Grid-interactive UPS and Data Centre potential to provide Fast Frequency Response and role in a low carbon energy system

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Abstract

Digitalisation is driving to build more and bigger data centres to provide digital services for the society. The energy consumption of these digital factories is growing and significant in comparison to other sectors while societies are facing challenges with energy transition to battle the global warming. Data centres, in other hand, use modern power infrastructure that could be leveraged to support energy transition and wider use of renewable energy sources.

Purpose of this thesis was to provide basic information about electrical system balancing, grid-interactive UPS in a data centre, and to assess the potential of data centres to provide Fast Frequency Response (FFR) to mitigate low inertia resulting from higher penetration of non-synchronous renewable energy sources in selected synchronous areas.

To answer the main research question about data centre's potential to provide FFR in relation to market volumes purchased by transmission system operators (TSO) from ancillary services markets, data centre capacities and UPS content were compared to FFR market volumes.

Results are proving that data centres could have a significant role in providing fast response and flexibility for the future electrical system. Some data centres are already providing frequency regulation with their UPS assets, and there seems to acceptance for the proposed solutions in the data centre market. Also, the suitability of UPS technology for frequency regulation has been proven in earlier pilots.

Leveraging data centre capabilities and existing assets for grid support enables higher penetration of renewables, replaces spinning fossil-based reserves from the system, reduces need to build dedicated reserves and reduces the cost of system balancing, carbon emission and embodied carbon in the system. Overall, the socioeconomical benefits of grid-interactive UPS and data centres are obvious and should be taken into consideration when determining future policies.

Keywords/tags (subjects)

EnergyAware UPS, grid-interactive, data centre, Fast Frequency Response, FFR, energy transition, inertia, frequency containment

Miscellaneous (Confidential information)

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1 Introduction

The transition to low-carbon energy sources is driven by local governments and European Union to meet commonly agreed goals to reduce greenhouse gas emissions in move towards climate neutral economy. This is shifting the generation of electricity from fossil-based fuels to use of renewable energy sources, such as wind and solar. By 2030, the share of renewable energy within European Union is targeted to achieve at least 32% (EC, n.d.).

The renewable power generation based on wind turbines and photovoltaic (PV) panels have some fundamental technical differences when compared to more traditional forms of power generation. Where traditional power generation is synchronous, having rotating generators directly connected to grid, solar and wind power generation are coupled to system via semiconductor converters and are non-synchronous. The variable nature of wind and solar energy, and the need for additional flexibility in the system to mitigate this, is well understood and discussed topic. But the impact of non-synchronous variable renewable energy (VRE) to system inertia, frequency stability and reliability is not a topic well known by wider audience. The higher penetration of non-synchronous power generation is causing the system inertia to reduce and makes the frequency containment more challenging (Ørum et al., 2018b, p. 7). This is resulting a need for new type and faster frequency containment reserves, as part of ancillary services market, to help to balance the system (Entso-e, 2019, p. 4).

Data centres with existing assets could provide this type of service (Alaperä et al., 2019, p. 5). This thesis is studying the potential of data centres to provide the required fast frequency response (FFR) for the power grid and comparing the amount of installed power infrastructure capacity within data centres to volumes of acquired frequency regulation capacity from the ancillary markets. Basic principles of system balancing, frequency containment and system inertia are also explained as it supports better understanding of the existing and future grid challenges and proposed solutions.

As the transition to renewable energy sources will require more flexibility and fast response from the system, leveraging existing assets within buildings and industry will reduce the amount of resulted investments and is cost effective solution according Nursimulu (2016, p. 11) and Alaperä, et al (2019, p. 5065). Also, as the existing assets are used more efficiently and is reducing need to build new additional reserve systems, it also reduces the embodied carbon emissions of the power system.

Use of new technologies as reserves in ancillary markets a) replaces the traditional spinning reserves based on fossil fuels and helps to reduce associated emissions and b) enable to reduce inertia floor in the system through fast response allowing to retire conventional power generating units (EirGrid & SONI, 2020c, p. 141; EirGrid & SONI, 2020e, p. 12).

The suitability of modern static UPS technology for frequency regulation has been proven in various pilots conducted with transmission system operators (Alaperä et al., 2019, p. 5; Svenska Kraftnät, 2018, p. 25). First data centres and commercial buildings are already participating in the reserve markets by utilising the new capabilities of modern UPS equipment (Eaton, 2019). These mentioned pilots and projects rely on UPS technology provided and developed by Eaton, while other UPS suppliers have also indicated similar developments of their products or already have similar capabilities (Di Filippi & Valentini, 2021; Fortum, 2022).

