FINAL REPORT PHASE 1

RoCoF Alternative Solutions Technology Assessment

High level assessment of frequency measurement and FFR type technologies and the relation with the present status for the reliable detection of high RoCoF events in a adequate time frame.

Report No.: 16011111, Rev. 005

Date: 17/08/2015

Project name:	RoCoF Alternative Solutions Technology Assessment High level assessment with regards to high RoCoF event detection, response time and FFR type technology solution status.	DNV GL Energy Advisory Palace House 3 Cathedral Street London SE1 9DE Tel: +44 20 7357 6080
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Date of issue:	23/06/2015	
Project No.:	16011111	
Report No.:	16011111, Rev. 005	

Task and objective:

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☐ Unrestricted distribution (internal and external)
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☒ No distribution (confidential)
☐ Secret

Keywords:
[Keywords]

Reference to part of this report which may lead to misinterpretation is not permissible.

Rev. No.	Date	Reason for Issue	Prepared by	Verified by	Approved by
001	07/05/2015	First issue Draft	Willem Uijlings	Mark Winfield	Colin MacKenzie
002	03/6/2015	Deliverable two added to report	Willem Uijlings		
003	11/6/2015	Final Draft report	Willem Uijlings		Colin MacKenzie
004	23/6/2015	Final report	Willem Uijlings	Wim Kuijpers	Colin Mackenzie
005	17/8/2015	Small update, punctuations, etc.	Willem Uijlings		Colin Mackenzie

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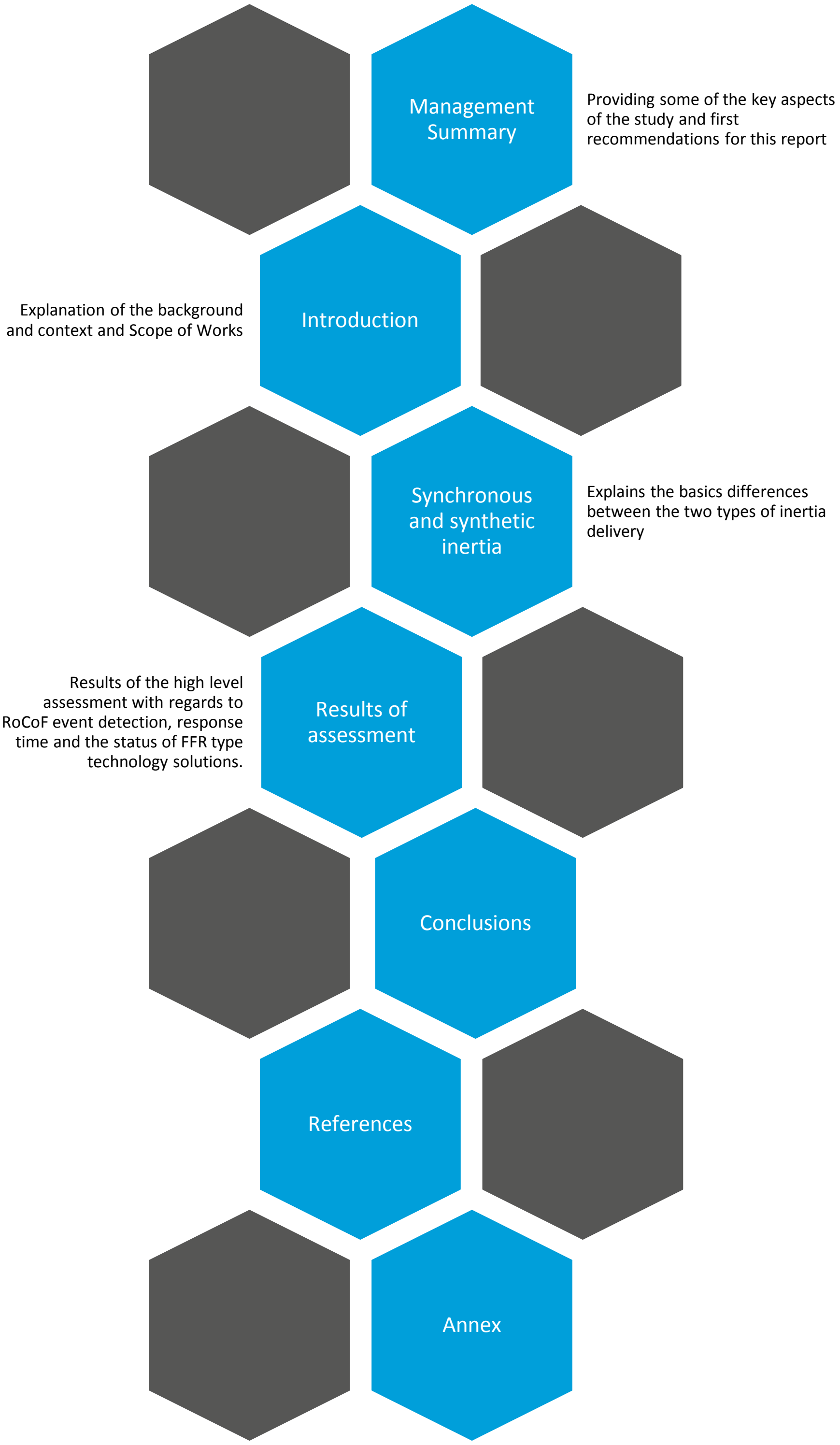

1 EXECUTIVE SUMMARY

In Ireland and Northern Ireland the governments are progressing an energy policy to deliver a more sustainable energy supply portfolio. With the growing share of Renewable Energy Sources in the island's generation portfolio, the inertia in the system is likely to decline. As a result, higher Rates of Change of Frequency (RoCoF) are likely to be seen on the system in future. For this reason the Commission for Energy Regulation (CER) and the Utility Regulator in Northern Ireland (UR) directed the TSOs to investigate complementary or alternative solutions to the inertia decline.

EirGrid commissioned DNV GL to consider the requirements, such as the speed of detection and a range of technologies available, for alternative solutions to help prevent large RoCoF events. The emphasis of the study was to provide a high level overview of the present technologies commercially available and their abilities to be used to prevent large RoCoF events. Particular attention was given to the possibility of utilising non-synchronous technologies able to provide synthetic inertia. The study researched the capabilities of synchronous technologies in less detail as such technologies are well understood in terms of their inertia capabilities.

The high level analysis of alternative solutions to help prevent large RoCoF events has delivered the following key conclusions:

Synthetic Inertia Devices

- The "synthetic inertia" Fast Frequency Response (FFR) type devices have the potential to provide a power response to help prevent high RoCoF events.
- However, the time period required to reliably activate a (synthetic)[1] FFR type device for the delivery of an effective power response poses some challenges. Within this total response time, the most challenging aspect is the period required to reliably detect and measure a RoCoF event to ensure the appropriate response to mitigate the event.
- Presently RoCoF detection is used for the purposes of anti-islanding disconnection protection. There is no proven track record for accurate RoCoF detection for the purpose of mitigation of RoCoF events.

All Technologies

- The technology analysis indicates that all 13, listed by EirGrid-SONI, have the capability to help prevent high RoCoF events. The criteria and metrics, introduced by DNV GL, for the assessment of the 13 technologies provide a preliminary suitability ranking, which is a combination of the effectiveness, technology maturity, lead time, ability to provide additional system services, and geographical flexibility between the technologies. The first top 6 technologies are all based on synchronous rotating mass (inertia) and without converters, therefore response is immediate without the need for RoCoF detection. The resulting weighted scoring system presents the following best suitable technologies:

    1. Synchronous compensators ;
    2. Reduction in the minimum MW generation;
    3. Rotating stabilisers;
    4. Pumped hydro;
    5. Flexible thermal power plant;
    6. "Parking"

[1] Synchronous (Non-synthetic) FFR type devices acting instantly and do not require activation

7. Battery technology;
8. CAES;
9. Flywheels;
10. Wind turbines;
11. HVDC interconnector;
12. Demand Side Management (DSM);
13. AC interconnectors.

- The technology assessments conducted in this report are high level. Further detailed analysis of costs, device technology characteristics and system impacts would be required to fully assess the suitability of specific technologies in preventing high RoCoF events.
- Synchronous Inertia is currently the most proven method of mitigating high RoCoF events and therefore these technologies, 1 to 6, have scored amongst the highest in the technology analyses. Synthetic inertia devices have the capability to provide adequate response to mitigate RoCoF events however their deployment for this purpose is less proven.
- The time required to activate a (synthetic) FFR type device for the reliable delivery of an effective power response needs further investigation, specifically with regards to the technology and methodologies which are capable to accurate measure and detection RoCoF in a suitable time frame.

2 INTRODUCTION

Background and Context

In Ireland and Northern Ireland the governments are progressing an energy policy to deliver a more sustainable energy supply portfolio. The target in Ireland is 40% of total energy consumption to come from Renewable Energy Sources (RES) by 2020. The Government of Northern Ireland also has an ambition towards 40% of all energy consumption to come from RES by 2020.

The thermal power plants of the island of Ireland largely facilitate system stability. With the future larger share of RES in the island's generation portfolio, the inertia in the system is likely to decline. Practically, therefore, higher Rates of Change of Frequency (RoCoF) are likely to be seen on the system in future. For this reason the Commission for Energy Regulation (CER) and Utility Regulator in Northern Ireland (UR) together decided[2] to change the Grid Code (GC) RoCoF requirements[3] that generators must be able to meet. The change aims to help facilitate the 40% RES target of 2020 in conjunction with keeping a resilient electricity Network.

The Grid Code modifications will only come into effect following confirmation from the Transmission System Operators (TSOs) that, from a system security perspective, they can be implemented. Hence, the power system will only be resilient if the connected electricity production installations are compliant with the proposed new Grid Code RoCoF requirements. To determine compliance, the CER commissioned the "Generator Studies Project"[4]. A similar project was established in Northern Ireland by the Utility Regulator[5].

In parallel, the CER and UR have directed the TSOs to investigate complementary or alternative solutions to the inertia decline which the RoCoF Grid Code modification is intended to allow in facilitating the higher future RES target. The aim of this parallel investigation is to establish whether the various possible complementary or alternative solutions can maintain sufficient inertia in the system (or response provision in sufficiently short timescales) such that RoCoF values do not exceed 0.5 Hz/s (or some higher value that is acceptable) measured over 500 ms.

EirGrid has commissioned DNV GL to carry out phase 1 of this investigation resulting in a well-rounded range of RoCoF controls for the future that fits the changing generation portfolio. This high level desktop study, phase 1, highlights potential credible options for further detailed analyses.

Scope of work (short outline)

EirGrid is seeking support to independently assess possible technology solutions to avoid high RoCoF events. Phase 1 focusses on a high level qualitative assessment of potential solutions to avoid the need, at present, to change the Grid Code (GC) RoCoF standard from 0.5 Hz/s to 1 Hz/s measured over 500 ms.

This document includes a high level assessment of:

- RoCoF detection and response time, which investigate:

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2 The CER 14/081 decision paper of April 4, 2014 states the RoCoF definition and the GC decision made in principle to increase the maximum RoCoF to 1Hz/s measured over a rolling 500ms time window.

3 The changes are included in the MPID 229 stating the new Rate-of-Change-of-Frequency (RoCoF) requirements.

4 The "Generator Studies Project" is a three year programme which investigates the ability of conventional generators to safely and reliably operate with higher permissible RoCoF levels.

5 Utility Regulator Decision Paper, Rate of Change of Frequency Modification to the Northern Ireland Grid Code

    - The differences between synchronous and non-synchronous (synthetic) responses in chapter 3;
    - The response time of synthetic devices and the break down into its components – measurement, signal, activation and ramp times, explained in chapter 4.1;
    - Methods of measuring Frequency and the detection of RoCoF together with how it can be applied to mitigating these events together with the explanation of methods used to reliably detect and respond to a RoCoF event within adequately short timescales, explained in chapter 4.2;
    - The different power electronic technology used for the different devices and the activation time, explained in chapter 4.3.

- FFR Type technologies, which investigate:
    - The technologies including the analysis of ramping time and the ability to provide high and low frequency response, explained in chapter 5.1;
    - A weighted scoring matrix to perform a technology assessment for each of the options, explained in chapter 5.2 and chapter 5.3;
    - The thirteen technologies and the characteristics (provided in one-page faceplates), explained in the Annex.

3 SYNCHRONOUS AND SYNTHETIC INERTIA

This chapter discusses the two types of inertia delivery to the power system. Synchronous and "synthetic" inertia are outlined in the following paragraphs. The basic differences between the two inertia types are also presented.

Synchronous inertia

Synchronous inertia is provided by all machines physically connected to the Grid via its electromagnetic field, and therefore its prime-mover is directly connected.

The electromagnetic connection, which naturally exists when using machines directly connected to the Grid, without the electrical circuit being interrupted or separated by power electronics, can be explained as follows:

- Motors[6]: For a motor, the electrical energy induces a magnetic field in the stator (rotating field) and rotor (static field). The two magnetic fields interact, creating a rotational mechanical force.
- Generators: For a generator this process is reversed. The machine is rotated by a mechanical force. The rotor (with its static magnetic field) induces a changing magnetic force in the stator which induces electrical energy.

It is for this reason that the effects on the electrical network have a direct impact on the mechanical energy of the such machines and vice versa. Thus when a system frequency event occurs, the machine will naturally react to the frequency changes in the electromagnetic field. This in turn results in the mechanical system reacting 'instantaneously' and force changes as a result. The amount of power extracted or generated from the rotating mass of a synchronous machine is naturally controlled by the principles of inertia physics. The amount of energy delivered is proportional to the mass of the rotating shaft of the machine and its prime-mover and the change in frequency squared.

