Methodological improvements of Resource Adequacy Assessments

Work Package 5
Final report

Scientific evaluation of the explanatory and analytical power of resource adequacy assessments with regard to extreme scenarios

Study on behalf of the
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Abbreviations

ASN	Autorité de sûreté nucléaire (French nuclear safety authority)
CEENS	Conditional Expected Energy not Served
CEP	“Clean energy for all Europeans”-package
CLOLE	Conditional Loss of Load Expectation
CO2	Carbon Dioxide
CRM	Capacity remuneration mechanism
CRS	Central reference scenario
DSO	Distribution system operator
EENS	Expected Energy not Served
EMR	Electricity Market Regulation 2019/943
ENTSO-E	European network of transmission system operators for electricity
ERAA	European resource adequacy assessment
EU	European Union
EU-MS	European Member State
EV	Electric vehicle
EVA	Economic viability assessment
FBMC	Flow-based market coupling
GW	Gigawatt
HVDC	High-voltage direct current
ICT	Information and communications technology
KPI	Key Performance Indicator
LOL	Loss of Load
LOLE	Loss of Load Expectation
LOLP	Loss of Load Probability
MAF	Mid-term adequacy forecast
MC	Monte Carlo (simulation)
NECPs	National energy and climate plans
RAA	Resource adequacy assessment
RE	Renewable energies
RPR	Risk Preparedness Regulation 2019/941
RS	Reliability standards
STSAA	Short-term and seasonal adequacy assessment
TSO	Transmission system operator
UCED	Unit commitment and economic dispatch

Executive Summary

On EU level, assessments of resource adequacy are today mainly framed by two different legislations, the Electricity Market Regulation 2019/943 (EMR) and the Risk Preparedness Regulation 2019/941 (RPR). While both Regulations do not explicitly refer to each other, overlaps regarding methodological approaches do occur in practice. Both regulations require modelling of the electricity system to analyse whether demand can be covered at the electricity markets under specific circumstances – under the EMR in the form of Resource Adequacy Assessments (RAA) and under the RPR in the form of analysing extreme events and short-term and seasonal adequacy assessments. This report therefore deals with the question whether a modelling tool used for RAA can also be applied (in an adapted form) under the RPR to assess extreme events.

Based on an analysis of the implementation of the respective requirements in EMR and RPR, we identified three different approaches to assess such extreme events using (adapted) RAA-tools which differ regarding their probabilistic degree. We call them the "full probabilistic approach", the "conditional probabilistic approach", and the "deterministic approach". The application of these approaches depends on the nature, the likelihood of occurrence and the predictability of the impact of the respective extreme event.

The full probabilistic approach aims at an unconditional probability and includes random variables with their respective probability distributions (i.e., for climatic conditions and unplanned outages). With regard to a detailed analysis of extreme events, this has the difficulty that an extreme event is only one unlikely outcome out of numerous alternatives or may even not be covered by the input data at all. For the purpose of RPR, it will typically be more informative to analyse the system under the condition that the extreme event is taking place – even though detailed information on an event may in principle also be derived in a full probabilistic approach with a deep-dive into the event by performing a 'critical hour analysis'.

A more specific analysis can either be performed stochastically or deterministically. When the analysis is stochastic (i.e., by means of availability of resources and climatic conditions) but assumes that the extreme event is happening, we refer to it as a conditional probabilistic approach. If also the usually stochastic / probabilistic variables are set deterministically, we call it the deterministic approach. Thus, using adapted RAA-tools under the condition that an extreme event is happening is more suitable for an explicit analysis of extreme events and enables the direct calculation of meaningful KPI (e.g., Loss of Load, Energy not served).

While in principle RAA-models used under EMR seem to be suitable to assess all kinds of extreme events, some adaptations may be necessary. Choices have to be made in particular regarding the economic viability assessment as well as the probabilistic elements of the RAA-tools. In order to extract and analyse extreme events in detail, deterministic elements may have to be applied to focus on these events. That, in turn, also affects the KPI being used in RAA (usually LOLE and EENS), which have to be then interpreted differently when assessing extreme events in this way. KPI derived from such adapted RAA-tools are no longer expected values, but rather express the severity of the analysed event assuming it occurs. In turn, if extreme events are assessed using probabilistic RAA-tools, a critical hour analysis has to be conducted to assess the severity of the extreme event, since the probabilistic approach will dilute the impact of the extreme event in terms of LOLE and EENS.

It remains unclear, however, whether such adapted RAA-tools for focused analysis of extreme events fall within the scope of the legislative framework of the EMR or of the RPR. More regulatory clarity seems needed here, as the regulatory framework of the analysis may also have an impact on the measures being applicable to manage the different impacts that such extreme events will have on the system.

1. Introduction

In summer 2019, two important legislations were published in the Official Journal of the European Union as part of the "Clean energy for all Europeans"-package (CEP)[1], which contain legislative provisions regarding the assessment of security of supply in the electricity sector:

- The Regulation (EU) 2019/943 on the internal market for electricity[2] (Electricity Market Regulation; EMR), with provisions for European and national Resource Adequacy Assessments (RAA[3]), and
- The Regulation (EU) 2019/941 on risk-preparedness in the electricity sector[4] (Risk Preparedness Regulation; RPR), with provisions on the identification and assessment of crisis scenarios on national, regional and European level.

Both Regulations require ENTSO-E to draft methodologies for the concrete implementation of the respective assessments, which have to be approved by ACER.

While both Regulations do not refer to each other, it becomes increasingly visible in practical implementation that the respective provisions do overlap regarding the assessment of extreme events.[5] On the one side, the RPR requires the identification of crisis scenarios and assessment of their impact as well as a short-term and seasonal assessment on resource adequacy. The EMR, on the other side, does not only require for a probabilistic assessment of resource adequacy in a mid-term time horizon (i.e., up to ten years ahead), but also for specific sensitivities on extreme events. The overlap becomes particularly visible with extreme weather events, which are both part of regional crisis scenarios as identified by ENTSO-E for implementation of the RPR as well as explicitly named by the EMR as extreme event to be analysed in the context of RAA.

This raises several questions, in particular:

1. How can extreme weather events be appropriately analysed with the modelling tools applied for RAA?
2. Are the modelling tools applied for RAA also suitable to assess other crisis scenarios identified pursuant to the RPR?
3. Which modifications (if any) are needed to use the modelling tools applied for RAA also for the assessment of extreme events?

In this report, we scientifically evaluate the explanatory and analytical power of modelling tools applied for RAA with regard to extreme events. The main aim is to evaluate whether extreme events should and/or can be analysed with existing RAA-tools, and if so, whether those tools may have to be adapted to account for the characteristics of the extreme events. Furthermore, we discuss how to interpret the results of those assessments of extreme events. The report therefore aims at providing input for answering the three questions above. In contrast, it is the not aim of this report to answer the question, which implications potential

1 Cf. European Commission (2019a).

2 Cf. European Parliament (2019a).

3 In this report, we use "RAA" generally for any RAA on a European, regional or national level and we use "ERAA" when we refer specifically to the European Resource Adequacy Assessment performed by ENTSO-E.

4 Cf. European Parliament (2019b).

5 In this report we summarize in the following the terms 'extreme events', 'crisis scenarios' and so-called 'stress tests in RAA' as 'extreme events', as there is no clear and common differentiation between those terms, but they rather refer often to the same kind of events (such as extreme weather events).

modifications of the modelling tools may have regarding the classification as assessment under the EMR or RPR, and which consequences this could have regarding the measures being taken to address such events. This should be subject to a political debate on European level.

In order to deal with the three questions raised above, the report consists of five chapters.

- In the **first chapter** we outline the background of the report.
- In the **second chapter** we compare legislation and respective methods relevant for the assessment of extreme events in the EMR and RPR, identifying differences, similarities, and ambiguities.
- In the **third chapter** we analyse relevant crisis scenarios identified by ENTSO-E and elaborate which elements of extreme events are already reflected in existing RAA in the Penta-region.[6]
- In the **fourth chapter** we discuss whether it is technically possible to assess extreme events with (adapted) RAA-tools (i.e., without necessarily being relevant for RAA based on the EMR).
- Finally, we conclude the analysis in the **fifth chapter**.

[6] The region of the Pentalateral Energy Forum (Penta-region) consists of Austria, Belgium, France, Germany, Luxembourg, the Netherlands and Switzerland.

2. Legislative and methodological comparison of RAA and RPR-assessments

In this chapter we compare the legislative framework of RAA- and RPR-assessments for extreme events. First, we provide an overview on the main legal provisions of the EMR and RPR as well as the subsequent documents describing the methodologies as drafted by ENTSO-E and approved by ACER, which are the basis for this report:

Relevant elements based on the EMR	Relevant elements based on the RPR
EMR: Art. 20, 23, 24, 25, 27.	RPR: Art. 1, 5, 6, 8.
ENTSO-E draft methodology for the European resource adequacy assessment[7]	ENTSO-E draft methodology for identifying the most relevant regional electricity crisis scenarios[8]
ACER decision 24/2020[9] on the methodology for the ERAA	ACER decision 07/2020[10] on the methodology for assessing regional electricity crisis scenarios, incl. Annex 1[11] on Art. 5 RPR
ENTSO-E draft methodology for calculating the reliability standard[12]	ENTSO-E draft methodology for assessing seasonal and short-term adequacy[13]
ACER decision 23/2020[14] on the methodology for calculating the reliability standard	ACER decision 08/2020[15] on the methodology for assessing seasonal and short-term adequacy

Table 1: Overview on the main legal provisions of the EMR and RPR and the subsequent regulation[16]

The Articles in the EMR and RPR basically require three different methodologies:

1. A methodology for Resource Adequacy Assessments (Art 23 EMR) – in the following RAA-method,

2. A methodology to identify crisis scenarios and analyse their potential impacts (Art 5 RPR) – in the following RPR-method[17], and

7 Cf. ENTSO-E (2019a).
8 Cf. ENTSO-E (2019b).
9 Cf. ACER (2020a).
10 Cf. ACER (2020b).
11 Cf. ACER (2020e).
12 Cf. ENTSO-E (2019c).
13 Cf. ENTSO-E (2019d).
14 Cf. ACER (2020c).
15 Cf. ACER (2020d).
16 See chapter 0 for detailed extractions of the relevant legal provisions and the subsequent regulation.
17 Art 5 RPR contains two elements. The first is the identification of relevant regional crisis scenarios and the second is the assessment of potential impacts of those crisis events. In the following, the term 'RPR-method' refers to the assessment of the potential impact of crisis events pursuant to Art. 5.

