European Network of
Transmission System Operators
for Electricity

Explanatory document of the proposal for assumptions and methodology for a Cost Benefit Analysis (CBA) compliant with the requirements contained in Article 156(11) of Commission Regulation (EU) 2017/1485 of 2 August 2017 establishing a guideline on electricity transmission system operation (System Operation Guideline Regulation – SOGR)

Version for public consultation

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1 List of acronyms

ACE	Area Control Error
CE	Continental Europe
LER	FCR providing units or groups with limited energy reservoir
FCR	Frequency Containment Reserve
FCP	Frequency Containment Process
FRR	Frequency Restoration Reserve
FRP	Frequency Restoration Process
FSM	Frequency Sensitive Mode
Non-LER	FCR providing units or groups without limited energy reservoir
NP RES	Non Programmable Renewable Energy Sources
RES	Renewable Energy Sources
SO GL	System Operation Guideline
$T_{min\ LER}$	As of triggering the alert state and during the alert state, time for which each FCR provider shall ensure that its FCR providing units with limited energy reservoirs are able to fully activate FCR continuously.

2 Introduction

2.1 Context and Scope of the Report

The System Operation Guideline (SO GL) drafted by European Network of Transmission System Operators for Electricity (ENTSO-E) with guidance from the Agency for the Cooperation of Energy Regulators (ACER) was approved in comitology in May 2016 and adopted by European Commission in August 2017.

Article 156(11) of the SO GL requires the definition of a methodology for a Cost-Benefit-Analysis (CBA) for assessing the time period required for FCR providing units or groups with limited energy reservoirs (LER) to remain available during alert state in Continental Europe (CE) and Nordic synchronous areas.

Within 12 months after the approval of assumptions and methodology by all regulatory authorities of the interested region, the TSOs of the Central Europe and Nordic synchronous areas shall present the results of their cost-benefit analysis, suggesting a time period between 15 and 30 minutes to be available during Alert State.

The main objective of the CBA methodology described in this document is the selection of the solution which minimises FCR costs without jeopardising operational security. The aforementioned time period that will be identified after the application of this methodology will be used as a requirement for BSPs using resources with limited energy reservoirs for FCR provision. These BSPs will have to make sure that, at any point during normal state, the LER resources have always an energy content that will allow them to remain available for the minimum time defined by the study during alert state, by using an energy charging strategy.

According to the Article 18 (2c) of SO GL the transmission system shall be considered in alert state when:

- absolute value of the steady state system frequency deviation is not larger than the maximum steady state frequency deviation; and
- The absolute value of the steady state system frequency deviation has continuously exceeded 50 % of the maximum steady state frequency deviation for a time period longer than the alert state trigger time or the standard frequency range for a time period longer than time to restore frequency.

The minimum time period defined implementing the present CBA methodology is a requirement which shall be fulfilled in alert state while the FCR provider shall ensure that the FCR from its FCR providing units or groups with limited energy reservoirs are continuously available during normal state (Article 156 (9) of SO GL regulation).

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The results of this study will be used by the TSOs to define the prequalification rules for LERs. In fact, after this study, each TSO should calculate the total minimum energy capacity that a LER should have in order to be prequalified for FCR provision.
The requirements for the operation of the above mentioned LER resources when frequency is within the standard frequency range are out of scope for this methodology.
This document provides the definition of the methodology meeting the requirements contained in Article 156 (11) of the System Operation Guideline Regulation, which shall constitute the basis for the subsequent implementation of the CBA.

2.2 Organisation of the Report

Section 3 provides an overview of FCR and EU regulation requirements for its provision. Section 4 outlines the key assumptions considered for the development of the methodology with respect to the timescale involved in the simulation model.

Section 5 illustrates the methodology, providing:

- The generic workflow of the procedure (input-output schemes);
- Methodology for the calculation of the power imbalance to be balanced by Frequency Containment Process (FCP) starting from historical frequency data and probability of grid elements outages;
- The probabilistic approach for assessing the operational security and system stability related to different scenarios with a defined minimum time period;
- Key hypotheses and descriptions of cost estimation;
- Description of the scenarios adopted to represent potential future developments of the power system and generation technologies.
- Outline of criteria for assessment of the time period required for LER to remain available during alert state including analyses of the stability risk during the most relevant real frequency events;

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3 Description of FCR

Frequency Containment Reserve (FCR) in the European Union Internal Electricity Balancing Market refers to operating reserves necessary for continuous containment of frequency deviations from nominal value in order to constantly maintain the power balance in the entire synchronous interconnected system.

A definition of FCR is provided in Article 3(6) of the SO GL where the FCR represents "the active power reserves available to contain system frequency after the occurrence of an imbalance".

Activation of this reserve results in a restored power balance at a frequency deviating from nominal value.

The FCR in a synchronous area is of utmost importance for the operational reliability of the area since it allows the stabilization of the system frequency in the time-frame of seconds at an acceptable stationary value in case of a disturbance or an incident. FCR depends on the reserve made available to the system by FCR providing units (e.g. generating units, controllable load resources and HVDC links). FCR provided by generating units is a fast-action, automatic and decentralized function that adjusts the generating units' power output as a consequence of the system frequency deviation. FCR is activated locally and automatically at the site of the FCR providing unit, independently from the activation of other types of reserves.

Further details on such topic can rather be found in the European Union SO GL. Especially, the guidelines require at article 156, at least for the CE & Nordic synchronous areas, that:

- An FCR providing unit shall guarantee the continuous availability of its FCR during the period of time in which it is obliged to provide FCR (with the exception of a forced outage);
- An FCR providing unit with an energy reservoir that does not limit its capability to provide FCR shall activate its FCR for as long as the frequency deviation persists;
- A FCR providing unit with an energy reservoir that limits its capability to provide FCR shall activate its FCR for as long as the frequency deviation persists, unless its energy reservoir is exhausted in either the positive or negative direction with the following clarifications:
    - during normal state, the FCR from FCR providing units with limited energy reservoirs shall be continuously available.
    - as of triggering the alert state and during the alert state, the FCR from FCR providing units with limited energy reservoirs shall be fully activated continuously for a time period to be defined according to a CBA. Where no period has been determined, each FCR provider shall ensure that its FCR providing units with limited energy reservoirs are able to fully activate FCR continuously for at least 15 minutes or, in case of frequency deviations that are smaller than a frequency deviation requiring full FCR activation, for an equivalent length of time, or for a period defined by each TSO, which shall not be greater than 30 or smaller than 15 minutes.

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4 Main assumption of the methodology

4.1 Simulation timeframe

The present CBA methodology shall be based on a realistic simulation model useful to understand the actual effects of LER on the frequency regulation in different scenarios.

A main issue that should be evaluated in order to define a proper simulation model for the FCR provision analysis is related to the timescale of phenomena involved.

The dynamic phenomena and regulations relevant in the frequency behaviour are the following:

- System inertia. The system inertia (both rotating and synthetic) limits the frequency gradient following a system disturbance. It has effect on a very short time scale (0÷15s) and it is crucial in limiting the frequency maximum/minimum values during a transient before the FCR comes in.
- FCR dynamic response. Each FCR providing unit delivers its FCR capacity with a specific dynamic trend related to its technical issues. The maximum delivering time is defined in SO GL Article154.
- FRR dynamic response. It is referred to the time scale in which both automatic and manual FRR are deployed (1÷15 min).

For the objective of the present CBA methodology proposal, both system inertia and FCR dynamic response phenomena will be neglected. The methodology has in fact the aim to investigate the effects of the limited energy reservoir of part of the FCR providers on the frequency regulation framework.

For the purpose of this methodology, the presence of LER has an effect on the system once the energy reservoir is depleted. According to the SO GL Article156(10) this depletion must occur not before 15 minutes after the triggering of an alert state or, in case of frequency deviations that are smaller than a frequency deviation requiring full FCR activation, for an equivalent length of time.

This means that the effects of LER depletion take place on a timescale much larger than the timescales in which inertia and FCR dynamic response show their effects.

If a contingency occurs on the system, the frequency drop with a gradient related to the synchronous system inertia until the FCR is completely deployed. The minimum frequency reached during the transient depends only on both system inertia and FCR delivery dynamics. The presence of LER does not affect the system frequency in this context, since LER deliver their reserve regardless of their reservoir.

According to these considerations, the problem related with the limited system inertia, due to the increasing penetration of inverter-based generation technologies, is independent from the presence of LER and from the dimensioning of their energy reservoir.

Moreover, the present CBA methodology has the aim to investigate the effect of LER regardless of their specific technology. LER could be inverter-based (e.g. electrochemical cells) or rotating (e.g. small hydro power plants); they could have indeed different effects on frequency transient due to their different inertia and FCR deployment dynamic.

The frequency quality analysis on short term (as affected by inertia and FCR deployment dynamic) goes therefore beyond the aims of this CBA methodology, because it does not affect the selection of the time period.

The simulation model implemented shall then take into account the FCR deployment without its dynamic response (considering the system always in a steady-state regarding the FCR) and the FRR deployment with its dynamic response.

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5 Methodology

The main objective of the CBA methodology proposal described in this paragraph is to identify the combination of minimum time period ($T_{min\ LER}$) of full activation during alert state, LER share and total amount of FCR to be procured in the synchronous area which entails the lowest FCR cost over a defined time horizon without jeopardising the system security. The FCR increase has only the aim to assess system stability risks and total cost of FCR in case of increasing total volume of FCR as requested by Article 156 (11 d) of the SO GL. It must be highlighted the FCR dimensioning is defined in Article 153 of SO GL, therefore it cannot be the subject of this CBA methodology.