"Synthetic" inertia (non-synchronous)

With synthetic inertia this direct electromagnetic connection between the Grid and the machine does not exist. Machines that are connected by means of power electronics to the Grid are therefore non-synchronous in principle. As a result, machines connected non-synchronously through power electronics can only provide synthetic inertia in principle, but not synchronous inertia.

The power electronic convertors are responsible for the electromagnetic separation between the machine and its prime-mover, and the Grid. The power electronics act effectively as a buffer between the grid and the connected machine. Therefore frequency changes in the grid do not directly affect the frequency of the machine connected and vice versa.

The reason for the use of power electronics is due to the mismatch in the form of energy between the Grid and the machine. The mismatch exists due to frequency differences. This mismatch is one of the main reasons why a direct electromagnetic connection is not possible or not efficient.

6 Synchronous compensators and rotational stabilisers operate under the same principles. Please note that most motors connected to the Grid are asynchronous machines and rotate just below the Grid frequency. Asynchronous motors will also contribute to inertia as soon as system frequency drops or rises and are therefore included in the synchronous inertia category. The synchronous inertia of an asynchronous machine is delivered through; decrease in supplied torque (power output) to the driven equipment (load reduction), and supplying rotating energy (inertia) with decreasing speed of motor and driven equipment.

Synthetic inertia needs to be established through power electronic controls because of this lack of natural electromagnetic connection and thus response between Grid and the machine. However, the power electronics can be used to subtract or add energy from or to the connected machine.

Notes

Further in this document the name "machine" is dropped and will be referred to as "device". The reason is that machines are mostly associated with mechanically rotating devices. However, non-rotating devices, such as using battery technology, are also included. Therefore the word device is thought more accurate.

This document refers to Fast Frequency Response (FFR) type technologies to indicate a device that can be applied to help prevent RoCoF events in the island power system.

References to synthetic FFR type devices are non-synchronous and connected to the grid by means of power electronics.

The reference to a "RoCoF event" in this document is defined as a (temporally short) change in system frequency, due to a power imbalance on the power system, that is fast enough to cause potential issues in the power system stability. This may result in the activation of RoCoF protection used for loss of mains protection on distribution- and transmission-connected generators which in turn will trip these generators from the network with potentially de-stabilising consequences of the network.

Renewable Energy Sources (RES) are nowadays[7] typically connected using power electronics. Therefore in general, RES sources are only capable of providing "synthetic" inertia responses.

In the following chapters we focus on the (synthetic) inertia FFR type devices. The reason for the focus on synthetic inertia is twofold:

- Declining synchronous inertia from conventional generators connected to the grid and therefore the need to investigate the possibilities for synthetic inertia; and
- The natural response of synchronous inertia which does not require any additional action or technology to provide its benefit and therefore does not need further study with regards to the present scope of works.

In other words, the challenge is to investigate whether synthetic inertia FFR type devices can be utilised to help prevent large RoCoF events as synchronous inertia declines. The declining synchronous inertia makes the "synthetic" inertia FFR type devices likely to be a more financially viable option provided the technologies can provide adequate service. Hence, expenditure on synchronous devices[8] used for the sole purpose of providing inertia to the grid, can only be recovered through the system service payments as opposed to revenue streams from energy generation.

The growing high availability of power electronic connected generation devices potentially provides the opportunity to use such "synthetic" systems to stabilise the power system.

7 Type 1, 2 and 3 modern wind turbines used asynchronous generators, directly connected to the system. At present, type 4 of modern wind turbine generators are used which is a full converter type and is now, at the time of writing this report, the standard.

8 Synchronous devices such as a synchronous condenser consist of a large generator (100 – 250 MVA), controls and protection cubicle's, step-up transformer and grid connection, etc.

4 ROCOF DETECTION AND RESPONSE TIME

This chapter analyses the measurement technologies and challenges to accurately detect a Rate of Change of Frequency event. Further it introduces the time components, and their typical durations, that contribute to the total response time of a proposed solution. It should be noted that this section discusses measurement techniques for the purposes of RoCoF containment and in this sense does not appraise the use of frequency detection for the purposes of static reserve provision or under-frequency load shedding.

4.1 Response time elements

The response time is the total time that is needed for a FFR type device to actively supply the grid with the service to help prevent high RoCoF events by delivering or taking energy to or from the power system. For synchronous technologies the response time is immediate. For power electronic connected technologies, able to provide synthetic inertia only as opposed to synchronous inertia, there is a delay between the RoCoF event and the response.

The response time for non-synchronous technologies depends on 4 different actions which all add to the time delay in response. The total response time for synthetic FFR type devices $T_{response}$ is the sum of:

- Measurement time, $T_{measurement}$ for the detection and measurements, (see chapter 4.2). $T_{measurement}$ is the time that is needed to detect and measure the severity of a RoCoF event;
- Signal time, T_{signal} to get the detection signal from the measurement to the FFR type device (see end of chapter 4.2). T_{signal} is the time that is required to get the activation signal from the detection and measurement system to the FFR type device. The delay typically depends on the communication system used and the distance to the FFR type device;
- Activation time, $T_{activation}$ for the FFR type device to actively deliver the power response to help mitigate the RoCoF event. (Chapter 4.3). $T_{activation}$ is the time that is required for the FFR type device to deliver the initial power response from the moment it receives the activation signal;
- Ramping time, T_{ramp} for the ramping of active power from the FFR type device (see chapter 5Annex). T_{ramp} is the time required to ramp up to the required active power response from the device once the activation signal has been received.

The equation of the response time to activation may be formulated as:

$$T_{response} = T_{measurement} + T_{signal} + T_{activation} + T_{ramp}$$

$T_{response}$ is thus the minimum time required for delivering or extracting the total power to or from the system. The power characteristic is technology dependent which includes ramp-rate of the technology used and the initial power capability of the technology.

The timescales required for an adequate response depend on the characteristics of the electricity Grid. The following parameters are of key importance:

- The amount of inertia of the Power System. With large well interconnected networks, single events may have little effect on the total grid frequency. The Island of Ireland is not meshed with another synchronous system and therefore inertia is scarcer than in larger meshed systems. As a result, single events, such as the loss of the largest single in-feed, or a voltage dip induced frequency dip, will impact the frequency in the Network[8]. To ensure that the Power System maintains sufficient inertia to withstand the impact of a single event, FFR services are likely to be required in a future where there is less synchronous inertia in the network;

- Size of largest single in-feed, largest single out-feed or potential MW loss, which can induce voltage and frequency deviations. Larger power changes in the grid will have a bigger impact as opposed to small power changes. As a result, larger single in-feed generation or loads connected to the grid will have a bigger impact on the stability of the grid if they are suddenly disconnected from the network compared to the sudden loss of small single generation or loads;
- The capability of the demand and generation technologies installed that can handle large RoCoF events. When demand and generation can handle large RoCoF events, the time required to stop the excursion is likely to be less critical. However, if the capability of handling RoCoF events is limited, the time to stop the excursion will be important and EirGrid would need to 'contain' and restore the frequency within specific time frames to avoid instability.

4.2 Technology introduction for frequency change measurement

There are different technologies to measure frequency such as measuring the angular velocity of the rotating voltage phasor, Fast Fourier Transform Analyses and voltage zero crossing measurements. Not all of these technologies translate directly into a Rate of Change of Frequency measurement.

At present, existing measurement technologies for RoCoF detection are primarily used to detect islanding of part of the distribution network and disconnect distributed generators from the network.

Disconnection of generation is required to avoid dangerous situations occurring in the islanded network. The danger occurs because Distributed Generators (DG), connected to an islanded network, continue operating as if their network voltage and frequency are still determined by the main network. The DG supplies active and reactive power as determined by the generator's local controllers. However, depending on the control strategy of the DG and the characteristics of the islanded network, power imbalances or frequency and voltage excursions will occur in the islanded network unless the DG is disconnected.

Such uncontrolled islanded network operation is unacceptable not only for the above reasons, but also because they have the potential to be dangerous when switching operations reconnect the islanded network to the interconnected system without full control of the synchronisation.

In this chapter we explain the assessment results for reliable detection times of technologies with regards to frequency measurements to inform on RoCoF events. The following high level assessment results are provided:

- Methodologies and technology (including proven and state-of-the-art) for measuring the system frequency deviations;
- Characteristic times for detecting frequency events and triggering a response;
- Reliability of detection. The relationship between the frequency event onset and the time at which the response is triggered.

[9] A Voltage Dip Induced Frequency Dip (VDIFD) event is where a frequency dip occurs due to the transient loss of wind generation following a significant transmission system fault.

Measurement technology

RoCoF and frequency measurement devices make use of the network voltage signal to calculate the frequency and possible changes in frequency. An example is provided in Figure 1. The voltage waveform is measured and the frequency deviation is calculated using the zero crossings of the voltage sine waves. A low-pass filter is used to eliminate high frequency transient voltage signals. The measured RoCoF is then compared with the relay settings.

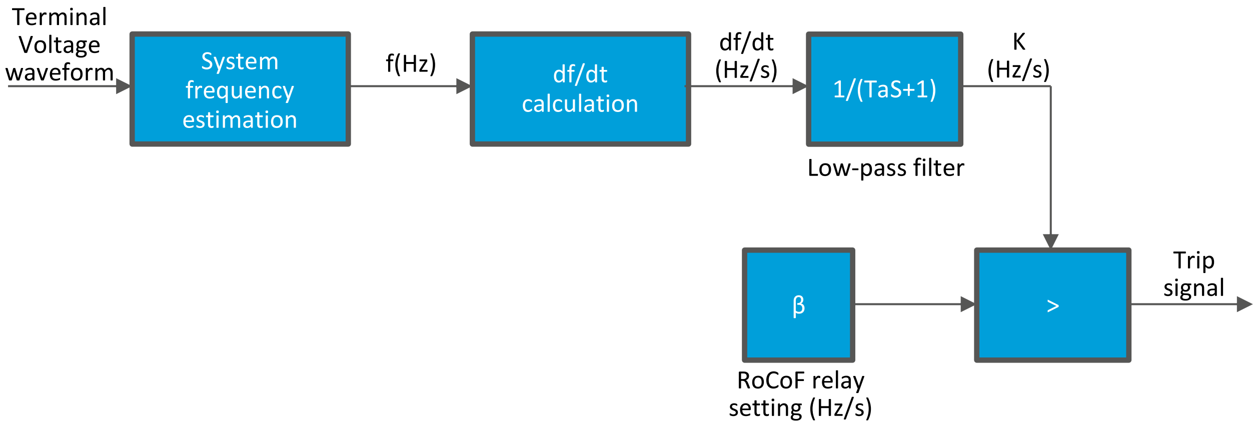

Figure 1: Simplified schematic diagram of RoCoF[10]

Several methods can be used to calculate the system frequency. One method is by calculating the time between zero crossings of the voltage of the grid, see Figure 2. The period of the sine wave is translated into a frequency.

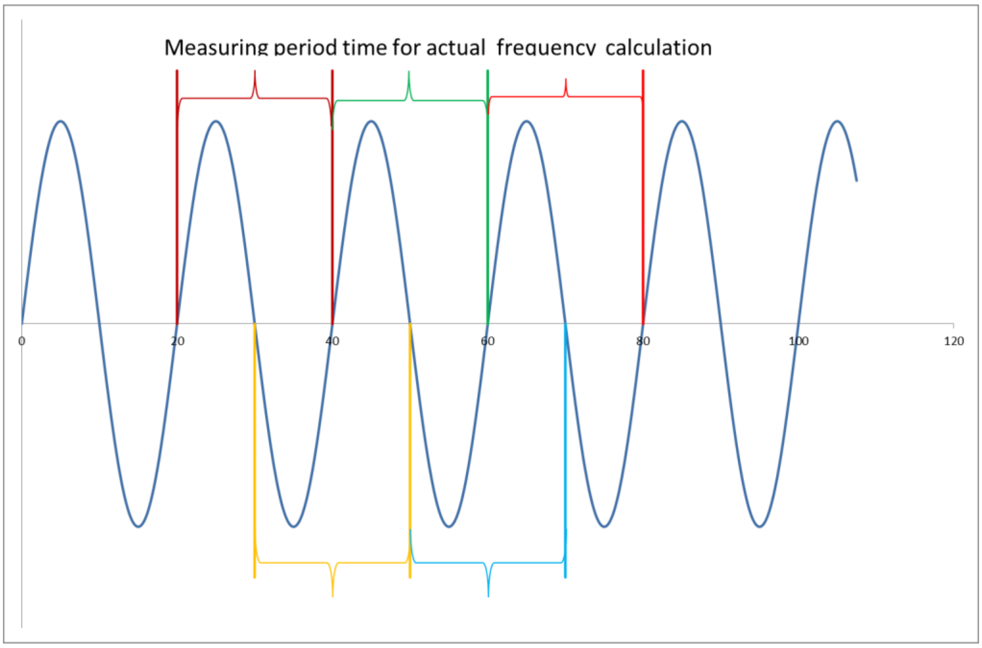

Figure 2: Principle measurement period time cycle to determine frequency

[10] Bohan Liu, University of Nottingham; Advanced ROCOF Protection of distribution systems, March 2012

By comparing the measurements of the sine wave cycle durations, the change in frequency is determined. The rate of change of frequency is then calculated by dividing the difference in frequency by the time between the measurements. See Figure 1.

For each half cycle a duration measurement can be performed; from this, the time between zero crossings of a complete sine wave can be compared with the complete sine wave a half cycle earlier. With this technique only complete sine waves should be used for measurement because of possible asymmetry of the voltage waveform (see Figure 3).