3. A methodology to assess potential risks for security of supply in the short and medium timeframe (short-term and seasonal adequacy assessment – STSAA; Art 8 RPR) – in the following STSAA-method.

All three methodologies, the RAA-method as well as the RPR-method and the STSAA-method are looking at the same effects, i.e., threats for security of electricity supply. Thus, they apply, in principle, similar modelling elements and look at similar indicators. Nevertheless, all three methodologies have their specific characteristics and have to be distinguished accordingly.

Similarities, differences and possible ambiguities in the legislative framework (regulation, methods, decisions) of RAA and RPR-assessments are identified in the following sub-chapters:

- Concerning the **aim and time horizon** of the assessments, we describe the purposes and the timeframe foreseen by the legislations / the assessments in sub-chapter 2.1.

- Concerning **scenarios**, we describe differences and similarities in the genesis / identification of scenarios to be assessed with the RAA-, RPR- and STSAA-method in sub-chapter 2.2.

- Concerning the **modelling approaches** for the assessment of extreme events, we analyse which approaches are in line with the respective legislative requirements as well as how key performance indicators should be interpreted in different approaches in sub-chapter 2.3.

2.1 Aims and time horizons of the assessments

First of all, it can be stated that the different assessments required according to the EMR (RAA-method) and the RPR (RPR- and STSAA-method) aim at answering different questions.

RAA-method

The aim of a RAA is to answer the question whether any resource adequacy concerns have to be expected in the mid-term, i.e. from one year to ten years ahead of the finalisation date of the assessment, on an annual basis.[18] This analysis serves inter alia as basis to identify the need for capacity remunerations mechanisms (CRMs).[19] Therefore, the underlying model analyses the overall adequacy of the electricity system[20]: It is probabilistic by nature and should reflect the most expected system developments and relevant scenario uncertainties.

RPR-method

The assessment pursuant to Art 5 of the RPR shall, first, identify relevant regional crisis scenarios, including the appearance of simultaneous electricity crisis scenarios, and second, rank those risks according to their impact and probability. This assessment therefore aims to answer the questions, which specific crisis scenarios may appear and how their impact may

[18] Cf. Art. 23 (1) EMR.

[19] Cf. Acer Decision 8/2020.

[20] Cf. Art. 23 (1) EMR.

look like, irrespectively of whether those scenarios have already been materialised in the past (like cold winters) or not (like large-scale cyberattacks). Assessments according to Art. 5 RPR do not contain any specific time horizon. The extreme events to be identified and analysed can in principle occur at any time in the future. The definition of a specific time horizon is only relevant to identify the framework conditions for the analysis of a specific extreme event (e.g., how many renewables will be installed at the time of the event, etc). While such assessments may contain probabilistic elements, they are in principle based on largely deterministic settings by nature.

STSAA-method

Finally, the assessment pursuant to Art. 8 RPR aims at answering the question whether any specific risks may occur in the short-term and seasonal timeframe, i.e., up to six months ahead, that are likely to result in a significant deterioration of the electricity supply situation. The focus is usually on such risks which are already expectable explicitly for the time period under consideration at the point of conducting the assessment (such as a cold spell for an upcoming winter season). Hence, the assessment shall support in preventing, preparing for, and managing electricity crises.[21] This assessment is in principle probabilistic and thus more similar to the RAA-method than to the RPR-method, but with potentially some deterministic elements due to the shorter time horizon and thus more available information on possible system states / developments.

2.2 Definition of scenarios to be assessed

The different aims and time horizons of the respective assessments have inter alia an impact on the definition of the scenarios to be assessed.

RAA-method

According to the EMR, RAA shall be based on appropriate central reference scenarios (CRS) of projected demand and supply including an economic viability assessment (EVA). The CRS may be complemented by appropriate sensitivities on extreme weather events, hydrological conditions, wholesale prices and carbon price developments. Art. 3 (6) of the ACER decision 24/2020 Annex I specifies that additional scenarios and/or sensitivities complementing the CRS should be of European relevance and may be based on different assumptions related to input data and scenario uncertainties, including different economic and policy trends relevant for resource adequacy.

ACER allows for realistic alternative approaches to historic climate years for climate data in central reference scenarios (i.e., synthetic climate years to incorporate climate change). Moreover, it acknowledges that, in the context of the ERAA modelling exercise, other scenarios and sensitivities pursuant to Article 3 (6) e) of the ERAA Methodology may rely on climate data beyond the one used for the central reference scenarios. In particular, when this data incorporates extreme weather events, which should be reflected by appropriate sensitivities to the CRS, pursuant to Article 23 (5) b) of the EMR.[22]

Furthermore, pursuant to Article 23 (5) c) EMR, a RAA should contain separate scenarios reflecting the differing likelihoods of the occurrence of resource adequacy concerns which the different types of capacity mechanisms are designed to address. Thus, a RAA analyses

[21] Cf. Art. 1 RPR.

[22] Cf. ACER Decision 24/2020, Recital (79) c).

both scenarios with potential adequacy concerns in a range of “expectable” situations, as well as scenarios with potential adequacy concerns that may contain extreme events.

The CRS in the ERAA have to be based on the baseline data, which stems from the national projected demand, supply and grid outlooks prepared by each individual TSO. These national forecasts shall be consistent with existing and planned national policies, including national objectives, targets and contributions, and other projections contained in the National Energy and Climate Plans (NECP) of the respective EU-MS. For this baseline data provided by national TSOs, an EVA for all central reference scenarios has to be performed. The ERAA report shall clearly show whether and how the baseline data has been modified by the EVA (i.e., which capacities were removed and added). Furthermore, additional scenarios may be analysed pursuant to Art 23 (5) (c) EMR, where they are necessary in order to analyse specific situations with differing likelihoods of occurrence (especially extreme events), which the respective capacity mechanism is designed to address.

RPR-method

For RPR-assessments, the methodology according to Art. 5 RPR, as developed by ENTSO-E and approved by ACER, identifies electricity crisis scenarios in relation to security of supply on the basis of at least the risks whose initiating events are rare and extreme natural hazards, accidental hazards going beyond the N-1 security criterion, exceptional contingencies, and consequential hazards including the consequences of malicious attacks and of fuel shortages. The scenario development for RPR-assessments is based on electricity crisis scenario candidates determined by national TSOs in cooperation with the competent national authority. According to the legislation, the RPR-assessment methodology shall provide for a probabilistic approach for evaluating impact and likelihood of each crisis scenario. According to ENTSO-E, a probabilistic approach is superior to a deterministic method and thus preferred, but the required minimum for evaluating the likelihood and impact measures of a crisis scenario is performing a deterministic calculation. The relevant electricity crisis scenario candidates are then aggregated into regional crisis scenarios. Each relevant regional crisis scenario has finally to be assessed on the European as well as on the national level.

STSAA-method

Furthermore, the RPR requires in Art. 8 the identification of potential risks which may occur in the upcoming weeks and months. The focus here is usually on those relevant regional and national crisis scenarios which can be expected to take place with a certain likelihood in the following six months, such as a possible cold spell in the next winter or a heatwave in the next summer. It does usually not cover events where the likelihood of occurrence is difficult to estimate and/or not specifically linked to seasonal effects, e.g., a Cyberattack.

Following this overview, the overlap between the EMR and RPR becomes particularly obvious regarding the scenarios to be analysed. The scenarios explicitly named as examples for sensitivities in RAA include scenarios which are partly also covered by regional crisis scenarios to be identified pursuant to Art 5 RPR and general adequacy concerns to be analysed pursuant to Art 8 RPR. This holds true, in particular, for extreme weather events as well as for hydrological conditions, the latter to the extent that they reflect extreme events such as draughts or floods. In contrast, other potential sensitivities of RAA, such as specific political or economic developments, are not covered by the RPR. This raises the question which regulatory framework is relevant for those measures which are deemed appropriate to deal with the respective events covered both by the EMR and RPR.

2.3 Modelling approaches to assess scenarios and key performance indicators

The different analytical aims and definition of scenarios inevitably influence the modelling approaches to be applied to analyse the impact on security of supply of the respective scenarios.

RAA-method

In the RAA-method it is obligatory to apply probabilistic calculations when assessing the overall adequacy of the electricity system to supply current and projected demands for electricity at Union or Member State level. This usually contains a probabilistic analysis of relevant parameters which can be expected by market participants and vary regularly within a range of “expectable” conditions in a CRS, in particular weather conditions and forced outages. Other parameters, such as fuel or carbon price developments, are usually kept constant within a RAA, or will be adjusted in the form of different so-called ‘appropriate scenarios/sensitivities’, complementing the CRS. Those explicitly also shall assess extreme weather events pursuant to Art. 23 (5) (b) EMR. Furthermore, the application of at least the probabilistic KPI Loss of Load Expectation (LOLE) and Expected Energy Not Served (EENS) is required. From our point of view only such scenarios/sensitivities may be classified as full probabilistic[23] in the context of this report, where impact and probabilities are known and a reasonable expectation from a market perspective is reflected (i.e., well-motivated and with transparently derived assumptions).