In order to reach that goal the methodology is organised in the following tasks:

- Frequency Containment Process (FCP) assessment in presence of LER based on simulations and considering a probabilistic approach for the main causes of frequency deviations. The activity aims to quantify the total FCR costs and FCR dimensioning considering different scenarios.
- Assessment of power system stability simulating the presence of LER during the most relevant real frequency events. There are complex sequences of events which can lead to significant power imbalances that cannot be investigated by means of probabilistic simulations. The proposed approach to overcome this modelling complexity is to simulate different scenarios of LER participation on FCR during the most relevant actually occurred events starting from recorded frequency data. The activity aims to verify that the combinations of time period, LER share and FCR dimensioning do not jeopardise system stability, potentially leading to a blackout state, even during most relevant real frequency disturbances.

The methodology will be based only on stability risk evaluation. It implies that the potential deterioration of frequency quality – related to different time periods - will be neglected.

The following paragraph will describe in detail the assumptions and methodology of in the CBA as well as the criteria for assessment to be adopted.

5.1 FCP assessment in presence of LER: Workflow

In this paragraph the workflow for assessing the FCP in presence of LER is presented.

The workflow takes as an input a set of variables identifying the scenario that shall be investigated. Besides the minimum time period $T_{min\ LER}$, several other variables are needed for FCP assessment – all this variables characterise a scenario. A description of the scenarios to be considered in the CBA and their main assumptions is reported in paragraph 5.7.

The output of the workflow is a cost associated to the scenario. The different scenarios can be then analysed by comparing these output costs. For a generic simulation scenario the process workflow is illustrated in Figure 1.

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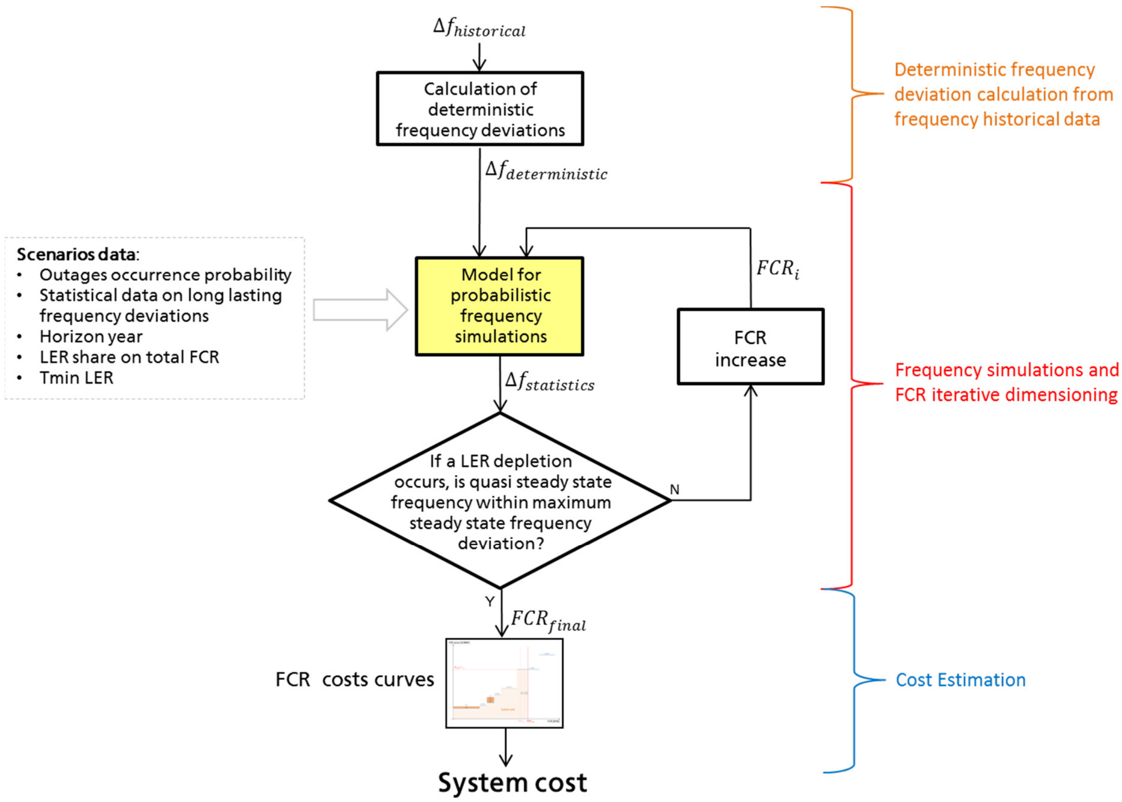

Figure 1 Process workflow

The process is summarized in the following steps:

1. The historical frequency trend ($\Delta f_{historical}$) is analyzed in order to define the deterministic frequency deviation as described in paragraph 5.2.
2. The probabilistic simulation model (paragraph 5.4) is used in order to calculate the statistics of simulated frequency (Δf_{sim}).
3. The simulated frequency statistics are analyzed in order to calculate the potential effects of LER depletion on system stability.
4. If the probabilistic analysis highlights LER depletions that entail the frequency deviation to reach the maximum steady state threshold, the FCR dimensioning is increased (by a defined power step) and another simulation is run.
5. The previous steps 2, 3 and 4 are repeated in an iterative process until the requirements defined in the step 4 are fulfilled.

   The final output of this iterative loop is the final FCR dimensioning value (FCR_{final}). This is the minimum increased FCR value that allows to avoid that LER depletion bring the frequency to reach the maximum steady state threshold.
6. The FCR_{final} is used to estimate the total system cost by using the reserve cost curves (as defined in paragraph 5.6.1.1).
7. The final output of the process is the total system cost.

As highlighted in Figure 1 the procedure can be split in four different sections:

- deterministic frequency deviation calculation from frequency historical data
- model for probabilistic frequency simulation
- FCR iterative dimensioning

- cost estimation

A detailed description of each section is provided in the next paragraphs.

5.2 Deterministic frequency deviation calculation from frequency historical data

The power imbalance on a synchronous area causes the frequency deviations that FCP and FRP must contain and restore.

The power imbalance can be described as the instantaneous difference between load and generation. Many factors can have an impact on power imbalance, for example:

- market induced effects due to the power difference between continuous ramping of load and discontinuous/stepwise ramping of generation according to the scheduling resulted from the market;
- outages of relevant grid elements (generators, loads, HVDC links, etc.);
- errors in load forecasts;
- forecast error of Non Programmable Renewable Energy Sources (NP RES) (e.g. Wind and solar);

Some of these phenomena are deterministic (e.g. market induced effects) - they can be predicted with good approximation.

Some phenomena can be evaluated only from a statistical point of view – e.g. it is theoretical possible to evaluate to probability distribution of forecast errors looking at the typical errors made in the past.

There are finally other phenomena that are only statistically foreseeable (e.g. outages).

A complete simulation of FCP and FRP should take into account all these effects, however, it can be difficult to get reliable information on all of them and it is even more challenging to estimate their evolution in the future.

The main source of information is of course the historical frequency records of each synchronous area. These data however are the results of the combination of all the different effects with the system reaction due to FCP and FRP.

Determining different power imbalance components from frequency data can be indeed a very complex process.

The power imbalance to be managed by FCP and FRP in the assessment will be calculated considering only the most relevant effects on the frequency, which are outages and the market induced effects. Other factors affecting power imbalance regarding forecast errors of loads and NP-RES are considered implicitly in long lasting frequency deviation (Paragraph 5.3) which are based on the statistical analysis on frequency historical data.

The outages will be modelled with a probabilistic Monte Carlo approach (Paragraph 5.4) – the market induced imbalances will be calculated starting from historical frequency data.

The market induced imbalances are generation-load imbalances caused by the change in generation set points according to the results of the market scheduling. These are one of the most important imbalance phenomena since they can cause an overcome of standard frequency range for several times every day.

The main characteristic of these deviations is that they occur in specific periods during the day, with specific trend patterns. They typically occur during the change of the hour

Thanks to this predictability, the phenomena are called deterministic frequency deviations[1].

[1] ENTSO-E, "Supporting Document for the Network Code on Load-Frequency Control and Reserves", 2013.

The deterministic frequency deviations will be analysed starting from the historical frequency data recorded by TSOs in the last 15 years, 2017 included.

A historical deterministic frequency deviation trend shall be calculated starting from frequency data of each synchronous area. As depicted in Figure 2, the deterministic frequency deviation considered in the FCP assessment will be obtained analysing historical frequency deviation and considering the settlement rules of the market.