The overall potential of UPS systems in data centres to provide fast frequency response has not been studied. This is important to understand and can help to create more willingness among data centre operators, transmission system operators, market regulators and legislators to leverage this hidden potential in the system. Gaining this understanding is becoming more relevant and urgent, as data centre operators like Microsoft (2020) are showing growing interest to support the grid and higher penetration of renewables (Greenpeace, 2019).

This study is limited to Nordic countries, Ireland and UK. These have a combination of limited size synchronous area and increasing penetration of renewable energy, while having advanced markets for frequency containment reserves to provide the required fast response. UK and Ireland are data centre hubs in Europe, and there's growing interest to build data centres to Nordics due to cool climate, reliable grid based on renewable energy and low cost of energy (Christensen et al., 2018). These locations face the challenges caused by non-synchronous renewable energy with high power demand by data centres, and as such, can be used as an example of future challenges in wider scale, while we move towards carbon neutral energy system and digitalised world.

To answer the question if data centres could have major contribution in providing fast frequency response and to evaluate the potential role of the data centres in future power systems to help to increase the share of renewables, this thesis focused on potential capacity of static UPS and battery technology inside data centres, that could be utilised for the fast frequency response (FFR), against the amount of acquired FFR from the ancillary markets. This is a recent technological development in UPS products while FFR is a new type of frequency containment reserve in the ancillary services markets, used specially to mitigate low inertia caused by high penetration of non-synchronous generation.

The use of a UPS and batteries for demand side response, such as time of use (TOU) and peak shaving or other purposes, is outside the scope of this thesis as these do not relate to low system inertia or fast response. Likewise use of data centre back-up diesel generators for the ancillary services is outside the scope of this thesis since a) they cannot provide a fast response within couple seconds and therefore fit better to be used for secondary reserves, and b) use of existing diesel engines would cause additional emissions and act against sustainability goals. Also, more strict environmental regulation may apply when for example exceeding defined running hours per year (UK Environment Agency, 2019).

As part of this work, the basic principles of electricity grid frequency, balancing, inertia, and frequency regulation are explained as these directly relate to concept of providing fast response with a data centre UPS. Also, fundamental principles of a UPS and grid-interactive UPS technologies are explained. This to create a theoretical framework and to help to form an overall picture and understanding about grid-interactive data centre concept for the reader.

2 Research methods

The research question is as follows: Can the power infrastructure of data centres provide a significant amount of frequency control for the needs of the electricity grid, and what is the potential capacity in data centres in relation to the required fast frequency response?

The matter is being clarified on the basis of existing information available from various sources. These include online publications and reports from transmission system operators, scientific articles, market research reports and the company's internal information on the equipment installation base and delivery volumes. This is supported by personal experience in the industry in terms of market, technology and solutions.

The subjects of the study are limited to three synchronous areas, the Nordic, Ireland and the United Kingdom. These are reviewed separately, as there are differences between synchronous areas in terms of mix of energy production, the size of the electricity system and the number of data centres.

2.1 Reliability of quantitative research

The research material relies on several sources and ways of looking at the issue to form an overall picture. The reliability and validity of these sources, and thus the overall reliability of the study, should be assessed according Vilkka (2007, pp. 149-152) and Toikko & Rantanen (2009, p. 122).

2.1.1 The needed volumes of Fast Frequency Response

This information is at the heart of the research question, and thus its reliability is paramount. The need for fast frequency response to manage contingency events in a system with low inertia has been addressed in several scientific articles and studies, for example by grid operators (Entso-e, 2019). These are suitable for creating a theoretical basis in the thesis when dealing with the effect of inertia in an electrical system.

The actual quantitative research utilizes reports and data published by the transmission system operators about the market capacity of the reserves. Thus, it is based on the actual and necessary volume of the market, which is another key factor in the research question. The reports of the transmission system operators and published reserve market data on the actual volumes on the market can be considered reliable and up-to-date information.