RPR-method

In the RPR-method pursuant to Art. 5 RPR, either a probabilistic or a deterministic method shall be applied for evaluating the likelihood and impact of specific crisis scenarios, assuming the event will occur.[24] A probabilistic approach shall be favoured over a deterministic one where appropriate (i.e., depending on the particular scenario and the nature of its uncertainty). However, ENTSO-E’s final report on the necessity for common tools or methods documents the overall feedback from TSO that in most cases likelihood and impact of crisis scenarios have to be quantified by expert judgements, since historical databases on crisis events in most cases do not allow for a quantification of impact and probability or even probabilistic calculations.[25] This would lead to rather deterministic approaches in quantitative analyses of the impact of such events. However, formalised (esp. quantitative) methods for assessing extreme events in the context of risk preparedness seem to be rare in general. However, if adequate tools were referenced, TSOs indicated the use of probabilistic approaches in the context of RAA. In addition, there is no specific legal requirement regarding the application of any KPI. Nevertheless, LOLE and EENS may likely be two interesting KPI as well in order to quantify the impact of a given extreme event, even though potentially not the only ones.[26]

STSAA-method

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[23] It should be noted that the theoretical construct of a full probabilistic approach, i.e. including all possible future outcomes exactly with their accurate probabilities, is not achievable in practice. The true distribution of stochastic elements is unknown and has to be approximated. Furthermore, all empirical models currently used apply some variables in a deterministic way, in particular to keep model complexity at feasible levels. In these cases, assumptions should reflect best available unbiased estimates.

[24] Cf. also ACER decision 7/2020 Annex 1, Art. 8.

[25] Cf. ENTSO-E (2021).

[26] There are also other KPI relevant in the context of resource adequacy / risk preparedness, such as the “P95 LOLE / EENS” which had been previously applied in the Belgian RAA (accounting for events occurring every 20 years) or “excess load” during LOLE-hours (quantifying the missing resource capacity).

The STSAA-method pursuant to Art. 8 RPR has in general to be performed by probabilistic calculations concerning climate conditions and forced outages of supply and grid elements. However, in such scenarios one or more of the usually probabilistic parameters in RAA will be limited to a small and more focussed number of input data series (such as a selection of winter scenarios) or deterministically designed events, while other parameters remain probabilistic. Furthermore, the relevant KPI for STSAA are LOLE and EENS as for RAA. However, the derived KPI must be interpreted carefully, since the probabilistic calculations may contain deterministic elements as specific parameter may be less variable in the shorter time horizon under consideration (e.g., information on unplanned outages of power plants). Thus, LOLE and EENS do not necessarily represent the average state / development of the system to be expected for a whole year as it is the case for CRS in RAA (mean expectation of market participants). Furthermore, within the STSAA it is obligatory to perform a spatial analysis of those hours where the Loss of Load Probability (LOLP) is not zero.[27] Such a spatial analysis of critical hours within a probabilistic assessment is also called critical hour analysis. It may also be applied to the other approaches in order to get more direct information about the hours contributing to overall LOLE-values within the whole set of MC-simulations.

In the following graph, this aspect of different probabilistic degrees of the assessments according to EMR (blue) and RPR (green) are shown, in relation to the different time horizons to be assessed and available tools for the assessment.

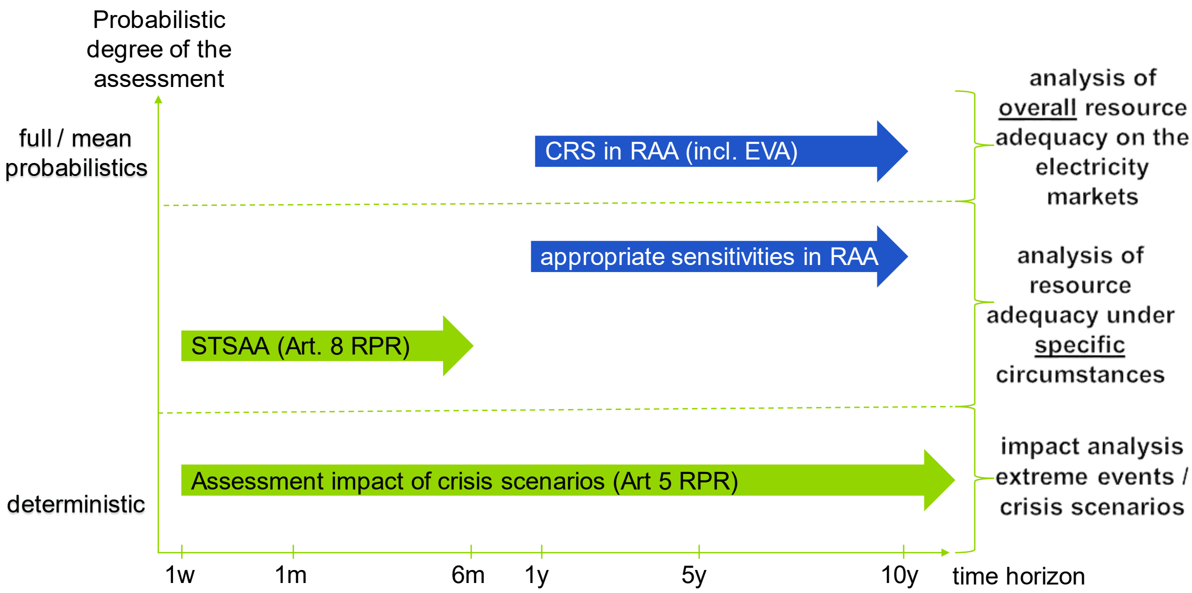

Figure 1: Overview on approaches for electricity system assessments in relation to the time horizon under consideration and the probabilistic degree of the assessments.

The figure demonstrates that RAA pursuant to the EMR and the analysis of extreme events pursuant to the RPR cover in principle similar time horizons. Even though there is no official definition of the timeframe to assess extreme events pursuant to Art. 5 RPR, it seems reasonable to apply the framework conditions of the near future (i.e., the upcoming years) to the analysis instead of conditions in 15 or 20 years, which are much more difficult to define. The STSAA only covers the shorter timeframe of up to six months.

Also, it is stated in ENTSO-E's '*Final report on the necessity for development of computational methods and tools for assessment of regional electricity crisis scenarios'* [28] that TSOs suggest the use of probabilistic resource adequacy calculations for analysing extreme

27 Cf. Art. 3 (8) of ACER (2020d).

28 Cf. ENTSO-E (2021).

events. However, TSOs describe that expert judgment is today the predominant method to assess likelihood and impact of most crisis scenarios in the RPR context. This contrast seems to be based on the general perspective, on the one side, that probabilistic assessments are favoured over deterministic approaches, and the acknowledgement, on the other side, that a better understanding of the impact of an extreme event requires a specific analysis of that event. We therefore see a gradual change in the preferred modelling approach from more probabilistic in the context of RAA to more deterministic in the context of extreme events.

We will therefore analyse technical possibilities in assessing extreme events with (adapted) RAA-tools in Chapter 4. We will examine, which adaptions of existing RAA-tools have to be done in order to enable appropriate assessments of extreme events and whether such adjusted RAA-tools are appropriate for the assessment of different types of extreme events identified pursuant to the RPR (i.e., reflected in the relevant regional crisis scenarios identified by ENTSO-E).

3. Relevant crisis scenarios identified by ENTSO-E and (extreme) events reflected in existing RAA

This chapter provides first for an overview of the relevant regional crisis scenarios which ENTSO-E has identified in cooperation with public and regulatory authorities of different levels pursuant to the RPR. More precisely, we describe under which circumstances the crisis scenario is initiated and what kind of challenges they bear for resource adequacy.

In a second step, we present the events that have been covered by sensitivities, in addition to the CRS, in recent RAA in the Penta-region. We will, on the one hand, categorise them by their type of event. On the other hand, we will group them by the applied methodology.

3.1 Characteristics of relevant regional crisis scenarios identified by ENTSO-E

ENTSO-E requested the TSOs of all Member States to submit candidates for crisis scenarios. Then, based on 231 submitted candidate scenarios, ENTSO-E constructed 31 relevant regional crisis scenarios which represent "*a present or imminent situation in which there is a significant electricity shortage, as determined by the Member States and described in their risk-preparedness plans, or in which it is impossible to supply electricity to customers*". In order to assess the scenarios with a view to consider them with RAA-tools, we will group the 31 scenarios by their type of initiating event (i.e., extreme weather, human-related, technical failures). We follow strongly the categorisation proposed by ENTSO-E.[29] In total, eight types of scenarios according to their initiating events were identified. Table 2 below lists all crisis scenarios and their respective type.

Cyber & physical attacks		
Cyber attack – entities connected to power grid	Physical attack – critical assets	Threat to key employees
Cyber attack – entities not connected to power grid	Physical attack – control centres	Insider attack
Extreme weather		
Storm	Cold Spell	Heatwave
Precipitation and flooding	Winter Incident	Dry period
Natural disaster		
Solar Storm	Volcanic eruption	Pandemic
Forest fire	Earthquake	
Fuel shortage		
Fossil fuel shortage (incl. natural gas)	Nuclear fuel shortage	
Human-related		
Human error	Strike, riots, industrial action	
Market-related		
Unforeseen interaction of energy market rules	Unwanted power flows	

29 Cf. ENTSO-E (2020b).

Technical failure		
Local technical failure with regional importance	Loss of ICT systems for real-time operation	Simultaneous multiple failures
Serial equipment failure		
Miscellaneous		
Power system control mechanism complexity	Unusually big RES forecast errors	Industrial/nuclear accident

Table 2: Identified relevant regional crisis scenarios by ENTSO-E.