Another technique that can be used for frequency measurement is Fast Fourier Transform Analysis (FFTA). The FFTA determines the frequency based on Fourier analyses which makes it possible to do this using only a part of the voltage sine wave. With the FFTA, a more continuous measurement can be achieved as opposed to the zero crossing detection and therefore is potentially faster. However, when only part of the sine wave is measured, transient signals could lead to incorrect assumption of the total sine wave characteristics. Acceptable accuracy is only expected if the voltage waveforms are not distorted. Changes of frequency in the grid may occur due to events that are prone to provide distortion. According to the studied literature[11] it is not evident that measurement techniques like FFTA provide better reliability for RoCoF detection than those based on zero crossing. As a result, a continuous measurement with the purpose of having a shorter measurement time, not awaiting the measurement of one or multiple full sine waves, does not automatically lead to a more reliable measurement.

Characteristic times for detecting frequency events

The RoCoF measurement needs to be robust and resilient against transients in the grid which are not caused by a loss in generation or demand. This is a significant issue because, although a change of frequency can be measured within a short time frame, additional time is required to be able to relate a frequency event to a correct RoCoF response.

System faults (short circuits) cause transients in the sine wave of the system voltage. Zero crossings of the voltage will shift even when the system frequency, based on the speed of the generators supplying the grid, does not change. Also switching operations in the grid will cause a sudden phase shift of the voltage at the moment of switching. As a result, the time between zero crossings will be longer or shorter and the calculated frequency will be lower or higher than the actual system frequency. Therefore a longer allowed time for a measurement is required to distinguish between a fault or switching event and a genuine RoCoF event. The RoCoF device must be stable under such circumstances and not be triggered. In Figure 3 an example is given of transients in sine waves as a result of a network fault in the power system. In the figure it is clear that there is both a voltage dip and frequency shift.

[11] The University of Manchester, UK, document: evaluation of RoCoF relay performances on networks with distributed generation.

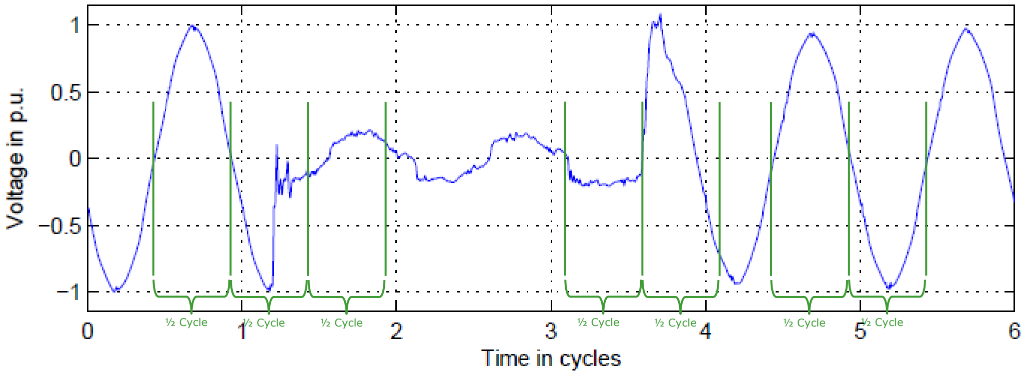

Figure 3: Voltage dip and temporarily phase shift in zero crossings[12]

Several functions are used to reduce inappropriate operation of RoCoF devices:

1. The frequency calculations are based on measurement of multiple sine wave cycles, as opposed to just one. The number of cycles used is, in general, adjustable for each measuring device[13]. Typical measuring windows are 2 – 100 cycles (40 ms to 2 seconds).
2. Employ a time delay to reduce the effect of possible transients in the signal. Typical time delays are 50 – 500 milliseconds.
3. Blocking of the RoCoF trip signal at temporarily reduced grid voltage. This prevents nuisance tripping during short circuit transients in the grid.
4. Blocking at an unexpectedly high rate of change of frequency. The maximum expected RoCoF can be determined for a system based on system inertia and loss of the largest single in-feed or load events. RoCoF devices are blocked for activation when frequency changes larger than the expected maximum are measured, since these high levels shall be discounted as being not credibly possible for a Power System typical RoCoF event.

Other reliability challenges for detection

System faults or switching with regards to the loss of a large single in-feed or load can result in frequency excursions such as the increase or decrease of frequency. The generators in the system will respond to these changes by providing an initial inertial response followed by primary governor control action. These control actions will restore the frequency. However, local generator control actions can result in damped frequency swings in the early cycles following an event. Figure 4 is an extract from the EirGrid-SONI report "RoCoF Modification Proposal–TSOs' Recommendations" to illustrate these effects. Studies performed by EirGrid and SONI indicate that a timeframe of 500 ms is an appropriate time for the initial frequency swings to dampen and for the system to reach coherency[14].

Please note that the graph in Figure 4 is not a measurement and is an illustrative example to better explain the transients and the challenges as a result.

12 Mikael Wämundson, Chalmers University Goteborg; Calculating voltage dips in power systems using probability distributions of dip durations and implementation, 2007

13 This can be an electronic relay.

14 EirGrid-SONI report "RoCoF Modification Proposal–TSOs' Recommendations".

Quote:”*simulations carried out by EirGrid showed that the RoCoF values are closely related to the window over which they are measured. Thus a RoCoF value calculated using a measuring window of 1ms, could be far greater than a value calculated using 100ms or 500ms as the relevant time frame, as illustrated. In the discussions at the working group, the TSOs argued that high RoCoF values that occur due to faults should be covered under the fault ride through clauses of the Grid Code.”*

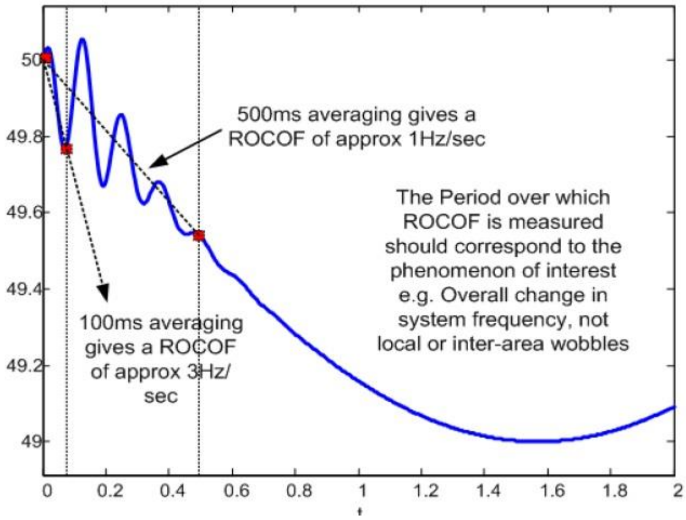

Figure 4: Excerpt from EirGrid-SONI report “RoCoF Modification Proposal–TSOs Recommendations”

The Cired Paper[15] ”Loss of Mains protection relay performance when subjected to network disturbances and events”, describes high level performance of several Loss of Mains protection relays. Best performance was achieved by those relays incorporating a delay time. A 0.5 second time frame was indicated as appropriate to reliably calculate the RoCoF. The work that the University of Strathclyde has performed[16], also provides the view that a time delay adds to the stability considering small scale system transients.

Time to get the activation signal from detection to the FFR type device (T_{signal})

T_{signal} is the time that is required to get the activation signal from the detection and measurement system to the FFR type device. The delay typically depends on the communication system used and the distance to the FFR type device. Sending a control signal is possible in a micro-seconds timespan if need be, however, delays may occur if using controllers that are remote from the site or if the signals need to be sent to a number of individual devices. The activation time of the power converter is slightly longer. The power source or energy storage medium behind the converter does not cause a noticeable additional delay.

Synthetic inertia relies on the capability of a system to supply or absorb sufficient energy in a given time window. This requires an excess generating capability available “on-the-fly” combined with the capability to instantaneously “burn up” significant power at any given time.

15 Cired 18th international conference on electricity distribution, 6-9 June 2005.

16 Dr Adam Dyśko, Ibrahim Abdulhadi, Xinyao Li, Dr Campbell Booth, University of Strathclyde; Assessment of Risks Resulting from the Adjustment of ROCOF Based Loss of Mains Protection Settings, (2013-2014).

4.3 Convertor technology and activation speed

The study recognises that different technologies may have different activation times with regards to the FFR type devices themselves, and therefore the time it takes to activate a FFR type device based on a certain technology was reviewed.

In this section we outline the FFR type technologies used. A high level capability overview is provided, indicating low and high-frequency response and their activation time needed to compensate for any reduction in system synchronous inertia. A selection of the technologies reviewed is listed in Table 3.

Review typical activation time for each of the non-synchronous FFR type used technologies

The activation time is the delay between receiving the signal to start and the delivery of the initial power response. The activation time is partly determined by the power electronic converters used to connect the technology to the network and partly by the synthetic FFR type device behind the power electronic converter. Power electronic convertors are quick in comparison to the Grid frequency; however, the ramp-rate of the synthetic FFR type device is potentially slower in comparison.

Table 1 lists the switching frequency and the resulting minimum activation times required for the power electronic converters used. Single phase systems are not considered. The table only applies for DC to three phase AC converters operating at a nominal grid frequency.

Table 1: Minimum activation times for common 3-phase DC->AC converter Technologies

Technology	f_s	t_{min}	Remark
6 pulse	300 Hz	6.7 ms	
12 pulse	600 Hz	3.3 ms	
3 level	600 Hz	3.3 ms	
N level	3·(2N-2)·50	2/(3·(2N-2)·50) ms	
PWM	f_s, typically a few kHz	$2/f_s$, typically ≈1 ms	switch frequency independent from utility frequency

Review of synchronous power electronic FFR technologies

Matrix converters and cyclo-converters are different from the above converter technologies, because an intermediate DC circuit is not included. Instead the power electronic switches (IGBT's) are directly connected to the AC voltage. Cyclo-converters produce an AC voltage of lower frequency than the input voltage frequency whereas matrix convertors are able to increase the frequency output by connecting the output phases to the right input phase at the time the input phase is closest to the output phase's target voltage. The advantage of this is the minimization of the amount of switches being used, and a relatively low switching frequency. This reduces system losses and costs, plus it increases reliability. The disadvantage is that the output voltage may not always be a pure sine wave, but contains harmonics.

The Insulated-Gate Bipolar Transistors (IGBTs) in matrix or cyclo-converters are controlled with a fixed frequency. The connected load will be supplied with voltage at a frequency that is the difference between the control and the grid frequency. A motor connected to matrix or cyclo-converters will be subjected to grid frequency changes, and thus show real inertia to the grid. Despite this possibility, typical operators of such motors require a constant motor speed, and thus the converter's control frequency will be adjusted to keep the output frequency constant, negating any inertia contribution. These converters can, on the other hand, also be used for providing synthetic inertia.

Table 2: Convertor operating frequencies for common 3 phase AC->AC convertor Technologies

Technology	f_s	Remark
Matrix converter	300 Hz	Technology can reduce and increase input frequency
Cyclo-converters	300 Hz	Technology is only able to reduce the input frequency

5 FFR TYPE TECHNOLOGIES

This chapter provides a high level assessment of the FFR type technologies that may be used to help prevent high rates of change of frequency events. EirGrid listed the 13 most likely technologies and modes of device operation to be implemented across the Island of Ireland transmission network.

5.1 Technology introduction

Table 3Table 3 provides the FFR type technologies considered by EirGrid that have the potential to deliver (synthetic or synchronous) inertia to the system. For each technology the capability of providing RoCoF mitigation services for low or high frequency events are indicated, together with the type of inertia provided; "synthetic" or synchronous.

Table 3: High level capability analysis - FFR type technologies

FFR type technologies	Low freq.	High freq.	Synchronous Inertia	"Synthetic" inertia
1) Synchronous compensators (new purpose built devices and retro-fitting of decommissioned generators, with/without flywheels);	Y	Y	Y	
2) HVDC interconnectors (HVDC converters);	Y	Y		Y
3) Various battery and flow battery technologies;	Y	Y		Y
4) Flywheels (high speed modular devices typically interfaced to the grid via power electronics);	Y	Y		Y
5) Rotating stabiliser devices (typically a multi-pole device incorporating a flywheel, which can be based on a Doubly-Fed Induction Generator or a non-synchronously operated asynchronous machine);	Y	Y	Y	
6) Wind turbines				
a) via converters;	Y	Y		Y
b) DFIG doubly-fed induction generator	Y	Y	Y	
7) Pumped hydro (assuming synchronous machines are deployed);	Y	Y	Y	
8) Compressed Air Energy Storage (CAES);	Y	Y	Y	
9) "Parking" of conventional generators i.e. operating generation plant at low MW output levels but with reduced/no capability to provide system services (e.g. operating reserve) at the lower output levels;	Y	Y	Y	
10) Reduction in the minimum MW generation thresholds of conventional generation while still leaving the plant with the capability to fully provide system services;	Y	Y	Y	
11) Construction of AC interconnectors to Great Britain;	Y	Y	Y	
12) Demand Side Management (DSM) technologies;	Y	Y		Y
13) Flexible thermal power plant.	Y	Y	Y	

Table 3 indicates that all technologies are in theory capable of helping prevent high RoCoF events. However, large technical differences for each of the technologies exists which affects the suitability for use across the Island of Ireland transmission networks.

5.2 High Level assessment of the technologies

The main characteristics of the 13 technologies, with regards to their ability to provide FFR services, are provided in the Annex of this report. The faceplates provided in the Annex for each of the technologies give a high level overview of the current capabilities at the time of writing this report. A subset of these characteristics is used to contribute to a weighted scoring system, provided in chapter 5.3.

The methodology applied for the technology assessment is high level and should be used as guidance and input for the phase 2 investigations.

Please note that the assessments of the technologies are with regards to the purposes of helping prevent large RoCoF events. Hence, the presented results shall not be interpreted as an assessment including all system services, other than for RoCoF. For the avoidance of doubt, this assessment is to consider the use of technologies for the purposes of RoCoF containment and not for the purposes of static reserve or frequency containment services.

