and customer mix, are another important factor. As VOLL is often load-weighted, it is important to understand how each customer class contributes to the total system load.

Other factors affecting VOLL and related to the market are its deregulation level, which describes the market maturity reached and the presence of interconnections with other systems and markets.

Distribution of VOLL values is right-skewed: for a few customers, interruption costs are very high

Emerging from a comparative analysis of the existing empirical studies on VOLL estimation, an initial observation is that significant differences exist between median and mean VOLL values. The mean VOLL (1544 \$/MWh - 77687 \$/MWh) is significantly higher than the median VOLL (0 \$/MWh - 42256 \$/MWh). Indeed, survey results tend to be heavily right-skewed, especially for commercial and industrial customers, because there is a small number of customers whose interruption costs are significantly higher than those of other respondents. Therefore, reporting median results may be more reasonable than reporting the mean values, since underlying distributions can be strongly right-skewed.

VOLL estimates depend on the energy intensity of the different customers

A second point emerging from the comparative analysis of existing empirical studies is that VOLL estimates are highly sensitive to several factors, including customer profile, timing and duration of outage, and the weighting of responses. In general, from the customer profile point of view, residential customers tend to have lower VOLL (0 \$/MWh - 17976 \$/MWh) than commercial and industrial customers (3302 \$/MWh - 77687 \$/MWh), while among the commercial and industrial customers, VOLL tends to be higher for small commercial and industrial customers (7329 \$/MWh - 77687 \$/MWh) than for large commercial and industrial customers (3302 \$/MWh - 42256 \$/MWh).

These results are consistent with the expected theoretical levels. Small commercial and industrial customers present, on the one hand, higher costs associated with ENS in respect to residential customers; on the other hand, smaller firms are less likely to prepare for operational risks through the use of interruptible contracts and back-up generation (as hedges against outages) than large commercial and industrial customers are, leading to generally higher VOLL results. Within the industrial sector, the mining and manufacturing sub-sector tends to show a higher VOLL than the other industry sub-sectors (such as services or public administration).

Mixed approaches to covering different consumer categories lead to the most accurate VOLL values

A third point emerging from the comparative analysis of existing empirical studies is that, from a methodological point of view, VOLL results based on non-survey techniques (such as macroeconomic analysis) are highly sensitive to assumptions, which should be tested and further supported by reasonable external evidence. Meanwhile, studies that try to combine the results from multiple surveys exhibit a large range in VOLL estimates depending on location and customer class. Studies using a combination of stated choice for residential customers and revealed preference for non-residential customers appear to be the standard in VOLL survey studies.

3.5.4 An applicative case: National Grid's use of VOLL

LOLE or LOLP analyses are typically performed on a system to determine the amount of generation capacity that needs to be installed to meet a desired reliability target, commonly expressed as an expected value, or LOLE in hours/year. In general, there is an inversely proportional relation between the capacity margin and the value of LOLE, even if it is neither linear nor symmetric. However, it is important to note how changes in capacity margin when they are low have a larger impact on the LOLE, compared to when they are higher. Investment toward ensuring a lower but constant capacity margin should be beneficial.

An example from National Grid is reported in Figure 3.5.

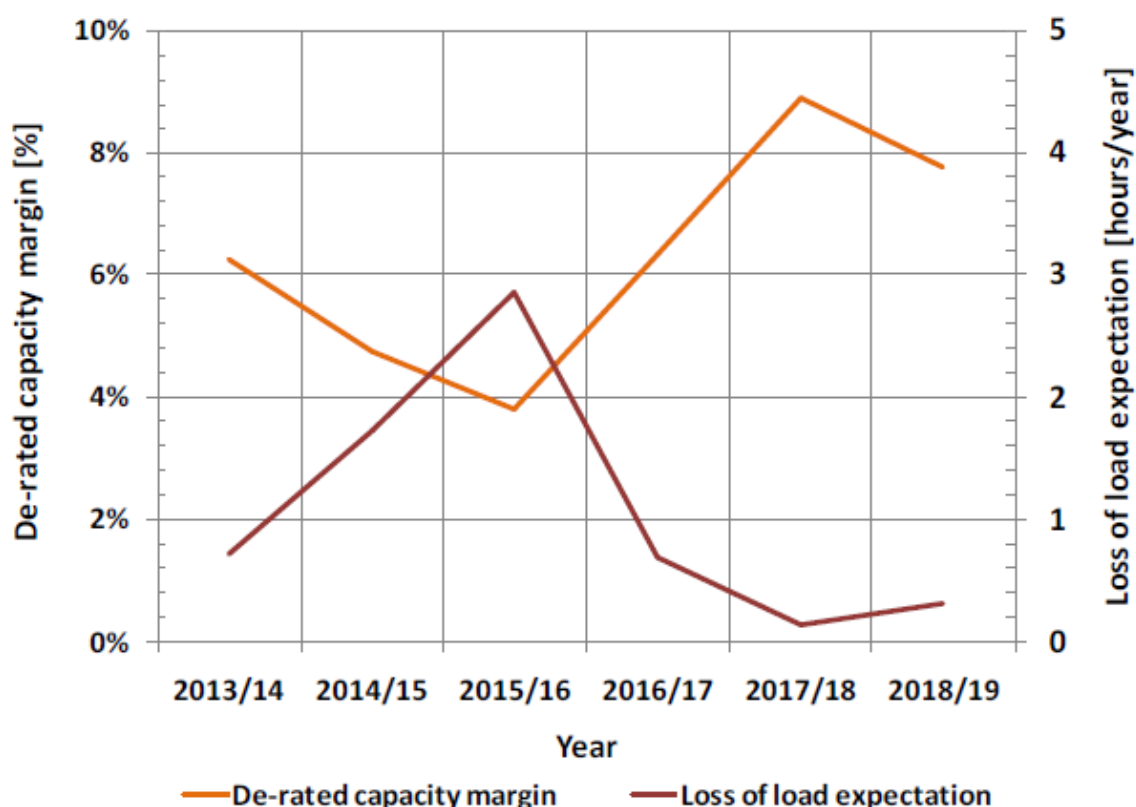


Figure 3.5 – Specular behaviour of de-rated capacity and LOLE

In setting the reliability standard for system adequacy, the UK Department of Energy & Climate Change has taken an analytical approach[20] which takes into account consumers' VOLL and the cost of new capacity. Again, VOLL represents the value that customers place on SoS, or alternatively the cost to customers of disconnection. The optimal level of SoS trades the cost of providing additional capacity against the associated benefit of a reduced chance of blackouts (Figure 3.1).

This method has the advantage of choosing a level of capacity that is explicitly linked to the value that consumers place on electricity (VOLL). Therefore, the optimal level of SoS

[19] Department of Energy & Climate Change, Reliability Standard Methodology, 2013.

[47] London Economics, The Value of Lost Load (VOLL) for Electricity in Great Britain, 2013.

is determined by the match between the incremental cost of insuring customers against blackouts and the cost of incremental blackouts to customers.

Reliability standard should be defined as a trade-off between the cost of new generation capacity and VOLL

As a result, the reliability standard is computed from two parameters: the cost of new generation entry and VOLL.

- CONE: The Gross Cost of New Entry (CONE) represents the cheapest cost of a new entrant peaking plant (i.e. to provide reserve with expected low utilisation). Gross CONE is the rental rate of the marginal peaking plant; that is, the yearly amount of revenue needed to pay for capacity such that the discounted value (NPV) of its operations is zero over its technical operating lifetime, assuming the plant does not earn energy market revenue.
- VOLL: as mentioned from the UK Department of Energy & Climate Change, London Economics has carried out a survey of domestic and business customers' VOLL at different times of the day and year [47]. This has been used to establish a single average VOLL for use in the Reliability Standard. The final VOLL is a weighted average of domestic customers and small and medium sized enterprises (SMEs) at times of winter peak demand.

The optimal Reliability Standard is the solution to an economic optimisation problem. This problem is to maximise the net benefit to consumers of having reliable electricity with respect to the level of system capacity. The solution is neatly comprised of the two above parameters, VOLL and CONE.

This optimal condition can be expressed as:

$$\frac{dEC}{dk} = - \frac{dBC}{dk}$$

Where EC is the cost of electricity and BC is the cost of blackouts, and the differentiated quantities are their incremental costs. An optimum is obtained where the incremental cost of electricity is equal to the ENS during a blackout, therefore not over/under estimating VOLL.

However, the cost of blackouts can also be expressed in terms of volume of lost load and EENS, while incremental electricity cost can be expressed as CONE:

$$CONE = \frac{dEC}{dk}$$

$$BC(K) = EENS(K) * VOLL$$

Substituting:

$$CONE = \frac{dEC}{dk} = - \frac{dEENS(K)}{dk} * VOLL$$

We see now that the incremental consumer cost is derived by the change in the expected cost of ENS for each incremental change in capacity for a defined level of VOLL.

This incremental change in EENS can be associated with an equivalent number of hours of lost load⁴².

$$\frac{-dEENS(K)}{dK} = LOLE$$

The CONE is equivalent to the LOLE monetised to the VOLL

Substituting all the terms in the first equation leads to:

$$CONE = LOLE * VOLL$$

This describes the relationship at optimum between the expected number of hours of lost load (supposing a homogeneous distribution of EENS), the CONE and the value consumers place on avoiding lost load.

3.6 **Main findings of theoretical analysis**

This theoretical analysis has listed the main methodologies and metrics adopted to assess both generation and system adequacy, highlighting their strengths and weaknesses.

GA assessment is based on consolidated methodologies but applied with significant differences in modelling different systems

Generation and system adequacy, limited to transmission level, can be generally evaluated adopting the same methodologies and calculating the same metrics for all MS, even with important differences in the detail of data to be considered, with which the system can be modelled; hence the possible causes of evaluated EENS (lack of power and/or of interconnection for GA, as well as branch overloads and network splitting for system adequacy).

Generation and network reinforcements can be selected on a cost-effective basis to solve adequacy problems

The EC's purpose, which is to obtain comparable standards for generation and system adequacy, relies on the fact that both adequacy evaluations address the ability of the system in the presence of involuntary disconnections; therefore, investments in generation and network reinforcements can be selected on a cost-effective basis to solve adequacy problems. It is worth noting that generation and transmission investments differ substantially for the actors involved (private investors on the one hand, and usually TSOs on the other⁴³), permitting procedural and investment costs.

⁴² In this case there is an approximation of the model: the distribution of EENS in time can be variable, therefore it is not possible to have a direct relation between EENS and LOLE, and it is not possible to calculate the amount of additional capacity necessary to solve it (i.e. an EENS of 100 MWh can be concentrated into one hour or distributed across 10 hours; in the former case, 100 MW of new capacity would solve all EENS, while in the second case, 10 MW would be sufficient).

⁴³ Private investors in network assets are less common than in generation.

[15] ENTSO-E, Scenario Outlook & Adequacy Forecast Evolutions, 2014.

[14] ENTSO-E, Target Methodology for Adequacy Assessment, 2014.

Not all the methodologies analysed are able to fulfil the EC request; in particular, an appropriate methodology should provide a metric to be compared with acceptable standards to establish whether a system is adequate.

Probabilistic methodologies capable of calculating EENS are useful in comparing the system cost of ENS and the investments needed to avoid it

Adequacy is a balance between the system cost of ENS and the investments needed to reduce/avoid such (Figure 3.1); therefore an appropriate methodology will be characterised by the ability to provide a metric useful for monetising the system cost of ENS for a period of at least one year. A probabilistic methodology able to calculate EENS is in line with these requirements, while a deterministic approach is more suitable for calculating the LOP in critical situations with respect to ENS.

Other metrics derived from EENS can be simpler but cannot provide the same information.

The resulting EENS, coupled with a VOLL value and calculated with an agreed-upon methodology encompassing the European perimeter[6], can be used in a CBA (section 3.5) to establish the acceptable level of EENS for a system, as well as a suitable standard. The definition of criteria to set an acceptable standard will be discussed in Chapter 6, considering the available information about current TSO best practices (Chapter 4).

The definition of a proper methodology and the metrics to be adopted should be based on theoretical fundamentals, appropriately oriented to an applicable and robust approach.

Many TSOs in the EU rely on probabilistic models to carry out adequacy assessments, and the ENTSO-E itself is moving in this direction, integrating its deterministic methodology with a comprehensive and shared probabilistic approach[14], [15].

ENTSO-E Target Methodology is the first practice that analyses the entire European System at once and includes the use of interconnection capacity

Target Methodology represents a grand effort by the ENTSO-E to overcome the present deterministic approach, adopting a selection of the best practices in use by its members in the assessment of individual country adequacies.

The strengths of the ENTSO-E Target Methodology are briefly summarised below; the model detail has been selected to assess GA, but interconnection capability is also modelled; in this way, investments which led to an increase in exchange limits can be evaluated.

One relevant peculiarity is that the entire European perimeter is analysed here; by respecting to single country adequacy, evaluations of two main advantages are achieved: the direct use of interconnection capacity and the consistency of hypotheses and data among countries.

Even an ideal methodology would rely on input data quality and completeness (i.e. the ability to model all the relevant aspects in adequacy evaluation).

The ENTSO-E takes advantage of the experience of several years of market modelling for the Scenario Outlook and TYNDP (Pan-European Market Database, PEMDB), concerning generation data, load and DSM, and network representation.

The assessment of weather-dependent effects related to load variation, generation patterns of wind and solar power plants, and hydropower inflows is based on the existing

Pan-European Climate Database (PECD), with coverage of over 10 years of historical data. A representation of the variability associated with RES generation is an important issue in determining the GA of the system.

Target Methodology is structured as a project under development and the initial approach will be complemented by additional elements following the process. The sharing of data and methodology are foreseen, and this transparency is an important point with respect to all stakeholders.

The main results/metrics defined are:

- LOLE
- LOLP
- Full load hours of generation
- RES curtailment
- CO₂ emissions

The use of the same scenarios adopted from TYNDP, and therefore the transmission investments CBA, is a remarkable advantage for obtaining a comparable approach, for investment both in generation and in transmission.

4 EMPIRICAL ANALYSIS: SURVEY ON ADEQUACY ASSESSMENTS WITHIN EU COUNTRIES

This chapter presents the findings from an empirical analysis on adequacy metrics and standards adopted in Europe. The aim of this analysis is to provide information on the ascribed importance and methodology of adequacy assessments carried out by MS or TSOs, with respect, in particular, to the metrics and standards currently used. From this analysis, similarities and differences are derived that indicate the gaps to be overcome if full harmonisation of adequacy standards is to be achieved. Firstly, the research approach is briefly presented (section 4.1). Secondly, the aggregated results of the research on public data are given (section 11.1), and findings from the elaboration of the SAI data (section 11.3) are presented. Thirdly, main findings drawn from the merging of aggregations from different sources are remarked upon (section 4.2).

4.1 Survey and analysis design

The original approach of the empirical analysis was based on a survey addressed to TSOs

In the original approach, the empirical analysis was intended to be based on a questionnaire developed in cooperation with the EC, in order to collect current information on all important aspects of adequacy assessments within the EU.

The questionnaire (Appendix A) was sent through the ENTSO-E, addressing all ENTSO-E TSOs.

The questionnaire was structured into seven different topics: 1) questions on definitions to verify whether consistent definitions are used; 2) the parties and processes involved in the adequacy assessments; 3) the methodology used for the assessments; 4) the metrics used for analysis; 5) adequacy targets; 6) economic considerations that may be involved; and 7) the transparency requirements. For each topic, up to twelve open questions were formulated where the respondents were given space to answer the questions freely.

In order to analyse the answers received from the survey, it was agreed that a two-step approach would be taken. Firstly, aggregation tables were created which allow aggregation of the answers into clearly defined categories, to alleviate the processing of the free text answers. In order not to lose relevant information, the category "other" was added to each question. The aggregation into these tables is meant to give an initial overview on the information provided by the respondents. In the second step, and with the theoretical analysis as an input, the results are used to reveal important similarities and differences in the practices of the MS.

However, due to a lack of responses to the questionnaire, it was necessary to abandon this original approach and to adopt a new one, based on the analysis of information publicly available on the websites of the institutions involved, especially reports related to GA. This new approach required additional effort and time due to the heterogeneous degree of transparency of the information openly available for the different systems, but in the end it provided a good orientation on what is occurring in the area in relation to GA.

The adopted approach is based only on existing public information

The alternative approach was to find answers to the questions from already existing information. Three different types of sources for this information were identified:

1. Public sources: TSO websites and the CEER Adequacy report [21].
2. Non-confidential replies to adequacy-related questions from the EC SAI, selected and provided by the EC.

The objective here is to identify key similarities and differences in generation and system adequacy assessments among the different EU countries. Based on these key similarities and differences, and the theoretical framework provided in Chapter 3, conclusions are drawn in Chapter 6 on the general identification of appropriate standards.

The aggregation tables reported in the next sections were thus completed to the extent that the answers could be found in these alternative sources.