Six of the identified crisis scenarios include some form of **cyber or physical attack** on ICT systems or physical assets. All countries represented in ENTSO-E can be potentially affected, even simultaneously. All parts of the electricity system could be potential targets, no matter if directly connected to the grid (TSOs, DSOs, power plants, major loads) or not (market participants, power exchange platforms, market makers). It is conceivable that the attacker successfully disrupts or destroys multiple targets at the same time, leaving the electricity system with less generation and transmission capacity.

Another seven crisis scenarios deal with **extreme and disruptive weather events**. They include extreme cold weather (cold spells, winter incidents), extreme warm weather (heat waves, dry periods) as well as events associated with heavy precipitation or strong winds (storms, floods), lasting for several days or a few weeks. On the one hand, an extreme weather event may induce a high level of electricity demand for heating or cooling. On the other hand, the availability of assets of the electricity system may be limited, when the weather event restricts their functioning or even damages or destroys it. For example, in dry periods the cooling water for thermal capacities can reach critical temperature levels or be less available, storms can disrupt HVDC connections, and floods may destroy some assets completely.

Five crisis scenarios represent the outbreak of a **natural disaster**. This includes forest fires, a volcanic eruption (e.g., in Iceland), an earthquake, a solar storm, and a pandemic. The consequence of a natural disaster is the unavailability of transmission lines or generating capacity, either due to damage / destruction of an asset or a short staffing of operating personnel (esp. in case of a pandemic).

Two more scenarios consider the possibility of a **fuel shortage**. This may affect the supply of fossil or nuclear fuels. The root of the shortage can be a disruption of fuel production, failures of the fuel supply system, or supply limitation due to political reasons or weather conditions, occurring in a period with high fuel demand and/or low storage levels. The shortage leads to a limited availability by the affected capacities.

Another two identified crisis scenarios are **human-related**. One scenario is induced by a human error of some individual working in the electricity system (TSO, DSO, generation unit). The second crisis scenario involves the inability or refusal of individuals in the electricity system to work, due to some kind of dispute leading to strikes, blockades, riots or other forms of social unrests. In these scenarios, one or multiple elements of the electricity system are not or not fully operational, bearing the danger of cascading events affecting further elements.

Two additional crisis scenarios deal with **market-related** risks. One addresses the risk of unwanted power flows in the system, for example induced by higher-than-expected infeed of renewables or atypical generation patterns. A massive deviation of physical power flows from the result of the market- and algorithm-based schedule could lead to congestion of network elements, voltage problems and overload of grid elements. The second scenario is initiated by an extreme behaviour of market participants (market panic), induced by, for example, a change in market rules or mechanisms, or unfamiliar market circumstances. This may lead to unusual market results and, consequently, unusual volumes and directions of trade flows. Both scenarios could, in the worst case, cause cascading failures of grid elements and result in involuntary load shedding or regional blackouts.

Four crisis scenarios consider **technical failures** of different types, including a local failure with regional consequences, the loss of ICT systems, failures of multiple assets at the same time and a serial equipment failure. This may inter alia disturb the functioning of the electricity markets, if TSOs cannot communicate with market participants, and/or market participants are unable to follow their schedules.

Three further scenarios are classified as **miscellaneous**, namely high RE forecast errors, a major industrial or nuclear accident, or problems related to the complexity of the power system control mechanism, and therefore different in nature. However, their consequences are comparable to the ones already described for the other event types. RES forecast errors are demanding for TSOs dispatch algorithms, similar to unwanted power flows. The consequences of a major industrial or nuclear accident would be comparable to a natural disaster. Consequences of power system control mechanism complexity corresponds to the impacts of technical failures.

3.2 Events reflected in existing RAA

In this subchapter we analyse the events being analysed in existing National or European RAA and where analogies to the identified crisis scenarios for risk preparedness can be found. Even sensitivities with only little or no analogy to the extreme events under the RPR can be useful here in order to understand how a (less probabilistic) assessment of extreme events may be applied.

Before diving into the individual RAA for analysing which events are analysed, it is helpful to recall the basics of the RAA methodology. As elaborated in Chapter 2.4, the central reference scenario (CRS) of a RAA is bound to use a probabilistic approach. There are two probabilistic elements that are modelled, without exception, in all of the considered RAA:

- **Forced outages** of electricity system assets: In a first step, assumptions regarding the outage rate and length on unavailability are made for generating units and HVDC lines. These parameters may differ due to technology and age of the respective unit or line. Then, a large number of samples from this pre-defined process is drawn. Each sample is a set of time series which specifies the availability of each generation unit and HVDC line in every hour of a year.

- **Weather conditions**: The stochastic process for the weather is usually constructed on the basis of climate years. A climate year is a set of variables that describes the weather conditions relevant for the energy system like temperature, wind speed, wind direction and solar radiation. The data is usually regionally differentiated and in hourly resolution. The climate years can be used to form time series regarding renewable feed-in and electricity demand for heating and cooling. The time series can be either constructed based on historic[30] climate years or on so-called synthetic[31] climate years, that are supposed to represent hypothetic but plausible weather conditions.

[30] Cf. r2b / Consentec (2021) and ENTSO-E (2019).

[31] Cf. Elia (2021).

A sample availability of capacity combined with a climate year, either historic or synthetic, can now serve as an input for a RAA model. To account for the wide variety of possible outcomes, the model is run many times with a large number of different system conditions. This Monte-Carlo simulation allows to analyse not only the range of possible outcomes but also the expected outcome (i.e., the mean of all observations).

Based on this, two options to consider extreme events in RAA-tools can be identified:

- The extreme events are reflected in the **existing input data** for the CRS of the RAA (i.e., forced outages and climate years used for the RAA). The probability density function of the results of the Monte Carlo-simulation represents the most extreme weather conditions and the most severe outage scenarios in its tails (see Figure 2). But the extreme event as such does not necessarily have a decisive impact on the general LOLE and EENS values derived from the RAA, as it may not appear often enough in the Monte Carlo simulations to become "visible" in the calculation of average LOLE-hours.[32] A critical hour analysis could thus be conducted which zooms into the relevant critical hours or MC-years to look at the direct impact of a specific extreme event only which is diluted in the full set of MC-simulations. The critical hour analysis can be directly based on the CRS.
- Where the extreme events have not taken place in the past yet or cannot be directly reflected in the input data, they can be considered within a **sensitivity analysis**. In those cases, a "translation" of the extreme event into input data which can be computed in the RAA-tool is required. This holds true in particular for anthropogenic or technical events, such as cyber & physical attacks, human-related events, market-related events or technical failures. Before analysing such events in a RAA, it has first to be defined which impact the event may have, e.g., on available generation capacities, transmission capacities or demand levels.

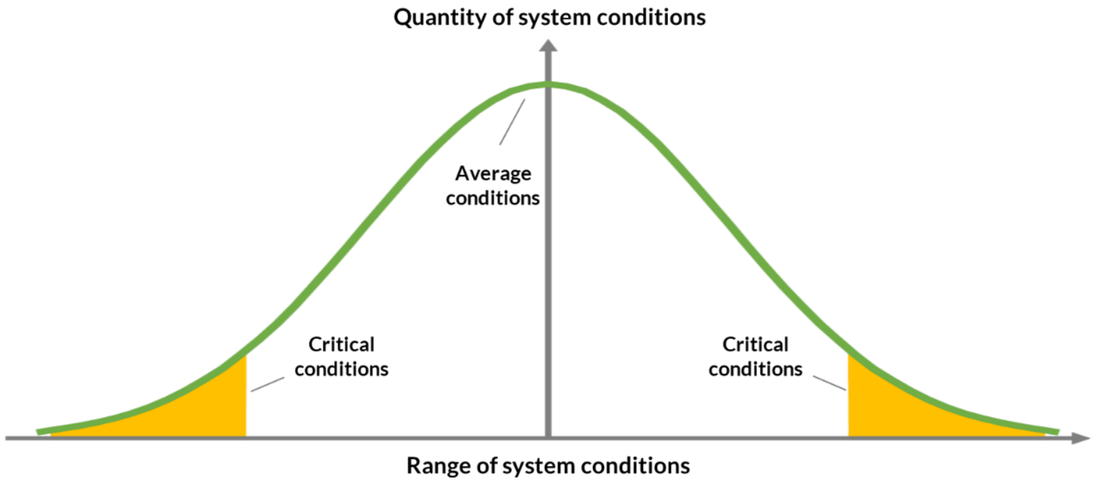

Figure 2: Probability density function of possible system conditions

The first approach is in principle connected to the general uncertainties which are reflected in RAA (i.e., weather conditions, forced outages) in the CRS. In contrast, the second approach reflects the explicit assessment of scenarios or sensitivities beyond the CRS which may be characterised by analogies to regional crisis scenarios identified by ENTSO-E. Such sensitivities are also foreseen by the EMR, which calls in Art. 23 (5) b) and c) for "*appropriate sensitivities on extreme weather events, hydrological conditions, wholesale prices and*

[32] It should be noted that the assessment may also be biased the other way, i.e., that too many / frequent extreme events are considered compared to what is expected (e.g., by the selection of very extreme climatic years) leading to LOLE / EENS above average.

carbon price developments" as well as "*separate scenarios reflecting the differing likelihoods of the occurrence of resource adequacy concerns which the different types of capacity mechanisms are designed to address.* "[33]

The following RAA are now analysed regarding the nature of events assessed and the methodological approach applied for this:

- ENTSO-E (2019e): Mid-term adequacy forecast 2019
- ENTSO-E (2020): Mid-term adequacy forecast 2020
- ENTSO-E (2021): European resource adequacy assessment 2021
- Elia (2021): Adequacy and Flexibility Study for Belgium 2022 - 2023
- TenneT (2020): Monitoring Leveringszekerheid 2020
- r2b / Consentec (2021): Monitoring the adequacy of resources in the European electricity markets
- RTE (2019): Mid-term adequacy report 2019
- PLEF (2020): Generation Adequacy Assessment April 2020

It has to be noted, that no sensitivities were found which explicitly aim at analysing extreme events for the purpose of risk preparedness under the RPR. However, some sensitivities represent events which may serve as a challenge for the electricity supply system under certain circumstances and show some analogies to extreme events. They could thus give insights in how to assess extreme events under the RPR. Other sensitivities, in turn, rather reflect for example different political decisions under discussion. These sensitivities do not necessarily unfold in a severity like the regional crisis scenarios by ENTSO-E and thus do not represent extreme events in the sense of the RPR.