The following list explains the criteria and metrics of the methodology introduced to assess the most suitable technology in helping to prevent high rate of change of frequency events. The technology characteristics that are relevant to use in the weighted scoring system were discussed and agreed with EirGrid. For this first assessment, the following 5 characteristics were selected to rank the 13 technologies for their FFR service capabilities:

- Technical application (Effectiveness)
    - The technical application of the technology used and its effectiveness is a combination of the energy delivery or consumption capability with regards to the quantity of power and the time required for correct application.
- Geographical flexibility
    - The distribution of inertia geographically across the power system is important from a stability perspective. The Island of Ireland is not meshed with another synchronous system and therefore inertia is scarcer than in larger meshed systems. As a result, single events, such as the loss of the largest single in-feed, will impact the frequency in the power network. Hence, spreading the inertia over multiple sources reduces the risk of losing a large provision of distributed inertia for an N-1 scenario and thus reduces system imbalances. Therefore geology or location plays a significant role in the suitability and benefit of some of the envisioned technologies and hence, not all technologies can be easily distributed across the Island of Ireland.
- Technology maturity with regards to help prevent large RoCoF events
    - Each of the technologies is in a specific development state which is associated with maturity including whether it has been deployed successfully elsewhere on a utility scale. DNV GL scored the maturity with regards to helping prevent large RoCoF events. The technology maturity score will in part inform the suitability of a particular technology in this regards.
- Lead time
    - Procuring a solution at the right time is of utmost importance. Therefore the lead time to build or modify a device or plant informs whether a technology could be applied in a timely fashion or that other solutions need to be implemented earlier in time. The lead-time in this category includes the installation of the equipment required but does not include the associated connection process. The connection process is challenging to quantify. A short lead-time is good, score 5, and a score 1 implies a long required lead-time of the technology.
- Additional system services benefits

- Different income stream opportunities will result in better commercial opportunities. Thus, technologies that are able to offer multiple system services are likely to be more commercially attractive since they tap into additional regulated revenue streams.

All scores are incorporated in the scoring matrix, Table 5, which quantifies the suitability of each technology to help prevent high RoCoF events. This scoring matrix is provided in chapter 5.3. A short explanation follows for each of the technologies explaining the 5 characteristics and the individual score for each technology after Table 5. The scoring system used is provided in Table 4.

Table 4: Scoring system to quantify the technology suitability with regards to FFR services

Score	Explanation
• 1	Poor
• 2	Unsatisfactory
• 3	Moderate
• 4	Satisfactory
• 5	Good

5.3 Weighted Assessment to quantify suitability of technologies

The Table 5 shows the preliminary quantification of the scoring methodology applied in this phase 1 project. For each of the 5 criteria a weighting factor is introduced on a 1-4 scale. As a result, the importance of each of the 5 criteria can be altered to influence the total score, using the weighting factors in the following order of importance:

- Effectiveness (weighting factor 4);
- Technology maturity (weighting factor 3);
- Lead time (weighting factor 3);
- Additional system service benefits (weighting factor 2);
- Geographical flexibility (weighting factor 1).

Please note that the assessments of the technologies are with regards to the purposes of helping prevent large RoCoF events. Hence, the assessment shall not be interpreted as an assessment for the suitability of a technology to provide other system services which it does not attempt to do so. For the avoidance of doubt this assessment is to consider the use of technologies for the purposes of RoCoF containment and not for the purposes of static reserve or frequency containment services.

Table 5: Matrix comparison

Nr.	Technology	Effectiveness	Geographical flexibility	Technology Maturity	Lead time	Additional system services	Total
	Factor	4	1	3	3	2	
1	Synchronous compensators	5	4	5	4	3	57
2	HVDC interconnectors;	3	1	4	3	4	42
3a	Battery technology - Flow battery	3	4	2	3	4	39
3b	Battery technology - Lead Acid	3	5	4	4	3	47
3c	Battery technology - Li-ion based	3	5	3	4	4	46
3d	Battery technology - Nickel based	2	5	3	4	3	40
3e	Battery technology - Sodium-Sulfur	3	5	3	3	4	43
4	Flywheels (high speed)	3	5	3	4	4	46
5	Rotating stabilisers	5	4	4	4	4	56
6	Wind turbines;	3	3	3	4	4	44
7	Pumped hydro	5	1	5	2	5	52
8	CAES	5	1	3	2	5	46
9	Construction of AC interconnectors	4	1	3	2	2	36
10	"Parking"	5	4	3	4	1	47
11	Reduction in the minimum MW generation	5	4	4	4	4	56
12	Demand Side Management (DSM)	3	5	2	3	3	38
13	Flexible thermal power plant.	4	3	4	4	4	51

The scoring matrix in Table 5 is limited and provides only a high level analysis. From the above results a subset of potential technologies can be selected and used for further analysis in the project phase 2.

In addition, other criteria that might be important for phase 2 can be added to the scoring methodology applied. The cost of each technology was at first used for the scoring of the technologies. The scope of the reported study in this document is high level and therefore not sufficient for the expenditure analyses comparing the technologies and hence, maturity was thought more useful instead.

Therefore the inclusion of expenditure, as an example, could be an important characteristic if considering alternative solutions to RoCoF in the future. This could provide information as to when a new technology can be best procured and what the duration of a contract period is likely to be. Hence, technologies at present not economically available but with high potential would not be excluded.

1) Synchronous compensator

Synchronous compensators are generators that are synchronised with the transmission network and operate as free spinning motors. Synchronous compensators are thus not mechanically driven by a prime-mover nor do they drive any load. In the past synchronous compensators were retrofitted decommissioned power plant generators where the prime-mover was decoupled from the generator. At present new package installations are also available on the market as an option.

- Technical application (Effectiveness) - Score: 5
  - Technical application of synchronous compensators are typically used to contribute to reactive power management but could also be used for improvement of synchronous inertia in the transmission system.
- Geographical flexibility - Score: 4
  - Synchronous compensators are not dependent on geology and therefor are flexible with regards to their installed locations in principle. However, for converted installations the flexibility is much reduced. Therefore we score the flexibility satisfactory.
- Technology maturity - Score: 5
  - The state of development for synchronous compensators is good and it is unlikely that significant improvements will be made with regards to the maturity of the technology. Furthermore the technology is commercial available for both converted installation and new build and has been deployed successfully.
- Lead time - Score: 4
  - The lead-time is dependent on the complexity of an existing installation or if the installation is a new build. However, the lead-time is considered relatively short and will most likely vary from 6 months to approximately 2 years from start to finish.
- Additional system services - Score: 3
  - Synchronous compensators are suitable to perform different system services including dynamic and steady state reactive power delivery to help control network stability and system voltage.

2) HVDC interconnectors

HVDC interconnectors are high voltage DC connection links that are primarily used to transport high amounts of energy over relatively large distances. In the context of this report HVDC interconnectors are assumed to be used as an interconnection to another synchronous power system and therefore would be able to provide the “synthetic” inertia responses desired here in terms of RoCoF support.

- Technical application (Effectiveness) - Score: 3
  - HVDC interconnectors are mainly used to transport high amounts of energy from one power system network to another. Therefore electricity trading is the primary reason for such an installation[17]. HVDC interconnectors can be designed for primary response and in that way help to prevent high RoCoF events. The technology is synthetic and therefore the response time needs to be taken into account.
- Geographical flexibility - Score: 1

[17] The exception is large (offshore) wind farms, which need the HVDC system to transport its energy from A to B using the most economical solution. However, these are not considered as part of the category stated in the title.

- The location plays a significant role for HVDC systems and is normally trading or distance related. As a result, HVDC interconnector technologies would not easily be distributed across the Island of Ireland since it makes little financial sense.
- Technology maturity - Score: 3
  - The technology has seen large improvements over the recent years and the current state can be classified as largely mature. As a result, DNV GL scored the maturity of HVDC interconnectors moderate.
- Lead time - Score: 3
  - Building long transport cable trajectories, especially offshore, requires a moderate amount of time. An estimated lead-time to build an HVDC interconnector is 3 to 6 years. In addition, difficulties in obtaining planning consents for the onshore converter stations can add considerable time to the lead time. Due to the UK HVDC planned and constructed projects, the report considers the up-grates required to existing HVDC to enable it to contribute synthetic inertia to the system.
- Additional system services - Score: 4
  - HVDC interconnectors are capable of covering a large variety of system services depending on the converter technology employed. Services from Voltage Source Converter (VSC) technology stations includes reactive power delivery, automatic voltage regulation, low minimum load, reversing the power flow, balancing, etc.

3) Batteries

Batteries are storage devices that chemically store electrical energy. Batteries operate at direct current by definition and therefore power electronic convertors are needed to supply a transmission system with power or to store power.

- Technical application (Effectiveness) - Score: 2-3
  - Battery technologies are mainly applied for energy storage. Battery power is instantly available from the terminals and therefore the power convertor is the main limitation for energy delivery. The rapid energy consumption capability however is much lower in capacity and therefore the technology is better suited to help prevent low frequency RoCoF events as opposed to high frequency RoCoF events. Li-ion and Lead Acid-batteries are relatively fast (total stored energy delivery can be used up in approx. 3 – 10 minutes). Battery technologies can only deliver synthetic inertia as opposed to synchronous inertia.
- Geographical flexibility - Score: 4-5
  - The technologies can be easily distributed across the Island of Ireland since there are virtually no location restrictions with some minor exceptions for flow batteries because of the more complex technology and additional space and auxiliary systems requirements.
- Technology maturity - Score: 2-4
  - The associated maturity for batteries is heavily dependent on the technology used. For flow batteries further development are likely to be required and deployment is not commercially established at the time of writing this report. However, Lead-acid batteries and Li-ion together with Nickel based battery technologies are mature. Sodium-Sulfur based batteries will sit in between the two groups. Still the technology is only able to provide synthetic inertia.
- Lead time - Score: 4-5

- The installation of a battery solution is relatively straight forward. As a result the typical lead-time to build a battery installation is short and is estimated between 3 months and 1 year from start to finish. The exceptions are flow batteries due to their technology maturity level and Sodium-Sulfur batteries due to having only 1 manufacturer supplying this technology.
- Additional system services - Score: 2-4
  - Batteries are able to offer multiple system services although not all are tested and validated within a European grid[18]. Frequency and primary reserve are examples where batteries could play a role together with the provision of reactive power.

4) Flywheel

Flywheels store energy as kinetic energy in a wheel with most of its mass at the rim. This fast moving mass ring is accelerated and decelerated by a motor/generator, thereby "charging" and "discharging" the system.

- Technical application (Effectiveness) - Score: 3
  - Flywheels are used for balancing services in a relative short time line (total stored energy delivery can be used up in <1 minute – 1 hour). During this time-frame, large amounts of energy can be stored and delivered which makes it suitable to help mitigate high rates of RoCoF. High speed flywheels are only capable of delivering synthetic inertia as a result of the connection to the grid through power electronics.
- Geographical flexibility - Score: 5
  - There are virtually no location restrictions for the flywheel technology and can be easily distributed across the Island of Ireland.
- Technology maturity - Score: 3
  - There are large improvements made over the last years with regards to the maturity of flywheels. For RoCoF applications, further developments are likely to be needed. As a result, DNV GL scored the maturity of flywheels for RoCoF as moderate.
- Lead time - Score: 4
  - The installation is relatively straight forward and the lead-time to build a flywheel installation is roughly estimated between 8 months and 1.5 years from start to finish. However, the number of flywheel manufacturers is relatively small and the installation time is therefore dependent on suppliers order lists and the specification for a particular installation.
- Additional system services - Score: 4
  - Flywheels have the potential to provide Fast Frequency Response, Primary and, in some cases, secondary response services.

5) Rotating Stabilisers

The rotational stabiliser technology that is selected here consists of a synchronously rotating machine that is directly connected to the grid. The machine is not mechanically driven by a prime-mover nor does it drive a load when running in normal operation. The synchronous machine can be designed with high number of pole-pairs. It possesses significant mass which enables it to provide a synchronous inertial

[18] http://forschung-energiespeicher.info/en/projektschau/gesamtliste/projekt-einzelansicht//Netzstabilisierung_mittels_Batteriekraftwerken/

response to the system for frequency deviations. In terms of RoCoF mitigation, the rotational stabiliser provides instantaneous inertial response due to its synchronous connection.

- Technical application (Effectiveness) - Score: 5
  - Rotational stabilisers are similar in nature to the synchronous compensator. The rotational stabiliser can provide additional synchronous inertia to improve the frequency stability of the transmission system.
- Geographical flexibility - Score: 4
  - Rotational stabilisers are not dependent on geology and therefore are flexible with regards to their installed locations.
- Technology maturity - Score: 4
  - The rotational stabiliser is based on mature technologies. The device can be deployed to provide synchronous inertia which is well understood in terms of RoCoF mitigation. The reason for scoring the technology satisfactory as opposed to good is the limited deployment at the time of writing this report with regards to RoCoF.
- Lead time - Score: 4
  - The lead-time is considered relatively short and will most likely vary from 6 Months to approximately 2 years from start to finish.
- Additional system services - Score: 4
  - Rotational stabilisers are suitable to perform different system services including dynamic and steady state reactive power delivery to help control network stability and voltage. Rotational stabilisers can also be modified to provide fast frequency response and primary operating response.

6) Wind Turbines

There are different types[19] of modern wind turbine generators. The now aged wind turbines, type 1 and type 2, were used with a constant-speed asynchronous generator, directly-connected to the power system and hence are capable of providing synchronous inertia. Few type 1 and type 2 wind turbine generators remain in operation while more modern commercial wind turbines operate at variable speed, and so their generators produce power at a frequency proportional to the rotational speed of the rotor. As a result, these turbine types require a variable frequency drive on the output of the generator terminals in order to convert the generator frequency to the grid frequency. The only exception being is the double-fed generators, type 3. In the recent past double-fed generators were the preferred technology to be used for variable speed wind turbines, in which the generator stator produces power directly at grid frequency and only the rotor power is produced at variable frequency. The latter requiring a power converter which typically handles only about one third of the total power. Having the stator windings of the generator directly connected to the power system makes it possible to provide synchronous inertia. Arguably this changed a few years ago with the full converter, type 4, technology and is at present most commonly provided since it delivers more flexibility for reactive power etc.