The analysis structure refers to different aggregations for the first and second data sources. In fact:

- SAI inquiry information has been reviewed to fit with the questions from the questionnaire; it must be highlighted that this source involves only 9 out of more than 40 TSOs, with information missing on many of the questions.
- Abundant information has been obtained from the web pages of TSOs, NRAs, and from the CEER Inquiry underlying data; nevertheless, these sources are aimed at answering questions different to those appearing on the original questionnaire. Thus a direct classification of the data into the questionnaire structure is not possible.

Appendix D includes a summary of the results obtained in both cases. The final considerations are derived from an overall analysis of the collected results (Chapter 6).

4.2 ***Main findings of empirical analysis***

From the research conducted via public sources (section 11.1), the following general conclusions may be drawn.

GA assessment is performed usually by TSOs, but public data show this evaluation is made in few countries

- Presumably (because information from 10 countries was not obtained), a relevant number of countries do not perform GA assessments, nor are these carried out with methodologies that assess only the measure of system security (e.g. reserve margin).
- All countries have an entity for ensuring system security (the TSO), and most countries may have an entity responsible for GA, but there is no clear (or no reported) mechanism based on the GA assessment meant to trigger measures to ensure GA.

Heterogeneity of GA methodologies provides proof of the opportunity to create a common approach

- Given the dispersion in the GA metrics and in the calculation methodologies, it is sensible to conclude that not only is there an absence of unifying methodology, but there is no trend of agreement on a common approach to achieve it.

Probabilistic methods of simulation are mainly used with different levels of modelling details

- In the case of countries that carry out a systematic assessment of GA, there is a positive trend toward the use of simulation methods to estimate GA. In general, it cannot be assumed that the same metric calculated with different methods (i.e.

accumulated probability curves versus the Monte Carlo simulation) will lead to the same result, and the same consideration can be made regarding the different levels of modelling accuracy adopted.

Possible underestimation of capacity need due to an overestimation of new investments if information is derived from operators

- In general, the evolution of generation is based on information provided by operators or developers. In no case was a criterion for considering the actual evolution of generation identified, either for new capacity or the decommissioning of existing plants. Experience shows that a significant portion of announced projects are not developed, or are subject to lengthy delays; therefore, estimations of GA based only on the information provided by developers may lead to over-estimation of the GA.

The assessment of GA depends on the methods adopted to estimate the contribution of renewable generation, which, in general, is underestimated

- Furthermore, the different methodologies used to consider the contribution to GA of intermittent generation (or to consider null contribution) may also lead to different values of GA for the same system.
- In general, the consideration of intermittent renewable generation is very simplified, and in many cases, it is considered that it does not contribute to GA. This may lead to an underestimation of the actual GA in the cases where penetration of renewables is medium or high.
- In no case was it mentioned how the operation of hydropower plants with reservoirs is considered. In countries with medium or high participation of hydropower in the generation mix, this factor is crucial for system security. In fact, in some of these countries, a dry year may be the most stressful situation in relation to GA. The use of historical series of generation data would ignore the possibility of operating reservoirs in a conservative manner, in order to increase GA (or equivalently, to reduce the risk of load shedding).

Cross border capacity is considered by few countries and often in a simplified way

- Regarding security, there are a few countries that consider the impact of cross-border support in their GA estimations. In general, the GA within the EU is strong, and there is sufficient interconnection capacity⁴⁴; if each country evaluates GA separately assuming a limited cross-border impact the risk is to obtain a total GA greater than the needed one.

VOLL is rarely quantified and, where it is, generally without a common methodology

- Although a portion of the countries have defined a VOLL value, this is rarely used to identify the socially optimal levels of GA.

Aggregated answers from SAI do not add significant information to the evidence from public data

These conclusions are consistent in general terms with those obtained by the research conducted through the SAI data (section 11.3).

⁴⁴ Perhaps not optimal from the point of view of commercial transactions, but good in relation to the support that a country may require during an emergency, which, due to strong GA, would represent a low percentage of its demand.

As the information received is from 9 TSOs (out of more than 40), no representative conclusions can be made from this analysis. Here are some considerations:

- GA assessments applied generally yield an indication of electricity scarcity (within a given system boundary, on a 1- to 5-year forecast basis).
- The system boundary applied is always a subset of the overall European interconnected system. Hence, assumptions on interactions (imports/exports) on the system boundary with the rest of the European interconnected system are highly determinative of the outcome.
- GA assessments in the best case include a calculation of expected balances of dispatchable and non-dispatchable generation, plus imports with which residual demand (demand remaining after response) can be fully covered, including the sophisticated modelling of random effects (weather, resource availabilities). However, the boundaries of each of the elements covered in this assessment are modelled precisely, whereas in practice there is always an unknown margin remaining before involuntary load disconnection would occur (e.g. embedded generation, self-response of generation and demand to balancing incentives, including broadcasting of stress situations, or temporary use of transmission security margins).
- There is little or no evidence of the dynamic modelling of market response to scarcity over time (generation investments, demand side response).
- GA assessments are not compared ex-post with actual levels of involuntary load disconnections; hence, no conclusions can be made about the accuracy of GA assessments to forecast involuntary load disconnections in absolute terms.
- Some countries use a 'marginal costs versus marginal benefits' approach to set an optimal adequacy level ($VOLL * LOLE \leq \text{marginal investment costs of a generator}$, applied for example in France, and in the Irish Single Electricity Market). Whereas this overcomes the problem of unknown margin between modelled and actual involuntary load disconnections, the unknown modelling inaccuracy on the boundaries of generation, demand, demand response, and import/export render the level of accuracy for actual marginal benefits unknown.
- In GA evaluations where VOLL is applied, an average system-wide VOLL is used without distinction in demand categories affected, time of day, or duration of modelled shortages.

5 DIAGNOSIS

This chapter, together with Chapter 6, aims to provide analysis and recommendations on:

- *Selection of appropriate metric(s) to assess generation and system adequacy within the IEM;*
- *Possible identification of metrics range necessary to avoid negative spill-overs across Member State borders from inappropriate generation and system adequacy standards being applied within the IEM.*

Specifically, Chapter 5 presents the relevant evidence of the theoretical analysis (Chapter 3) and the findings of the assessment of current practices in the EU (Chapter 4) in order to obtain a clear view of the main topics to be considered in the conclusion and recommendations phase, presented in Chapter 6.

In these chapters, adequacy will be addressed as system adequacy, with reference to the definition of section 3.1 where the concepts of GA, transmission adequacy and system adequacy were introduced. The assumption is that the integration of generation and transmission adequacy is the more effective way to assure a reliable supply.

5.1 **When are Adequacy Metrics needed?**

The starting point to formulating sound recommendations is to identify the expected use of the metrics and the related standards.

Adequacy metrics are applied over the whole process of generation and transmission assessment and planning

The international experience and the theoretical analysis show that in the context of this study, the metrics are, or can be used for, the following objectives:

- (1) To assess the current situation in the individual MS and/or the EU as a whole in relation to adequacy;
- (2) To define objectives of adequacy (the standards). It is clear that the objectives should be referred to a particular metric;
- (3) As a step forward in defining the standards, to identify the values of that metric which maximises the social welfare. In this case the optimal value of the metric is minimising the cost of possible investments to increase reliability, plus the cost of the EENS;
- (4) To identify the needs of investments in transmission or generation capacity to meet the adequacy objectives, either in terms of achieving a predefined (arbitrary) value of the metric, or to achieve the socially optimal value of this parameter;
- (5) To create mechanisms aiming to incentivise (or force) investments in transmission or generation capacity when/where the adequacy values are below the targets.

The appropriate metric has to consider the specific application in the planning process

Based on the aforementioned use of metrics, it is possible to formulate some questions in relation to selecting the most appropriate metric for each of the identified uses:

- Which metrics are appropriate to achieving each of the aforementioned objectives?
- Given a particular objective, which metric is most appropriate to achieving it? Alternatively, in other terms, what is the quality of the metric in relation to the

objective? For instance, if the objective is to define the optimal value of a standard in terms of social welfare, some metrics (like reserve margin or LOLE) are deemed unable to measure the loss of social welfare due to EENS.

- What are the possibilities for an accurate calculation of the value of each metric? For instance, if the target is to measure the EENS in a country, the actual value is highly dependent on the possibility of being supported by neighbouring countries during an emergency. Therefore, in this case, the methodology for calculating the actual value of the metric needs to properly consider the effect of the cross-border capacity (available transmission capacity [ATC], net transfer capacity [NTC]) and the availability of capacity in the neighbouring countries.
- Given the metric and the calculation methodology, is all the necessary information available? What are the limitations of the methodology in relation to the quantity and quality of this information?

In the next sections, the above issues are analysed and answers are given to each of the questions in the framework of the current situation in the EU.

5.2 Association between objective and appropriate metrics

EENS is the only metric that proves to be appropriate for all the planning applications

Based on the analysis carried out as part of the theoretical and empirical analyses, described in chapters 3 and 4, the following metrics have been selected:

- (1) Reserve Margin
- (2) P95
- (3) LOLP-LOLE
- (4) EENS
- (5) Expected frequency and duration of outages (EFDO)
- (6) Social value of EENS (EENS*VOLL), or a more complex calculation

The following table shows an initial assessment of the aptitude of each of the above metrics in relation to the above-mentioned “uses” of the metrics. In brackets are the references to a more detailed description of each concept.

Table 5.1 – Uses of the Metrics

Metric	Assess the situation	Define adequacy objectives	Identify optimal values of each metric	Define need of capacity to achieve the adequacy targets	Create mechanisms to incentivise investments
Reserve Margin	Not applicable (1)	Not applicable	Not applicable	Not applicable	Not applicable
P95	Applicable(2)	Applicable(2)	Not applicable(4)	Partly applicable(5)	Applicable(2)
LOLE-LOLP	Applicable(2)	Applicable(2)	Not applicable(4)	Partly applicable(5)	Applicable(8)

Metric	Assess the situation	Define adequacy objectives	Identify optimal values of each metric	Define need of capacity to achieve the adequacy targets	Create mechanisms to incentivise investments
EENS (absolute and relative value)	Applicable	Applicable	Applicable	Applicable	Applicable
EFDO	Applicable(3)	Not applicable(6)	Partly applicable(6)	Applicable(7)	Applicable(7)
Social value of EENS (9)	Applicable	Applicable	Highly applicable	Highly applicable	Applicable

(1) One minimum requirement of a metric is to allow the comparison of adequacy in different countries/zones. In this case, countries with the same value for the selected metric may have very different values for reliability. For instance, we may assume two systems, one with 10 units of 100MW and another with 50 units of 20MW; in both cases, all units have a Forced Outage Rate of 10%, and the demand is 850MW. This means that the only difference is in the size of the units. The following figure compares the accumulated probability of having some capacity available:

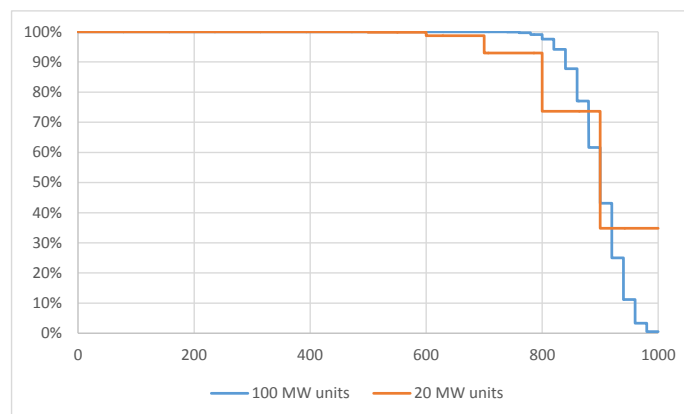


Figure 5.1 – Generation Availability, Accumulated Probability

Furthermore, the probability of meeting a load of 850 MW is 74% with the 100 MW units, and 88% in the case of the system with 20 MW units. However, if the load is 950 MW, the probability of meeting that load would be 11% in the system with 100 MW units, and 35% with the 20 MW units. It is clear that in both cases the reserve is the same, 17% in the case of 850 MW of demand and 5% when the load is 950MW.

Although this comparison may appear extreme, there are real-world cases in which the probability of covering the load can be highly variable dependent on small load variation:

- Small systems with some large units in relation to demand;
- Poorly interconnected systems with limited generation capacity.

(2) In principle P95, LOLE and LOLP measures, with different ways of showing the results, the probability of meeting the load is indicated. These metrics allow the assessment of the situation in a particular country and the comparison of the reliability among different countries. However, depending on the methodology used to calculate these metrics, the resulting values may be more or less representative of actual reliability in the assessed country. For instance, LOLP calculated taking into consideration only forced outages of units, and ignoring renewable contributions or support from neighbouring countries, will yield a poor representation of actual reliability. Therefore, the use of these metrics can be considered appropriate so long as the quality of the respective calculation methodology leads to values representative of the actual reliability in the country. In Figure 5.2 it is clear that a load shedding of any magnitude will produce more EENS on Day-1 than on Day-2. Therefore, metrics based only on probabilities of duration of non-supply are not good estimators of the EENS, and therefore cannot measure the impact of load shedding on social welfare.

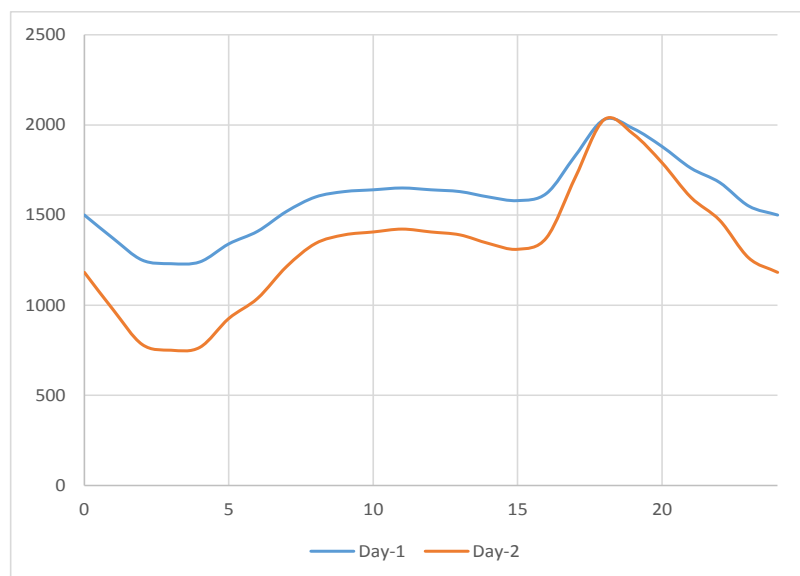


Figure 5.2 – Typical daily load curves

- (3) EFDO is not a single value, but a matrix with a value of probability or EENS linked to each cell of that matrix, which in turn represents a value of frequency and duration of load shedding. This matrix provides a richer panorama of the situation in the assessed country or region, but it is difficult to use a matrix to compare the situation across different countries, or to define a standard. However, as analysed below (point9), if EENS is used in combination with values of VOLL for different frequencies and durations of load shedding, this may be a very worthwhile metric.
- (4) P95, LOLE and LOLP cannot provide a direct estimation of the social cost of EENS. Thus, it is not possible to use them to find the socially optimal value of those parameters. However, where a direct calculation of EENS is possible, an estimation from LOLP can be obtained. For instance, for the load curve named Day-1 in Figure 5.2, as the LOLP calculation leads to a curve of probability of supplying the load, this curve permits the estimation of the probability of meeting

the load each hour, as shown in Figure 5.3, as well as the expected EENS for each hour⁴⁵. Hourly results are shown in Figure 5.4.