Market-related

Several sensitivities deal with events related to political and market developments. The spectrum of scenarios is wide and the underlying changes in market rules or political decisions affect thermal generation capacities, carbon prices as well as cross-border transmission.

In the light of increased efforts to establish ambitious environmental policies on national and European level, ENTSO-E (2021) conducted in its ERAA 2021 a "Low thermal capacity" scenario for 2025 and 2030 in addition to the CRS. In this scenario, a total of 21.7 GW of thermal capacity was removed by 2025. In 2030, the thermal capacity is approx. 36 GW lower compared to the CRS. This loss was not compensated by additional units of other technologies. Especially two aspects motivated this analysis: First, many countries have politically determined coal phase-out plans. Due to increased political efforts to reduce CO_2-emissions, the adoption of more ambitious phase-out plans is conceivable, putting pressure on coal and lignite units directly. Second, by imposing higher carbon prices, politics can put coal and lignite capacity indirectly under pressure. Under a sufficiently high carbon price, coal and lignite assets will become unprofitable and eventually leave the market.

A similar scenario had also been analysed as part of the Mid-term Adequacy Forecast (MAF) 2019.

[33] Please recall Chapter 2.3 for a more elaborate description of the relevant provisions.

Another sensitivity regarding the accelerated decommissioning of fossil fuel plants was conducted by Elia (2021). In the "EU-LessCoal"-scenario 12.5 GW less coal and lignite capacity for 2025 and 9.6 GW less capacity for 2030 was assumed. As for the Low-Carbon sensitivity in the MAF 2019, the accelerated efforts towards environmental policies were the main motivation for the sensitivity. The assumptions were backed by an analysis by Bloomberg NEF, who stated that the economics-driven phase-out of coal and lignite capacity due to their unprofitability will unfold more rapidly than the currently stated phase-out plans in national legislations.

Apart from the closure of coal and lignite capacity, PLEF (2020) conducted a sensitivity that focused on potential risks for gas capacity. A reduced profitability of gas units was applied, due to a high share of renewable in-feed to the European electricity grid. It was assumed that high levels of renewables in the market, with marginal costs of zero, can lead to lower price levels, worsening the economic viability of gas units. In this scenario, a total of 7.6 GW gas capacity in the Penta-region was identified to be at risk of being mothballed due to low profitability and thus removed from the available capacities for this sensitivity.

In r2b/Consentec (2021), two "Increased sector coupling" sensitivities were modelled, where higher carbon and hard coal prices were assumed in combination with increased electricity demand from sector coupling technologies. These conditions put pressure on carbon-intense technologies and cause a shift towards gas and renewables. The sensitivities were motivated by the expectation of more ambitious climate protection measures in Europe compared to the reference scenario.

Similarly, TenneT (2020) introduced a system integration scenario where the penetration of sector coupling technologies is significantly stronger than in the reference scenario (i.e., +1.6 million heat pumps, +2 million EV).

PLEF (2020) assumed a reduced net transmission capacity between Switzerland and its neighbours in a sensitivity. The background of this reduction was that by the time of publication it was not clear whether Switzerland would be included in the flow-based market coupling (FBMC) by 2025.

Elia (2021) also included sensitivities where transmission capacity is curtailed for political reasons. In the EU, Member States are legally bound to allow transit flows, even when they suffer from the risk of unserved demand within their borders. For the UK, however, these rules do not apply after Brexit. Belgium is highly interconnected with the UK. Therefore, two additional sensitivities were included as a robustness check where the availability of the interconnectors between the UK and the EU are limited. In the sensitivity 'UK-not2BE', the Nemo Link interconnector between Belgium and the UK was assumed to be unavailable in times of scarcity in the UK. In the sensitivity 'UK-not2EU', this applies to all interconnectors between the UK and the European mainland.

All in all, the sensitivities described above are mainly relatively far away from the market-related extreme events covered by the RPR.

Technical failure

As elaborated above, extreme events regarding the outage of assets are to some extent included implicitly in the CRS of all considered assessments, due to the probabilistic character of forced outages in RAA. Furthermore, some RAA include a particular sensitivity to assess extraordinary outage situations observed in the past.

Belgium and France, largely dependent on nuclear power, conducted sensitivities addressing potential situations characterized by lower availabilities of nuclear power plants. Elia (2021) included sensitivities in its RAA with a reduced availability of French nuclear units since French imports play a considerable role for the Belgium resource adequacy. More precisely, it was assumed in three sensitivities that two, four or respectively six additional nuclear units are not available during the winter period, as such situations arose in the recent winter periods. These sensitivities were identified as relevant for multiple reasons. The French nuclear fleet is ageing and might be unavailable due to prolonged maintenance periods. Additionally, the availability of the nuclear fleet has been declining for the past five years and was overestimated in that period. Moreover, the assessment refers to publications of the French TSO and public authorities which consider additional unavailabilities as well, deviating from the published unavailability forecasts.

RTE (2019) addressed this aspect by a sensitivity where a prolonged unavailability of nuclear units after their 10-year inspection is assumed. Additionally, they conducted a critical hour analysis within the CRS of a situation of simultaneous unplanned nuclear unavailabilities, comparable to winter 2016-2017, when the French Nuclear Safety Authority (ASN) instructed a temporary shutdown of several nuclear power plants due to a technical failure of a component.

PLEF (2021) also considered a sensitivity with less nuclear availability (-1.7 GW in France and -1.19 GW in Switzerland).

Extreme and disruptive weather events

In the French NRAA by RTE (2019), two past extreme situations, that are reflected in the CRS input data set, were inspected more closely. First, a prolonged cold wave like the European cold wave in February 2012 where the historic peak electricity demand in France was recorded. Second, prolonged periods of light or no wind, causing extraordinarily low in-feed of wind generation units. Such a situation was observed for example in January 2012.

r2b / Consentec (2021) added the climate year 2017 to their original set of climate years 2009-2013 for the CRS because of the occurrence of the so-called ‘Dunkelflaute’, an event characterised by low temperatures and thus high heating demands, combined with low wind and solar in-feed for a prolonged period.

Elia (2021) used a set of 200 synthetic climate years per target year to take climate change and plausible extreme weather events into account in their CRS.

In its report, PLEF (2020) also conducted a critical hour analysis for this three-week period in January 2017 (‘Dunkelflaute’), when overall demand was high in the Penta-region due to low temperatures, with low wind in-feed levels at the same time. This situation was of particular interest, because situations with high residual demand are expected to be especially stressful in the near future, with a higher share of renewables in the system.

Cyber or physical attacks, natural disasters, fuel shortage, human-related

For other groups of extreme events, no analogies to the sensitivities in the analysed RAA could be found. These extreme events are characterised by a simultaneously low or non-availability of electricity system assets. Additionally, there is limited data on impact and likelihood of such events, making it difficult to translate such extreme events into appropriate input data for RAA. Since RAA are bound to a probabilistic assessment, they cannot be considered in a CRS without sufficient information on likelihood and impact on the input data. If deemed relevant for the scope of a RAA, such events would most likely be considered within a dedicated sensitivity.

Even though the sensitivities described above do not explicitly represent extreme events in the sense of the RPR, their respective modelling approach in the RAA-context reflects different options which are also relevant for the analysis of extreme events.

	ENTSO-E (2019e)	ENTSO-E (2020)	ENTSO-E (2021)	Elia (2021)	TenneT (2020)	r2b/Consentec (2021)	RTE (2019)	PLEF (2020)
Cyber & physical attacks	-	-	-	-	-	-	-	-
Extreme weather	CRS	CRS	CRS	CRS	CRS	CRS	CRS & Critical hour analysis	CRS & Critical hour analysis
Natural disaster	-	-	-	-	-	-	-	-
Fuel shortage	-	-	-	-	-	-	-	-
Human-related	-	-	-	-	-	-	-	-
Market-related	Sensitivity analysis	-	Sensitivity analysis	Sensitivity analysis	Sensitivity analysis	Sensitivity analysis	-	Sensitivity analysis
Technical failure	CRS	CRS	CRS	CRS & Sensitivity analysis	CRS	CRS	CRS & Sensitivity analysis	CRS & Sensitivity analysis
Misc.	-	-	-	-	-	-	-	-

Table 3: Overview on methodological approaches for the sensitivities in the analysed RAA

Table 3 demonstrates that the sensitivities in RAA today are basically limited to those events which are directly reflected in the input data of the CRS (i.e., extreme weather, technical failure) or can be considered without much effort by an adjustment of the scenario framework (i.e. market-related and / or politically induced developments of generation capacity, transmission capacity, demand). This helps to get a better understanding on how specific extreme events could be analysed via a critical hour analysis or dedicated sensitivities. Nevertheless, there is not much practical experience (at least in the RAA under consideration) on how the wide range of extreme events identified by ENTSO-E under the RPR can be appropriately analysed based on RAA-tools.

4. Analysis of options for assessing extreme events with (adapted) RAA-tools

In this Chapter we investigate whether and how (groups of) extreme events covered by the RPR can be appropriately assessed regarding their impact on the security of electricity supply with (adapted) RAA-tools from a technical/modelling perspective. We discuss the applicability of three different technical options for assessing different types of extreme events and examine how the respective KPI shall be interpreted. In the second sub-chapter we first discuss potential adaptions of RAA-tools, which may be needed to enable the assessment of extreme events with RAA-tools. Second, we give a recommendation on the suitability of the different approaches for assessing (groups of) extreme events.