Technical application (Effectiveness) - Score: 3

[19] Type 1 – Conventional Induction Generator; Type 2 – Variable Rotor Resistance Induction Generator; Type 3 – Double-Fed Asynchronous Generator; Type 4 – Full-Convertor type

- Although the double-fed induction generators are capable of providing synchronous inertia[20], new turbines tend to be of the full convertor type and can deliver only synthetic inertia. There is some research needed to allow all generators to be used in a very small time frame to provide a sufficient amount of FFR services. Another aspect is that the turbines can only contribute inertia if there is sufficient wind. At the same time additional inertia is arguably only needed at the time of high wind penetration.

- Geographical flexibility - Score: 3
  - In the Island of Ireland, the existing offshore wind farm capacity is small. The Onshore wind farms capacity is far greater and is spread out over the Island of Ireland. As a result, the geographical locations are not expected to be an issue for potential FFR services. However it should be noted that FFR services provided by wind farms will be dependent on the geographic location of turbines that are capable of providing the service.
- Technology maturity - Score: 3
  - Wind turbine technology is mature although large developments are still on-going. In terms of RoCoF maturity, DNV GL provided a moderate score. The double-fed turbines have the capability to provide inertia, however, new turbines will be of the full convertor type. At present, several wind turbine manufacturers offer FFR response services for the full convertor type generators. However, the deployment of this function for RoCoF is not known. As a result, and since the older technology can already provide inertia in principle, DNV GL scored the maturity moderate.
- Lead time - Score: 4
  - To build a wind farm, especially offshore, takes a relatively long time from start to finish. However, changing the software on existing turbines (if possible) has a short lead-time and is estimated at 1 to 6 months.
- Additional system services - Score: 4
  - If sufficient wind is available, wind technology can provide multiple system services. However, also in the case of delivering additional system services, the turbines can only contribute if there is sufficient wind.

7) Pumped hydro

Water is pumped into the upper basin upon “charging” by a pump and allowed to flow down again through a turbine upon discharging and thus the construction requires an upper and a lower basin. The lower basin can be specially built or an abandoned mine or cavern.

- Technical application (Effectiveness) - Score: 5
  - The power range of pumped storage devices are suitable for delivering sufficient synchronous inertia although significantly lower than that of a gas or coal fired power plant.
- Geographical flexibility - Score: 1
  - Geology plays a significant role and the technology cannot be easily distributed across the Island of Ireland.
- Technology maturity - Score: 5

[20] DNV GL high level view is that the converter control delivers constant torque control at a high bandwidth and therefore any synchronous inertia is very transient and rapidly negated by the torque control loop. Therefore DNV GL concludes that additional research is required to better understand the possibilities of DFIG technologies to provide inertia in the Island of Ireland.

- Pumped storage installations are mature and it is unlikely that large technology changes are expected. In addition, the pumped hydro installations are currently providing inertia to the system. As a result, DNV GL scored the maturity of pumped hydro as good.
- Lead time - Score: 2
  - To build a pumped storage plant takes a relatively long time from start till finish. However, there will be no new build plant for the sole purpose of providing FFR services. No additional auxiliaries are required for the installations. The existing plant already provides inertia within the limitations of the grid code because of the very nature of the synchronous generators used.
- Additional system services - Score: 5
  - Pumped hydro has the capability to provide multiple system services.

8) Compressed Air Energy Storage (CAES)

Compressed Air Energy Storage (CAES) makes use of underground caverns where air is compressed for storage and decompressed in order to release the stored energy.

- Technical application (Effectiveness) - Score: 5
  - In terms of frequency stabilization, a CAES plant operates like a normal gas turbine power plant by providing inertia, primary, secondary and tertiary response.
- Geographical flexibility - Score: 1
  - CAES at utility scale requires a suitable underground cavern and is therefore geology dependent and thus the geology plays a significant role in its suitability for use at a certain location. In addition, the locations that CAES can be placed in Ireland and Northern Ireland are limited.
- Technology maturity - Score: 3
  - At the time of writing this report, only two grid scale compressed air energy storage installations operate worldwide. The installation is complex and there are still substantial developments to be expected. As a result, DNV GL scored the maturity for CAES moderate.
- Lead time - Score: 2
  - To build a new CAES plant takes a relatively long time from start till finish. The planned installation in the Island of Ireland is in principle likely to provide inertia.
- Additional system services - Score: 5
  - CAES is able to offer multiple system services including reserves, ramping and dynamic and steady state reactive power.

9) Construction of AC interconnectors

An AC interconnector with GB would result in both islands becoming a single synchronous network. The amount of power being transferred through a synchronous interconnector is limited by pre-loading of the cable by charging current and transfer limits caused by the cable impedance.

- Technical application (Effectiveness) - Score: 4
  - In case a loss of generation occurs in the Island to Ireland, both the inertia in GB and the inertia in the Island of Ireland will start to supply the power imbalance. The ratio between their contributions will be equal to the ratio of inertia present in both parts of the power system. This solution provides a larger synchronous system, and thus results

in lower RoCoF events in case of loss of a generator or a high load. This is one of the reasons why the continental synchronous system is less vulnerable than the small systems, such as the Island of Ireland[21].

- Geographical flexibility - Score: 1
  - For interconnectors the location plays a significant role with regards to its suitability and this technology can typically not easily be distributed across the Island of Ireland.
- Technology maturity - Score: 3
  - AC interconnectors are fully developed and it is unlikely that large technology improvements will be made with regards to the RoCoF capability. However, if an interconnector was to be built in the Island of Ireland, the distance would be one of world's longest sub-marine AC cables which is likely to challenge current technology. As a result, DNV GL scored the maturity of the AC interconnector moderate.
- Lead time - Score: 2
  - Building long transmission cables, especially offshore, requires a moderate amount of time. An estimated lead-time to build an AC interconnector is estimated to take 2 to 5 years from start to finish.
- Additional system services - Score: 2
  - Although the all Island grid will be strengthened by a sub-marine AC interconnector with GB, the problem is the limitation of power transfer for long HV AC cables because of charging current preloading.

10 & 11) "Parking" and reduction of the minimum MW generation.

Definition: "Parking" of machines refers to the possibility of operating generation plant at low MW output levels thus getting the same level of inertia as at higher output levels but providing greater headroom for non-synchronous generation to be accommodated on the system.[22] Reducing minimum load provides the similar benefit of maintaining inertia whilst providing headroom for non-synchronous renewable generation. The major difference between parking and reducing the minimum generation level is that for reducing the minimum load, system services can be maintained when a unit reduces its minimum generation level. However, low minimum loads will introduce higher emission levels. There may be minimal emission difference between a low NOx turbine and its traditional variant at low load[23].

- Technical application (Effectiveness) - Score: 4
  - "Parking" is in general aimed at conventional thermal power plants. The main application of parking is to provide the synchronous inertia of the machine to the network where otherwise the plant would have been disconnected from the grid when not dispatched. However, the emission of the plant is likely to see a large increase when operating at a reduced minimum load[24].
- Geographical flexibility - Score: 4
  - The location plays some role since it relates to the existing power plants.
- Technology maturity - Score: 4
  - The technology is mature to operate a power plant at its minimum critical load. When reducing the minimal load or for "parking" technology developments likely to be required.

[21] National Grid SOF document

[22] EirGrid-SONI RoCoF Alternative Solutions Project.

[23] 2014-June OGP views on LCP BREF_Final.pdf

[24] Joseph J. Macak III, Evaluation of Gas Turbine Startup and Shutdown Emissions for New Source Permitting; Department of Environment Protection, Florida, Project: 0110037-011-AC , (2014)

As a result, DNV GL scored the maturity of "parking" moderate and for reduced minimal load, satisfactory.

- Lead time - Score: 4
    - If not operated lower than the critical minimum load, there is no lead-time involved. When low-NOx burners are required for a typical plant the lead-time required will be between 6 months to 1.5 year from start to finish and depends on its major overhaul maintenance schedule.
- Additional system services - Score: 1-4
    - The normal system services are available associated with the technology when operated in minimal load but plants that are in "parking" operation have reduced system service capabilities. The only, potentially big, advantage of the "Parking" methodology is that the system services was not available if the plant was disconnected from the grid at periods when its power generation capacity was not required.

12) Demand Side Management (DSM)

Demand side management is most often regarded as a solution to net congestion, by time-shifting large electrical loads such that local overloads do not occur, and the total available network capacity is more efficiently utilized. The DSM that is possibly available at present or in future is demand reduction, EV charging, large industrial loads, data centres, etc.

- Technical application (Effectiveness) - Score: 3
    - The technical application of the technology used and its effectiveness is arguably challenging due to the associated small energy delivery or consumption capability. To control large amounts of distributed devices to aggregate a useful amount of power is complex. Although the technology for each individual device is mature, controlling a large portfolio of devices in an efficient and effective manner has not been proven in practice outside of a test environment. However, there are large data centres in the Island of Ireland that could arguably deliver the service with sufficient capacity. As a result the score is set to moderate.
- Geographical flexibility - Score: 5
    - Location plays a significant role to be able to aggregate a sufficient amount of frequency response power at a certain point in the network. As a result, not all geographical areas in the Island of Ireland can be theoretically provided with DSM. However, important locations, such as cities, could potentially have sufficient installed DSM devices and therefore arguably the geographical flexibility is good.
- Technology maturity - Score: 2
    - The technology of the DSM (demand reduction, EV charging, large industrial loads, data centres, etc.) might prove to be valuable for providing additional system services. However, the maturity for providing RoCoF is at the time of writing this report not proven. There are several challenges that need to be solved before DSM will be able to provide FFR services within the time window required for helping prevent large RoCoF events. In short the challenges are: sufficient aggregated capacity, detection technology, novel communications and new TSO operational controls. As a result, DNV GL scored the DSM technology for RoCoF, unsatisfactory to be currently applied.
- Lead time - Score: 3
    - At the time of writing this report, the lead-time for an effective DSM system is arguably likely to take a period of approximately 4 years. The 4 years will include the design,

philosophy, new and existing network cable use, control centres, potential DSM identification and communication, etc.

- Additional system services - Score: 3
  - With the DSM system, multiple system services could potentially be provided.

13) Flexible thermal power plant

Fast response gas turbines are arguably the most suitable and secure technology to be able to operate as a flexible thermal power plant. Fast response gas turbines are conventional open-cycle gas turbines (OCGT) coupled to a generator, running mostly on natural gas or light oil. These power plants have lower efficiencies than combined cycle power plants (CCGT), in closed cycle plants the hot turbine exhaust gas is used to power a steam cycle. However, some CCGT plants are capable run off running in OCGT mode.

- Technical application (Effectiveness) - Score: 4
  - Flexible thermal power plants are used for primary and secondary response as well as to provide peak demand when required. Modern[25] CCGT plants can have a by-pass stack which allows the unit to operate more flexibly, increasing the ramp-rate by avoiding the limitations of the steam boiler. The plants use synchronous machines which provide synchronous inertia to the system is synchronised to the Network. The benefit of synchronous inertia will only fully be realised if all units in the plant are synchronised. As this is not always the case the score provided is 4.
- Geographical flexibility - Score: 3
  - The geographical location is not a significant factor with regards to the suitability of the technology, assuming a suitable gas supply. As a result, flexible thermal power plants are relatively easy to distribute across the Island of Ireland provided that fuel supply is not a major issue.
- Technology maturity - Score: 4
  - Flexible thermal power plants are relatively expensive and are not considered for the sole purpose of providing FFR services. Efficiencies, if running in OCGT mode, are low and therefore operating expenditures are high.
- Lead time - Score: 4
  - The technology is very mature and can be considered as an off the shelve product. Depending on the order books of the Original Equipment Manufacturer (OEMs), the lead-time for an OCGT installation is relatively short and estimated between 10 months to 2 years for large (150+ MVA) machines.
- Additional system services - Score: 4
  - Flexible thermal power plants are capable of providing primary and secondary response and are used for peak demand. However, OCGT plants typically do not run 365 days 24/7 due to their lesser efficiency and higher emissions. The plant is more than capable of delivering further system services.

25 Also without bypass stack CCGT become more and more flexible. When it comes to inertia, CCGT and OCGT are comparable. Ramping up (primary response) might be slower.

6 CONCLUSIONS

This high level study shows that the technology to provide synthetic inertia is available. However, this first Deliverable of Phase 1 does not determine whether synthetic inertia will be able to replace any synchronous inertia in the system or the economics of this. There is a need to fully understand the complications and risks in order to implement synthetic inertia in the system.