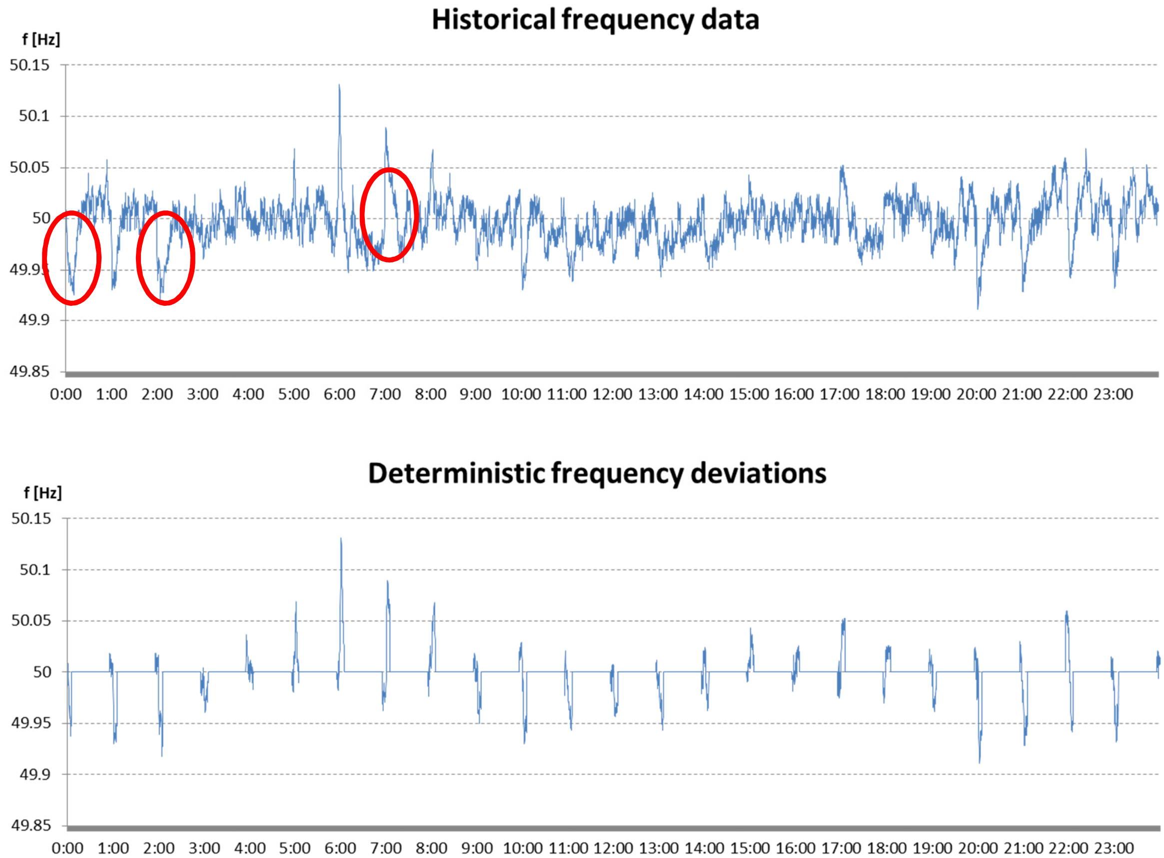

Figure 2: Example of a day trend of historical frequency data and deterministic frequency deviation

The deterministic frequency deviation trend is further analysed in order identify the potential overlap with other phenomena. In particular overlaps with specific recorded outages in the synchronous area shall be identified and eliminated.

Since the outages are taken into account separately via the Monte Carlo approach, the identified actually occurred events shall be neglected.

The deterministic frequency deviation $(\Delta f_{deterministic})$ represents one of the input of the probabilistic simulation model.

5.3 Long lasting frequency deviations

During the operation of each synchronous area, some events in which the frequency deviation cannot be restored to 50 Hz by FRP can occur (even without the triggering of an alert state).
During these events (long lasting frequency deviations) the frequency remains around the standard frequency range over a prolonged period without triggering the alert state.
Long lasting frequency deviations are typically related to the exhaustion of FRR in a single LFC area. It may happen that, due to contingencies on a single LFC area, the total amount of available FRR of that area is

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activated – this activation can be however not enough to restore the frequency deviation to zero because the dimensioned FRR is less than the power imbalance caused by the contingencies. In this situation part of the power imbalance is constantly balanced by FCR in the whole synchronous area potentially causing a long lasting frequency deviation. The FRR of other LFC areas not affected by the contingencies are unable to restore the frequency deviation to zero because it is not only activated based on frequency.

Considering the exhaustion of FRR by the means of long lasting frequency deviation, allows to avoid taking into account the saturation of FRR in the simulation model block diagram.

This kind of events shall be taken into account since they may overlap with other sources of frequency deviation such as outages.

Since the long lasting frequency deviations are unpredictable events, the best way to consider them is via a probabilistic approach.

By analyzing the frequency historical trends recorded by TSOs in the last 15 years, 2017 included, is possible to characterize the phenomena from a statistical point of view.

The analysis will consider as long lasting frequency deviation all the events with an average steady state frequency deviation larger than the standard frequency deviation over a period longer than the time to restore frequency.

Taking into account several years of frequency trends for each synchronous area, the analysis shall determine:

- number of occurrences of these events;
- the typical duration;
- a representative frequency deviation trend.
- typical time of occurrence, if highlighted by statistical analysis.

These synthetic statistical information shall be used as an input for the probabilistic Monte Carlo simulation model.

The Monte Carlo model shall then simulates the long lasting frequency deviations randomly during the year and accordingly to the aforementioned statistical information.

5.4 Model for probabilistic frequency simulation

The frequency simulation model is the main tool to analyze the effects of LER on the frequency compared to the actual operational condition for Load-Frequency Control and Reserves.

The simulation model can be represented as an input-output model as shown in Figure 3

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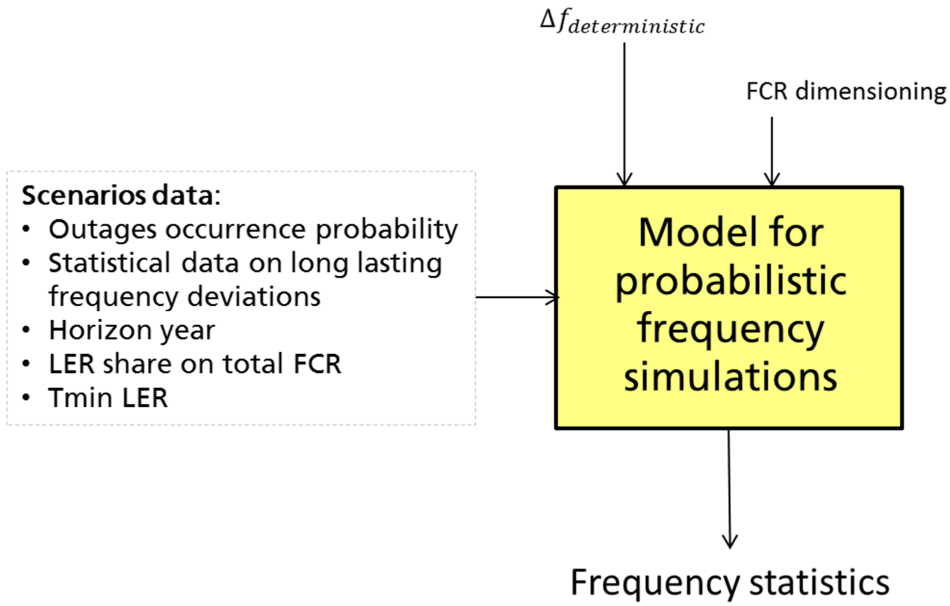

Figure 3

The aim of the model is to simulate the Load–Frequency Control Process adopting a probabilistic approach.

The model shall be able to simulate both FCP and FRP for each synchronous area and therefore to calculate a probabilistic frequency ($\Delta f_{probabilistic}$) in different scenarios.

As discussed in 4.1 the simulations neglect both system inertia and FCR dynamic response, while the steady state FCR effects and the FRR (with its dynamics) are taken into account.

The input data considered for calculating the probabilistic frequency shall be:

- FCR: total amount of frequency containment reserve in the whole synchronous area. The FCR will be reduced when a depletion of LER occurs, since their FCR is no longer available;
- FRR full activation time;
- A list of outages of relevant grid elements which bring to a change in power imbalance. Probability of occurrence of outages by type of event and by generation technology shall be obtained by means of statistics about historical data considering at least:
  - ENTSO-E transparency platform data;
  - Information collected in the LFC report related to the most relevant power imbalances (power imbalances greater than 1000 MW);
  - Research studies based on statistics of unit failure.
- The deterministic frequency deviations as described in 5.2;
- The statistical information related to long lasting frequency deviation defined according to paragraph 5.3.

5.4.1 Monte Carlo approach

The probabilistic approach has the objective to calculate several operational conditions for the Load-Frequency Control Process, taking into account deterministic frequency deviations, the long lasting frequency deviation and the outages effects.

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This kind of approach can be implemented by using Monte Carlo algorithms in which a large number of years are simulated: contingency will then occur depending on their probability.

A schematic workflow for the algorithm is depicted in Figure 4.