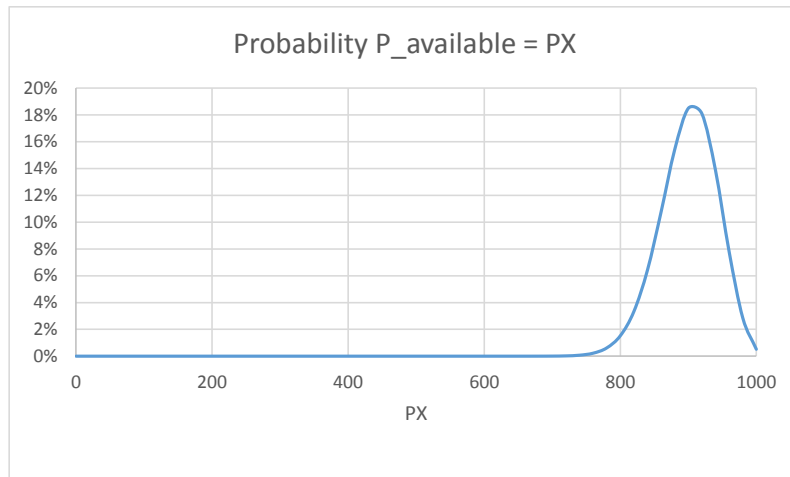


Figure 5.3 – Probability of capacity availability

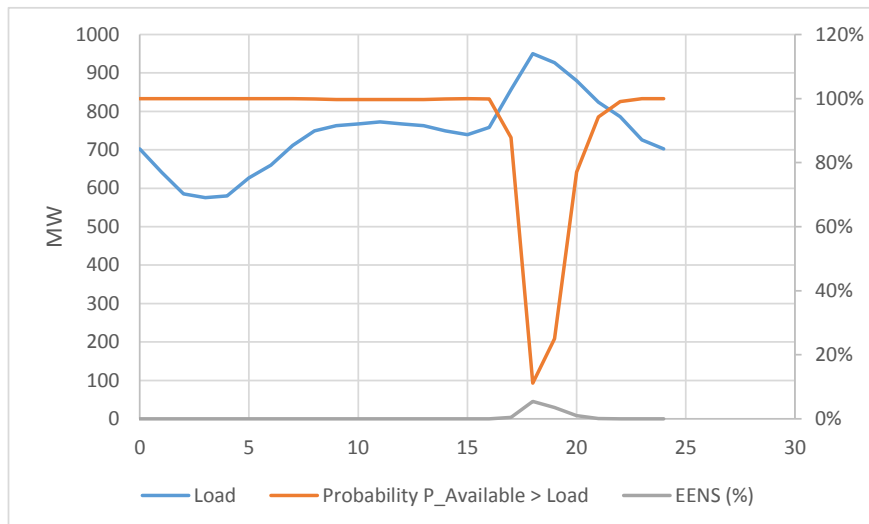


Figure 5.4 – Hourly probability of capacity availability

- (5) As also described in section 3.5.4, it is possible to use the LOLE calculation to obtain a rough estimation of the social value of ENS by multiplying the LOLE by the VOLL. However, the quality of the calculation will be lower than that achieved with the most appropriate methodologies because EENS is considered a constant during hours with LOLE.
- (6) The EFDO provides a very comprehensive description of the situation in a country in relation to adequacy; however, this is a set of values, rather than a single value that could be used to define adequacy objectives, or to identify the optimal values of each metric. If the adequacy objectives are defined in terms of the social value of the ENS (i.e. VOLL for each frequency and duration of load shedding as explained in point(9) below), EFDO is the metric that provides the most appropriate information on the supply situation in a country or region.

⁴⁵As $EENS_h = \int pa * \text{prob}(D_h - pa) * dpa$, for $0 \leq pa \leq D_h$, where D_h : demand in hour h. $\text{prob}(x)$ is the probability of having “x” MW available, which is calculated as part of the LOLP estimation.

- (7) In spite of the observations in point(6) above, if properly used the EFDO provides good information for an accurate estimation of the social costs of the ENS.
- (8) In U.S. capacity markets, the capacity requirements are set based on achieving a standard value of LOLE (currently one day without full supply every ten years). However, there is no direct relationship between this standard and assessment of the impact on social welfare.
- (9) The social value of EENS is the only metric that allows the measurement of the social impact of EENS in economic terms. Consequently, it is the only metric suitable for obtaining real optimisation of the trade-off between the value of adequacy and the cost of adequacy. However, for the purpose of simple comparison, it is not very appropriate, as it would require reference to an indicator of the total value of the electricity supply to understand its relevance.
- (10) The simplest manner in which the social value of EENS can be estimated is to multiply this value directly by the VOLL. However, as the VOLL depends on several factors, including frequency and duration of outages, a more representative metric could be calculated (if there is appropriate information on EFDO) as:

$$SCEENS = \sum_{f,d} VOLL_{fd} EENS_{fd} prob_{fd}$$

Where:

- SCEENS: social cost of EENS
- f: index representing each of the samples of frequency of outages (f=1....F)
- d: index representing each of the samples of duration of outages (d=1....D)
- VOLL_{fd}: VOLL for an outage that has an index of frequency "f" and index of duration "d"
- EENS_{fd}: EENS for an outage that has an index of frequency "f" and index of duration "d"
- Prob_{fd}: probability of an outage that has an index of frequency "f" and index of duration "d"

A probabilistic methodology should be used to assess GA and different probabilistic metrics can be used to gain sensibility on GA aspects

From the previous analyses, it is evident that the applicability of a metric depends on the final use assigned to it.

For the purposes of a conceptual assessment of adequacy and comparison among countries, all of the probabilistic metrics are appropriate; however, as long as the use of a metric is oriented to identify the needs of transmission or generation capacity to meet the adequacy targets, only the more sophisticated metrics are appropriate.

Probabilistic metrics provide different levels of detail in the EENS social cost estimation

Furthermore, in order to set capacity requirements with economic criteria, it is necessary to identify the values that maximise the social benefit (equivalent in this case to minimising the social cost of EENS plus the cost of the additional capacity). In this case, the number of appropriate metrics becomes smaller. In this context, it is possible to make a ranking of metrics:

Table 5.2 - Ranking of Metrics

Ranking Order	Metric	Comments
1	Social value of EENS calculated with EFDO (SCEENS, in point10 above)	This metric provides the best approach to an accurate estimation of the social cost of EENS. However, it requires a large volume of information, which is in some cases intrinsically difficult to obtain, such as the VOLL discriminated according to frequency and duration of outages
2	Social value of EENS calculated as EENS * VOLL	Less accurate than the above, but with less difficulty to obtain the required information, mainly the VOLL
3	EENS	Does not provide information on the social value of adequacy but allows a more accurate assessment of the impact on the reliability of supply
4	LOLP-LOLE	Very common metrics, but limited in usefulness for defining capacity needs. In some jurisdictions these are used for this very purpose but as standards are not economically supported, their use leads to non-optimal values of capacity requirements
5	P95	Similar to but less accurate than LOLE-LOLP

5.3 **Quality of calculation of the metrics**

Accuracy of input data and methodology affect the metric's quality

Due to the limited value of deterministic metrics, the following analysis considers only probabilistic metrics.

The analysis carried out in section 5.2 relies on the assumption that, in all cases, each metric is representative of actual system reliability. However, depending on three factors, the metrics may yield different levels of quality. The three factors are:

- (1) Variables considered in the calculation
- (2) Methodology used to calculate the metric
- (3) Input data used in the calculation

In this chapter the impact of these three factors on the quality of the metrics are analysed.

5.3.1 *Variables used to calculate the metrics*

Random and non-controllable system variables affects adequacy level

The adequacy is impacted by a large number of random and non-controllable variables:

- Unexpected outages of generation or transmission facilities;
- Availability of primary resources, mainly in the case of intermittent RES;
- Transmission capacity limits and availability;
- Variability of the load;
- Support (or lack of support) from neighbouring countries.

Cross-border capacity, intermittent generation and demand response have to be considered to obtain realistic adequacy assessment

It is worthwhile to mention that in [3], the CE working document establishes that "An objective, fact-based and comprehensive assessment of the GA situation should take account of the expected impacts of the Union policy on energy and the Union policy on the environment". This document lists the principles that should be taken into consideration in order to reduce uncertainty and increase the reliability and objectivity of adequacy assessments:

- Recognise the cross-border dimension of electricity systems and markets;
- Include reliable data on wind and solar power;
- Include the potential for demand response;
- Distinguish between "missing money" and "missing capacity".

The empirical analysis described in Chapter 4 shows that in few cases are all of these factors considered in the calculation. The most frequent cases are:

- RES availability is ignored or considered in a very simplified manner. This may lead to a significant underestimation of the adequacy potential issues. For instance, the below curves⁴⁶ showing accumulated probabilities of capacity

⁴⁶These values correspond to actual data from the Canary Islands.

availability consider the availability of thermal units only (red), as well as the total (including wind generation) availability (blue). In this example, the thermal installed capacity is 937MW and the installed wind capacity is 106MW. Here the load that can be supplied with 95% probability is 708 MW when wind is not considered, and 731MW when wind is included in the calculation. This means a contribution of 23 MW to adequacy, or about 20% of the wind installed capacity.

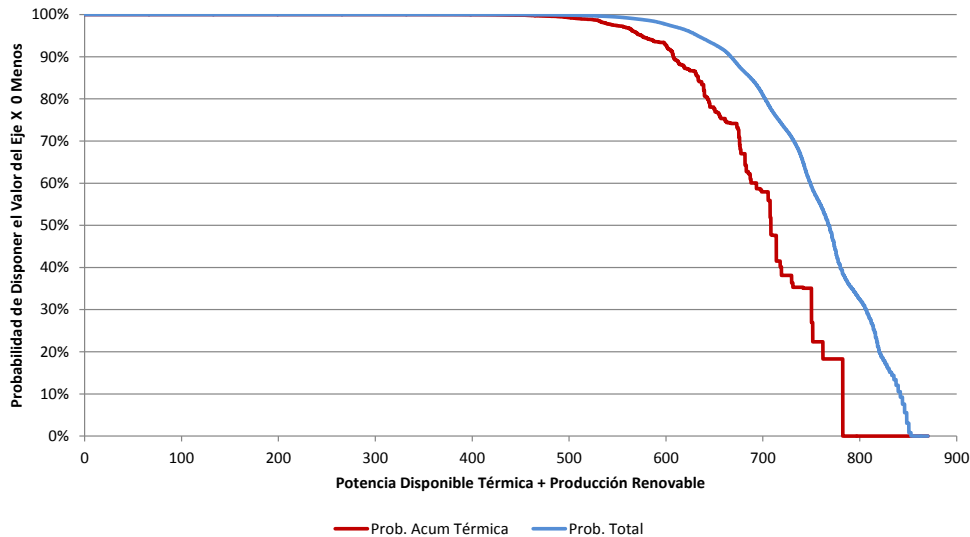


Figure 5.5- Convolutions, Thermal and Wind probability curves – Accumulated Probabilities of total Capacity Availability

- Transmission capacity limits: non-consideration of the transmission capacity limits and outages of lines may lead to underestimation of the adequacy. Nevertheless, the actual impact of transmission requires a specific analysis; in some cases this may be very important, in others it may be negligible. Because semi-analytic methods such as convolutions are not appropriate to measuring the impact of transmission constraints or outages, the only way to assess the impact on adequacy of these variables is through Monte Carlo simulations.
- Variability of load: in several cases for LOLE-LOLP calculations, only the annual peak load is considered. However, the probability that low generation availability may occur on the day of the annual peak is very low. A proper adequacy assessment should consider the load as a stochastic variable. Furthermore, the availability of intermittent RES depends on the month; therefore, the assessment of adequacy only on the peak day may lead to an error, as the seasonal variation of RES is not considered. Figure 5.6 shows the calculation of LOLP in a system⁴⁷ with three different criteria:
 - (1) Each month the probability of meeting the maximum demand of that month is calculated;
 - (2) Each month the average probability of not meeting the daily peak load is calculated;

[3] Commission Staff Working Document, *Generation Adequacy in the internal electricity market - guidance on public interventions*, 2013.

⁴⁷As in the previous bullet.

(3) Each month a convolution is carried out of the hourly load, with the curve of accumulated probability of capacity availability. This is equivalent to considering the average probability of not meeting the load each hour.

It is possible to verify that the difference between cases 1 and 2 is on average 3%, and between cases 1 and 3, 4.5%. It is also considered the monthly variation of wind availability, as shown in Figure 5.7. In this case, there is some compensation between wind and load that mitigates the monthly variation. This is particular to this system and cannot be generalised to other systems.

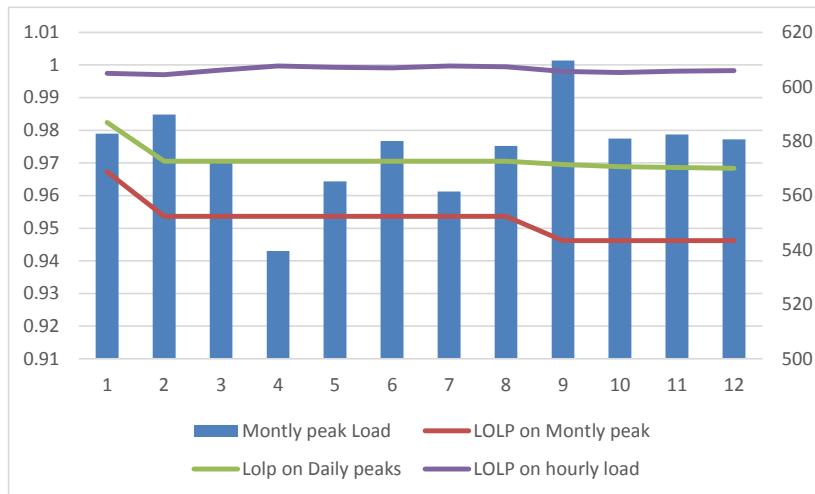


Figure 5.6 – LOLP for Different Considerations of the Load

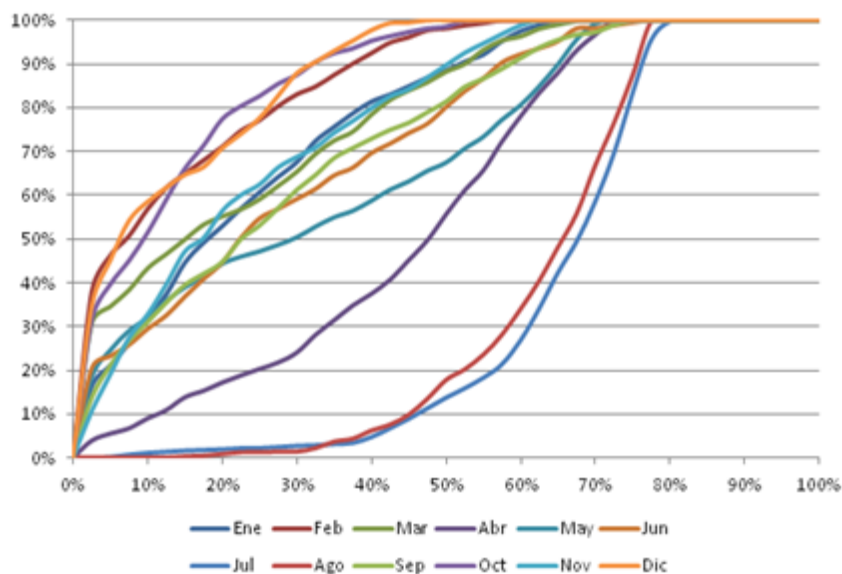


Figure 5.7 – Accumulated Probability Curves for Wind Generation

- Support from Regional Countries (i.e. the cross-border dimension): the contribution of neighbouring countries, or, in more accurate terms, regional cooperation, can improve adequacy substantially in interconnected countries. However, assessment of the regional adequacy requires much more complex calculations, firstly because the number of variables increases substantially, and

secondly because it is only possible to assess the regional adequacy through Monte Carlo simulations.

Figure 5.8 shows the peak demand in two systems (C and T) that can be met with a given probability (LOLP). In the same figure, the sum is shown of the individual demands that can be met with the same probability if the systems are interconnected, along with the increase in percentage. For instance, for a 99% probability of meeting the demand, when the systems are isolated this would be possible with 533 MW in system C and with 580 MW in system T; this means the total demand met with that probability would be 1133 MW. If on the other hand the systems are interconnected, it would be possible to meet at the same probability a demand of 1236 MW, which is 11% greater.

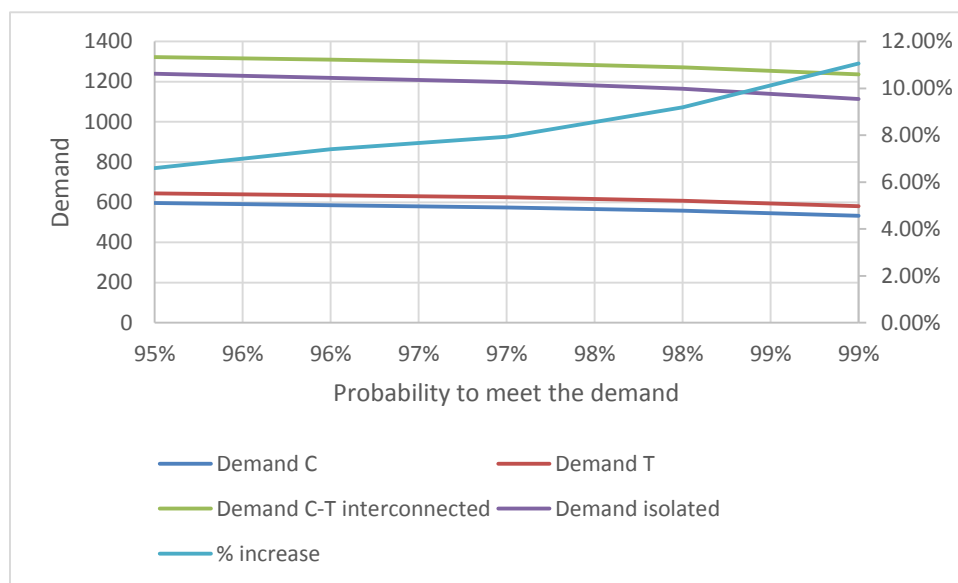


Figure 5.8 – Impact on Adequacy of Cross-Border Support

This simple example shows the importance of taking cross-border support into consideration in calculating the adequacy of interconnected systems. The empirical analysis has shown that this is not the case in most of the countries analysed.