DNV GL concludes the following observations:

1. The "synthetic" fast frequency response (FFR) type devices have the capability to provide a power response to help prevent high RoCoF events. However, reliable RoCoF detection requires to be taken into consideration. The review here of the time needed to activate a FFR type device for the delivery of an effective power response indicates challenges and the need for further investigation;
2. The total "synthetic" inertia responses time is the largest obstacle for providing effective "synthetic" inertia. Within this total response time, the most challenging aspect is the period required to robustly detect a RoCoF event. The response time is the sum of measurement-, signal-, activation- and ramping time;
3. With relay protection technology commonly used at present, 30ms is necessary to detect any change in frequency. However, to detect any change accurately more time is required. The Cired paper[15] indicates that damped frequency swings following a system event, such as those depicted in Figure 4 in chapter 3.3 as an example, are likely to delay robust RoCoF event detection by as much as 0.5 seconds which would be too long for effective response to avoid all high RoCoF events. Therefore the Cired report[26] reviewed here estimated that the time needed for reliable detection is already 0.5 seconds;
4. To prevent a RoCoF event of 1 Hz/s measured over a time window of 500ms, the reliable response time should be much shorter than 0.5 seconds. This is challenging according to the explanation in previous point 3. However, there may be a way which would help to overcome the reliability problem while still providing a suitable response time.
5. At this moment there is no proven track record for accurate RoCoF detection for the purpose of mitigation of RoCoF events as opposed to anti islanding disconnection;
6. Different aspects of the challenge to utilise "synthetic" inertia FFR type devices to mitigate RoCoF events need to be analysed in more detail. In particular, the combination of measurement methodologies used and the likely electricity networks characteristics with regards to damped frequency swing durations;
7. The largest challenge at present for non-synchronous devices with regards to the time that is needed for detection and measurement of a RoCoF event only affect non-synchronous FFR type devices. Different measurement technologies and strategies need to be investigated to be able to provide efficient and economic "synthetic" inertia solutions that meet all system requirements. Until that time, synchronous solutions are likely to continue to be needed;
8. The technology analysis indicates that all 13, listed by EirGrid-SONI, have the capability to help prevent high RoCoF events. The criteria and metrics introduced by DNV GL, for the assessment of the 13 technologies provide a preliminary quantification ranking of suitability between the FFR type technologies. The effectiveness and therefore the capability of synthetic inertia technologies

[26] Cired 18th international conference on electricity distribution, (6-9 June 2005)

is impacted by the issues raised in relation to fast and accurate RoCoF detection, hence the top 6 ranked technologies are all synchronous based directly connected AC solutions (no invertor technology for frequency conversion). The resulting weighted scoring system presents the following best suitable technologies:

1. Synchronous compensators ;
2. Reduction in the minimum MW generation;
3. Rotating stabilisers;
4. Pumped hydro;
5. Flexible thermal power plant;
6. "Parking"
7. Battery technology;
8. CAES;
9. Flywheels;
10. Wind turbines;
11. HVDC interconnector;
12. Demand Side Management (DSM);
13. AC interconnectors.

9. The technology assessments conducted in this report are high level. Further detailed analysis of costs, device technology characteristics and system impacts would be required to fully assess the suitability of specific technologies in relation to mitigation against high RoCoF events;
10. The assessment indicates that a combination of technologies may be required to resolve potential future RoCoF issues.

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/21/ Tesla website 2015: 10 kWh $3,500

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8 LIST OF ABBREVIATIONS AND ACRONYMS

- Alternative Current (AC
- Commission for Energy Regulation (CER)
- Compressed Air Energy Storage (CAES)
- Direct Current (DC)
- Distributed Generators (DG)
- FFR type device: Term used by EirGrid for technologies able to provide synthetic or synchronous inertia with sufficient response time to mitigate frequency excursions (FFR type devices)
- Fast Fourier Transfer Transform Analysis (FFTA)
- Fast Frequency Response (FFR)
- Grid Code (GC)
- Insulated-Gate Bipolar Transistor (IGBT)
- Northern Ireland Utility Regulator (UR)
- Pulse Width Modulation (PWM)
- Rate Of Change Of Frequency (RoCoF)
- Renewable Energy Sources (RES)
- System Operability Framework (SOF)
- Transmission System Operators (TSOs)

ANNEX

This section of the report holds all key information for the FFR type technologies analysed. For each FFR technology the key parameters are captured in a so called face plate. The face plate presents a sheet of facts. Each face plate has 16 key parameters which are explained below.

Faceplate explanation

ID	Items	Value
1	Suitable to help prevent RoCoF events	Traffic light **Green** = good, **Amber** = moderate, **Red** = not suitable or highly inefficient.
2	Type of Frequency response	The Ability to Respond to a High or Low frequency event.
3	Inertia constant H	"H" is expressed in seconds and is in general associated with synchronous rotating machines. The inertia constant is the time for the machine to come to a standstill while supplying the nominal power as stated on the faceplate. As an example, a machine with inertia of 3 seconds could deliver the nominal power, starting at the nominal rated rpm, it would take 3 seconds for the machine to come to a standstill. However, in practise this means that the energy delivery of the machine is much smaller due to the limited frequency range the machine can operate in before the over and under frequency protection is triggered (47.5 Hz – 52.0 Hz)[27].
4	Energy to Power (E/P) ratio (for storage)	The ratio is associated with storage technologies and is the energy content divided by the nominal power stated on the faceplate and yields time. Thus, the power to energy ratio is equal to the shortest possible discharge time while supplying the nominal power as stated on the faceplate. In general, technologies using power electronics are determined by limitations of the power convertors and, in the case of energy storage, by the energy storage capacity.
5	Typical power capacity	Typical power range of an installed installation in MW
6	Typical Energy content (for storage)	Typical energy range of an installed installation in MWh
7	Charging time (for storage)	Typical charging time only applies to technologies which store an amount of energy and is the minimum time required to fully charge the technology from 0 to a full charge.
8	Ramp-time	Time needed to provide maximum power from 0 to full load[28]
9	Efficiency/ Energy consumption	The energy efficiency of a nominal charge-discharge cycle, or the energy consumption of the technology with regards to the stand-by losses.

[27] Source: The Grid Code , Issue 5 Revision 13, (2015)
[28] Ramp-time should not be confused with inertia

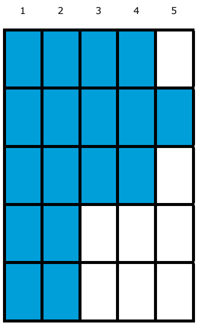
10	Expected lifetime	Expected lifetime of the energy storage medium (batteries), or of the entire installation.
11	Capital expenditure	All provided capital expenditures for the technologies are high level estimates and are used for high level comparison as opposed to precise numbers that can be used to calculate rule of thumb installation costs. Precise numbers that can be used to calculate rule of thumb installation costs are outside of scope of the present study. The capital costs used here are high level estimates to compare technologies and shall only be analysed for this exact purpose i.e. as a rough comparison indication.
12	Economy of scale	Scoring of the economy of scale to enlarge the capacity (the higher the score the more cost effective)
13	Technology matureness	Scoring of the current matureness of the technology at present compared to the other technologies provided in this document
14	Future development potential	Potential for future development of the technology, including possible natural constraints which influences the ability for use in Ireland and Northern Ireland
15	Capital expenditure per MW(h)	Scoring of the installation cost at present compared to the other technologies provided in this document. A score of 1 indicates a high expenditure as opposed to a score 5 which indicates a less cost intensive technology.
16	Expenditure development after 2020	Expected future operating or capital cost progress.

1) Synchronous Compensators/condensers

ID	Items	Value	
1	Suitable to help prevent RoCoF events	Techno- / Economic	[traffic light]
2	Type of Frequency response	Bi-directional (High, Low)	
3	Inertia Constant H	3	[seconds]
4	Energy to Power (E/P) ratio (for storage)	-	[seconds]
5	Typical power capacity range	50 to 250 MVA	[MVA]
6	Typical Energy content (for storage)	Up to 0.4	[MWh]
7	Charging time (for storage)	10 seconds	[time]
8	Ramp-time	Instant power[29]	[time]
9	Energy Consumption	5-10%	[%]
10	Expected lifetime	30 years	[years]
11	Capital expenditure	See text	[EUR/typical installation]

ID	Items	Comment
12	Economy of scale	
13	Technology matureness	
14	Future development potential	
15	Capital expenditure per MW	See text
16	Expenditure development after 2020	See text

Score



Short description of the technology key characteristics

Synchronous compensators are not mechanically driven nor do they drive anything and rotate at synchronous speed with the network. They are capable of providing reactive power and inertia to the grid, identically to a synchronous generator.

In order to increase inertia, the rotor can be equipped with a flywheel. Decommissioned generators may be used, decoupled from the prime-mover and equipped with a pony motor in order to bring them up to synchronous speed before being connected to the network. Although the generator does not supply power to the network, the stabilising influence of the generator is still available and can contribute to reactive power management. Reactive power management is a service the generator would have originally designed for.

However the synchronous compensator is mainly associated with existing built machines, new installations could be applied with matrix or cyclo-convertors. When primarily used for limiting RoCoF,

[29] When the technology is charged, the rotating mass is spinning at nominal revolution in sync with the Grid (if connected). Therefore power is available instantaneously.

only a fraction of the kinetic energy can be used when operating as a synchronous machine due to the limited allowed frequency upper and lower limits of the Grid. To increase the use of its kinetic energy requires implementing the compensator as a double-fed machine. In this case, the machine operates at a speed which is the sum or difference between the grid frequency and the control frequency. In addition to the intrinsic inertia present in the rotating machine, the control frequency can be manipulated in order to provide synthetic inertia on top of the intrinsic inertia.

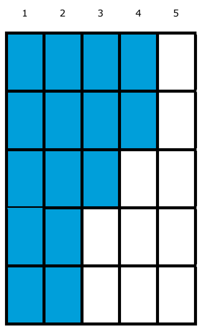
Double-fed compensators are wound rotor machines, with either slip rings, double stator winding sets or rotating transformers providing the control power to the rotor. Double fed machines can also be equipped with a flywheel for providing additional mass and therefore inertia. As such, a compensator can provide larger equivalent inertia as opposed to a synchronous compensator.

There is a large difference in capital cost depending on the use of new or existing built machines, type of machine, etc. This makes any cost estimate inaccurate. However to be able to quantify the suitability of the technology, a scoring of 2 was applied for capital cost.

2) HVDC interconnector (with Great Britain)

ID	Items	Value	
1	Suitable to help prevent RoCoF events	Techno- / Economic	[traffic light]
2	Type of Frequency response	Bi-directional (High, Low)	
3	Inertia Constant H	-	[seconds]
4	Energy to Power (E/P) ratio (for storage)	-	[time]
5	Typical power capacity range	Up to 500 MW[30]	[MW]
6	Typical Energy content (for storage)	-	[MWh]
7	Charging time	inverter dependent[31]	[time]
8	Ramp-time	Instant power[32]	[time]
9	Efficiency	95	[%]
10	Expected lifetime	30 years	[years]
11	Capital expenditure	600,000,000.00[33]	[EUR]

		Comment	Score
12	Economy of scale		
13	Technology matureness		
14	Future development potential		
15	Capital expenditure per MW[34]		
16	Expenditure development after 2020		



Short description of the technology key characteristics

HVDC interconnectors do not explicitly encompass energy storage, and as a result, they are not inherently capable of providing inertia replacement by themselves. They are, however, capable of regulating their power in response to the network frequency at one of the two endpoints. At that endpoint, the interconnector is capable of providing inertia compensation, while at the other endpoint, the interconnector acts like an irregular load, placing part of that demand on the other network's inertia. Furthermore, although HVDC does not explicitly have storage it is possible to use he DC capacitors to draw short bursts of energy, like other capacitor based storage technologies.

30 The power capacity of HVDC technology in relation to currently installed capacity in Ireland and Northern Ireland is considered. Source: NG, Interconnectors Investor Relations leaflet, February 2013

31 HDVC lines needs to be charged before it can transport energy due to its capacitive behaviour.

32 When the HVDC connector is charged, power from the interconnector is instantly available.

33 East West 500mw Interconnector with Britain. Source: EirGrid press release: Commercialisation of fibre optic cable in conjunction with €600m Interconnector project will provide Irish businesses with additional 7Tb/s capacity, (29-3-2009)

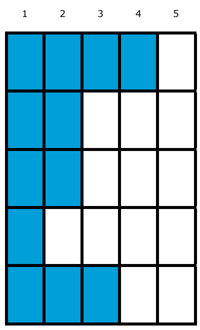
34 A score of 1 indicates a high expenditure as opposed to a score 5 which indicates a less cost intensive technology.

Alleviating frequency issues in one network automatically means an aggravation of the situation in the other one, and thus is only useful if the other network is significantly more stable.

3a) Battery technology: Flow battery

ID	Items	Value	
1	Suitable to help prevent RoCoF events	Techno- Economic	[traffic light]
2	Type of Frequency response	Bi-directional (High, Low)	
3	Inertia Constant H	-	[seconds]
4	Energy to Power (E/P) ratio (for storage)	> 8 hours	[time]
5	Typical power capacity	Up to several MW	[MW]
6	Typical Energy content (for storage)	No configuration limit	[MWh]
7	Charging time (for storage)	More than 24 hours (1.4 kWh/min)	[time]
8	Ramp-time	instant	[time]
9	Efficiency	85 %	[%]
10	Expected lifetime	> 5000 cycles	[years]
11	Capital expenditure	not yet established	[EUR]

ID	Items	Comment	Score
12	Economy of scale		
13	Technology matureness		
14	Future development potential		
15	Capital expenditure per MWh	Highly dependent on scale	
16	Expenditure development after 2020		



Short description of the technology key characteristics

Flow batteries are batteries that do not use traditional cells. This brings two distinct advantages as opposed to traditional cell based batteries:

1) The relatively low marginal cost of adding capacity, which comes down to the cost of increasing reactant container size and adding more reactant.

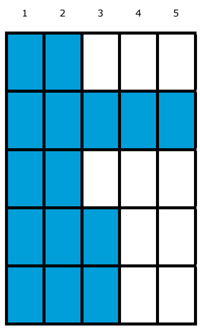
2) The second advantage is the ability to instantly "charge" the system, by replacing a container full of "discharged" reactant with a container full of "charged" reactant from elsewhere.

However, the most important disadvantages of flow batteries is the low volumetric energy density which is much lower than any cell based system. As a result, flow batteries tend to lend themselves for long term storage of electricity. The price per unit of power is relatively high due to the reactants flow chemistry and thus the complex pump system and plumbing around the cell stack.