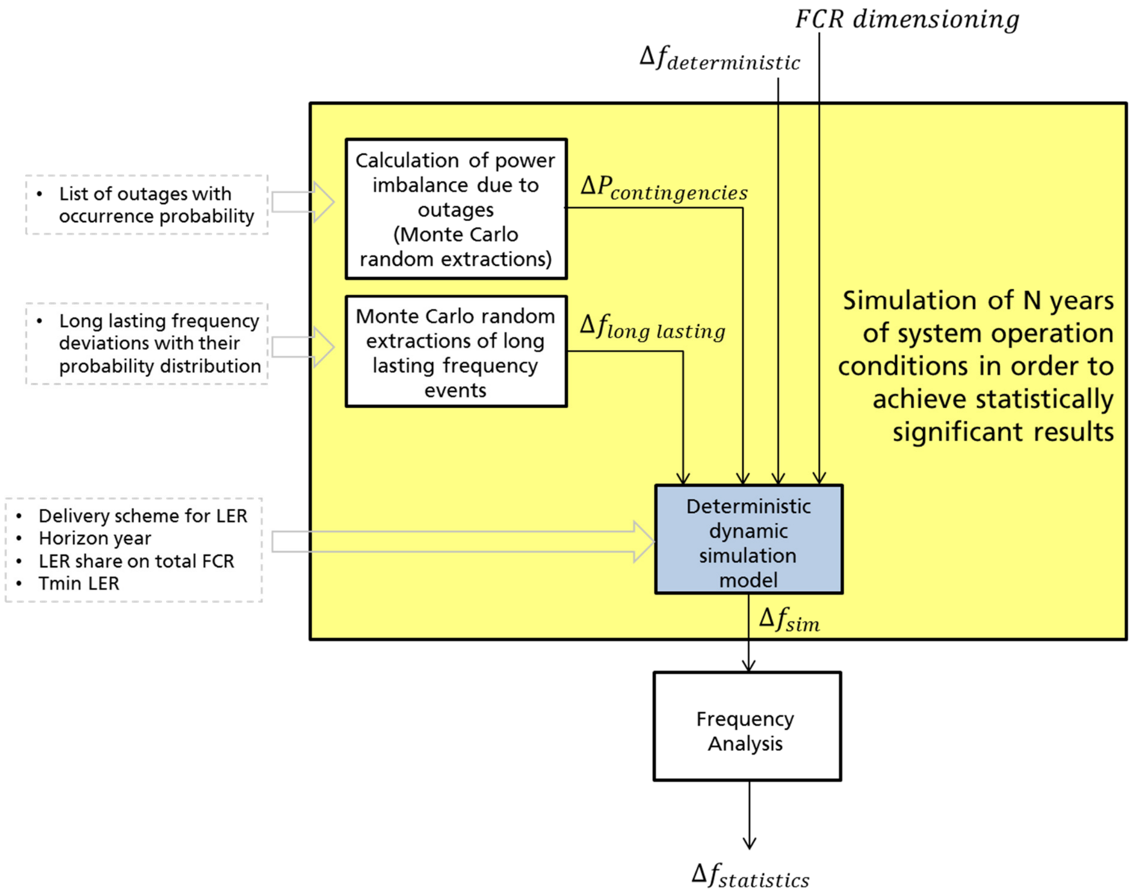

Figure 4 Monte Carlo simulation schematic workflow

The coloured area represents the process that shall be repeated N times in order to simulate the widest possible operational condition of the system. N parameter must be large enough to reach statistically significant results.

Each simulation represents a possible condition of the system over a year.

The power imbalance due to outages is calculated starting from a list of possible contingencies with their own probability of occurrence. There must be a block able to generate randomly the outages taking into account the actual failure rate of each element in the considered list.

The block shall also be able to randomly extract the long lasting frequency deviation events, starting from their typical frequency of occurrence.

Contingency events (combination of outages and long lasting frequency deviation events) will be considered as stochastically independent from each other. This is an approximation of the real system operation, in fact a correlation between outages and significant frequency deviation caused by other factors could occur, e.g. an unplanned outage of a generation unit can be caused by the activation of its under frequency protection, increasing the power imbalance even during critical conditions.

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Contingencies and deterministic frequency deviation are input for the deterministic dynamic model (5.4.2) that simulates a simplified load frequency control process calculating the frequency deviation.

Each simulation generates as an output a trend of frequency deviation.

A further block integrates the information from all the simulated years. The decision of whether increase FCR or not in order to compensate a depletion of LER which cannot be outweighed by residual FCR providers will then be made considering all the simulated years in order to be the most representative as possible of all the potential operational conditions that FCP and FRP have to deal with.

5.4.2 Simulation model block diagram

A logical diagram for the simulation model is shown in the following Figure 5.

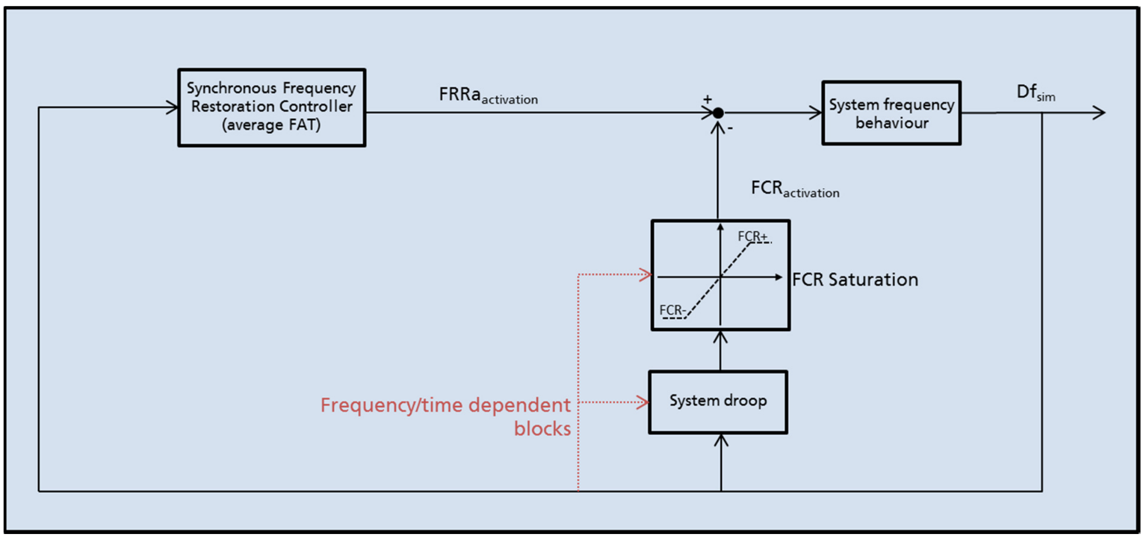

Figure 5

The model is referred to a whole synchronous system. Each block is described in the following paragraphs.

Synchronous Frequency Restoration Controller

The FRP has the aim to control the Frequency Restoration Control Error towards zero. Where a Synchronous Area contains more than one LFC Area the Frequency Restoration Control Error - or Area Control Error (ACE) - is calculated from the deviation between the scheduled and actual power interchange of a LFC Area (including Virtual Tie-Lines if any) corrected by the frequency bias (K-Factor of the LFC Area multiplied by the Frequency Deviation).

Since the implemented model simulates the system of the whole synchronous area the entire Cross-Border Load-Frequency Control Process could be then neglected.

The Synchronous Frequency Restoration Controller models indeed only the proportional–integral action of FRP on frequency error Δf_{sim}.

The whole Frequency Restoration Process of the synchronous area is modeled with a single controller with a Full Activation Time (FAT) calculated as an average of the FAT of all the LFC areas belonging to the synchronous area weighted on FRR K-factor.

The Synchronous Frequency Restoration Controller does not model the saturation of FRR. The resource is considered without limitations since the FRR-exhaustion-related phenomena are taken implicitly into account considering the Long Lasting Frequency Deviation events.

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The simulated FRP operates only on the disturbances caused by the outages as both Standard Frequency Deviations and Long Lasting Frequency Deviations already implicitly involve an activation of FRR. The model shall be developed in order to distinguish the two different kind of disturbance and to activate FRR only in relation to the outages.

FCR Saturation

The saturation block models the limited availability of FCR of the synchronous area.

The FCR saturation values depend on the dimensioning criteria adopted in each synchronous area.

With this block is possible to model the behavior of LER with a defined minimum time period in which they must provide FCR.

This block is then frequency-dependent: if part of the FCR is provided by LER, the saturation values must be reduced once they have depleted the energy reservoir.

System droop

The system droop block represents the global MW/Hz curve of the whole synchronous area.

The curve is the sum of the different MW/Hz curves of LFC areas which are part of the synchronous area.

Also this block is frequency-dependent: if part of the FCR providers is given by LER, the droop varies once they have depleted the energy reservoir.

System frequency behavior

The block models the relationship between power imbalance and frequency deviation.

5.4.3 Simulation of energy depletion of LER

In the SO GL Art.156 (9) is specified that LER must be continuously available during normal state.

The LER are considered without energy limitations while frequency remains inside the standard frequency range. Once the simulated frequency exceeds this range, the model starts to calculate the activated energy and the residual energy in the reservoir.

The residual energy is taken into account even if the alert state is not yet triggered; this choice of implementation is due to the fact that the alert state is triggered after the alert state trigger time.

Considering a generic situation in which the alert state is triggered, the actual trigger of the alert state occurs after a period with a frequency deviation beyond the standard frequency deviation. For example, in Nordic synchronous area, the alert state can occur due to a frequency deviation continuously above 250 mHz for at least 5 minutes.

Considering the Nordic system thresholds, even if the period between the overcoming of ±100mHz and the trigger of alert state can be considered as normal state, it is very unlikely that the LER can keep their energy reservoir fully available in this situation.

The actual energy consumption during this transition from normal state to alert state shall be then taken into account.

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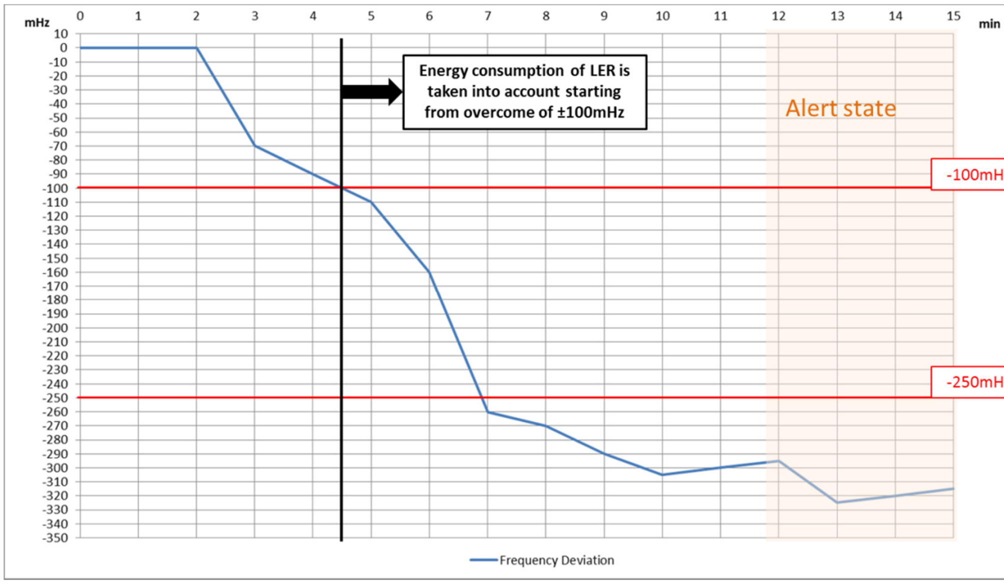

Figure 6: Starting thresholds for LER consumption analysis (Example referred to Nordic synchronous area)

The starting value of the reservoir energy level will be equal to half of the equivalent reservoir energy capacity. The equivalent energy capacity (E_{max}) is calculated for each time period ($T_{\min LER}$) with the following formula:

$$E_{max} = 2 * \frac{T_{\min LER}}{60} * FCR_{LER} \qquad [MWh]$$

Where FCR_{LER} is the FCR provided by LER [MW].