In general, this analysis shows that the case of random variables affecting adequacy can be managed by using the probability theory and Monte Carlo simulations.

Network and generation resources management influence adequacy level

Further to non-controllable random variables, there are manageable issues that affect the adequacy and that should be considered in the calculation:

- Maintenance levels of units;
- Operation of reservoirs;
- Commissioning of new capacity;
- DSM and energy efficiency.

The empirical analysis carried out in Chapter 4 did not find any reference to these issues. Nevertheless, these aspects may have an important impact on adequacy.

- Unit maintenance: in markets, the maintenance period is usually scheduled when market prices are low, linked to those periods with high availability of RES and/or low demand. However, the concentration of maintenance into a period of few months can lead to transferring the adequacy problem to that period.

Therefore, part of the maintenance could be scheduled in periods with high demand, or with low RES availability.

From the perspective of adequacy assessment, maintenance cannot be ignored; however as this is a matter to be decided by generation capacity owners⁴⁸, it is necessary to obtain information from the generation operators (or else to make assumptions based on historical values, or the expected behaviour of agents). In both cases, there is a significant probability of errors.

- Operation of reservoirs: several EU members have a significant volume of generation based on hydropower plants, with reservoirs or with upstream regulation. The strategy of operating these reservoirs may lead to a lack of water during dry periods, and therefore the impossibility of operating at full capacity in those periods. As dry periods often affect entire regions, a lack of water can affect several hydropower plants simultaneously.

From the perspective of adequacy assessment, it is possible to consider the operation of reservoirs with a Monte Carlo approach; however, simulation of the optimal operation of reservoirs does not necessarily reflect the strategy that plant owners may use when bidding in the markets.

In addition, the availability of water may vary considerably from one year to another therefore, the analysis of different hydropower conditions (normal, dry, wet) should be envisaged.

- Commissioning of new capacity: in general, the evolution of available generation taking into consideration the commissioning of new capacity (or the decommissioning of old) is based on information provided by operators or developers. During the empirical analysis, in no case was a criterion to consider the actual evolution of generation identified, either in terms of new capacity or decommissioning of existing plants. Experience shows that a significant proportion of announced projects are never developed, or are subject to lengthy delays, so estimation of adequacy based only on information provided by developers may lead to an overestimation of GA (therefore an underestimation of possible problems). However, this is a complex issue; official information on cancellations of (or delays in) new capacity is generally announced late. While it is possible to formulate assumptions based on historical information, complemented by Monte Carlo simulations on new capacity delays or cancellations, it would be difficult to use these results in making decisions on new capacity, in triggering last-resort mechanisms, or in requesting additional capacity from markets.

GA assessment accuracy can be influenced by lack of knowledge regarding market operators' management strategies

In conclusion, unlike with random variables that can be managed using the probabilistic theory, the impact on the adequacy of certain decisions made by market participants is much more difficult to consider, and the possibility of errors is therefore greater.

⁴⁸In some jurisdictions, generators may require the authorisation or agreement of the TSO in scheduling maintenance outages.

5.3.2 Methodology to calculate the metrics

Main scenario drivers require a probabilistic modelling

As mentioned in the previous section, probabilistic metrics need to consider multiple uncertainty factors:

- Volatility of the demand;
- Random failures of generation units and transmission facilities;
- Maintenance schedules of generation and transmission equipment;
- Stochastic nature of some primary resources: water, wind, solar radiation, etc.;
- Rules and criteria of operation of hydroelectric plants with reservoirs;
- Etcetera.

Thus it is necessary to consider at least the probabilistic characterisation of all of the following factors:

- River discharges are spatially and temporarily correlated, but historical series usually exist that would allow such characterisation;
- Wind forecasts remain inaccurate and records are usually limited to recent history;
- New onshore wind and solar generation have areas available with lower generation factors (the best areas having already been utilised), so it is necessary to forecast the generation patterns of new onshore wind/solar plants;
- Hydroelectric energy availability depends on the reservoir operation strategies established by the owners of plants;
- Maintenance schedules are defined by plant owners, but they impact on system reliability;
- The time that a unit may remain out of service depends on the type of failure and the availability of resources to repair it promptly;

Because the large number of variables and the different probabilistic characterisations of each variable, as already mentioned in section 3.3.2, a Monte Carlo approach is needed.

The Monte Carlo model has the ability to consider all relevant information of the system status

Monte Carlo models can represent, with detail, the generation and transmission system using random number techniques to simulate a wide range of possible states of the system. These models take into account demand uncertainty (including interruptible loads and DSM), transmission capacity and outages, wind uncertainty, hydro inflow uncertainty, reservoir storage uncertainty, forecast accuracy, river-chain scheduling constraints, thermal start-up times, and participant behaviour in response to forecast prices and risks.

Monte Carlo techniques are based on a dispatch model that uses random numbers to simulate the availability of generation units, wind production, etc. The simulation of different random states within the dispatch model allows the calculation of the non-supplied energy, as well as other economical parameters such as total costs to meet demand, marginal costs, etc. By generating a large number of system states, it is also possible to calculate:

- LOLP as the number of states with ENS / total number of states,
- LOLE = LOLP * duration

- EENS: expected value of energy not supplied

This methodology presents the possibility of covering different aspects relevant to the system:

- It is possible to include the transmission system with representation of failures in transmission facilities;
- It allows the consideration of reservoir operation (the dispatch model should be able to optimise reservoir operation);
- Using multi-regressive and multidimensional random number generators, it is possible to consider spatial and temporal correlations of some variables such as river discharge;
- Etcetera.

The main drawback of this methodology is that it requires a very large number of simulated states. For instance, because the LOLP value is normally very low (e.g. 1/5000), the number of simulated states to measure LOLP with a reasonable confidence interval (i.e. 95%) may be extremely large; therefore the calculation time may limit the usefulness of the method, even if multicore programming techniques and technological developments help to overcome this limitation.

On the other hand, the Monte Carlo simulation allows a detailed representation of the system, also obtaining economic information like dispatch costs and marginal costs. The method also allows the use of metrics based on efficiency. Furthermore, a sequential simulation model allows the estimation of the frequency and duration of load shedding and is therefore the only methodology that permits the estimation of the EFDO metric.

The Monte Carlo methodology is the most suitable for a comprehensive adequacy evaluation

To conclude this section, it should be pointed out that:

- Abundant information is required together with long processing of that information in order to obtain a probabilistic characterisation of the key variables;
- The Monte Carlo methodology is able to consider the transmission system, operation of reservoirs, or maintenance of units, but a huge number of simulations is needed to calculate the metrics with the required level of accuracy.

5.3.3 *Input data for calculation*

Abundant information and estimation is needed for a consistent modelling of the system

The methodologies described for adequacy metric calculations require abundant information, including:

- Forced outage rates of generation units, which can be based on historical information for existing units, or on information provided by manufacturers in the case of new equipment;
- Historical information or surveys on intermittent RES generation. Some recent studies show that it is necessary to have multiple data sources on wind speeds in order to characterise the probabilities of different levels of wind generation. Furthermore, it is necessary to take into consideration the spatial spread of wind generation, because the greater the distance between wind farms, the lower the

correlation. Figure 5.9 shows the correlation in the UK of wind speeds at different sites. When there are multiple wind farms spread across a territory that is electrically interconnected, the permanency of supply can increase, as the probability of lack of wind throughout the entire region decreases with distance. This information is necessary for a proper characterisation of wind availability.

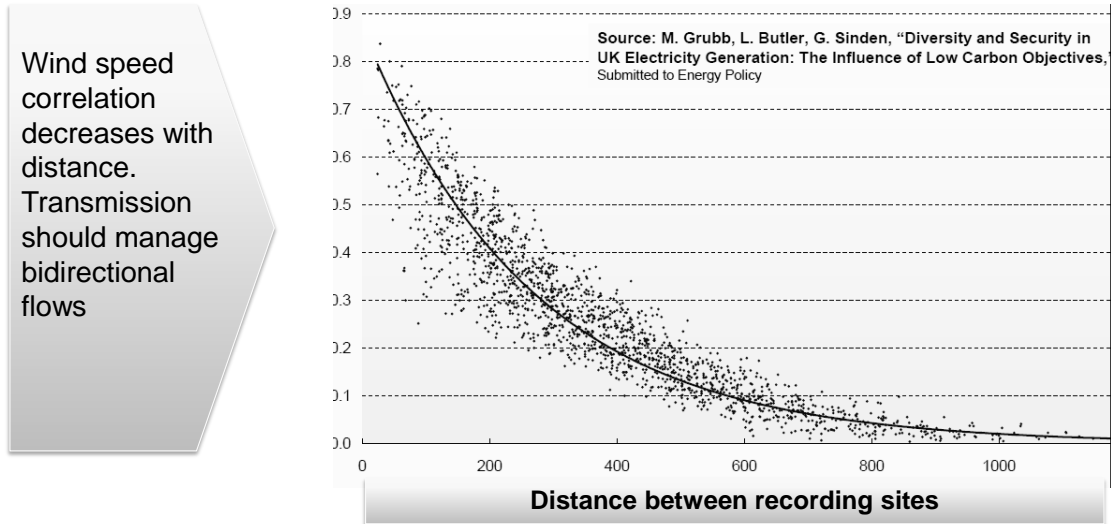


Figure 5.9 - Correlation between Wind Speeds and Distance

- Capacity availability of hydropower plants: normally, hydropower plants with reservoirs are designed for operation during peak hours. However, in order to operate at the rated capacity, a minimum amount of energy is necessary. Figure 5.10 shows the minimum energy necessary (areas in blue) to dispatch power (P) in a typical daily load curve. This energy increases as shown in Figure 5.11. The same figure shows the MWh necessary to dispatch an additional MW. The conclusion is that in dry years, there is certain probability that some peak hydropower plants will not be able to operate at full capacity, mainly due to the fact that a dry period will affect all the hydropower plants in a region. Furthermore, in some cases hydropower plants have the obligation to permanently release a minimum volume of water, thus reducing the energy available for operation in peak hours. However, the energy available during dry years is related to the operation strategy of the hydropower plant. A conservative operation will keep a minimum volume of water stored, to ensure the energy necessary to operate at full capacity in dry years; but economic optimisation may lead to less conservative operation. From the perspective of the adequacy metric calculation, it is necessary to make assumptions on how hydropower plants with reservoirs will be operated. In the case of a Monte Carlo simulation, there are computer programmes that optimise the operation of a reservoir by taking into consideration a VOLL value. The higher the VOLL, the more conservative the operation. However, an optimised simulation will not necessarily reflect the actual operation of a hydropower plant

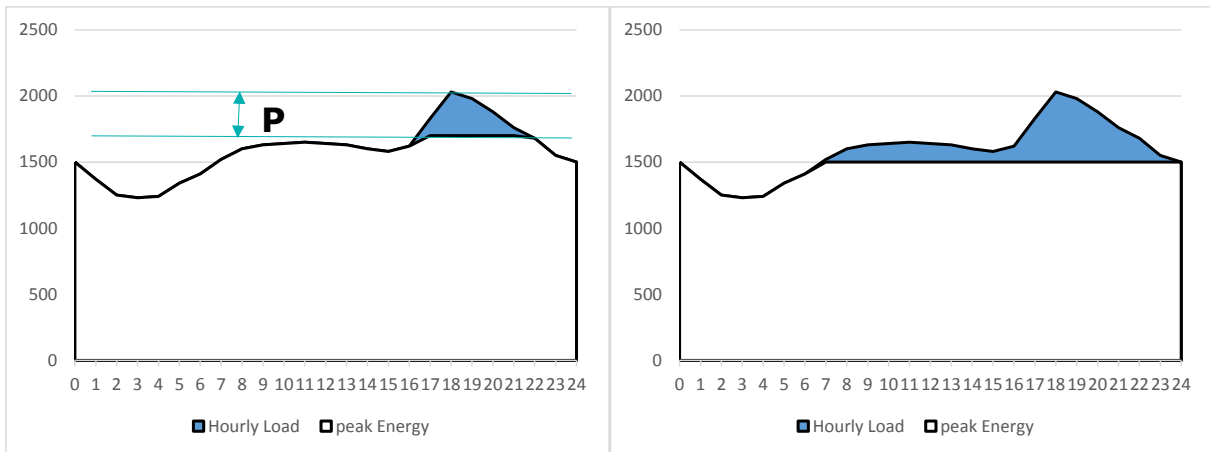


Figure 5.10–Different energy necessary to dispatch a capacity, P

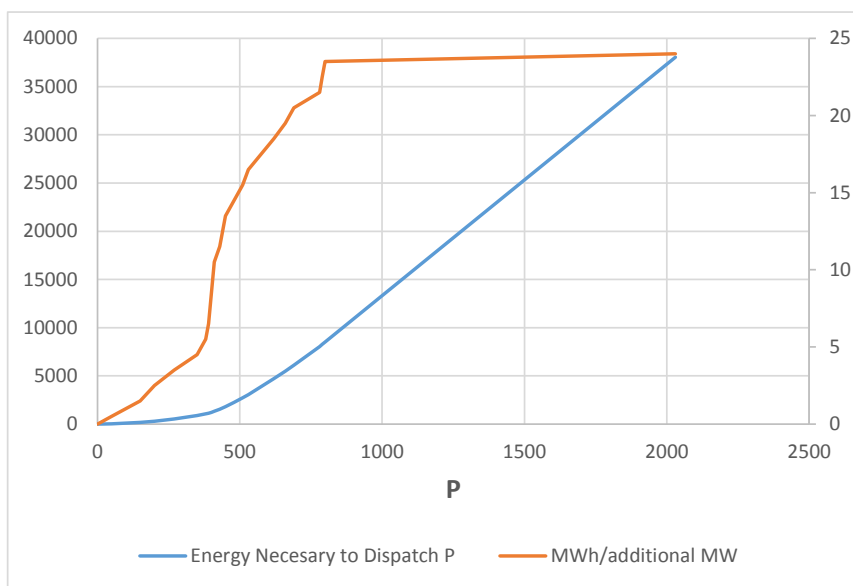


Figure 5.11 - Energy increase to dispatch a capacity, P

- Maintenance of units: for the short term, the TSO normally has information on the scheduled maintenance of generation units, but in the long term, it becomes necessary to make assumptions on this issue. As in the case of hydropower operation, there are simulation computer programmes that optimise the maintenance of units, aiming to minimise the negative impact on the system. However, depending on the jurisdiction and the attributes of the TSO, the owners of plants will not necessarily schedule a similar maintenance plan.
- Load: there are standard methods for forecasting the evolution of load, but further to the average trend obtained with the standard techniques, it is necessary to consider the impact of weather on load. Monte Carlo simulation models can include a random generation of weather variables, and therefore adjust the daily load accordingly.
- DSM: it is necessary to obtain information on the available DSM (as interruptible loads), specifically loads that can remain disconnected during the full duration of a period with insufficient capacity, as well as information on the reliability of the disconnection of such loads.
- Commissioning and decommissioning of capacity: this information is based on announcements from generators. However, as previously mentioned, it is

common that some new projects be cancelled or delayed. Some assumptions are necessary on this issue.

Not only does the Monte Carlo simulation need the average values of key parameters, it also needs variances and self-correlation in order to provide realistic adequacy estimation

Conclusions on the information necessary to estimate adequacy metrics:

- In all cases, abundant information is necessary to estimate metrics representative of the current or forecast situation in a country or region.
- In cases where information depends on decisions made by market participants, the forecast may be subject to significant error. Although there are models and statistical techniques that allow optimisation of the operational decisions by hydropower plants, the commissioning of new capacity, or the maintenance of units, such results may be appropriate for a centrally planned electricity sector but are of doubtful utility in the case of electricity markets.
- The use of sophisticated Monte Carlo simulation models allows the generation of synthetic series of certain variables like weather, river discharge, wind, solar radiation, etc., reproducing the statistical parameters of historical series. It is necessary that such synthetic generation reproduce not only the average values of key parameters, but also the variances, self-correlation, and cross (spatial) correlation.

5.4 ***Mechanisms to ensure adequacy***

The changes in the regulation of the electrical power industry worldwide have modified the traditional reliability approaches. In the vertically integrated utility, under cost-of-service regulation, reliability was achieved by centralised utility planning at all levels: generation, transmission and distribution. However, with the development of electricity markets, investments are no longer centrally decided; therefore the market regulation must make certain that, if needed, the appropriate economic incentives exist for each one of the activities so that quality of supply is maintained at socially optimal levels.

Adequacy evaluation is influenced by the market framework

Several issues have appeared and have challenged the idea of whether a competitive electricity market can lead to a sustainable and efficient power sector. Experiences have shown that electricity markets are usually measured not only against sound economic principles, but also against both government and consumer expectations in tariffs, GA and prices. In some cases, electricity markets have been considered “bad” because energy prices become volatile or manifest strong spikes, or because insufficient generation capacity is available when needed, without due consideration for initial conditions or externalities that may cause or affect some of these results. The important lessons learned are that electricity trading arrangements in an electricity market need to take into consideration the particular characteristics of the system where the market will be implemented, and equally importantly, to take into consideration the political and social constraints and expectations, in order to include the necessary mechanisms to achieve or adequately address such expectations.