3b) Battery technology: Lead Acid batteries

ID	Items	Value	
1	Suitable to help prevent RoCoF events	Techno- / Economic	[traffic light]
2	Type of Frequency response	Bi-directional (High, Low)	
3	Inertia Constant H	-	[seconds]
4	Energy to Power (E/P) ratio (for storage)	> 10 minutes	[time]
5	Typical power capacity	Up to several MW	[MW]
6	Typical Energy content (for storage)	Up to several MWh	[MWh]
7	Charging time (for storage)	24 hours	[time]
8	Ramp-time	instant	[time]
9	Efficiency	85 %	[%]
10	Expected lifetime	500 cycles or 10 years	[years]
11	Capital expenditure	€ 250 per kWh	[EUR]

		Comment	Score
12	Economy of scale		
13	Technology matureness		
14	Future development potential		
15	Capital expenditure per MWh		
16	Expenditure development after 2020		



Short description of the technology key characteristics

The technology for lead acid batteries is mature. Per stored kWh, lead acid batteries are at present one of the cheapest batteries. Lead acid batteries have long life when they are held constantly in a full state of charge but cycle life is limited. These properties make lead acid batteries suitable for UPS applications, however less suitable for cyclic applications.

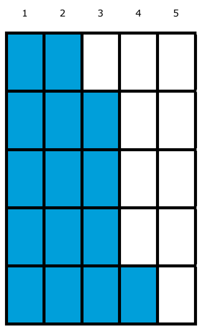
The recycling infrastructure is well established due to its large market volume and efficient with an estimated 99 % of batteries being recycled in the developed world.

3c) Battery technology: Li-Ion batteries

ID	Items	Value	
1	Suitable to help prevent RoCoF events	Techno- | Economic	[traffic light]
2	Type of Frequency response	Bi-directional (High, Low)	
3	Inertia Constant H	-	[seconds]
4	Energy to Power (E/P) ratio (for storage)	> 5 minutes	[time]
5	Typical power capacity	0 - 100 MW	[MW]
6	Typical Energy content (for storage)	0 – 10 MWh[35]	[MWh]
7	Charging time (for storage)	1 hour	[time]
8	Ramp-time	instant	[time]
9	Efficiency	90 %	[%]
10	Expected lifetime	3000 cycles or 15 years	[years]
11	Capital expenditure	$ 350 per kWh[36]	[USD]

Comment **Score**

ID	Items
12	Economy of scale
13	Technology matureness
14	Future development potential
15	Capital expenditure per MWh
16	Expenditure development after 2020



Short description of the technology key characteristics

The name Li-ion applies to a family of battery chemistries as opposed to a single battery type. Li-ion batteries make use of lithium ions for the charge transport inside the cell together with an organic electrolyte. This results in higher cell voltages and thus a higher energy density as opposed to water-based chemistries (lead-acid and nickel based). These properties makes Li-ion batteries the dominant technology for mobile energy storage including phones and cars.

Lithium-ion batteries show best lifetime when kept around a 50 % state of charge, while avoiding a state of charge of 100% or 0%. Cycle life increases when cycles get smaller. This makes them suitable for cyclic applications. Significant developments are on-going and aimed at increasing energy and power density, lowering the price and improving safety.

35 No configuration limit

36 Tesla website 2015: 10 kWh $3,500 battery pack (350 USD/kWh). This is lower than that of Nickel and Sodium-Sulfur based batteries but is only a recent development. For the technology being installed as an industrial application approx. 1000 EUR per kWh could be calculated. However, considering the earlier stated development at the time of writing this report, providing a high level estimation of capital expenditure is challenging.

3d) Battery technology: Nickel batteries

ID	Items	Value	
1	Suitable to help prevent RoCoF events	Techno- Economic	[traffic light]
2	Type of Frequency response	Bi-directional (High, Low)	
3	Inertia Constant H	-	[seconds]
4	Energy to Power (E/P) ratio (for storage)	> 10 minutes	[time]
5	Typical power capacity	Up to several MW	[MW]
6	Typical Energy content (for storage)	Up to several MWh	[MWh]
7	Charging time (for storage)	4 hours	[time]
8	Ramp-time	instant	[time]
9	Efficiency	85 %	[%]
10	Expected lifetime	1000 cycles or 15 years	[years]
11	Capital expenditure	€ 500 per kWh	[EUR]

		Comment	Score (1–5)
12	Economy of scale		2
13	Technology matureness		4
14	Future development potential		2
15	Capital expenditure per MWh		2
16	Expenditure development after 2020		2

Short description of the technology key characteristics

Nickel-based batteries make use of either a combination of Nickel Cadmium or Nickel Metal Hydride. A large amount of cells is needed to achieve a desired voltage due to its low cell voltage of 1.2 Volts per cell.

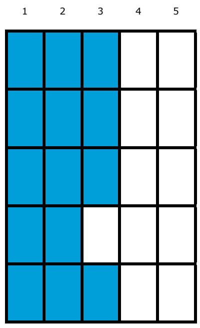
Nickel based batteries are more robust and reliable than lead-based batteries. Nickel based batteries have better performance at low temperatures, and are capable of delivering higher peak power than a lead-acid battery of the same energy content.

Nickel-based batteries are also significantly more expensive as opposed to lead-based batteries.

3e) Battery technology: Sodium Sulfur

ID	Items	Value	
1	Suitable to help prevent RoCoF events	Techno- / Economic	[traffic light]
2	Type of Frequency response	Bi-directional (High, Low)	
3	Inertia Constant H	-	[seconds]
4	Energy to Power (E/P) ratio (for storage)	7 hours	[time]
5	Typical power capacity	Up to several MW	[MW]
6	Typical Energy content (for storage)	Up to several MWh	[MWh]
7	Charging time (for storage)	7 hours	[time]
8	Ramp-time	instant	[time]
9	Efficiency	85 %	[%]
10	Expected lifetime	4500 cycles or 15 years	[years]
11	Capital expenditure	€ 500 per kWh	[EUR]

ID	Items	Comment	Score
12	Economy of scale		
13	Technology matureness		
14	Future development potential		
15	Capital expenditure per MWh		
16	Expenditure development after 2020		



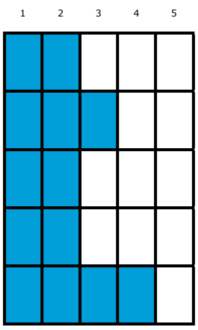
Short description of the technology key characteristics

Sodium-Sulfur batteries are currently only supplied by the Japanese firm NGK. They work with molten reactants at high temperature. The cells are therefore enclosed in thermally insulated modules, which are subsequently placed in racks. This property makes them mostly suitable for large scale stationary applications. Currently installed systems are among the largest battery based energy storage systems in the world. Sodium-Sulfur systems are primarily built for renewable power integration, with systems having a stored-energy to power ratio in the range of 6 to 8 hours.

4) Flywheel (high frequency)

ID	Items	Value	
1	Suitable to help prevent RoCoF events	Techno- / Economic	[traffic light]
2	Type of Frequency response	Bi-directional (High, Low)	
3	Inertia Constant H	-	[seconds]
4	Energy to Power (E/P) ratio (for storage)	> 1 minute	[time]
5	Typical power capacity	Up to 10 MW	[MW]
6	Typical Energy content (for storage)	Up to 1 MWh	[MWh]
7	Charging time (for storage)	1 minute to 1 hour	[time]
8	Ramp-time	instant[37]	[time]
9	Energy Consumption[38]	10 %	[%]
10	Expected lifetime	25 years, ∞ cycles	[years]
11	Capital expenditure	15,328,000.00[39]	[EUR]

		Comment	Score
12	Economy of scale		
13	Technology matureness		
14	Future development potential		
15	Capital expenditure per MW		
16	Expenditure development after 2020		



Short description of the technology key characteristics

Flywheels store energy as kinetic energy in a wheel with most of its mass at the rim. This fast moving mass ring is accelerated and decelerated by a motor/generator, thereby "charging" and "discharging" the system. Contrary to batteries, they are not cycle life limited, and their storage capacity does not degrade with age. Being continuously rotating machines, flywheels exhibit relatively high levels of energy loss. As a result, flywheels are mostly suitable for applications which require continuous charge/discharge operation, at such a high frequency that batteries would be very short lived.

37 When the technology is charged and therefore the flywheel is spinning the power is instantaneously available.

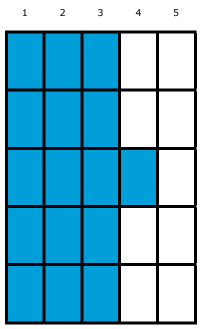
38 The energy consumption of a flywheel is energy related as opposed to power capacity related. As a result, a flywheel with an energy content of 1 MWh consumes approx. 100 kW/hour

39 5 MWh Flywheel, Source; J.H.W. Uijlings, DNV KEMA, Report: System Service Provision An independent view on the likely costs incurred by potential System Service Providers in delivering additional and enhanced System Services, (2012)

5) Rotating stabiliser

ID	Items	Value	
1	Suitable to help prevent RoCoF events	Techno- Economic	[traffic light]
2	Type of Frequency response	Bi-directional (High, Low)	
3	Inertia Constant H	40	[MWs/ MVA]
4	Energy to Power (E/P) ratio (for storage)	40	[s]
5	Typical power capacity	50-200	[MVA]
4	Typical Energy content (for storage)	Up to 0.7	[MWh]
7	Charging time (for storage)	2 - 10 minutes	[time]
8	Ramp-time	Instant power	[time]
9	Energy consumption	1,000-4,000	[kW]
10	Expected lifetime	30 years	[years]
11	Capital expenditure	See Text	[EUR/typical installation]

		Comment	Score
12	Economy of scale		
13	Technology matureness		
14	Future development potential		
15	Capital expenditure per MW		
16	Expenditure development after 2020		



Short description of the technology key characteristics

The rotational stabiliser technology that is selected here consists of a synchronously rotating machine that is directly connected to the grid. The machine is not mechanically driven by a prime-mover nor does it drive a load when running in normal operation. The synchronous machine can be designed with high number of pole-pairs although an increase of speed adds more inertia energy as opposed to an increase in weight. It possesses significant mass which enables it to provide a synchronous inertial response to the system for frequency deviations. In terms of RoCoF mitigation, the rotational stabiliser provides instantaneous inertial response due to its synchronous connection.

The machine is capable of providing other system services, including dynamic reactive power support and steady state reactive power.

When primarily used for limiting RoCoF, only a part of the kinetic energy can be used. To increase the use of its kinetic energy requires implementing the stabiliser as a double-fed machine. In this case, the machine operates at a speed which is the sum or difference between the grid frequency and the control frequency. In addition to the intrinsic inertia present in the rotating machine, the control frequency can be manipulated in order to provide synthetic inertia on top of the intrinsic inertia. In this way, the rotor can produce a rotating field that is synchronous to the grid frequency, while its actual speed of rotation is below synchronous speed.

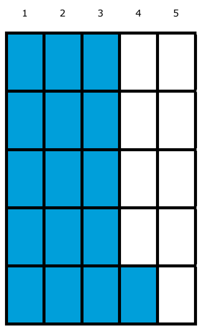
Double-fed compensators are wound rotor machines, with either slip rings, double stator winding sets or rotating transformers providing the control power to the rotor. Double fed machines can also be equipped with a flywheel for providing additional mass and therefore inertia. As such, a compensator can provide larger equivalent inertia as opposed to a synchronous compensator.

The rotor is typically powered by a variable frequency drive in order to produce a rotating field at the right speed. If the feed frequency to the rotor is held constant, a double fed synchronous machine produces inertia in the same way as a conventional generator does.

6) Wind

ID	Items	Value	
1	Suitable to help prevent RoCoF events	Techno- / Economic	[traffic light]
2	Type of Frequency response	Bi-directional (High, Low)	
3	Inertia Constant H	depending on design	[seconds]
4	Energy to Power (E/P) ratio (for storage)	-	[time]
5	Typical power capacity	Up to 8 MW[40]	[MW]
6	Typical Energy content (for storage)	-	[MWh]
7	Charging time (for storage)	-	[time]
8	Ramp-time	5 minutes	[time]
9	Energy consumption	-	[%]
10	Expected lifetime	30 years	[years]
11	Capital expenditure	2,264.00 EUR/ kW[41]	[EUR]

	Comment	Score
12	Economy of scale	
13	Technology matureness	
14	Future development potential	
15	Capital expenditure per MW	
16	Expenditure development after 2020	



Short description of the technology key characteristics

Wind turbines technology exists in a variety of generators types. The 3 most common types are:

- asynchronous generators;
- permanent magnet generators, and;
- double-fed generators.

The first two types, asynchronous generators and permanent magnet generators, produce power at a frequency proportional to the rotational speed of the rotor. As a result, these turbine types require a variable frequency drive in order to convert the generator frequency to the grid frequency. However, the double-fed generator produces power at a frequency equal to the sum of the rotational speed and the armature feed frequency. The feed power is typically provided by a small variable frequency drive.

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40 At the time of writing this report, up to 3 MW is installed in the Island of Ireland

41 Source: J.H.W. Uijlings, DNV KEMA, Report: System Service Provision An independent view on the likely costs incurred by potential System Service Providers in delivering additional and enhanced System Services, (2012)

Turbines using asynchronous generators and permanent magnet generators do currently not provide inertia to the grid. However, variable frequency drives technology can be programmed to provide synthetic inertia.

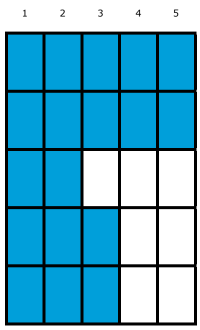
The inertia stored in the generator’s rotor and the turbine blades can deliver the stored kinetic energy to the grid.

In the case of a double-fed generator, the wind turbine provides synchronous inertia to the grid in a similar way to a conventional power plant. With a double-fed generator the stator can be directly coupled to the grid. The rotational speed of the rotor is affected by frequency changes, provided the frequency of the power fed to the armature remains constant.