At the depletion of energy reservoir, the LER stop to provide FCR – it means that both MW/Hz curve and the total amount of FCR on the system are modified.

5.5 FCR iterative dimensioning

The aim of the present CBA is to assess the system costs associated with different minimum time period in which LER must provide FCR considering their impact on stability risk. The simulation model used to calculate the probabilistic frequency error in presence of LER amongst FCR providers is expected to quantify a potential worsening of frequency compared to a condition in which all the FCR providers are without energy limitations.

It is expected that the more $T_{\min LER}$ decreases the more it is possible that LER could deplete as a consequence of a particular combination of outages and deterministic frequency deviations.

Due to security reasons, it is assumed that a LER depletion can be acceptable only if it never brings to a saturation of FCR. In other words, a LER depletion shall never entails the steady state frequency to overcome the maximum steady state frequency deviation.

If a LER depletion occurs, the activated FCR provided by LER disappears. This activated FCR must be replaced by residual non-LER providers. The residual non-LER providers must have a sufficient not yet activated FCR to replace the depleted LER activated FCR.

Two generic examples related to CE synchronous area are reported in the following Figure 11 and Figure 12.

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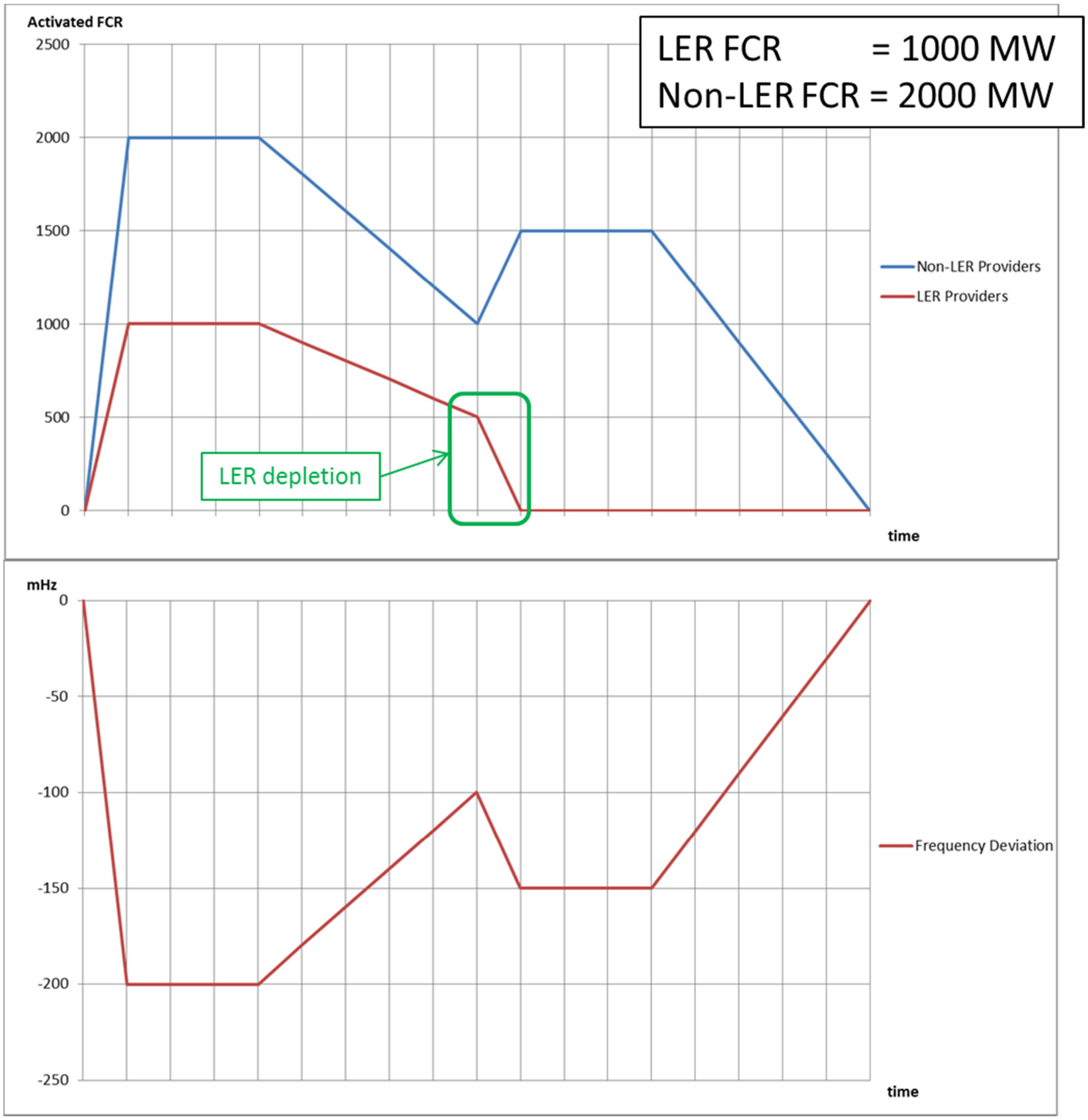

Figure 7: Acceptable situation - depleted LER can be replaced by non-LER

In Figure 11 is shown a situation where the LER depletion is acceptable since it does not jeopardise system stability. There are 1000 MW of LER FCR and 2000 MW of non LER FCR.

The full FCR activation occurs due to a power imbalance. The frequency deviation reaches a stable value equal to maximum steady state frequency deviation (200 mHz in CE).

The FRR starts to restore frequency.

At the moment of LER depletion, the LER are providing 500 MW of FCR. This contribution can be replaced by non LER since these sources are not saturated: the total non-LER FCR is 2000 MW, of which only 1000 MW were activated before LER depletion.

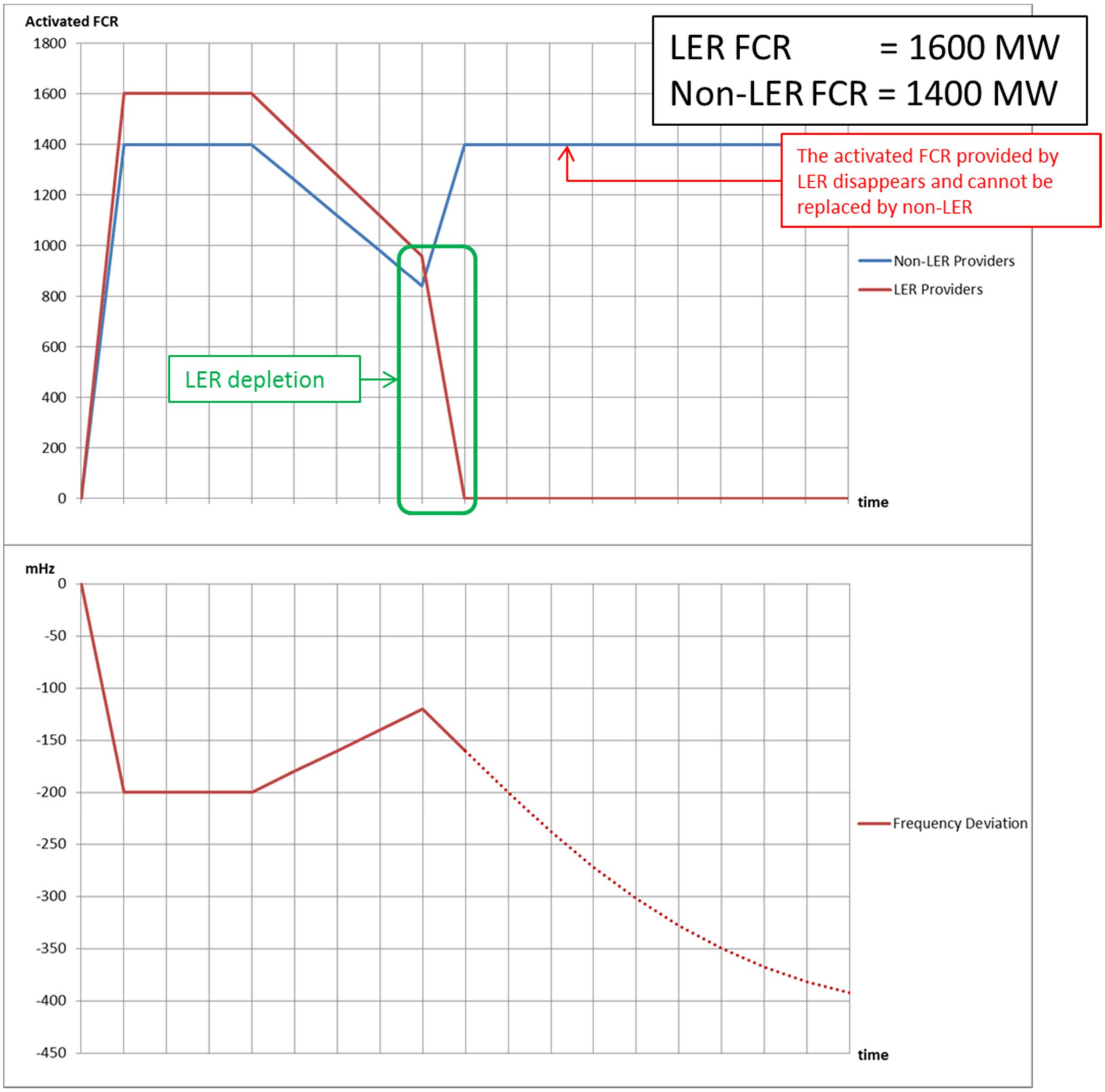

Figure 8: Not acceptable situation - depleted LER cannot be replaced by non-LER

In Figure 12 is shown a situation where the LER depletion is not acceptable. There are 1600 MW of LER FCR and 1400 MW of non LER FCR.