4.1 Technical options for assessing extreme events in RAA-tools

In order to investigate whether and how (groups of) extreme events can be appropriately assessed with (adapted) RAA-tools from a technical/modelling perspective, we pick up the discussion of Chapter 2.3, whether extreme events may be assessed by more deterministic approaches or full probabilistic approaches. From our point of view, in general every extreme event can be analysed with (adapted) RAA-tools, as long as they materialise on bidding-zone levels and can therefore be addressed by such tools.[34] Also, ACER indicates the use of adapted RAA models to analyse extreme events according to Art. 8 RPR, as it states in its decision 8/2020 Annex I on the STSAA Methodology, that "*the Methodology for the seasonal adequacy assessments builds on the ERAA methodology whereas short-term Adequacy has a reduced uncertainty due to the availability of weather forecasts*".

In the following, we analyse three general technical options, differing in the probabilistic degree, and the respective needs and prerequisites for assessing extreme events using such (adapted) RAA-tools:

(1) **Full probabilistic approach:**[35] In this approach extreme events are considered with their respective probability, and also all other (in RAA normally) probabilistic elements remain probabilistic. In this approach the impact on the input data, as well as the probability of occurrence of the extreme event has to be known/given. The contribution of the relevant extreme event(s) on the KPI is expected to be comparably low, since the respective probabilities of occurrence of those extreme events is typically (very) low as well.

(2) **Conditional probabilistic approach:**[36] In a conditional probabilistic approach, the extreme event under consideration is fixed, while forced outages and/or climate years potentially remain probabilistic to that extent not directly affected by the ex-

[34] It should be noted that extreme events which occur only locally (e.g., floods in local valleys) cannot be assessed within (adapted) RAA-tools, as those tools focus on the relation between overall demand and supply, while e.g. grid elements within bidding zones or at distribution grid level are not applied.

[35] It should be noted that the theoretical construct of a full probabilistic approach, i.e., including all possible future outcomes exactly with their accurate probabilities, is not achievable in practice. The true distribution of stochastic elements is unknown and has to be approximated. Furthermore, all empirical models currently used assume that some variables are deterministic, in particular to keep model complexity at feasible levels. In these cases, assumptions should reflect best available unbiased estimates.

[36] The term "conditional probabilistic approach" in this report also covers probabilistic assessments, where one or more assumptions deviate from the mean expectation of market actors. This does not necessarily mean that assumptions deviating from those historically observed are classified as a conditional probabilistic approach. In contrast the assessment may take into account most recent developments or major uncertainties and if the assumptions are well motivated and quantitatively based on a reasonable analysis in a transparent manner, probability and impact are given/known and thus enables performing a full probabilistic assessment.

treme events under consideration. The probability of occurrence of the relevant extreme event in the assessment is 100 % by definition, even though the probability of occurrence in reality may be unknown, and only the impact on the input data has to be known/given. The contribution of the scenario on KPI is thus assumed to be high.

(3) **Deterministic approach:** In a deterministic approach the extreme event and all other (in RAA normally) probabilistic elements which have an impact on the supply situation are fixed, for example when an event with specific weather patterns comes along with a specific outage of power plants, demand levels, etc. The probability of occurrence of the extreme event is 100 % by definition. However, the probability of occurrence in reality may be unknown since only the impact on the input data (i.e., on generation, demand, etc) has to be known/given in order to analyse the impact of the event on the supply situation. Consequently, the KPI are basically determined by the extreme event under consideration.

Particularly for the full probabilistic approach, an additional critical hour analysis has to be performed to analyse the direct impact of a specific extreme event, since the probabilistic character of the assessment will dilute the impact on the electricity supply situation. This holds potentially also true for the conditional probabilistic approach – depending on the concrete probabilistic degree, if the impact of the extreme event is diluted by probabilistic elements. And even in a deterministic assessment an analysis of the most critical hours may give additional insights on the extreme event under consideration, exceeding those from the KPI's (e.g., what part of the load had to be curtailed in the most critical hours of the modelled year).

Depending on the given approach, the derived KPI have to be interpreted differently. In the deterministic and conditional probabilistic approach, the impact on the supply situation (i.e., loss of load and energy not served) is quantified, assuming that the crisis event occurs. Thus, the KPI derived from these approaches do not reflect the loss of load expectation (LOLE) or expected energy not served (EENS) on electricity markets in the sense of RAA and the respective reliability standards (RS). This only holds true for the full probabilistic approach reflecting mean expectations of possible system conditions.[37] In the deterministic approach, it is the loss of load (LOL) and the energy not served (ENS), in case the extreme event occurs (i.e., not the global expected values – LOL**E**; **E**ENS). In the conditional probabilistic approach, it is a conditional LOLE / EENS (CLOLE / CEENS), expressing the LOLE and EENS when an event occurs with the probability of 100 %, while other unfavourable circumstances may occur or not.

Figure 3 illustrates this for an assumed extreme event of an extraordinary heat wave. It has to be noted, that the influence of the heat wave on load and RE infeed is automatically implemented, if the respective climate year (or period) is covered. Furthermore, it is assumed in this illustrative example, that:

- one out of ten climate years contains heat wave (10%)
- LOL is zero in all years except heat wave years
- during heat wave year, additional power plant outages can be 7, 10 or 13 GW (each assumed to be equally likely), additionally not available, e.g. due to fuel shortages caused by low river levels, restricted river cooling or generally reduced capacity during heat waves,

[37] It should be noted that this also doesn't hold true in the full probabilistic approach if a critical hour analysis is applied, since there the critical situations are analysed directly and independently from their probability of occurrence within the whole set of MC-simulations.

- the heat waves is leading to respective LOL of 0 hours (for 7 GW), 5 hours (for 10 GW) and 10 hours (for 13 GW).

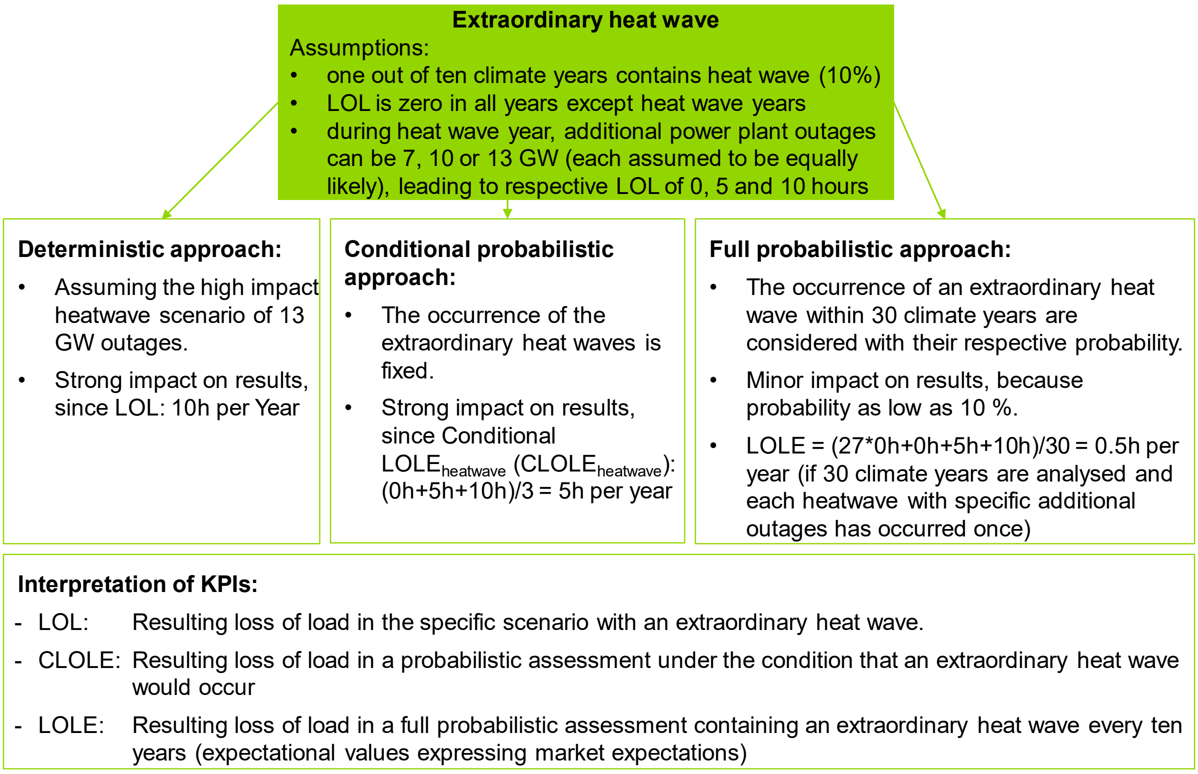

Figure 3: Comparison of modelling approaches for the example of a heat wave.

The example illustrates that the choice of the approach to be applied to assess extreme events strongly depends on the aim of the analysis. If the impact of an extreme event is to be assessed specifically, a deterministic or conditional probabilistic assessment seems to be preferable, since the KPI directly reflect the impact of the event. Furthermore, it is easier to parametrize and less computationally demanding compared to a full probabilistic assessment. Within a full probabilistic assessment, a critical hour analysis has to be applied in order to analyse the direct impact of an extreme event mirrored in the input data. However, it may be reasonable to choose this approach if a full probabilistic assessment is required anyway (i.e. in the context of RAA).

In general, all these options (deterministic, conditional probabilistic and full probabilistic plus critical hour analysis) are suitable to assess the need for and size of additional safeguard measures against extreme events in order to meet the legal requirements of the RPR. Such measures would safeguard security of supply of a MS above the efficient market level of resource adequacy (i.e., the reliability standard) and therefore will have to be addressed outside the market, since the market players would not prepare themselves for these 'unlikely' extreme events.