The challenge of ensuring the adequacy in the competitive integrated framework

The traditional approach to ensuring GA in vertically integrated utilities was to install enough capacity based on long-term planning, itself based on load forecasts and reliability studies that determined the reserve necessary to achieving certain reliability targets. The transmission was planned accordingly, to allow delivery of the installed generation.

With the introduction of competition, central planning was abandoned and investment decisions in generation were transferred to the liberalised market. As a result, the SoS of the liberalised electricity system was made dependent on investments by individual market players in generating capacity and demand response.

In the case of transmission, most countries maintained centralised planning. In the case of the EU, such planning is the responsibility of TSOs. While transmission expansion is planned to allow for delivery of all the installed generation, some internal transmission bottlenecks exist in the EU.

Adequacy responsibility is in charge of governments that have the possibility of applying different measures to guarantee it

Generally, the electricity market has been organised as an energy-only market, in which only units of electrical energy are traded. No separate payment is made for the availability of the generation capacity of power stations, and the cost of this capacity must therefore be recovered from the units of electrical energy sold. In other cases⁴⁹, capacity mechanisms (payments) were introduced, with the aim of improving adequacy through economic incentives. Other mechanisms to protect GA include strategic reserves or last-resort tenders for additional capacity.

Therefore, the mechanisms to ensure adequacy become a relevant issue in countries that have introduced competitive markets.

Responsibility for ensuring GA seems to be clearly defined across Europe. In almost all countries (15 out of 17⁵⁰) this is attributed to the national governments. In some cases, there are specific and transparent mechanisms to ensure adequacy. However, in several other cases, although the responsibility for adequacy has been assigned, there is neither a target (in terms of an appropriate metric) nor a mechanism to ensure that the adequacy targets are achieved.

The ultimate use of adequacy metrics is to facilitate the implementation of an effective and efficient mechanism to ensure adequacy. EU countries currently employ four types of mechanisms:

- Centralised planning: although all EU MS have electricity markets, in some cases there are still state-owned utilities that may follow the instructions of an electricity policy authority in relation to installing capacity to ensure adequacy. Although this practice may produce negative impacts on the markets, it would be very difficult to discourage this practice and replace it with market-oriented alternatives.
- Last-resort measures: in some cases, laws or by-laws establish the possibility that a Ministry or NRA (or a directed entity such as the TSO) may intervene with a tender for the construction of new production units to ensure SoS.

In some cases, the authority has the right to deny authorisation for an intended shut-down of a generation unit if that unit is relevant to maintaining adequacy.

- Strategic reserves: some generation capacity is set aside by the market to ensure SoS in exceptional circumstances, which can be identified when prices in the day-ahead, intra-day, or balancing markets increase above a certain

⁴⁹In the U.S., Latin America and Russia.

⁵⁰Those that answered the CEER questionnaire, section 11.1.

threshold level, or else as requested by the TSO under pre-defined circumstances.

- Capacity remuneration mechanisms: some of Europe's thermal generation assets have become uneconomic because a level of dispatch is substantially below the originally expected generation, therefore the owners of these units may be interested in decommissioning them despite the fact they can be necessary to achieve the GA targets. To address this issue and to attract new investment, some countries have advanced implementation capacity mechanisms "to encourage investments in new generation to address the adequacy problem".

There are different ways to identify and describe Capacity Mechanism (CM): price-based, volume-based or capacity markets⁵¹. In all cases, payments are assigned to the capacity necessary to achieve a certain metric (that is, appropriate metrics are a key component of capacity mechanisms).

- Energy-only markets: several EU countries rely on markets for achieving proper adequacy.

The success of energy-only markets in achieving an appropriate level of adequacy will be related to the establishment of a scarcity price sufficient to attract necessary investments in capacity or trigger demand response. Although the theory establishes that the efficient scarcity price is the VOLL in energy only, the careful consideration of markets should be given on regulatory intervention to scarcity prices according to a generic VOLL as, in practice, the VOLL highly depends on the type of usage, time of use and duration of disconnection.

From the perspective of this study, it is necessary to describe the relationship between this mechanism and the adequacy metrics. In this case, the adequacy metrics are only used to monitor adequacy, as the market will decide the incorporation of new capacity including demand response and the metrics rather than indicate a scarcity or involuntary load disconnection.

Disregarding the context or the actions, it is always necessary to assess adequacy to ensure SoS

The mechanisms to protect adequacy rely in every case on the proper identification of the capacity needs to achieve the adequacy targets, which in most of the mechanisms are based on the values of one or more metrics.

The quality of the results are linked to an appropriate correspondence between the metric target and the actual reliability within the system. Therefore, the effectiveness of any mechanism is closely linked to the quality of the metric, in the sense described in section 5.3. Inversely, a metric that is not properly calculated (whether due to the methodology, the variables considered, or the quality of the input data) may lead to inefficient (or even ineffective) values of new capacity, regardless of the effectiveness of the mechanisms to attract the requested investments.

Investments in transmission or generation capacity can be evaluated in a single adequacy assessment process and model

⁵¹For details, please see reference [50], which describes ACER definitions of capacity mechanisms.

Some additional comments on the impact of transmission on adequacy: In the EU, transmission is centrally planned. Although it would be possible to offer criticism on the efficiency of the planning process, in general, the current system yields low internal congestion in MS, in spite of increasing difficulties in the construction of new lines. Cross-border interconnections, where progress has been much slower than planned, are another matter. The methodology to optimise adequacy should be able to jointly optimise generation and transmission expansions in order to achieve adequacy. Presently, a good number of computer programmes for the joint planning of generation and transmission are commercially available. Of course, generation will only aim to ensure adequacy, but this methodology is appropriate to identifying the optimal trade-off between generation and transmission to achieve adequacy.

6 CONCLUSIONS AND RECOMMENDATIONS

Adequacy is a key requirement for an electricity market, and yet markets have experienced some difficulties in ensuring viable levels of adequacy. So-called market failures⁵² are, to a great extent, principally responsible for the difficulty in achieving socially optimal levels of adequacy in electricity-only markets. For this reason, some countries or regions have adopted additional measures to protect adequacy.

This chapter summarises the main contents of the study, recalling in particular the adequacy metrics currently used in the EU, and it aims to provide recommendations on:

- *how to define or employ those metrics deemed more appropriate within the IEM;*
- *how to select the model to be adopted to apply the proper methodology for the calculation of metrics;*
- *how optimal value of the metrics (from a social welfare perspective) should be obtained to assure generation and system adequacy in an interconnected electricity system.*

6.1 Selection of appropriate metrics

Current use of metrics to assess reliability is heterogeneous and not only based on probabilistic approach

Theoretical analysis (Chapter 3) has pointed out the necessity of metrics to quantify the adequacy level of an electricity system and the empirical analysis (Chapter 4) confirms that most countries use a metric to assess adequacy even if there is lack of uniform methodologies to estimate the metrics.

The choice of the metric is relevant to the purposes associated with its calculation (section 5.2) and a ranking of the appropriate metrics oriented to identify the needs of transmission or generation capacity to meet the adequacy targets with economic criteria has been presented in Table 5.2. Empirical analysis results highlight how metrics adopted are not those in a first position of merit in the ranking.

The Monte Carlo approach should be used to assess EENS with common tools and shared scenarios

The main evidences derived from the assessment process are listed below:

- Establish a single metric to be used in all MS, to allow comparison of the situations in each MS (section 5.2);
- Establish EENS as a preferred metric (section 5.2);
- Employ a common methodology and tools (computer programme⁵³) capable of obtaining comparable results from metric calculation to ensure that quality is appropriate and that differences between MS metrics are not due to differing methodologies (section 6.2);
- The selected tool should be based on the Monte Carlo simulation representing all the relevant variables, including internal transmission bottlenecks and cross-border support (section 6.2);

⁵² Please see Appendix D for details.

⁵³ Practical experience shows that models with the same apparent methodology may produce different results, because of details in the algorithm or assumptions in the hypotheses. A common model can guarantee the avoidance of differences due to such reasons; otherwise, a fine-tuning of different tools would be needed to obtain comparable values of adequacy.

- An EU-wide assessment of adequacy carried out by the ENTSO-E could be the basis of national detailed analysis.

Please note that, although the “ENTSO-E Target Methodology for Adequacy Assessment” [15] is sufficiently in line with this recommendation, it would be convenient to extend a common methodology and tools to all MS.

Adequacy targets are often missing and there is no clear evidence on how these targets are fixed

The current situation on adequacy targets in the EU is as follows:

- Several MS have established standards, generally in terms of LOLE;
- However, information is lacking on the criteria used to establish those standards;
- There is also a lack of a common methodology to set the standards.

The analysis of single countries shows that in only a few cases are the values of the adequacy standards based on cost optimisation (marginal cost to increase adequacy = marginal benefit).

The following three recommendations apply to GA assessments of MS with an explicit GA mechanism and to transmission adequacy assessments in all MS:

Appropriate adequacy targets should be based on the profitability of investing in generation and transmission compared to the EENS cost for final consumers

The recommendations on the use of a metric and standards to define adequacy objectives are:

- Establish a common methodology to set standards, based on obtaining the metric value that minimises the EENS cost ($EENS * VOLL$) plus the additional capacity cost (section 6.3);
- Request that MS provide calculations of the VOLL with a common methodology, to ensure that quality is appropriate and that metric differences are not due to different methodologies (section 6.4);
- Use a common methodology and tools capable of obtaining comparable results to ensure that quality is appropriate and that metric differences are not due to different methodologies. The tools should be able to manage the representation of all the relevant variables, including internal transmission bottlenecks and cross-border support (section 6.2).

The assessment of the investment should be made based on a CBA

The optimal quantity of additional capacity should be calculated to optimise costs. The recommendations to address this objective are:

- Use software with the characteristics proposed in sections 6.3 and 6.2 to identify the needs of additional generation capacity/demand-response/interconnection capacity needed to meet the adequacy targets.
- As the additional capacity may be installed in different MS, a non-binding recommendation on how to locate and share the additional capacity would be convenient (section 6.5).
- An optimisation model could identify interconnection capacity reinforcements that would enable the optimal location of additional generation capacity and inform MS accordingly (section 6.2 and 6.3).

It is important to mention that, after the capacity needs for achieving standards are defined through an appropriate methodology, it will be necessary to put into place a mechanism to promote the corresponding investments in new capacity.

Responsibility and possible strategies to ensure adequacy can be different but should be harmonised

The empirical analysis has shown that most MS already have an institution responsible for adequacy, but the scope of this responsibility varies. As observed previously (section 5.4), there are four explicit approaches to mechanisms to ensure adequacy:

- Last-resort tender (no information on how these mechanisms have been or might be used);
- Strategic reserves;
- Capacity mechanisms (such as capacity markets, capacity payment, or reliability options);
- Reliance on the market, combined with transmission planning.

International experience reveals other mechanisms that, while not mentioned among the EU cases, might be used: obligations of suppliers to compensate for interruptions (and therefore incentivising suppliers to procure proper reserves); balancing obligations of suppliers; and scarcity prices based on VOLL.

6.2 **The Common Model**

The Monte Carlo methodology must be used

Based on the analysis carried out in section 5.3.1, the recommendation is to use Monte Carlo simulation models, given that the only possible alternative (the multiple convolution algorithm) cannot address certain relevant issues:

- Transmission constraints and outages;
- Operation of hydropower plants with reservoirs;
- Maintenance optimisation;
- Frequency and duration of load shedding.

A common model is needed to ensure the consistency of the adequacy assessment

Furthermore, the consideration of other relevant factors can be managed with differing levels of detail (for instance, intermittent RES, DSM, or load volatility). Therefore, the most appropriate way to ensure that results in different MS are comparable and consistent is by use of a common model. Although a common methodology would seem an appropriate manner to achieve consistency, practical experience has shown that different implementations of the same methodology with different computer programmes can lead to disparate values, either because of details within the algorithms or the use of different solvers. Therefore, the possibility of ensuring consistency would further require recourse to a common methodology, a common computer programme, or else a fine-tuning of different comparable tools.

The common model should include the contribution of renewable sources, interconnection and DSM to system adequacy

The key components of such a computer programme were analysed in Chapter 5. Furthermore, it would be proper to employ a sequential simulation model using the Monte Carlo technique in order to consider (at least) outages of generation and transmission (time of occurrence and duration), RES production, demand variability (or weather and its impact on demand), and hydropower production.

Monte Carlo analysis requires a high number of sampling to ensure the convergence of the results

As the accuracy of Monte Carlo models depend on the number of random samples, it would be necessary to establish common criteria to ensure that different results be linked to actual different adequacies, and not to sampling dispersion. For instance, the number of samples could be selected with the aim that the 95% confidence interval be lower than a fixed % (e.g. 5%) of the estimated value of the selected parameters.

ENTSO-E Target Methodology is a first example of a common model

ENTSO-E Target Methodology, briefly described in 3.3.2 and 3.6, has the aim of defining a methodology with which adequacy at European level can be assessed, applying a Monte Carlo approach and also defining the main data necessary to obtain a common model. Pros and cons of Target Methodology in relation to the aim of this project are summarised in the following section.

6.2.1 ENTSO-E Target Methodology strength and weakness

The ENTSO-E Target Methodology can be considered an approach to the common model, although some of the requirements mentioned in the previous section should also be included. For the moment, Target Methodology has not been applied excluding a pilot phase, but it represents the first tentative attempt to define European adequacy as a whole with a consistent probabilistic approach; still, areas for improvement of the methodology can be presented, in particular:

Main data representing the systems are adopted by the Target Model, but additional details are needed for a complete Monte Carlo approach

- The origin of thermal generation data and their characterisation should be better clarified, with particular regard to forced and planned outages (standard/manufacturer/historical values).
- Random RES generation based on historical series should be considered in the calculations.
- It is recommendable that a uniform approach be implemented in order to track the evolution of generation, whether through new capacity or the decommissioning of existing plants. Experience shows that a significant portion of announced projects are never developed, or are subject to lengthy delays, so that estimation of GA based only on information provided by developers may lead to underestimation.
- Reserve allocation is different from country to country, and cost minimisation should consider reserve sharing and its impact on system adequacy
- It is not clear whether or how transmission reserve margin on interconnection is included in the model; adequacy evaluation can be affected by this data.

Target Methodology is in line with expectation but requires some clarifications and improvements

- How the probabilistic method is applied, and to which variables, must be clarified. The number of samples must also be specified.
- Whether a sequential or non-sequential approach is adopted for the probabilistic calculation must be clarified, even if a preference for the former is expressed.
- The inclusion of the representation and modelling of internal transmission constraints, which exist in a significant number of MS, is recommended.

Additionally, in certain cases, some internal transmission constraints are not binding in normal operation, but may be so in emergencies when flows may express a different pattern.

- ATC and other transmission constraints based on power flow is initially applied to the analysis, while Flow-Based is considered as an alternative. Flow-Based is a better approximation of reality and should therefore be adopted. Furthermore, the methodology used to calculate ATC values is very conservative; although it makes sense for commercial operations, during an emergency it would generally be possible to transfer significant additional power, in order to support countries with problems.
- Representation of the system is limited at the interconnection level, initially without forced or planned outages (LOI could be one of the main causes of EENS).
- In order to provide accurate information about the possible location of needed additional capacity, a subdivision of countries with internal constraints should be used, introducing additional internal sub-areas and interconnections.
- It is recommendable to adopt a probabilistic methodology to consider the contribution of intermittent RES to adequacy. In the case of medium or high penetrations of RES, ignoring their contribution may lead to the underestimation of adequacy and consequently trigger last-resort mechanisms, with the consequential cost of adding unnecessary generation.

On the other hand not including the variability of RES may lead to an underestimation of the adequacy problem and more in general to necessary capacity to cover possible fast change in power production (ramp).

Target Methodology provides probabilistic results even if the attention is not focused on EENS and its economic value

- Even if EENS is clearly a product of the adequacy analysis, it is not included in the main results; however, its evaluation is necessary to obtain the monetisation to be used in CBA.
- The association of EENS to a geographical area (country or internal subdivision) could be important to defining possible countermeasures and to drive possible investments. VOLL is country specific, therefore the socially optimal level of reserves may lead to a situation where countries with high VOLL may support (or contribute toward improving) the adequacy of neighbouring countries with a lower level of VOLL. How to deal with this issue is one of the key issues addressed in the final part of this study (see section 6.3).
- The presence of interconnections and of a complete model should provide the possibility of evaluating not only GA, but also investments in internal and cross-border capacity increases.
- The ENTSO-E approach is limited to analysis of future interconnections (TYNDP) without considering the issue of exchangeability of interconnector capacity and generation capacity to solve adequacy problems. All possible solutions should be analysed in order to select the most economical investment.

There is no mention of the standards to be applied and no evidence is given regarding the economic value of adequacy

- Standards to define whether the results obtained are adequate for assuring an acceptable level of adequacy have not been established; each country has its own metrics and standards, though it may be possible to verify each country standard, or to define European standards for the entire network.