After the full FCR activation and a partial restoration of frequency deviation thanks to FRR, the LER depletion occurs.

At the moment of depletion the LER are providing 960 MW of FCR while the non-LER are providing 840 MW of FCR.

The 960 MW of LER disappears but they cannot be replaced by non LER since they can provide only up to 1400 MW.

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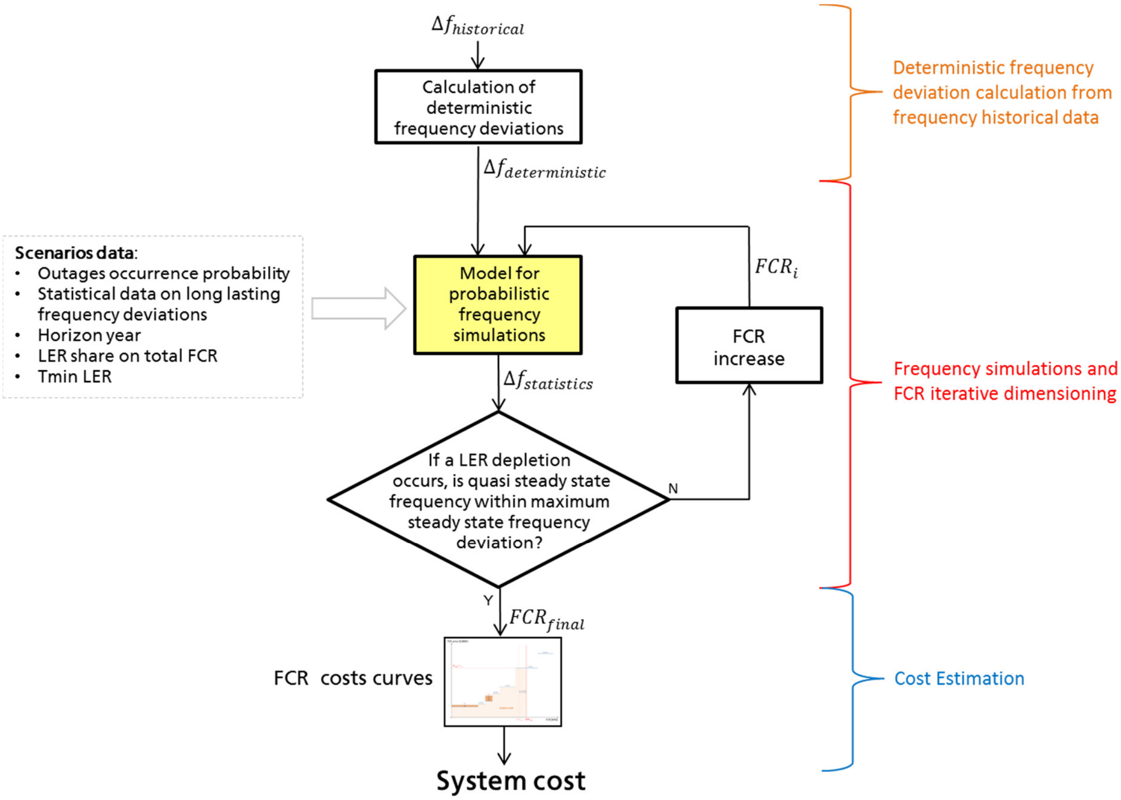
The power imbalance caused by LER depletion cannot be covered by the residual non-LER FCR. As a consequence, the frequency deviation cannot be contained and starts to decrease (partially limited only by FRR activation).

In high LER penetration scenarios, the described requirement entails that an energy depletion must never occur.



The workflow contains an iterative process in which, if the requirements on LER depletion are not fulfilled, the FCR total amount is gradually increased.

The iterative process stops once the requirements on LER depletion are fulfilled.

5.6 Assumption and description of cost estimation

An increase in FCR entails an increase of system costs that shall be assessed.

The cost estimation related to each $T_{min\ LER}$ in different scenarios is an evaluation of FCR system costs considering the total amount of FCR defined with the iterative dimensioning process.

It is possible that when $T_{min\ LER}$ decreases, a greater volume of FCR is needed to fulfil the stability requirements.

It must be highlighted that the increase in FCR does not directly represents a real option to cope with the limited energy of LER. This approach has only the aim to assess system stability risks and total cost of FCR in case of increasing total volume of FCR as requested by Article 156 (11 d) of the SO GL.

5.6.1 Costs associated to an increase in FCR

An ideal FCR providers' cost curve shall be defined assuming that:

- A competitive FCR market is developed to reflect the costs of FCR provision.
- The offered cost curve perimeter extends to the whole synchronous area without constraints between LFC areas and LFC blocks belonging to the synchronous area.

Both providers with limited energy reservoir (LER) and unlimited energy reservoir (non-LER) are considered in the FCR providers cost curve definition (Figure 9).

A specific cost (€/MW) is then associated to the providers for their available FCR (MW).

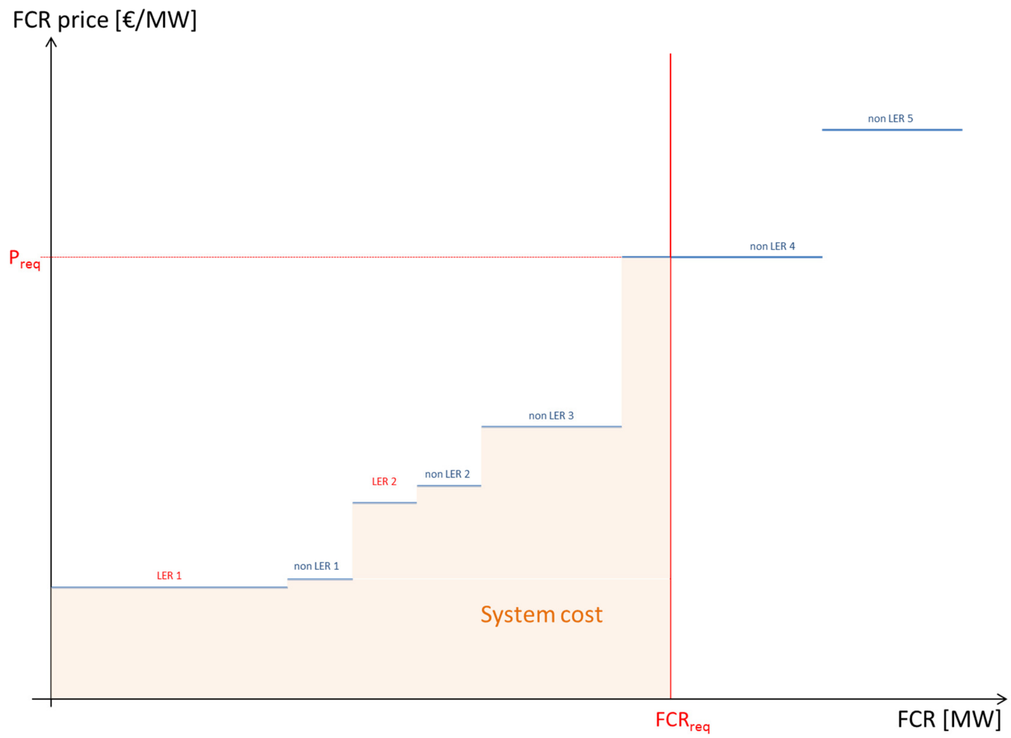


Figure 9: FCR ideal costs curve

The synchronous area FCR requirements as a result of the iterative process described in 5.5 (FCR_{req}) intercept the costs curve on a generic marginal cost P_{req} and the coloured area of Figure 9 represents the FCR costs of the synchronous area.

A decrease of $T_{min\ LER}$ can have a dual effect on the FCR costs:

- if the system need a larger amount of FCR because of the presence of LER with less reservoir capacity, the required FCR increases;
- a smaller $T_{min\ LER}$ entails lower investment costs for LER, then the costs curve varies: the costs of FCR provided by LER decrease.

These effects are shown in the Figure 10.