If, in turn, the overall resource adequacy on the electricity markets is to be assessed, potential extreme events should be considered with their respective probability of occurrence in the full probabilistic RAA, within relevant CRS and appropriate sensitivities. Such full probabilistic approaches may be used to assess the need for a market-wide CRM taking into account relevant extreme events. A member state might be interested in safeguarding against such extreme events, if adequacy concerns are identified within this approach – not necessarily outside the markets.

In PLEF (2020), two illustrative examples for both a full probabilistic and a conditional probabilistic approach can be found, even though they do not deal with real extreme events in a narrow sense:

- A full probabilistic approach was applied to analyse the given CRS. In addition, a critical hour analysis with specific simulations was conducted to analyse an extreme event which had taken place in January 2017, where relatively critical system conditions where present since electricity demand was high due to low temperatures in Europe and, at the same time, RES infeed was low because of weak wind.

- Furthermore, the Low Gas sensitivity represents a conditional probabilistic approach. Here, 7.6 GW gas capacity is identified to be at risk of mothballing due to low profitability and exogenously removed from the calculation while the other elements of the simulation remain probabilistic (see also section 3.2).

4.2 Adaptions of RAA-tools and discussion on the choice of appropriate modelling approaches

When assessing extreme events with RAA tools, some **adaptions** of the tools may be needed, determined by the choice of the beforementioned approaches:

- Assessing extreme events in a **full probabilistic approach** doesn't require adaptions of the model itself. However, the likelihood of occurrence of extreme events and their impact (i.e., how much is the electricity supply affected and for how long?) need to be parameterized. If extreme events are to be analysed where no or only little historic observations are available, the likelihoods and impacts may need to be based on expert judgements. It could be sensible to conduct simulations with a set of different likelihoods to assess how sensitive the results are to the experts' guesses.

- When assessing extreme events with a **conditional probabilistic approach**, the simulation of investment decisions (i.e., the EVA) should be disabled, since investments are not possible in the short timeframe when extreme events occur and the market would not invest anticipating the extreme event, as they usually occur only very rarely but are assumed to occur in the assessment.

- When assessing extreme events with a **deterministic approach**, the simulation of investment decisions (EVA) should also be disabled, for the same reasons as for the conditional probabilistic approach.

To quantify the direct impact / severity of an extreme event within a full or conditional probabilistic approach, we recommend conducting a critical hour analysis. Otherwise, the severity may be diluted or may not be visible, due to the comparatively low likelihood of occurrence of extreme events within a probabilistic MC-simulation.

Even if it is technically possible to assess extreme events with a full probabilistic approach, a deterministic or conditional probabilistic approach to directly analyse the impact of extreme events is in general more suitable, because a full probabilistic assessment aims at an unconditional LOLE and a critical hour analysis is needed to analyse the direct consequences of the occurrence of the extreme event. In contrast, in a conditional probabilistic and in particular in a deterministic approach the explicit consequences of the assessed extreme event are identified (more) directly and theses approaches are easier to model and less computational demanding. Furthermore, the probability of occurrence doesn't have to be known given, because it is assumed to occur with 100% probability by definition in these approaches.

In Table 4 the categories of extreme events contained in the relevant crisis scenarios identified by ENTSO-E according to Art. 5 and 6 RPR are summarized. For every category we give a recommendation whether it is possible and appropriate to assess them with (adapted) RAA-tools based on one of the aforementioned approaches.

Category of extreme event	Recommended modelling approach / explanation
Extreme weather	Extreme weather events in historic climate years considered in existing RAA are automatically included in a full probabilistic approach. Furthermore, considering climate change in RAA may lead to account for more frequent / critical extreme weather events in the future. In order to analyse the direct impact of these specific events a critical hour analysis would be suitable. To directly analyse the severity of extraordinary extreme weather events (e.g., occurring in 1/50 years), we recommend a deterministic or conditional probabilistic approach.
Technical failures	Concerning technical failures, our recommendation depends on the concrete specification of the extreme event. If the technical failures influence the availability of resources (generation assets, load or HVDCs), and there is historic evidence to derive probabilities and impact they should be analysed by a full probabilistic approach. The necessary adaptions only belong to input data and thus are relatively easy to parametrize. To assess extraordinary technical failures or other for electricity markets rather uncommon technical failures, like the loss of ICT systems followed by the loss of communication possibilities between TSOs and market participants, we recommend applying a deterministic or conditional probabilistic approach (for an explanation see category on cyber-attacks, etc. below).
Market related	Concerning market related extreme events, our recommendation also depends on the concrete specification of the extreme event. For price sensitivities, like the recent gas price peak or carbon price increases, we recommend assessing the event with a full probabilistic approach. Different price assumptions may lead to substantial differences in the economic viability of resources, which should be considered when assessing the scenario. For other specifications of market related extreme events like unwanted power flows in the system, induced, for example, by higher-than-expected infeed of renewables or atypical generation patterns, we rather recommend assessing the event with a deterministic or conditional probabilistic approach (for an explanation see category on cyber-attacks, etc. below).
Cyber- & physical attacks	Concerning the other five types of extreme events, we recommend assessing those (in the context of electricity market modelling rather uncommon events) directly within a deterministic or conditional probabilistic approach, because:

Natural disasters **Fuel shortage** **Human related** **Miscellaneous**	• the aim of assessing those extreme events should from our perspective be an analysis of the impact if the assumed extreme event occurs, • they are relatively difficult to parametrize appropriately in a full probabilistic assessment, as the likelihood of occurrence and impact of those extreme events are difficult to quantify or may even be arbitrary, since there is no or only little empirical evidence of such events, • the market cannot be assumed to prepare for such an unknown or uncommon event. Thus, no investment decisions should be allowed in the model reacting only on the occurrence of the extreme event, • no critical hour analysis is needed to directly assess the severity of the extreme event (even though a critical hour analysis might still provide for additional information in the context of a conditional probabilistic approach).

Table 4: Recommended modelling approaches for assessing extreme events.

Extreme events with a sufficiently high probability of occurrence, from a market perspective, may be appropriately assessed using full probabilistic approaches and with non-adapted RAA-tools. This, in particular, holds true for extreme events concerning climatic conditions or availability of resources, which are already covered by the input data of the RAA. However, to assess the severity of such extreme events more directly or to assess other extreme events with very low or unknown probability of occurrence, we recommend a conditional probabilistic or deterministic approach using an adapted RAA-tool, since no investments of market participants are to be assumed in case of those events, the assessment is much easier to conduct and the results express the impact of the extreme events more directly, without the need for a critical hour analysis.

5. Conclusions

While evaluating the explanatory and analytical power of resource adequacy assessments with regard to extreme events, we identified three different approaches to assess those events using (adapted) RAA-tools as long as they materialise on bidding-zone levels and can therefore be addressed by such tools:

1) the full probabilistic approach (in the sense of RAA),
2) the conditional probabilistic approach, and
3) the deterministic approach.

The EMR requires a probabilistic approach for the Central Reference Scenarios (CRS) of RAA in order to consider uncertainties in prevailing climatic conditions and unexpected unavailabilities of resources and transmission capacities. Therefore, extreme events in these two categories that were observed in the past and covered by the selected input data are implicitly reflected in the CRS with their expected likelihood of occurrence.

Beyond that, some existing RAA extend their analysis by specific appropriate sensitivities on other aspects than climatic conditions and outage rates using either a conditional probabilistic or deterministic approach, or a critical hour analysis within the full probabilistic approach, to gain deeper insights on the impact of specific events, even though many of them do not represent extreme events in the context of the Risk Preparedness Regulation 2019/941. Especially extreme weather events and extraordinary outage scenarios have been assessed in the past, as well as market-related scenarios regarding the development of carbon and commodity prices or political framework conditions. Other types of crisis scenarios, i.e., natural disasters, cyber-attacks, or nuclear accidents, have not been assessed in current RAA.

Which of the three approaches described above is the preferred option to analyse extreme events depends on the nature, the likelihood and the predictability of the respective event. However, for the analysis of extreme events in the context of RPR the full probabilistic approach has the difficulty that such events are – by definition – one unlikely outcome out of numerous more likely alternatives. For the purpose of RPR, it will thus be more informative in most cases to analyse the system under the condition that the extreme event is taking place. Thus, for very rare and extraordinary events, which need to be parametrised specifically, conditional probabilistic or deterministic approaches using adapted RAA-tools are more suitable.

In a conditional probabilistic or deterministic approach necessary adaptions affect the possibility of investments (EVA) because no market anticipation is possible as well as particularly the probabilistic nature of the RAA-models, as rare events being part of a probabilistic assessment will hardly be visible, even though they have to be addressed by appropriate risk preparedness measures according to the RPR. Consequently, the necessary adaptions also affect the KPI being used in RAA (usually LOLE and EENS), which have to be read in a different way compared to those derived from the CRS in RAA. When analysing extreme events based on a conditional probabilistic or deterministic approach, the outcome will inevitably deliver (high) LOL(E)-values, since the underlying assumption is that the respective extreme event occurs with 100 % probability. Thus, these KPI do not longer represent expected values (as it is the case in RAA), but rather express the impact of the analysed extreme event, assuming its occurrence.

While we demonstrated that extreme events covered by the RPR can in principle all be analysed with adapted RAA-tools, it needs to be discussed whether such an analysis still falls under the scope of RAA according to the EMR. In other words, the delimitation between appropriate sensitivities accompanying the CRS in RAA and the assessment of extreme events with adapted RAA-tools in the RPR context are unclear. A clarification seems to be necessary as this will have an impact on the measures that Member States are allowed to implement in order to address extreme events and on the framework conditions to be respected.