- The final aim of each metric is to measure adequacy, and the notion of adequacy is of interest because it has a social value. In that sense, it can be considered that each metric and its related standard is a (in general, implicit) proxy of the impact of adequacy on social welfare. Therefore, metrics could be ranked based on their effectiveness in measuring the social value of adequacy. This justifies the effort to isolate a single and sound metric. The related standard would be country-specific, as it is linked to the VOLL.
- As mentioned, beyond the calculation of VOLL, it is necessary to obtain a monetisation of EENS, even if the definition of a methodology to calculate EENS is not directly a part of ENTSO-E Target Methodology.

6.3 **Optimal values of the metric**

Weakness in the current definition of metrics and standards

In several cases in the EU and other regions, metrics and standards have been set through a rather subjective decision, despite it being evident that the setting of a standard (and the necessary generation or transmission capacity to achieve such a standard) has an economic impact on consumers. The recommendation is to set the standard with the goal that it be representative of the value (or a reasonable proxy) of the socially optimal level of reserve.

Key factors for standard definition are based on the economic evaluation of EENS

The optimal values of any metric should arise from a CBA (or social welfare maximisation). However, there are several issues to take into consideration in this optimisation:

- VOLL values are country specific; therefore, the optimisation of the values of metrics may lead to different target adequacy levels in different countries. This may lead to a situation where countries with a higher VOLL support the adequacy of countries with a lower VOLL. Nevertheless, this should not be considered a problem but a consequence of market integration.
- For GA, the simplest way to calculate the optimal value of a metric seems to assume that the quantity of a peaking technology like gas turbines (GTs) will be adjusted until it achieves the minimum cost of this additional reserve, plus the cost of EENS. However, the assumption that the additional reserve is covered by GTs (or any by other fixed technology) may lead to a sub-optimisation. The best solution is to use an optimal expansion model for this task that allows the consideration of the effective use of new generation needed to compare the effect of different size and technology.
- Modelling inaccuracy of involuntary load shedding: the detailed modelling of a power system is complex, mainly when the objective is to measure the EENS. Particularly because EENS is an event of very low probability in the EU. There is an unknown margin between virtually simulated shortages and the critical level of a shortage that would actually incur involuntary load shedding in practice. Therefore, it is necessary to be aware that any optimisation may be biased by this inaccuracy.

VOLL valorisation has an effect on adequacy level

Regarding acceptable standards it is important to underline that the relation of system cost to VOLL value, which can be different from country to country (section 3.5.1), and the availability of different solutions to limiting EENS, can imply different levels of acceptable EENS for each country. In this way, a lower VOLL can make higher EENS

values acceptable. Furthermore, two countries with same VOLL may have different optimal levels of adequacy due to historical reasons or load composition. This difference can lead to a country that is more attractive to investors than the other, also considering possible lower requirements of return on investments, and therefore in the capital cost.

6.4 **VOLL estimation**

VOLL calculation is complex and affected by several factors, starting from the methodology to obtain the necessary data

Interruptions may prevent customers from doing whatever they had planned, from work to enjoying dinner. Therefore, the cost of an interruption is commonly referred to as 'benefits foregone due to a supply interruption'. This is considered a benefit because, for most customers, the pleasure obtained from doing the things that the electricity supply allows them to do is greater than the price they pay for electricity supply. This benefit is also referred to as the WTP for the electricity supply (section 3.5.1).⁵⁴

As the cost of interruptions differs depending on how long they last or who is affected, it is normally measured through the VOLL, in the cost per unit of electricity (i.e. kWh) to an average customer. The VOLL is also variable and influenced by several different factors, so that its final estimation is normally an average of the VOLL across different circumstances. There are five main factors affecting the VOLL:

- Types of customers: for instance, households have a different cost of interruption than industry would.
- Duration of a single interruption may also affect the valuation, because customers may adapt to the situation (so that the additional cost of an interruption decreases over time); or on the contrary, customers may grow angry with the situation.
- Perceived reliability level influences the extent to which customers prepare themselves for potential interruptions. Customers in areas with high reliability are not prepared for interruptions and are more affected than those in areas with overall lower quality.
- Occurrence time: activities interrupted due to outages depend on the time of day, the day of the week, and even the season. For instance, an interruption during the night is hardly noticed, while one during daytime hours in the summer will impact air conditioning, and one during daytime in the winter will impact electrical heating.
- Notification: advance notice of the interruption enables people to prepare and rearrange their activities, thus minimising the cost of the interruption.

As seen from the analysis, the only methodology that can obtain appropriate information to estimate the VOLL should be based on information regarding the WTP. Only surveys with an appropriate design and number of samples can provide an accurate estimation of WTP.

The multitude of factors that affect the cost of interruption for customers make analysis a complex task that must be developed in different stages in order to achieve two main objectives:

⁵⁴Theoretically, the WTP to avoid an interruption should be equal (in the margin) to the willingness to accept an identical interruption. However, the estimation of these two magnitudes usually differ.

1. Develop a deep understanding of the characteristics of the interruption cost for the different kind of customers of the utility; and
2. Define practical figures, indices and recommendations to be implemented by the authority that will use the VOLL, in order to include the developed knowledge regarding the cost of interruptions in the planning and operation of the power system.

The main phases of the estimation of interruption costs and the economic impact on a country's economy cover the following issues:

- Design of the field survey
- Development of the field survey
- Estimation of the cost of interruptions
- Estimation of the economic impact of interruptions on the country's economy
- Definition of figures for internal analysis and decision-making

6.5 ***Integrated Generation and Transmission Planning***

New generation location in an open market cannot predict future system need

There are three issues that affect the location of new generation:

1. The common practice in EU MS is that generation expansion arises from independent decisions taken by the market participants, while transmission is centrally planned and developed by the incumbent TSO. Therefore, new generators are not responsible for the investments necessary to allow delivery of the produced electricity to markets. This approach is consistent with targeted market design, but it faces some difficulties in relation to the issue of system adequacy.
2. In several MS, transmission tariffs are only paid by consumers; in other cases, generators have to pay a part, but not related to their contribution to costs. These tariffs do not have any localisation signal (normally they are postage-stamp based).
3. Electricity market prices are, in most cases, independent of the location of generators or loads within a country.

Due to the reasons mentioned above, generators do not have any incentive to optimise the location of new plants from a system perspective, taking into consideration overall economy or system reliability. On the other hand, TSOs optimise the transmission system for decisions made by new generators. This potentially leads to the sub-optimisation of the system, and to increases in difficulty or cost vis-à-vis the adequacy standards.

New generation location can be based on signals provided by network planning based on adequacy assessment

Although integrated planning of generation and transmission may not be compatible with a free market, there are market-based solutions that are already in use in other jurisdictions:

- Locational nodal prices;
- Locational transmission tariffs;
- Payment of transmission investments by beneficiaries.

Furthermore, the planning process could identify the needs of quantity and location of all new generation necessary to achieve the standards, and could inform the investors and authorities responsible for adequacy.

6.6 *Spillage risk*

Heterogeneous metrics and standards increase spillage risk

As long as different metrics and standards are used to define and enforce capacity requirements to achieve adequacy, negative spill-overs of adequacy, in the shape of frequent support from one country with excess capacity to another with a deficit, may occur.

- However, as long as this support is properly priced, there is no damage for any of the parties.
- Furthermore, in most cases, this support will be in the form of exports arising from the operation of the day-ahead, intra-day, or balancing markets. It will not be explicit.

Non-harmonised incentive policy undermines market competitiveness

However, distortions may occur in the case of mechanisms to incentivise or force additional capacity in order to achieve adequacy.

- Improperly designed last-resort mechanisms may allow entry into the market of otherwise non-competitive units. This may bring market prices to be valued below competitive equilibrium, damaging generators that entered the market accepting the price risk, but assuming that all their competitors face the same risk.
- Capacity remuneration mechanisms also can create distortions to the competitive equilibrium. The equilibrium in energy prices, as shown in Figure 6.1, are different in the case of capacity payments. An investor in generation in a market with some sort of capacity payment needs a lower energy price to obtain a certain return on investment than would be the case in an energy-only market. Furthermore, CM reduces revenue volatility. Assuming that the primary resources and investment costs are the same in both countries, generators in the country with CM will have the opportunity to export to the other, obtaining additional benefits that are not based on competitive advantages but on implemented regulatory mechanisms. This is inefficient, and somewhat unfair.

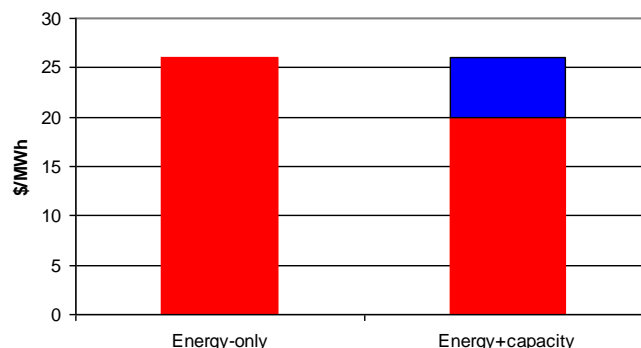


Figure 6.1 - Equilibrium Price with and without Capacity Payments

- In theory, reliability options do not produce this type of distortion, as the capacity payment is offset by the reduction of revenues during periods when market prices are higher than the option strike price. The reduction in volatility still exists but it

has a minor impact. However, this requires that regulation not distort the option fee, for instance by setting a floor. Figure 6.2 shows the equilibrium energy price in the case of an energy-only market, and then with reliability options. The equilibrium price of the energy is the same, the difference being that generators who sold reliability options receive an up-front payment for revenues that they would otherwise collect when the wholesale price (WP) is greater than the strike price (SP).

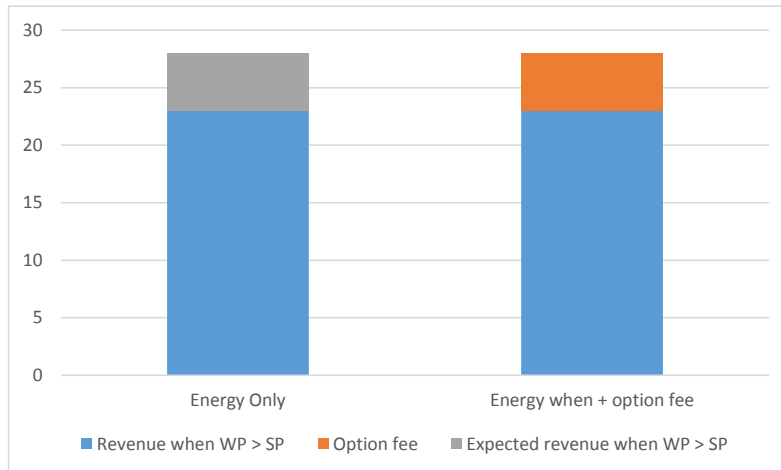


Figure 6.2 - Equilibrium Price with and without Reliability Options

Price cap should be aligned with VOLL

In the case of an energy-only market, inappropriate price caps (quite different from VOLL) in all market segments (but especially on imbalance pricing) may produce distortions. Cap prices above the VOLL would promote more capacity than is socially optimal, and cap prices below the VOLL would produce the inverse effect. In markets with good adequacy, this distortion will be negligible, as the impact of cap prices on average energy prices will be low.

Spillage risk can be reduced by using a common model and homogeneous metrics and standards

In summary, spillage may occur due to differences in the metrics or standards, or due to energy market intervention mechanisms to incentivise adequacy. If the metrics are homogeneous and calculated with a similar methodology, only in the case of the interventions would this spillage produce negative effects and distortions to the markets.

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8 APPENDIX A – QUESTIONNAIRE STRUCTURE

This section contains the questionnaire. Respondents were asked to fill the “answer” fields for each question and, when appropriate, to provide references to relevant sources in the *References* field.

8.1 Questionnaire format

CONTACT PERSON

Question	Answer
Contact person for queries related to this Questionnaire	
Company name /Country	
Role of the contact person within the company	
Email address	
Phone number	

DEFINITIONS

	Question	Explanation	Answer	References⁵⁵
1.1	How do you define “adequacy” and “security” assessment (a possible definition is included in Appendix A)	We ask respondents to provide information on how they define, describe and articulate the concepts of security and adequacy. (Please explain any differences with our proposed characterisation and provide your view on the best way to characterise the concept)		
1.2	Do you think that separate notions of adequacy (generation and system), as presented in Appendix A, are useful for analytical purposes? Why?			

⁵⁵Legislative, regulatory decisions, other relevant documents and data sources. Please provide web links when available.

PROCESSES INVOLVING ADEQUACY ASSESSMENTS

	Question	Explanation	References⁵⁶
2.1	<p>Which of your institution's responsibilities/activities/processes entails an adequacy assessment, and what is it used for?</p> <p>Please provide information on:</p> <ul style="list-style-type: none">a) Purpose of the assessment (see examples of answers)b) Frequency of the assessmentc) Office in charge of carrying out the assessmentd) Time horizon		
2.2	<p>Is any capacity remuneration mechanism in place or in development in your country?</p>	<p>We consider a capacity remuneration system to be any policy measure granting public authorities direct or indirect control over the evolution of the generation fleet. These include, for example:</p> <ul style="list-style-type: none">• Capacity availability payments	

	Question	Explanation	References ⁵⁶
2.3	Is there any incentive scheme for demand flexibility implemented or under study in your country?	<ul style="list-style-type: none"> • Capacity obligations placed on load serving entities • Strategic reserve procurement by the system operator. For a description of these mechanisms see example.⁵⁶ <p>Please indicate also if (and what portion of) demand can participate in the spot market and in the markets in which balancing services are procured by the SO.</p>	

⁵⁶http://www.elia.be/~media/files/Elia/Grid-data/Strategic-Reserve_UserGuide.pdf

METHODOLOGY TO ASSESS ADEQUACY

	Question	Explanation	References⁵⁶
3.1	Provide a broad outline of the methodology to assess system or generation adequacy.	<p>We only expect a high level description of the methodology here, as more detailed information is requested in the following questions.</p> <p>Please specify at least if the methodology is:</p> <ul style="list-style-type: none"> • Deterministic • Probabilistic <ul style="list-style-type: none"> ○ Simulation based ○ Analytical 	
3.2	How is the transmission network modelled for the purpose of the adequacy assessment?	<p>We expect the answer to this question to cover both the domestic transmission network and cross border interconnection.</p> <p>We would like the respondents to highlight, at least:</p> <ul style="list-style-type: none"> • The granularity of the network model representing the internal network • How neighbouring networks are represented • If load flow calculations are obtained with simplified (load analysis method) or alternate current methods 	

	Question	Explanation	References⁵⁶
3.3	What are the main variables that feature in the models used to assess adequacy?	We would like to receive information about the main variables ⁵⁷ , but we encourage respondents to add variables or to point out those that are not relevant in the context of their adequacy assessment (explaining why).	
3.4	For each of the variables indicated in previous answers, please clarify the origin of the data and the sources of information	Where pertinent please explain if data are: <ol style="list-style-type: none"> 1. Based on a time series (backward looking) 2. Forecasted 3. Obtained from simulation (i.e. probabilistic estimation of RES productions on the basis of historical data) 4. Gathered from the market (e.g. on planned generation investments) 5. Gathered from grid connection applications 6. Gathered from DSOs 	

⁵⁷demand curve, demand side response (contracted capacity or voluntary price-based/scarcity driven), installed generating capacity (including generation connected to the distribution network), generation capacity for generators running on non-intermittent primary sources, generation capacity for generators running on intermittent primary sources, availability of non-dispatchable generators primary sources, pumped-storage constraints due to reservoir volume, hydropower reservoir seasonal constraints, availability of system components, dispatching criteria for thermal generators (merit order based on costs..), operating reserve (FCR, aFRR, mFRR and RR requirements), internal and cross-border transmission capacity and flows (see also question 0)

	Question	Explanation	References⁵⁶
3.5	What assumptions about cross-border flows are made for the purpose of assessing adequacy?	<p>We would like respondents to highlight assumptions on cross-border flows during both normal and emergency conditions.</p> <p>Please cover both net-imports and net-exports.</p> <p>Please explain the rationale for the modelling choice that you describe.</p>	
3.6	What is the time granularity of the modelling exercise supporting the adequacy assessment?		
3.7	Please specify which sensitivity scenarios are normally included in adequacy assessment.		
3.8	Is there any procedure to validate the adequacy model in respect to historical	Back test procedure can be adopted to validate adequacy model or define adequacy standards.	

	Question	Explanation	References⁵⁶
	results?		
3.9	What form of coordination with neighbouring SOs takes place for the purpose of assessing adequacy?		
3.10	What is the source of the main modelling tool(s) that you use?	<p>We would like to know if software tools are:</p> <ul style="list-style-type: none"> • developed in house, or • external tools, please specify name and provider 	
3.11	Are you considering any modification to your present adequacy assessment?	If so, please indicate the areas in which the new methodology will improve over the current and the time foreseen for the change to be operative	
3.12	Do you have any plans to improve coordination of adequacy assessments with your neighbouring	If so, please indicate the countries involved and whether the initiative is cast within the ENTSO-E's activity programme e.g. [Annual Work Programme].	