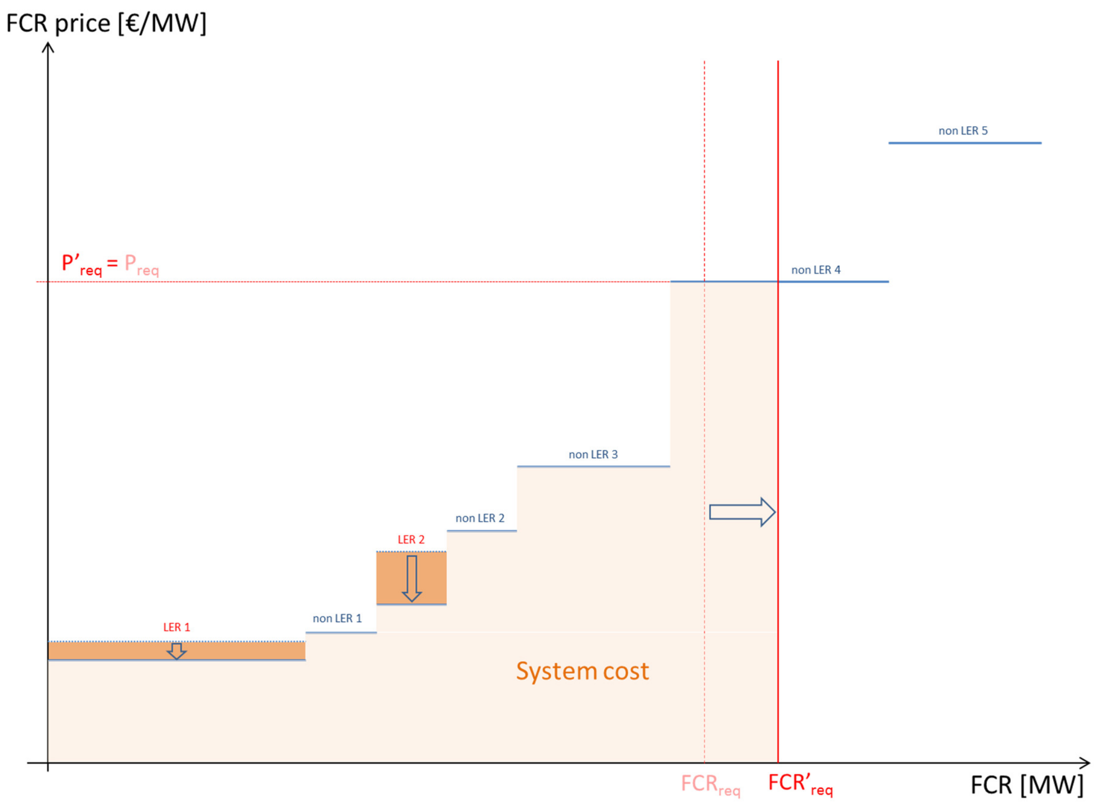


Figure 10: FCR ideal costs curve with a decrease of Tmin LER.

A higher $T_{min\ LER}$ entails both a potential reduction of FCR cost (due to the lesser increase of FCR volume needed) and an increase of due to higher costs of LER (related to greater investment costs).

The global effect on the total cost is indeed related to the combination of these two separated effects.

It should be noted that these effects take place even without an actual variation in the FCR marginal cost.

The dependence between $T_{min\ LER}$ and system costs must be deeply investigated to find out the $T_{min\ LER}$ that minimise the total FCR costs.

The main aspects that should be taken into account to describe this dependence are:

- the relationship between $T_{min\ LER}$ and required FCR. The required FCR is the value resulting from an iterative process and is dimensioned in order to avoid stability issues in presence of LER.
- A significant FCR market costs curve for both LER and non-LER on a whole synchronous area. (5.6.1.1).
- The costs variation of LER as the $T_{min\ LER}$ varies. This variation can be related to the increased cost of investments due to greater $T_{min\ LER}$ (5.6.1.2)

5.6.1.1 FCR costs curve

Conventional non-LER plants costs

This kind of approach is very useful since in this way it is possible to model the costs of non-LER FCR providers (hydro and thermoelectric plants) in terms of:

- Energy price;

- Marginal production cost.

All the providers without energy reservoir limitations are considered as conventional FCR providers– these kind of producers typically operates on both ancillary services (e.g. FCR) and energy markets.

There is a relationship between the quantity that these providers can offer on ancillary markets and the energy that they can offer on the energy market.

The costs of ancillary services are then related to the price of energy as traded on energy market.

The typical relationship between the FCR costs and the marginal production costs is shown in Figure 11.

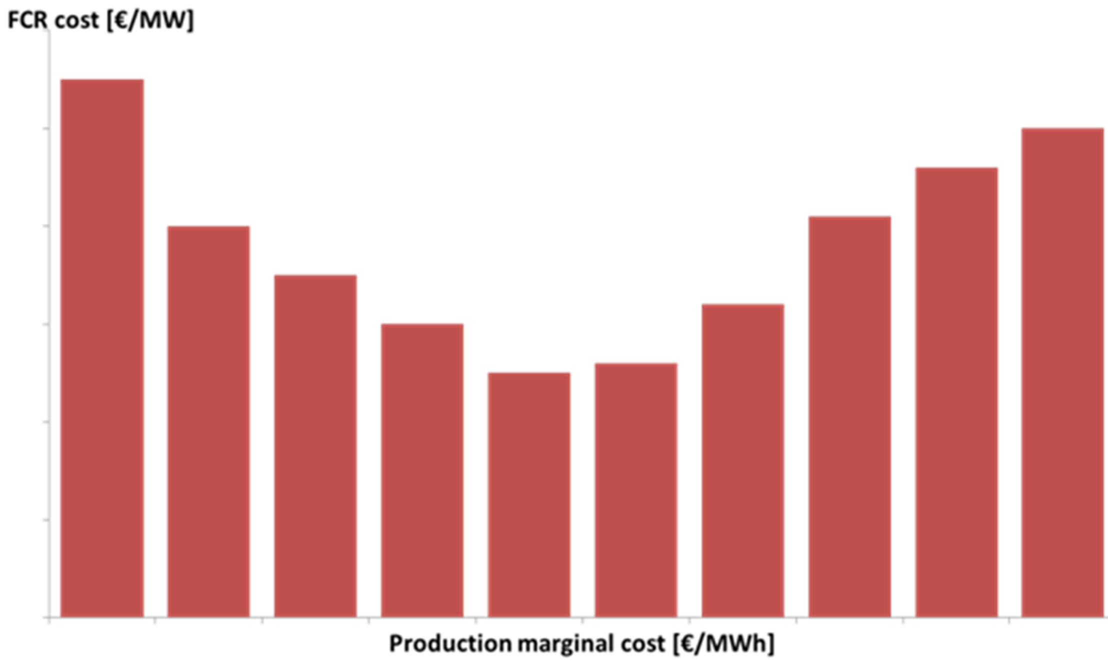


Figure 11: Dependence between FCR cost and variable cost for conventional plants

The FCR cost has a minimum value in correspondence to the marginal energy price (as determined on the energy market). In Figure 11 the energy price is then around the central columns.

The illustrated cost structure can be explained considering that FCR is a symmetrical service: providers must run their plants at a power level from which it is possible to decrease and increase power output of an amount equal to the FCR capacity. This entails a constraint in terms of power that can be sold on the wholesale energy market.

A low-variable-cost plant should sell as much energy as possible if the energy price (EP) is higher than its marginal costs (MC). This implies running the plants at their maximum power output.

Selling FCR would reduce the energy sold on the market; thus the FCR cost can be calculated as the hindered margin related to this reduction.

The cost per unit of the margin is:

$$EP - MC$$

This is also the cost associated to the sale of FCR service for low-variable-cost plants (left columns in Figure 11).

The relatively high-variable-cost plants (right columns in Figure 11) are in the opposite conditions when the energy price is lower than their marginal costs.

Neglecting the technical minimum output, these plants are out of the market and should be kept off (zero power output). Selling FCR would mean running the plants at least at the offered FCR capacity (in order to guarantee the downward reserve). It entails an economic loss equal to the difference between plant's marginal cost and energy price:

MC - EP

This value can be considered as the cost per unit of FCR for those type of plants.

If the minimum output (MO) is taken into account, the provider must run its plant at a higher power output (MO + offered FCR) – resulting in a higher economic loss and indeed to a FCR cost per unit higher than MC – EP.

Since the decision to run or not a relatively high-variable-cost plant during low energy price periods is made taking into account several factors (the possibility to sell FCR is just one of them), the economic loss related to the production of minimum output should be only partially charged on FCR cost.

Based on the previous considerations it is possible to assume that the most economic non-LER are those with marginal costs closer to energy price.

LER plants costs

The FCR cost for LER shall be calculated taking into account the investment to be sustained by new or existing LER providers in order to be qualified for FCR provision and considering a defined time period requirement. An illustrative trend of LER FCR cost is reported in Figure 12.

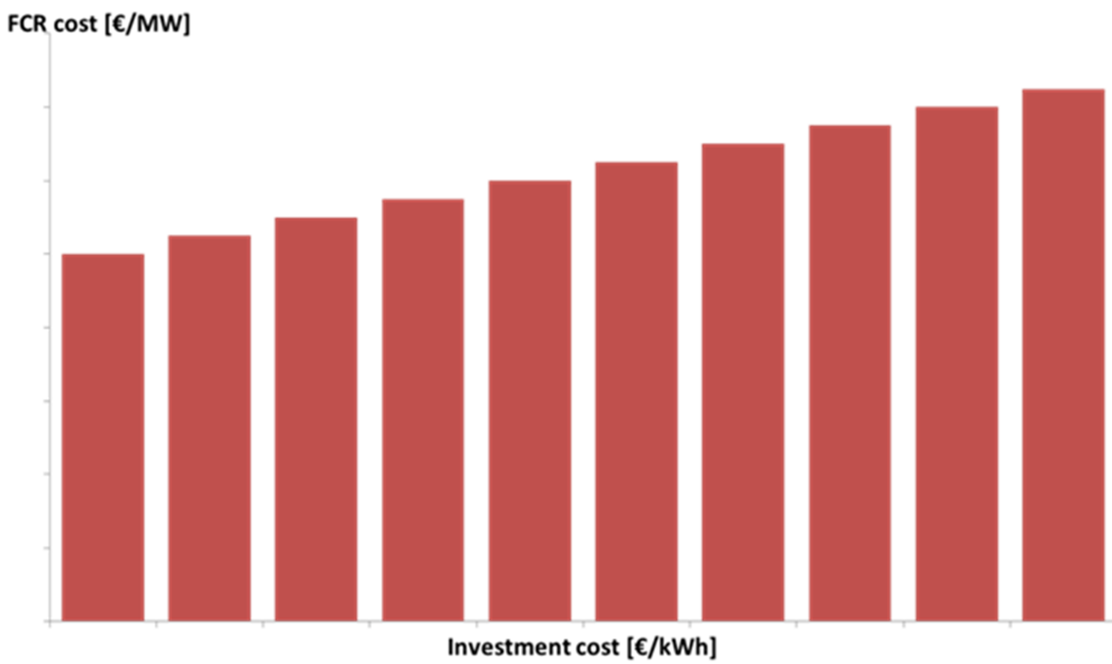


Figure 12: Dependence between FCR cost and investment cost for LER plants

The cost estimation will be performed in the methodology considering at least the following LER technologies:

- Pumped storage;

- Battery Energy Storage System (BESS), including electric vehicle batteries provided with V2G technology;
- Other limited energy technologies (e.g. flywheels and supercapacitors) will be considered if their energy storage capacity can fulfil at least with the minimum time period (15 minutes).