7) Pumped hydro

ID	Items	Value	
1	Suitable to help prevent RoCoF events	Techno- Economic	[traffic light]
2	Type of Frequency response	Bi-directional (High, Low)	
3	Inertia Constant H	2.7	[seconds]
4	Energy to Power (E/P) ratio (for storage)	> 3 hours	[time]
5	Typical power capacity	Up to 3 GW	[MW]
6	Typical Energy content (for storage)	Up to 10 GWh	[MWh]
7	Charging time (for storage)	3-8 hours	[time]
8	Ramp-time	Approx. 3 minutes[42]	[time]
9	Efficiency	80 %	[%]
10	Expected lifetime	30+ years	[years]
11	Capital expenditure	Geology dependent	[EUR]

ID	Items	Comment	Score
12	Economy of scale		
13	Technology matureness		
14	Future development potential		
15	Capital expenditure per MWh		
16	Expenditure development after 2020		



Short description of the technology key characteristics

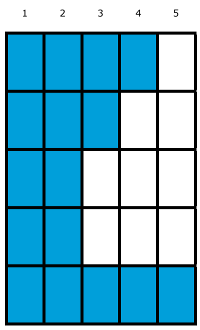
Pumped storage hydroelectricity requires an upper and a lower basin. The lower basin can be specially built or it can be a river or the sea. Water is pumped into the upper basin upon "charging" by a pump and allowed to flow down again through a turbine upon discharging. As a result of its similarity in operation to hydropower, the properties (such as achievable ramp rate) of a pumped storage plant during discharge are similar. Switching over from "charge" to "discharge" requires reversal of the direction of rotation of the pump/turbines, or separate pumps and turbines in case a faster switch time is required. The scale of this operation is comparable to that of larger hydro generation stations, and it is currently the most economical technology to store large amounts of energy. Its main disadvantage is its reliance on suitable geology, and the potential damage to vulnerable nature.

42 Approximately 3 minutes is needed from start, due to the water column used, additional power delivery need some time to prevent mechanical damage. Please note that the ramp-time should not be confused with inertia and hence when the technology is providing energy and thus synchronised with the power system, inertia is provided instantaneously

8) Compressed Air Energy Storage (CAES)

ID	Items	Value	
1	Suitable to help prevent RoCoF events	Techno- / Economic	[traffic light]
2	Type of Frequency response	Bi-directional (High, Low)	
3	Inertia Constant H	4	[seconds]
4	Energy to Power (E/P) ratio (for storage)	Site specific	[seconds]
5	Typical power capacity	Up to 500 MW	[MW]
6	Typical Energy content (for storage)	Up to several MWh	[MWh]
7	Charging time (for storage)	8 hours	[time]
8	Ramp-time	5 minutes[43]	[time]
9	Efficiency	-[44]	[%]
10	Expected lifetime	30 years	[years]
11	Capital expenditure	Up to 500 MW	[EUR]

	Comment	**Score**
12	Economy of scale	
13	Technology matureness	
14	Future development potential	
15	Capital expenditure per MWh	
16	Expenditure development after 2020	



Short description of the technology key characteristics

Currently, only two grid scale compressed air energy storage installations operate worldwide. In CAES plants, the gas turbine does not have a compressor, but it runs from the pressure stored underground instead. The plant will run during periods of peak demand and thus at high electricity prices. The pressure of the underground air storage is restored during periods of low electricity prices using an electrical pump.

The technology utilises the fact that a normal gas turbine uses approximately 1/3 of the total turbine power for driving the compressor. When using CAES, this 1/3 becomes available as electricity during periods of peak demand, while periods of low demand are used to build up pressure in the storage. This technology is known as diabetic CAES.

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43 To start the process it will take approximately 5 minutes. Please note that the ramp-time should not be confused with inertia and hence when the technology is providing energy and thus synchronised with the power system, inertia is provided instantaneously

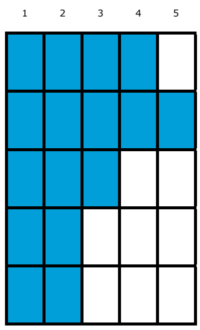
44 The efficiency is related to the technology and operation strategy and as such cannot be proved in general.

In terms of frequency stabilization, a CAES plant operates like a normal gas turbine power plant by providing inertia, primary, secondary and tertiary response. CAES at utility scale requires a suitable underground cavern and is therefore geology dependent.

9) AC interconnector (with Great Britain)

ID	Items	Value		
1	Suitable to help prevent RoCoF events	Techno-	Economic	[traffic light]
2	Type of Frequency response	Bi-directional (High, Low)		
3	Inertia Constant H	-		[seconds]
4	Energy to Power (E/P) ratio (for storage)	-		[time]
5	Typical power capacity	Up to 1 GW per link		[MW]
6	Typical Energy content (for storage)	-		[MWh]
7	Charging time (for storage)	not applicable		[time]
8	Ramp-time	instantaneous		[time]
9	Efficiency	95-97 %		[%]
10	Expected lifetime	30 years		[years]
11	Capital expenditure	1250 EUR/kW		[EUR]

		Comment	Score
12	Economy of scale		
13	Technology matureness		
14	Future development potential		
15	Capital expenditure per MW		
16	Expenditure development after 2020		



Short description of the technology key characteristics

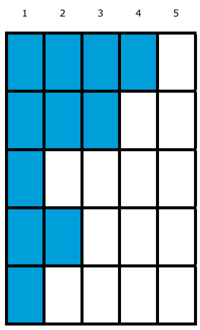
An AC interconnector with Great Britain requires both islands to become a single synchronous network. The amount of power being transferred through a synchronous interconnector is determined by the ratios of inertia in both networks and as a result will influence both systems directly compared to HVDC technology. With HVDC technology the power or frequency response can be programmed as required.

In case a loss of generation occurs in All Ireland, both the inertia in Great Britain and the inertia in Ireland will start to supply the power imbalance. The ratio between their contributions will be equal to the ratio of inertia present in both parts of the network. Inertia in GB is significantly larger than that in All Ireland and therefore most of the inertia and primary response will come from Britain. The interconnector should be capable of carrying a large portion of the maximum loss of generation in Ireland, at least during the time it takes for the secondary response in Ireland to react and correct the imbalance. However, it should be noted that the requirement for VAR compensation over a long marine cable circuit poses significant technical and cost implications.

10) "Parking"

ID	Items	Value	
1	Suitable to help prevent RoCoF events	Techno- Economic	[traffic light]
2	Type of Frequency response	Bi-directional (High, Low)	
3	Inertia Constant H	5.5 on average[45]	[seconds]
4	Energy to Power (E/P) ratio (for storage)	-	[seconds]
5	Typical power capacity	Up to 480 MW[46]	[MW]
6	Typical Energy content (for storage)	-	[MWh]
7	Charging time (for storage)	not applicable	[time]
8	Ramp-time	instantaneous	[time]
9	Efficiency	-	[%]
10	Expected lifetime	30 years	[years]
11	Capital expenditure	Up to 480 MW	[EUR]

		Comment	Score
12	Economy of scale		
13	Technology matureness		
14	Future development potential		
15	Capital expenditure per MW		
16	Expenditure development after 2020		



Short description of the technology key characteristics

Definition: "Parking" of conventional generators i.e. operating generation plant at low MW output levels but with reduced/no capability to provide system services (e.g. operating reserve) at the lower output levels.

"Parking" puts the station in a mode of operation which resembles that of a synchronous condenser, albeit with the ability to quickly ramp up power delivery and keep delivering power through the prime-mover. Efficiency in this mode of operation will be poor and depending on the method to keep the plant in "park"-mode the emissions such as NO_x could be beyond the station's permit limits and the depreciation of lifetime may be adversely affected. A detailed investigation on the possibility of this mode of operation is required before a power station can be "parked".

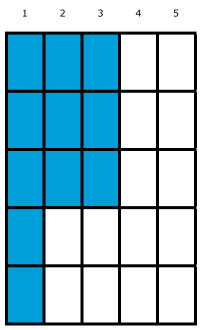
[45] EirGrid indicate that there are machines with an H of 8

[46] Currently installed in the Island of Ireland

11) Reduction in the minimum MW generation thresholds

ID	Items	Value	
1	Suitable to help prevent RoCoF events	Techno- / Economic	[traffic light]
2	Type of Frequency response	Bi-directional (High, Low)	
3	Inertia Constant H	5.5 on average[47]	[seconds]
4	Energy to Power (E/P) ratio (for storage)	-	[time]
5	Typical power capacity	Up to 480 MW[48]	[MW]
6	Typical Energy content (for storage)	-	[MWh]
7	Charging time (for storage)	not applicable	[time]
8	Ramp-time	instantaneous	[time]
9	Efficiency	-	[%]
10	Expected lifetime	30 years	[years]
11	Capital expenditure	Up to 480 MW	[EUR]

		Comment	Score
12	Economy of scale		
13	Technology matureness		
14	Future development potential		
15	Capital expenditure per MW		
16	Expenditure development after 2020		



Short description of the technology key characteristics

Reduction in the minimum MW generation thresholds of conventional generation while still leaving the plant with the capability to fully provide system services. There is a limit to reducing the minimum load of the machine. For a CCGT, the total power generation can be reduced to a certain extent. This includes shutting down of the Steam turbine and reducing the Gas turbine load to 50%. Low NOx burners are required to keep the emissions to an acceptable level at a 50% operation mode. A lower load than 50% for a GT at present will introduce an increase of emissions (such as NO_x) which most likely will be beyond the station's permit limits allowance.

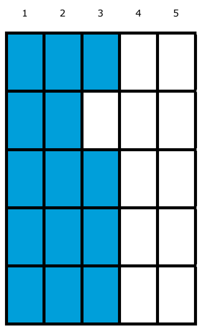
[47] EirGrid indicate that there are machines with an H of 8

[48] Currently installed in the Island of Ireland

12) Demand Side Management (DSM)

ID	Items	Value	
1	Suitable to help prevent RoCoF events	Techno- / Economic	[traffic light]
2	Type of Frequency response	Bi-directional (High, Low)	
3	Inertia Constant H	-	[seconds]
4	Energy to Power (E/P) ratio (for storage)	-	[time]
5	Typical power capacity	-	[MW]
6	Typical Energy content (for storage)	-	[MWh]
7	Charging time (for storage)	-	[time]
8	Ramp-time	-	[time]
9	Efficiency	-	[%]
10	Expected lifetime	-	[years]
11	Capital expenditure	-	[EUR]

		Comment	Score
12	Economy of scale		
13	Technology matureness		
14	Future development potential		
15	Capital expenditure per MW		
16	Expenditure development after 2020		



Short description of the technology key characteristics

Due to the broad range of technologies that can be incorporated in a DSM device, typical faceplate data is not provided. Demand side management is most often regarded as a solution to net congestion, by time-shifting large electrical loads such that local overloads do not occur, and the total available network capacity is more efficiently utilized. However, some loads do not need to operate at a fixed power level, a good example being electric car chargers.

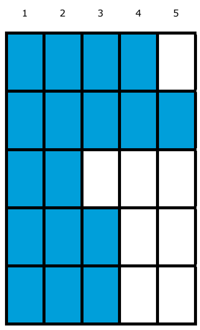
Regulating the charging power within reasonable limits does not affect their function. As a result, demand reduction, EV charging, large industrial loads, data centres etc. can be programmed to respond to network frequency in order to alleviate power imbalance: charge power is increased at a high or rising frequency, while charge power is decreased at a low or falling frequency. Therefore, the load can also provide an amount of inertia replacement and primary response. The amount of useful power that becomes available with this method is limited because of the network capacity constraints. However, time shifting may be used to provide primary, secondary and tertiary response to a limited degree.

In the Island of Ireland there are large data centres that form an opportunity to use DSM.

13) Fast responding gas turbines (Flexible thermal power plant)

ID	Items	Value		
1	Suitable to help prevent RoCoF events	Techno-	Economic	[traffic light]
2	Type of Frequency response	Bi-directional (High, Low)		
3	Inertia Constant H	5.5		[seconds]
4	Energy to Power (E/P) ratio (for storage)	-		[seconds]
5	Typical power capacity	Up to 500 MW[49]		[MW]
6	Typical Energy content (for storage)	-		[MWh]
7	Charging time (for storage)	not applicable		[time]
8	Ramp-time	5 – 8 minutes[50]		[time]
9	Efficiency	35 – 42 %[51]		[%]
10	Expected lifetime	30 years		[years]
11	Capital expenditure	-		[EUR]

	Comment	Score
12	Economy of scale	
13	Technology matureness	
14	Future development potential	
15	Capital expenditure per MW	
16	Expenditure development after 2020	



Short description of the technology key characteristics

Fast response gas turbines are conventional open-cycle gas turbines (OCGT) coupled to a generator, running mostly on natural gas or light oil. These power plants have lower efficiencies than combined cycle power plants (CCGT) and hence in closed cycle plants the hot turbine exhaust gas is used to power a steam cycle.

However, the advantage of the absence of a steam cycle is the capability to have higher ramping rates. Therefore the increase and decrease in power is fast and thus capable of quickly reacting to demand shifts. Therefore OCGTs are used to create value from high electricity market prices.

49 Flexible power plants are not only peaking plants and hence multiple units can be considered to form a total capacity

50 Please note that the ramp-time should not be confused with inertia and hence when the technology is providing energy and thus synchronised with the power system, inertia is provided instantaneously

51 European Commission, Study on the state of play of energy efficiency of heat and electricity production technologies, (2012)

Full power from cold can be generated within 15 minutes. Further an open-cycle gas turbine power plant provides inertia just like any other conventional power plant in addition to its high ramp rate capability. This increases its potential for providing primary and secondary response.

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