	Question	Explanation	References⁵⁶
	countries?		

METRICS FOR ADEQUACY

	Question	Explanation	References⁵⁶
4.1	Which indicators do you use to measure adequacy?	If multiple indicators are computed for different purposes, please list them and for each one explain its purpose.	
4.2	Is the use of those metrics the result of a regulatory or legal requirement?	If so, please clarify which Authority is responsible for selecting the adequacy metrics in use.	

ADEQUACY TARGETS

	Question	Explanation	References⁵⁶
5.1	What adequacy targets (levels or “standards”) do you pursue?	<p>We would like to know to what level of the metrics presented in the previous section does an “adequate” system (or generation fleet) correspond.</p> <p>If the target is expressed in terms of range please report the range.</p> <p>If different target levels are relevant in different decision-making processes please illustrate them.</p>	
5.2	Which Authority sets/approves the adequacy target levels?		
5.3	How are the target levels of the adequacy metrics set?		
5.4	If the target levels for adequacy are the result of a cost-benefit analysis, please provide a	<p>We expect to learn what the main variables of the cost-benefit analysis are leading to the target level of adequacy.</p> <p>In particular we would like to know:</p>	

	Question	Explanation	References⁵⁶
	high level description of such cost-benefit analyses.	<ul style="list-style-type: none"> • how the incremental cost of increasing “adequacy” is assessed, i.e. which are the main drivers considered and how each of them is estimated • how the benefit of increasing adequacy is assessed. 	

ECONOMIC CONSIDERATIONS IN THE ADEQUACY ASSESSMENT

	Question	Explanation	References⁵⁶
6.1	How do economic considerations enter your adequacy assessment?		
6.2	If economic considerations enter your adequacy assessment, who sets the VOLL?	VOLL is the Value of Lost Load and is a measure of the cost of energy not supplied for consumers.	
6.3	How is the level of VOLL that you use calculated?	We would like to receive as detailed information as possible on the methodology used to estimate VOLL by the respondent.	
6.4	Is VOLL used in your adequacy assessment differentiated by consumer type and/or by type of service interruptions (such		

	Question	Explanation	References⁵⁶
	as: time of the day, day of the week, and/or duration of the interruptions)?		
6.5	What is the level(s) of the VOLL assumed in adequacy calculations and how often is it revised?		

TRANSPARENCY

	Question	Explanation	References⁵⁶
7.1	What information are you required to publish and/or to send to the regulator or government on the adequacy assessment?	<p>Please illustrate the information and data published or sent to the regulator/government for each of the following heading:</p> <ul style="list-style-type: none"> • General methodology • Network models, simulation and optimisation algorithms • Assumptions on the main variables • Sensitivity analysis • Outcomes <p>of the adequacy assessment.</p> <p>Please provide a description that allows us to characterise the level of detail of the information provided to the government/regulator on the one hand and to the public on the other hand.</p>	
7.2	What information are you required to publish and/or	Please illustrate the information and data published or sent to the regulator/government for the	

	Question	Explanation	References⁵⁶
	to send to the regulator or government on the target?	<p>target:</p> <ul style="list-style-type: none"> • Origin or methodology • Validation method • Argumentation <p>Please provide a description that allows us to characterise the level of detail of the information provided to the government/regulator on the one hand and to the public on the other hand.</p>	
7.3	What information are you required to publish and/or to send to the regulator or government on the VOLL?	<p>Please illustrate the information and data published or sent to the regulator/government for the VOLL, if applicable:</p> <ul style="list-style-type: none"> • Origin or methodology • Validation method • Argumentation <p>Please provide a description that allows us to characterise the level of detail of the information provided to the government/regulator on the one hand and to the public on the other</p>	

	Question	Explanation	References⁵⁶
		hand.	

8.2 **Objectives of the questionnaire**

The questionnaire investigates:

- a) *What institutions carry out adequacy assessments in the Member States and for what purpose?*

We have preliminarily identified three broad contexts in which adequacy assessment are typically carried out:

- System monitoring: countries in which the development of generation capacity is fully market driven can be expected to carry-out adequacy assessments in order to verify if the foreseen investments in generation assets result in an adequate generation fleet and comply with overall system adequacy requirements, presuming transmission network adequacy;
- Generation fleet development: countries implementing policy measures to drive investment in generation capacity, such as capacity remuneration schemes, can be expected to carry out adequacy assessments in order to set the targets pursued through public intervention;
- Network development: since in Europe a planning approach is implemented on transmission network development, adequacy assessments are carried out to support network development decisions. We envisage that the logic of such adequacy assessments can be different depending on whether policy measures to steer the development of generation capacity are implemented or not. In particular:
 - where policy measures to steer the development of generation capacity are implemented, we would expect that adequacy assessments would be carried out in order to determine, jointly, the optimal path of generation and transmission investment (we refer, in this case, to a *system adequacy* assessment);
 - where no policy measures to steer the development of generation capacity are implemented, we would expect that adequacy assessments be carried out in order to determine the optimal path of transmission, considering the expected evolution of the generation fleet as exogenously given (we refer, in this case, to a *transmission adequacy* assessment).

- b) *What methodology is implemented to assess adequacy?*

We are investigating various elements which, together, characterise the methodology to assess adequacy. These include:

- type of approach adopted: deterministic or probabilistic;
- adequacy metrics: the indices used to set adequacy benchmarks or targets, against which actual or foreseen system conditions are assessed. (EENS, LOLE, LOLP, reserve margin...);
- the time horizon for adequacy evaluation;
- the role of economic considerations in setting adequacy benchmarks or targets; this involves, in particular, investigating if the adequacy benchmarks or target levels are the outcome of some form of cost-benefit assessment;
- modelling: we investigate multiple features of the modelling process, including:
 - demand forecast and possible consideration of its variability with temperature;
 - generation fleet definition and availability factors;

- renewable energy, and the availability of primary sources;
- environmental constraints (i.e. hydropower reservoir seasonal constraints);
- network topology and load flow modelling;
- generation unit dispatch criteria (cost minimisation, market model...);
- outages of network elements and limits on cross-border flows/capacity;
- requirements related to system security (reserve definition, generation flexibility, DSM, transmission reserve margin on interconnections).

c) *Target adequacy levels*

We are collecting information on the level of the adequacy benchmarks or targets selected in Member States, how they are set and, when possible, how the accuracy is validated with respect to real economic costs/benefit balance.

8.3 **Clarifications**

Some concepts covered by the questionnaire might be defined, presented, or articulated in different ways and in different contexts. In this section we clarify the meaning we give to some terminology, focussing on the aspects that we believe are most relevant to understanding the questionnaire.

We would encourage respondents to provide information on how they define, describe and articulate the same concepts as well as highlight any different meaning that they give to the terms that we use.

a) Adequacy vs. security

We understand the concepts of *adequacy* and *security* as differing mainly in the time horizon to which they refer. Adequacy assessments take a long-term perspective in that they support decision-making on (or evaluation of) the endowment of transmission and generation assets, basically in a planning perspective. In intuitive terms, adequacy assessments address matters such as: "is there (or will there be) enough transmission and/or generation capacity to meet demand under security conditions at all times?"

Security takes a short-term perspective in that it supports decision-making on the use of the existing stock of assets, typically in the context of system operations. In intuitive terms, security assessments address problems such as: "is the system able to withstand sudden disturbances with available transmission and generation resources now and in the near future?" Security analyses support decisions on several issues, among others: configuration of the (existing) transmission network, operating reserve requirements.

Different tools are used in adequacy and security assessments mainly because the set of information available for and the computational requirements of the two analyses are different.

In this project we focus on adequacy issues.

b) System vs. generation adequacy assessment

Adequacy assessments can be carried out on a power system as a whole and on different aspects of that power system. We distinguish the aspects of generation adequacy and network adequacy distinctively, where network adequacy is subdivided in transmission adequacy and distribution adequacy. Generation adequacy is considered as the ability of the power system to balance generation and imports with demand and exports under security conditions at all times, assuming only constraints on power availability, imports/exports and possibly some constraints on power exchanges between congested areas in the network. Transmission and distribution adequacy are considered as the ability of the network under scope to transmit or distribute supply to demand under security conditions at all times, assuming generation adequacy.

We would encourage respondents to clarify the type of adequacy assessment carried out in relation to scope, time horizon and purpose.

c) *Metrics definition*

Adequacy metrics are indicators by which levels of adequacy are measured. Adequacy metrics and their definitions occur in a wide variety of ways. We have used the following metrics definitions:

The reserve margin method is a well-known deterministic methodology, still in use in several MS, for the generation adequacy evaluation. This criterion is based on the limit of how close the load should be allowed to come to installed capacity. The reserve margin is therefore defined as the ratio of the installed or available capacity to the maximum annual load, minus one.

Expected Energy Not Supplied (EENS) is a measure of the amount of electricity demand, calculated in MWh, which is expected not to be met generally by generation and system in a given year.

Energy index of reliability (EIR) and energy index of unreliability (EIU) are equal to normalisation of EENS obtained dividing by the total energy demanded; this ensures that large systems and small ones can be compared on an equal basis and evolution of the load in a system can be tracked.

Also System Minutes (SM) is obtained from EENS normalised by peak demand.

Loss of Load Expectation (LOLE): average number of hours/year for which the load is expected to exceed the available capacity (alternatively average number of days on which the daily peak load is expected to exceed the available generating capacity)

Loss of Load Probability (LOLP): probability that the load will exceed the available generation; it is often limited to the ability to meet annual, weekly peak load.

95th percentile (P95): the number of hours during a very cold winter (once every 20 years) during which the load cannot be covered by all means at disposal.

Capacity margin: The average excess of available generation capacity over peak demand, expressed in percentage terms. Available generation capacity takes into account the contribution of installed capacity at peak demand by adjusting it by the appropriate or availability factors which take into account the fact that plants are sometimes unavailable due to outages.

Frequency and duration of expected outages: an illustration of the results of the probabilistic risk measures in terms of tangible impacts for electricity customers. This is based on decisions around how the electricity system would operate at a time when supply does not meet demand, and the order and size of mitigation actions taken by the System Operator.

Respondents are encouraged to provide their own definitions for the metrics they use, if they deviate from the ones provided.

8.4 ***Adequacy standards definition***

Besides the indicators which are used to measure adequacy (the metrics mentioned under c)) target levels for each indicator may be defined to set an absolute threshold level for adequacy. If adequacy according to the indicator is below target, adequacy measures may be considered or decided that bring the adequacy indicator to the desired level.

Instead of using absolute target levels of adequacy indicators for decisions on adequacy measures, benchmarks may be used comparing the costs of the adequacy measures with the difference of economic costs of adequacy before and after adequacy measures (i.e. the economic benefit of the adequacy measures).

The metrics defined under c) would logically lead to the following list of standards that could be applied:

Target levels:

Reserve margin : $\geq X$ (MW or %)

EENS: $\leq z$

EENS * VOLL⁵⁸ $\leq Q$

LOLP: $\leq x$

LOLE: $\leq y$

Benchmark:

$\{\text{EENS (before adequacy measures)} - \text{EENS (after adequacy measures)}\} * \text{VOLL} \geq$
costs of adequacy measures.

The questionnaire also provides some other examples and respondents are encouraged to provide their own definitions for the standards they use, if they deviate from the ones provided.

⁵⁸VOLL (Value of Lost Load) corresponds to the estimated total damage caused by interruptions divided by the amount of electricity not delivered in a given time period (usually an year). VOLL is also defined as the value (€/kWh) an average consumer puts on an unsupplied kWh of energy, rather than the cost of an unsupplied kWh, or as the customer's WTP to avoid an additional period without power.

9 APPENDIX B - STATE AID INQUIRY DATA AGGREGATION

This appendix is included in a dedicated excel file.

10 APPENDIX C – PUBLIC DATA

This appendix is included in a dedicated excel file.

11 APPENDIX D - SUMMARY OF RESULTS FROM EMPIRICAL ANALYSIS

11.1 Contents

This Appendix includes a summary of the empirical analysis.

11.2 Aggregated answers from public sources

Wide research on the web and in selected documents was conducted to obtain information on current practices regarding Generation and System Adequacy.

The CEER's assessment complemented with web research constitutes the benchmark data source

Part of the gathered information was obtained from the document "Assessment of electricity GA in European countries" [21] prepared by the CEER and based on questionnaires addressed to TSOs and NRAs. The CEER analysed current practices and methods used to assess GA across Europe, based on answers received from 20 CEER members and observer countries. The CEER report includes already processed information but also provides orientations for identifying the web pages of the entities that presumably offer further information on these issues. Although most of the information was obtained directly from the web pages, the CEER questionnaire guided the research. The structure of the findings is based on the CEER report, but the summary tables below and the issues presented in the analysis have been tailored to the information obtained from the web.

In addition, complementary information on issues not considered by the CEER report (e.g. VOLL) was found on the web pages of the national TSOs, ENTSO-E, and the NRAs.

Heterogeneous data are processed in specific aggregations for specific key issues

As the collected information has a heterogeneous structure (and not homogenous, as could be obtained from a questionnaire), the data was processed accordingly, with ad hoc classification of selected issues. Therefore, there are no general tables, but the information underlying each issue is customised to a specific set of possible answers.

In some cases it was necessary to interpret the information found on the web pages; therefore, some error in the classification is possible but not likely. For these reasons, we preferred to describe the total number of findings on each issue, rather than to identify the specific institution from which the information was obtained (TSOs or NRAs).

Key issues are extracted from public data

Based on the information found in the web research and in some selected documents, it has been possible to draw a reasonable number of answers to the key issues⁵⁹. Investigated key issues are presented in the BOX on the next page.

23 Countries covered by public data processing

Data was obtained from the following 23 countries (at least enough information to address one of the proposed issues):

⁵⁹ The key issues do not necessarily correspond to the questions in the original questionnaire, but they are organised according to the information found in the web research.

- Austria
- Belgium
- Czech Republic
- Denmark
- Estonia
- Finland
- France
- Germany
- Great Britain
- Hungary
- Iceland
- Ireland
- Italy
- Lithuania
- Luxemburg
- Netherlands
- Norway
- Portugal
- Romania
- Slovenia
- Spain
- Sweden
- Switzerland

In the following sections the findings obtained for each key issue are summarised. All the findings are included, country by country⁶⁰, in Appendix C.

⁶⁰The classification N/A corresponds to the case when information was not found on the consulted web pages on the issue. Therefore, in several cases there may be a positive answer to a direct question, so the positives shown in the tables should be considered as minimums.

KEY issues addressed with public data

1. Role of the Institutions on GA: refers to the institutions responsible for processing, monitoring and reporting the GA estimation, as well as the type of reporting provided.
 - 1.1. Institution responsible for ensuring GA
 - 1.2. Institution responsible for performing or processing GA assessments
 - 1.3. Institution responsible for monitoring GA
 - 1.4. Reporting authority
 - 1.5. Reports
2. Reliability metrics and targets: identifies the reliability metrics used and how they relate to GA
 - 2.1. Reliability standard used to measure GA
 - 2.2. Reliability standard target
 - 2.3. Actions taken in event of non-fulfillment of the target
3. Metric Calculation Input Data: describes the basic information used to calculate the metric values
 - 3.1. How system stress (or non-appropriate GA) is defined
 - 3.2. Are key scenarios considered in the adequacy assessment? Are these scenarios in line with the SO&AF scenarios?
 - 3.3. The main principles of the methodology for establishing load forecast (historical data, parameters, etc.). How are uncertainties on load modeled?
 - 3.4. What are the key scenarios used for load forecast? Are these scenarios consistent with those used by the ENTSO-E to elaborate the SO&AF?
 - 3.5. Does the methodology include economic (e.g. GDP), policy (e.g. energy efficiency measures) and demographic drivers? Where do the data come from?
 - 3.6. Does the methodology include contributions from demand response? Where do the data come from?
4. Consideration of uncertainties: describes how some stochastic issues are approached for calculation of the metric
 - 4.1. What are the principles of the methodology to assess the evolution of generation capacity (investments, decommissioning)? Where do the data come from?
 - 4.2. How are uncertainties on generation (e.g. unplanned outages) modeled? How are reliable generation technologies (nuclear, thermal, non-variable RES) considered?
 - 4.3. How is generation from variable output (e.g. RES) taken into account in the analysis? Does the analysis include existing or future potential storage capacity?
 - 4.4. How are balancing reserves (including ancillary services) as well as emergency instructions taken into account in the process?
 - 4.5. What are the key scenarios used for generation forecast? Are these scenarios consistent with those used by the ENTSO-E within the SO&AF?
5. Methodology to calculate the metric: identifies the methodology used to calculate the metrics
 - 5.1. Provide a broad outline of the methodology (probabilistic/deterministic approaches; simulation-based analytical) to assess system or generation adequacy.
 - 5.2. What are the key adequacy forecast scenarios? Are these scenarios consistent with those used in the SO&AF? Do they also include an analysis at a smaller scale (e.g. regional)?
6. Consideration of Transmission: describes what method (if any) is used to consider transmission in the metric calculation
 - 6.1. Is the assessment based on a "copperplate" approach, or does it consider a detailed modeling of the internal transmission constraints?
 - 6.2. What assumptions about cross-border flows are made for the purpose of assessing adequacy?
7. Availability and Use of Value of Lost Load (VOLL) Concept: describes whether the VOLL concept is used and how
 - 7.1. VOLL availability
 - 7.2. Data on availability
 - 7.3. Use for planning
 - 7.4. Estimation Method

11.2.1 Institutional issues

Government mandates TSOs in most countries as responsible for GA assessment

Table 11.1 - Institutional Issues

Issue	Government /Ministry	NRA	Market/TSO	Others	N/A
Institution responsible for ensuring GA	10	3	2	Market participants (4)	6(*)
Institution responsible for GA assessment	7	1	12	-	3
Institution responsible for monitoring GA	4	7	9		7(*)
Reporting authority	2	2	3	ENTSO-E (DN)	15(*)
Reports	In 6 cases, GA reports with a 1- to 10-year horizon				

(*) In some cases, both the NRA and Ministry or the TSO and Ministry share responsibility.