Also the evolution of the costs will be investigated and considered in the different scenarios (as detailed in 5.7).

It is possible to investigate also LER that can provide other services beside the FCR, such as electric vehicles frequency response, battery systems coupled to PV/Wind plants, etc.

In those cases the plants are developed for services that are different from providing FCR. The investment costs should be then only partially charged on the FCR costs.

On the other hand, for those plants providing FCR implies allocating part of the power and energy capacity to this specific service, resulting in a reduction of the power and energy capacity available for their "main assignment". This reduction results into costs that should be charged on the offered FCR.

Offering quantity

It is possible to associate an available FCR quantity for each different conventional technology (nuclear, coal, lignite, CC gas turbine, hydro, battery, etc.).

The available FCR quantity is related to:

- the possibility of each different technology to provide FCR in compliance with technical requirements (i.e. deployment dynamic).
- the installed power for each different technology, which can change in future scenarios.

Building of FCR market curve

Taking into account the previous considerations, it is possible to build a cost/quantity curve for the synchronous area by ordering all the cost/quantity pairs.

The data required to build the curve are:

- Energy market results (energy market prices);
- An estimate of production marginal costs of the different generation technologies installed in the synchronous area;
- An estimate of the investment costs for LER plants.

5.6.1.2 Dependence of LER FCR cost from minimum time period ($T_{min\ LER}$)

If the $T_{min\ LER}$ increases, the LER must be equipped with a larger reservoir. This requirement has an effect on the cost of FCR provided by LER plants, since it entails a greater investment cost (Figure 12).

This dependence could be further investigated in order to distinguish between already existing plants (which have to adapt their energy/power ratio) and future plants (which will invest in larger reservoirs).

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5.7 Scenarios description

Scenarios are defined to represent potential future developments of the energy system and regulations. Scenarios are also defined in order to address uncertainties and assess the impact of different assumptions which can affect the results of the cost-benefits analysis.

The present CBA will explore different scenarios in terms of:

- **Share of LER in the FCR provision mix.** The share of the LER can be affected by the cost effectiveness of LER but also by other factors, such as the presence of a market based procurement of FCR, or other technical and regulatory impacts on LER deployment. For this reason, the proposed approach is to analyse different shares of LER in the FCR provision mix (10-100% range with 10% discretization).
- **Time horizon.** All the analyses will be performed considering the evolution in the mid-long term of the generation portfolio, demand forecast, transmission system development, fuel costs and LER investment costs. The CBA will define periodical snapshot years and will interpolate results between the years. The process described in 5.1 will then be applied considering the scenarios developed in ENTSO-E TYNDP[2] which can be adopted as robust reference scenarios because of their well-established definition process.

The process described in 5.1 will be applied at least over two time horizons among the short term (1-5 years range), medium term (5-10 years range), and long term (10-15 years range).

In the medium and long term ENTSO-E developed many alternative scenarios considering different assumptions for the system development. Each scenario entails a significant computational effort, for this reason a single scenario has to be selected among the ENTSO-E TYNDP alternatives. The selection is based on the identification of the scenario which is considered the most representative for assessing the future development of FCP, with a potential significant reduction of conventional FCR providers compared to the actual conditions. The ENTSO-E TYNDP scenarios proposed for each time horizon will be the following:

- Short term: ENTSO-E TYNDP 2020 scenario
- Medium term: ENTSO-E TYNDP 2025 gas before coal scenario (GBC)
- Long term (10-15 years range): ENTSO-E TYNDP 2030 distributed generation scenario (DG)

Furthermore, in order to evaluate the best solution in terms of minimum activation period which is not greater than 30 or smaller than 15 minutes, the interval of possible solutions have to be explored applying the process with an opportune discretization. The proposed discretization is 5 minutes, thus the results considering 15, 20, 25 and 30 minutes as minimum activation period will be assessed.

The set of combinations to be analysed for each time horizon are summarized in Table 1:

[2] http://tyndp.entsoe.eu/tyndp2018/

		LER share on total FCR providers									
		10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Tmin LER	15 min										
	20 min										
	25 min										
	30 min										

Table 1 Different combinations of LER share and Tmin LER to be assessed in the CBA

The workflow described in paragraph 5.1 allows to calculate for each combination both FCR dimensioning [MW] and its costs [€].

In order to convert monetary costs which characterize different time horizons into a single present value, a discount rate can be used.

One single pan-European societal discount rate will be used to calculate the Net Present Value (NPV) of FCR costs for each combination of LER share and Tmin LER reported in Table 1. This shall be a real discount rate of 4%[3] applied assuming 2019 as starting year of the minimum time period requirement and the last simulated snapshot year as ending year of the assessment.

The results for each year within the ending year of the assessment are derived from the results of the snapshot years described above aggregating across years as follows:

- For years from the starting year of the minimum time period requirement (2019) to the first snapshot year the results of the first snapshot year will be extended backwards.
- For years between snapshot years (two or three depending on the number of simulated time horizons) the results will be linearly interpolated between the snapshot years.

All costs are discounted to the CBA implementation year, and expressed in the price base of that year.

The CBA implementation will allow to determine the combination of time period, LER share on total FCR provider and FCR dimensioning which entails the lowest social cost over the time horizon without jeopardising the system stability during the most relevant real frequency events. The approach to evaluate the impact of a defined time period on system stability during the most relevant real frequency events is described in paragraph 5.8.

[3] The proposed discount rate is coherent with assumptions made in other CBA developed in Europe in the energy sector and already approved by the European Commission: https://www.entsoe.eu/Documents/SDC%20documents/TYNDP/ENTSO-E%20cost%20benefit%20analysis%20approved%20by%20the%20European%20Commission%20on%204%20February%202015.pdf

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5.8 Assessment of power system stability during the most relevant real frequency events in presence of LER

According to Article 156(11 d) of the SO GL, shall be considered also the LER impact on system stability risks for each synchronous area.

The probabilistic approach aforementioned has the aim to assess the effects of LER depletion on a wide set of possible system conditions as calculated by the Monte Carlo method.

The model used for the probabilistic approach is a simplification of the real power system – it neglects important phenomena (such as lines overload, voltage problems, etc.) that only a complete synchronous area dynamic simulation could take into account.

Indeed, there are certainly important possible sequences of events that cannot be tested with the proposed Monte Carlo simulation also because the historical period of observation does not guarantee an adequate probabilistic representativeness of those rare occurrences.

In order to test the LER effects at least in some of these possible sequence of events, it is needed to simulate the most important actual grid disturbances that each synchronous area experienced in the past 15 years.

For Continental Europe, for example, it will be tested the system disturbance on 4 November 2006 and 28 September 2003 blackout in Italy (for the effects on the rest of the system).

During these events the FCP had a crucial role in avoiding a further deteriorating of the system conditions and in help to restore the stability.

Since these extreme working conditions are possible, it is fundamental to assess how the system with LER would react.

This assessment shall be done testing the system with LER on the same frequency conditions that occurred in the past. In other words, the real grid disturbances shall be simulated considering the presence of LER and assessing how the potential energy depletion would have affected the frequency.

The real frequency data recorded during the events shall be used as an input of the simulation model described in 5.4.2; it shall be verified if the LER would have been depleted during the disturbance and if this depletion would have been the cause of further critical worsening in the power system conditions.

		LER share on total FCR providers									
		10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
T_{min} LER	15 min	Y/N	Y/N	Y/N	Y/N	Y/N	Y/N	Y/N	Y/N	Y/N	Y/N
	20 min	Y/N	Y/N	Y/N	Y/N	Y/N	Y/N	Y/N	Y/N	Y/N	Y/N
	25 min	Y/N	Y/N	Y/N	Y/N	Y/N	Y/N	Y/N	Y/N	Y/N	Y/N
	30 min	Y/N	Y/N	Y/N	Y/N	Y/N	Y/N	Y/N	Y/N	Y/N	Y/N

Table 2 Assessment of power system stability during the most relevant real frequency events for different combination of LER share and Tmin LER – Pass/fail condition (Y/N)

Each combination of LER share-$T_{min\ LER}$ reported in Table 1 shall be tested on these events. For each scenario, the result of the test shall be a pass/fail (Y/N) condition.

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The combination of LER share-$T_{min\ LER}$ passes the test if it does not endanger system stability in the most relevant real frequency events simulations. If the combination of LER share-$T_{min\ LER}$ worsens operational security potentially leading to a blackout state during these events the LER share-$T_{min\ LER}$ combination will not be considered acceptable (fail condition).

Only the LER share-$T_{min\ LER}$ combination which passed the assessment of the most relevant real frequency events are taken into account for the identification of the best combination, adopting as a criteria for selection the lowest NPV FCR cost.

The CBA aims then to identify the combination of time period, LER share and FCR dimensioning which entails the lowest social cost over the time horizon without jeopardising the system stability during the most relevant real frequency events.

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