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Appendix: Relevant legislative elements

Aims and time horizons of the assessments:

Regulation (EU) 2019/943 (EMR)	Regulation (EU) 2019/941 (RPR)
Art. 23 (1) EMR: The **ERAA shall identify RA-concerns** by assessing the **overall adequacy of the electricity system** to supply current and projected demands for electricity at Union level, at the level of the Member States, and at the level of individual bidding zones, where relevant.	**Art. 1 RPR:** […] rules for cooperation between Member States with a view to **preventing, preparing for and managing electricity crises** in a spirit of solidarity and transparency and in full regard for the **requirements of a competitive internal market for electricity**. **Art. 5 (3) RPR:** The proposed **methodology shall include at least the following elements**: (a) a consideration of all relevant national and regional circumstances, including any subgroups; (b) interaction and correlation of risks across borders; (c) **simulations of simultaneous electricity crisis scenarios**; (d) **ranking of risks** according to their **impact and probability**. **Art. 8 (1) RPR:** […] methodology for **assessing seasonal and short-term adequacy**, namely monthly, week-ahead to at least day-ahead adequacy, which shall cover at least the following: (a) the **uncertainty of inputs** such as the probability of a transmission capacity outage, the probability of an unplanned outage of power plants, severe weather conditions, variable demand, in particular peaks depending on weather conditions, and variability of production of energy from renewable sources; (b) the **probability** of the occurrence of an **electricity crisis**; (c) the **probability** of the occurrence of a **simultaneous electricity crisis**.
Recital (44) EMR: **Medium to long-term assessments** are mainly used to identify adequacy concerns and to assess the **need for capacity mechanisms** whereas **seasonal adequacy assessments** are used to alert to **short-term risks** that might occur in the **following six months** that are likely to result in a **significant deterioration of the electricity supply** situation.	
ACER Decision 8/2020: The **ERAA methodology** shall mainly be	**ACER Decision 8/2020:** Seasonal assessments performed using the

used to **identify adequacy concerns** and to **assess** the **need for capacity mechanisms**. **Art. 23 (1) EMR:** The **European resource adequacy assessment** shall cover each year within a **period of 10 years** from the date of that assessment.	**STSAA** (short-term and seasonal adequacy […] methodology shall be used to **analyse risks** that might occur **six months ahead** and that are likely to result in a **deterioration of the electricity supply** situation.

Definition of scenarios to be assessed:

Regulation (EU) 2019/943 (EMR)	Regulation (EU) 2019/941 (RPR)
Art. 23 (5) EMR: **(b)** is based on appropriate **central reference scenarios** of projected demand and supply including an **economic assessment** […] and appropriate **sensitivities** on **extreme weather events**, hydrological conditions, wholesale prices and carbon price developments; **(c)** contains separate **scenarios** reflecting the **differing likelihoods of the occurrence** of resource adequacy concerns which the different types of **capacity mechanisms are designed to address**; **Acer Decision 24/2020 Annex 1:** **Art. 3 (3):** The **baseline data for the ERAA** stems from the national projected demand, supply and grid outlooks prepared by each individual TSO. These **national forecasts** shall be **consistent with existing and planned national policies**, including: (a) national objectives, targets and contributions, and other projections contained in the **NECPs** […]. To this aim, the assumptions of the **central reference scenarios** shall align with the measures and actions defined by MSs pursuant to Article 10(5) of Electricity Regulation and with implementation plans pursuant to Article 20(3) of Electricity Regulation. **Art 3 (4):** For **all central reference scenarios**, the EVA shall be performed on the baseline data described in the previous paragraph. The **ERAA report** shall clearly show whether and **how the baseline data** has been **modified by the EVA**.	**Art. 5 (2) RPR:** The **proposed methodology** shall **identify electricity crisis scenarios** in relation to system adequacy, system security and fuel security on the basis of at least the following risks: (a) rare and **extreme natural hazards**; (b) **accidental hazards** going beyond the N-1 security criterion and exceptional contingencies; (c) **consequential hazards** including the consequences of malicious attacks and of **fuel shortages**. **Art. 6 (1) RPR:** ENTSO-E shall, on the basis of that methodology […] identify the most relevant electricity crisis scenarios for each region. **Art 8 (2) RPR:** […] The **methodology** shall take into account the specificities of each Member State's energy sector, including specific **weather conditions** and **external circumstances**. **Recital (11) RPR:** 'ENTSO-E' and the Member States should, respectively, **determine concrete regional and national electricity crisis scenarios**. That approach should ensure that all relevant electricity crises are covered, taking into account regional and national specificities such as the topology of the grid, the electricity mix, the size of production and consumption, and the degree of population density. **Recital (14) RPR:** On the basis of the **common methodology**

Art 3 (5): The **ERAA** shall **rely** on the following **central reference scenarios**: a) With CMs […] b) Without CMs […]. **Art 3 (6):** ENTSO-E may **complement** the central reference scenarios with **additional scenarios and/or sensitivities** with European relevance, e.g., to assess the robustness of the identified resource adequacy concerns. Such scenarios and/or sensitivities may be based on inter alia the following elements: (a) different assumptions related to input data and scenario uncertainties, including different economic and policy trends relevant for resource adequacy; […] (e) consideration of **extreme weather events** and hydrological conditions; **ACER Decision 24/2020 Recital (79) c):** […]. ACER also allows for realistic alternative approaches for climate data in central reference scenarios. ACER observes that, in the context of the ERAA modelling exercise, other scenarios and sensitivities pursuant to Article 3(6)(e) of the ERAA Methodology may rely on climate data beyond the one used for the **central reference scenarios**. In particular, **extreme weather events** should be **reflected by sensitivities** in line with Article 23(5)(b) of the Electricity Regulation;	**for risk identification**, the ENTSO for Electricity should regularly draw up and update **regional electricity crisis scenarios** and identify the **most relevant risks** for each region such as **extreme weather conditions**, natural disasters, fuel shortages or malicious attacks. **Art. 6 No. 3 ENTSO-E method:** **(g)** A **probabilistic method** for evaluating both impact and likelihood of each crisis scenario is usually superior to a deterministic one (and thus **preferred**). However, the **required minimum** for evaluating the likelihood and impact measures of a **crisis scenario** is performing a **deterministic calculation**, based on […]; **(h)** In case of the **most relevant regional electricity crisis scenarios**, ENTSO-E may propose **use of a scenario specific probabilistic method** **ACER Decision 7/2020:** **Art. 10:** Electricity **crisis scenario candidates** determined by TSOs in cooperation with the national competent authority. **Recital (29) ACER Decision 8/2020:** Seasonal assessments performed using the **STSAA** (short-term and seasonal adequacy […] methodology shall be used to **analyse risks** that might occur **six months ahead** and that are likely to result in a **deterioration of the electricity supply** situation.

Modelling approaches to assess scenarios and key performance indicators:

Regulation (EU) 2019/943 (EMR)	Regulation (EU) 2019/941 (RPR)
Art. 23 (1) EMR: The **ERAA** shall be based on a transparent methodology which shall ensure that the assessment: […] **(h)** applies **probabilistic calculations**; […] **(j)** includes at least the following indicators referred to in Article 25: - '**expected energy not served**', and	**ACER decision 7/2020 Annex 1 Art. 8:** During electricity crisis scenario **identification and evaluation**, either a **probabilistic or a deterministic method** of evaluating the **likelihood and impact of a crisis** shall be used. A probabilistic method shall be favoured over a deterministic one where appropriate. ENTSO-E shall propose the use of a scenario-specific method (or methods) for evaluating the likelihood and impact measures relevant to the particular scenario and the nature of its uncertainty when appropriate. **Art. 6 (3) ENTSO-E method:** **(g)** A **probabilistic method** for evaluating both impact and

- ‘**loss of load expectation**’;	likelihood of each crisis scenario is usually superior to a deterministic one (and thus **preferred**). However, the **required minimum** for evaluating the likelihood and impact measures of a **crisis scenario** is performing a **deterministic calculation**, based on […]; **(h)** In case of the **most relevant regional electricity crisis scenarios**, ENTSO-E may propose **use of a scenario specific probabilistic method** **Recital (17) RPR:** To improve those adequacy assessments (i.e., STSAA), the ENTSO for Electricity should develop a **common probabilistic methodology** for them […]. **Recital (29) ACER Decision 8/2020:** Seasonal assessments performed using the **STSAA** (short-term and seasonal adequacy […] methodology shall be used to **analyse risks** that might occur **six months ahead** and that are likely to result in a **deterioration of the electricity supply** situation. **Art.3 ACER Decision 8/2020 Annex I:** **1.** All **seasonal adequacy assessments**, whether carried out on national, regional or Union level, shall be **based on the probabilistic method** described in Annex I. […] **7. Seasonal adequacy assessments** shall be based on any relevant metrics, including **LOLE, LOLP and EENS**. **8.** The seasonal adequacy assessment shall consist of the following steps: **a.** Run of **Monte Carlo probabilistic assessmen**t with UCED model, as defined in Annex I; **b. Spatial analysis** on seasonal basis to detect zones with adequacy risk, meaning hours with probability that part of demand might be not supplied (LOLP is higher than 0); **c.** Temporal analysis on weekly basis to detect periods with adequacy risk; **11.** The **short-term and seasonal adequacy assessments** shall use a **probabilistic methodology** to assess adequacy for the concerned period. The methodology shall follow a Monte Carlo method to reflect the **variability of weather** as well as the randomness of supply and transmission **unplanned outages**. **12. Monte Carlo simulations** shall be built combining the **weather-dependent variables** and **random outages**. Each weather scenario consists of a realistic combination of demand (accounting for temperature dependency), wind, solar and hydro inflow time-series. From each weather scenario, the relevant time period is selected, i.e., the season, month or week under consideration. Each set of weather scenarios is further associated with a relatively large number of random unplanned outage samples, that is, randomly assigning **unplanned outage patterns** for thermal units and interconnections.