The results show that, although there are institutions responsible for assessing the GA in more than half of the countries, in few cases the reports are complete and systematic.

TSOs are most often the institutions responsible for assessing and monitoring the GA.

In some cases, there is government responsibility for protecting the GA, whether directly or through the TSO, by organising tenders for additional capacity.

11.2.2 Reliability and Generation Adequacy Metrics

Wide variety of metrics used to assess GA in different countries

Table 11.2 - Reliability and Generation Adequacy Metrics

Issue	Reserve margin	LOLE/LOLP	Expected non-supplied energy	Others	N/A
Reliability Standard used to measure GA	2	11	-	Frequency deviation (1)	9
Reliability standard target	Between 10% and 35% (*)	Between 3 and 8 hours of interruption per year			
Actions in event of non-fulfilment	Gov. or NRA authorised to launch tenders for additional capacity Other types of measures Capacity market				

(*) Not strictly comparable, as in some cases (e.g. SP) the margin is on the firm capacity, which may be lower than the nominal capacity (e.g. firm capacity of wind plants is lower than 10%)

In general, we find no clear relationship between the GA metrics and actions for preventing lack of supply.

No clear criterion to set the metric target.

11.2.3 Metric Calculation Input Data

System stress evaluation can provide the adequacy assessment with information

Table 11.3 - System Stress Measures

Issue	GA metric (LOLE, LOLP)	% of Reserves	Ad hoc parameters	N/A
How system stress is defined	2	3	5	13

Although in most cases there is no specific definition of "system stress", there are adequacy assessments, as seen in the following table.

Adequacy assessment depends on main scenario variables and their underlying drivers

Table 11.4 - Variables Considered in GA Estimation

	Demand Growth	Nuclear phase-out	RES penetration	Other generation sources	SO&AF	N/A
Scenarios considered in the adequacy assessment	10	1	4	5	7	6

It is difficult to systematise these answers, as the criteria used to define input data and the corresponding methodology are country-specific. As expected, in all cases offering relevant information, there are demand forecasts. Most of the cases uses as reference either SO&AF or other information from the ENTSO-E.

Table 11.5 - Load Forecast Variables

Issue	Historical data	GDP	Temperature	Others	Uncertainty modelled?	N/A
Main principles of the methodology for load forecast	11	10	4	3	-	7

In general, historical and GDP growth data are used jointly. In one case expected electricity prices are used. There are no explicit answers on uncertainty modelling, but temperature is among the reasons for demand volatility.

Table 11.6 - Scenarios for Load Forecast

Issue	Single demand scenario	Several scenarios	Consistent with SO&AF	N/A
Key scenarios used for load forecast. Are they consistent with the SO&AF?	4	11	3(*)	8

(*) The number where SO&AF is explicitly mentioned, but not necessarily the number where it has been considered.

In general, several scenarios are used (typically two or three). In most of the cases SP&AF is not considered, while in others it is only partially considered.

Table 11.7 - Policy and Energy Efficiency in Load Forecast

Issue	Policy	Energy Efficiency	N/A
Does the methodology include policy and energy efficiency measures?	11	7	21

In general, policy and energy efficiency are considered.

Table 11.8 - Origin of Data Used for Load Forecast

Issue	Statistical or other Gov. or Public Sources	TSO	TSO and other Public Sources	Unreported source	N/A
Where do the data come from?	6	2	2	6	9

Table 11.9 - Demand Response

Issue	Included	Not included	N/A
Does the methodology include contribution from demand response?	5	10	7

It is worth mentioning that, in three cases, demand response schemes are in place although they are not included in the methodology to calculate GA.

11.3.1 Consideration of uncertainties

Sources of uncertainty can influence GA assessment

Table 11.10 - Sources for Evolution of Available Generation

Issue	Generators, investors, association of producers	Government targets	Experts	TSO	N/A
Methodology to assess the evolution of generation capacity (investments, decommissioning)	14	4	1	3	5

Main uncertainty is connected to the availability of production sources

Most of the information comes from existing generators and investors. This creates some uncertainties in the medium- and long-term, as on the one hand some investments can be cancelled (experience shows that this happens with a significant proportion), while on the other hand others can be postponed or cancelled based on a perception that there will be an excess of additional generation that may push down prices.

Table 11.11 - Modelling of Generation Availability

Issue	Monte Carlo Simulation	Deterministic	Probabilistic	Deterministic + probabilistic	N/A
How are uncertainties (e.g. unplanned outages) on generation modelled?	2	7	3	3	8

The probabilistic factor is interpreted as a calculation of the probability of having some capacity available (value P or greater). In this case, the probability of meeting demand, D, is obtained from this curve, when P=D. No explicit references on whether these curves take into consideration intermittent RES.

The deterministic cases are based on either the reserve margin or on the fulfilment of the N-1 condition.

Table 11.12 - RES Modelling

Issue	RES through Monte Carlo	Deterministic approach to RES	RES output=0	Storage (only PS)	Storage not considered	N/A
How is generation from variable output taken into account? Does the analysis include existing or future potential storage capacity?	1	11	4	4	8	9

In the deterministic case, there are three approaches:

- To assume that intermittent RES makes some contribution to supply in peak hours (from 5 to 20% of installed capacity)
- Intermittent RES represented as a generation series based on historical data
- Probability curve (1 case)

Only existing or planned water-pumping storage is considered.

Table 11.13 - Balancing Reserves

Issue	Added to capacity requirements	Not considered	Future available capacity to meet requirements assessed	N/A
How are balancing reserves and other AS and emergency instructions taken into account?	6	6	3	10

Information on this issue is rather dispersed, as GA usually considers the total availability of generation necessary to meet the peak load. However, more detailed analysis should consider that further to total capacity, enough qualified capacity should be available to provide a minimum volume of frequency, and enough voltage regulation capacity to protect system stability.

Single-country, multi-scenario analysis has to adopt assumptions consistent with those shared for centralised assessment

What are the key scenarios used for the generation forecast? Are these scenarios consistent with those used by the ENTSO-E within the SO&AF?

Table 11.14 - Scenarios for Generation Forecast

	Several Scenarios	One scenario	Consistent with SO&AF	N/A
Key scenarios used for generation forecast? Are they consistent with the ENTSO-E within the SO&AF?	11	3	7	12

Although in most cases several scenarios are used, the manner in which they are defined can differ:

- Adaptation of existing generation to environmental requirements (1)
- Phasing out of nuclear plants (1)
- Delays/cancellation of ongoing generation projects (7)
- Peak load due to meteorological impact on demand (1)
- Several variables (1)

In some cases, there are no references to the use (or non-use) of SO&AF; in which case the response is considered as no.

11.3.3 Methodology to calculate the metric

To assess GA both deterministic and probabilistic methods are currently in use

Table 11.15 - Methodology for GA Calculation

Issue	Monte Carlo	Deterministic	Probabilistic	Deterministic + Probabilistic or Monte Carlo	N/A
Outline of the methodology to assess system or generation adequacy.	7	5	2	1	11

A Monte Carlo simulation performs an hourly simulation of the system. There is no information on which variables are considered to be stochastic.

A deterministic method aims to estimate the reserve margin during peak hours.

Probabilistic methods are based on the calculation of the probability of capacity availability.

11.3.4 Consideration of Transmission

Internal transmission network is rarely considered, cross-border capacity is taken into account with simplification of the related modelling

Table 11.16 - Internal Transmission Modelling

Issue	Considered in detail	Only main constraints	Not considered	N/A
Is a detailed modelling of the internal transmission constraints considered?	1	3	10	11

In general, the answers argue for the existence of a few important internal constraints; therefore, it is not necessary to model national transmission systems.

Table 11.17 – Cross-Border Flows Modelling

Issue	Neighbouring countries are modelled and simulated	Deterministic assumptions on flows in the interconnections	No cross-border flows are considered	N/A
Assumptions about cross-border flows?	5	7	4	10

Only in the cases where the neighbouring countries have been modelled with some level of detail would it be possible to assess the impact of external support on adequacy. Ignoring external support leads to a strong underestimation of the GA, and therefore may trigger alarms or last measures when such may not be necessary.

11.3.5 Availability and Use of VOLL Concept

VOLL measures are missing in most cases and mainly based on surveys when available

Table 11.18 - Existence of VOLL values

Issue	Yes	N/A
VOLL availability	9	15

Table 11.19 - Use of VOLL for Planning

Issue	Yes	No
Is VOLL used for planning?	3	6

Table 11.20 - VOLL Estimation Method

Issue	Surveys	Production function	Set by regulations
VOLL estimation method	5	3	1

Some important comments on the availability and use of VOLL:

- Relatively few countries have calculated the value of VOLL.
- However, in most cases, the objective of obtaining a VOLL value has been for its use in incentives regulation or for other purposes, not for planning.
- In some cases surveys aimed to obtain information for incentives regulation.

11.4 Aggregated answers from the SAI data

SAI data are available only for a limited number of countries so no representative findings can be derived from them

Twelve questions from the SAI were related to adequacy and adequacy assessments. For these questions, non-confidential answers were available from 9 TSOs. Depending on the extent and detail of the answers provided, the answers cover several questions from the original questionnaire. In the following sub-sections, answers are aggregated to the 7 sub-categories of questions extracted from the original questionnaire.

The elaboration of relevant data are reported here for the sake of completeness even if they do not add any relevant information to the analysis.

Aggregation details can be found in Appendix B.

11.4.1 Definitions

No answers to these questions could be derived from the SAI data.

11.4.2 Adequacy processes

No answers to these questions could be derived from the SAI data.

11.4.3 Methodology

Table 11.21 – Methodology to assess adequacy (1)

Country ID	TSO	Provide a broad outline of the methodology to assess system or generation adequacy.					How is the transmission network modelled for the purpose of the adequacy assessment?			What are the main variables featuring in the models used to assess adequacy?					
		deterministic	probabilistic	both	experience based	number of random samples	transmission network	zonal network	regional network	generators	demand	interconnection capacity	internal congestion	demand response	other
BE	Elia		x						x	x	x	x			
DK	Energinet.dk		x					x	x	x	x			x	
FR	RTE		x						x	x	x	x	x	x	x
GB	SONI														
HR	HOPS	x													
IE	EirGrid		x												
IT	Terna			x											
PL	PSE S.A.	x								x	x				1)
PT	REN		x							x	x	x			
SE	SVENSKA KRAFTNÄT			x											

1) Required reserves

Table 11.22 - Methodology to assess adequacy (2)

Country ID	TSO	Question	What assumptions about cross border flows are made for the purpose of assessing adequacy?				What is the time granularity of the modelling exercise supporting the adequacy assessment?		Please specify which sensitivity scenarios are normally included in adequacy assessment						Is there any procedure to validate the adequacy model in respect to historical results?		What form of coordination with neighbouring SOs takes place for the purpose of assessing adequacy?		What is the source of the main modelling tool(s) that you use?		
			flows based on hist. Data	NTC	imports assumed	regional modelling of d & s	CBF = 0	hourly	merging similar hours	generation fleet evolution	demand evolution	internal network reinforcement	cross border capacity	demand side response	reserve allocation	sophisticated modelling	regular benchmarks (ex-post)	information exchange	common adequacy model	outsourced (industry standard)	outsourced (other)
BE	Elia		x				x								x			x			
DK	Energinet.dk						x								x						x
FR	RTE				x		x								x		x				x
GB	SONI																				
HR	HOPS																				
IE	EirGrid						x		x	x											
IT	Terna																				
PL	PSE S.A.										x										
PT	REN		2)				x														x
SE	SVENSKA KRAFTNÄT																				

2) 10%

11.4.4 Metrics of adequacy

Table 11.23 - Metrics for adequacy

Country ID	TSO	Question	Which indicators do you use to measure adequacy?					Is the use of those metrics the result of a regulatory or legal requirement?			if yes: who is responsible for selecting the metrics									
			EENS	LOLE	LOLP	p95	capacity margin	others	No	Yes: legal obligation	Yes: regulatory obligation	Ministry	NRA	TSO	NEMO					
BE	Elia			x			x			1)		x								
DK	Energinet.dk		x	x	x						x									x
FR	RTE				x															
GB	SONI																			
HR	HOPS																			
IE	EirGrid				x															
IT	Terna		x	x	x															
PL	PSE S.A.											x								
PT	REN		x	x																
SE	SVENSKA KRAFTNÄT		x	x	x															

1) LOLE(95)

2) Load Supply Index (LSI)

3) Margin to cover N-1

11.4.5 Adequacy targets

Table 11.24 - Adequacy targets

Country ID	Question	What adequacy targets (levels or "standards") do you pursue?										target range	Which Authority sets/approves the adequacy target levels?				How are the target levels of the adequacy metrics set?						
		Annual LOLE <N1	Annual LOLE(95)<N2	EENS < N3% of consumption	Value of EENS < N4	no congestions	marginal costs =	marginal benefits	Capacity margin > N5	Other	N1 (LOLE)		N2 (LOLE95)	N3 (EENS/Consumption)	N4 (EENS)	N5 (Capacity margin)	Other	SO	NRA	Ministry	Parliament	historical planning	sophisticated CBA
BE	Elia	x	x								3	20								x			
DK	Energinet.dk	x									0,1						x						
FR	RTE	x					x				3						x					x	
GB	SONI																						
HR	HOPS																						
IE	EirGrid	x					x				8						x					x	
IT	Terna																						
PL	PSE S.A.								x						18%	1)							
PT	REN	x								2)	8												2)
SE	SVENSKA KRAFTNÄT																						

1) Year ahead: 18%; Month ahead: 17%; Day ahead: 14%; Day ahead (centrally dispatched units): 9%

2) p(LSI<1)<5%

11.4.6 Economic considerations

Table 11.25 - Economic considerations in the adequacy assessment

Country ID	Question	How do economic considerations enter your adequacy assessment?					In case economic considerations enter your adequacy assessment, who sets the VOLL?			How is the level of VOLL that you use calculated?					Is VOLL used in your adequacy assessment differentiated by consumer type and/or by type of service interruptions (such as: time of the day, day of the week, and/or duration of the interruptions)		What is the level(s) of the VOLL assumed in adequacy calculations and how often is it revised?		
		CBA	VOLL at adequacy target	MIC = VOLL (calculated)	MIC = VOLL (assumed)	None	VOLL by SO	VOLL by NRA	VOLL proposed by SO, approved by NRA	VOLL proposed by SO, approved by Ministry	surveys in other countries	customer surveys	macroeconomic analysis	case studies	published by NRA	one value for all	large customers + small consumers seperated	no voll	range
BE	Elia																		
DK	Energinet.dk																		
FR	RTE	x		x					x										
GB	SONI																		
HR	HOPS																		
IE	EirGrid			x															
IT	Terna																		
PL	PSE S.A.																x		
PT	REN																x		
SE	SVENSKA KRAFTNÄT																		

11.4.7 Transparency

Table 11.26 - Transparency

Country ID	TSO	What information are you required to publish and/or to send to the regulator or Government on the adequacy assessment?								What information are you required to publish and/or to send to the regulator or Government on the target?					What information are you required to publish and/or to send to the regulator or Government on the VOLL?									
		Publish	Sent to NRA	Sent to government	General Methodology	Network Models	simulations	assumptions	sensitivity analysis	outcomes	Publish	NRA	Government	origin	methodology	validation method	argumentation	Publish	NRA	Government	origin	methodology	validation method	argumentation
BE	Elia	x	x								x	x												
DK	Energinet.dk																							
FR	RTE																							
GB	SONI																							
HR	HOPS																							
IE	EirGrid		x								x													
IT	Terna																							
PL	PSE S.A.			x																				
PT	REN			x																				
SE	SVENSKA KRAFTNÄT																							

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