2.1.2 Number of data centres and electricity consumption

The issue has been studied in several scientific articles (Andrae & Edler, 2015, pp. 132-133). The approach has often been theoretical. Data centre energy consumption and power capacity is derived from estimated age, number, loading factor and energy consumption of the IT equipment, added with estimated cooling demand and its estimated energy efficiency. Finally adding the estimated losses of power infrastructure (Shehabi et al., 2018). Although the estimates are based on very accurate measurements for individual devices, the overall margin of error can be considerable. The estimates of different studies have varied greatly, and even the estimates of the same researchers have changed considerably between studies in a few years (Koronen et al., 2019, p. 4). Therefore, these are more indicative studies and need to be treated with some criticism.

In addition, market research data for data centres can be used, based on data collected by the market research institute from data centre operators. Based on this, estimates can be made of the total floor area, power capacity, etc. of the data centres in selected areas. The data can be considered reasonably reliable, and the potential error comes from scaling the values to reflect the entire, or specific, market.

This data can also be combined with data based on data centre reporting and measured figures for energy consumption, load utilization rate, energy efficiency, etc. collected by the EU JRC (Bertoldi et al., 2017). Data centres participating in the European Code of Conduct for Data Centres program must follow the provided rules for reporting and data, so this can be considered reliable as long as sample base matches the average market. Throughout the sample in 2017, there were 289 data centres in the Europe, and based on this, it is possible to draw conclusions about the performance of data centres for the entire market.

In addition to market research data, statistics offices are collecting and publishing information of energy use of various sectors. This data, when available, is transparent and reliable when reported accurately by the market. Also, in case of Ireland, transmission system operator publishes estimations about data centre energy use. As this is based on their own grid and measured data, and permits, it can be considered reliable.

2.1.3 UPS equipment install base

An essential object of research and part of the research question is the UPS capacity in data centres whose potential for frequency regulation is being assessed. To determine this, market research reports for UPS equipment can be used to give an estimate of the number of UPS units in data centres, which is the largest single application for a UPS. This data can be combined and compared with the company's (Eaton) own data on equipment deliveries and install base. This should give a value of the same order of magnitude as other market estimates. The UPS market research data is based on figures reported by UPS suppliers and is expected to be normally reasonably reliable, even some inconsistencies do occur between reports. The company internal data is available with the accuracy of an individual order and unit shipment. Thus, it can be considered accurate and reliable. Possible error is coming from estimated market shares when scaling Eaton product quantities to the total equipment base in a country or region.

2.1.4 Data aggregation and comparison

It is appropriate to compare the estimates obtained by different methods. If all research methods are reliable, the results should be similar. As the research methods and source material are partially based on estimates, the results may show large differences.

Before analysing the data, it is therefore important to make a more detailed description of what data is being evaluated and how different data are related to each other, and how different data are combined to produce new data. This helps to avoid false assumptions and thus improves the validity and overall quality of the study (Toikko & Rantanen, 2009, p. 122).

Because it is not necessary to obtain very accurate figures to create an understanding on the magnitudes and potential of data centres, this study allows for reasonably large margins of error without resulting wrong conclusions about the research question.

2.2 Qualitative research

Qualitative research is used to create a theoretical framework when evaluating the suitability of UPS technology for frequency regulation, and to assess market and grid development and the need for frequency containment reserves. For UPS equipment, there is previous research data in the form of theses, dissertation, and scientific articles. Author has been collaborating with others in producing some of the peer-reviewed scientific articles. As the author of the thesis has been actively involved in the development of this new grid-interactive technology for UPS equipment, the accuracy and timeliness of the data can be trusted when the data is presented objectively and ethical principles are followed in the study (Ojasalo et al., 2015, pp. 48-49).

The theoretical basis related to the reserve market and the electricity system is based on scientific articles and research reports. In particular, the studies and conclusions produced by the experts of the transmission system operators can be considered reliable because they have the best understanding about the system in question. The reserve market and rules are changing, and therefore earlier conclusions regarding technology should be re-evaluated in relation to market changes.

2.3 Relevance of the study

This research is relating to current and future issues of the electricity system, data centres and society, and its relevance and usability of the results can be assessed through these aspects (Toikko & Rantanen, 2009, p. 125).

First, the client for the thesis produces the technologies for the proposed solution, so the work is relevant to the client, although the purpose may be to demonstrate leadership rather than to gain direct business benefits from the research.

Second, climate change is one of the biggest challenges to society and primary driver for energy transition. This is based on higher penetration of carbon-free or low-carbon energy sources such as solar and wind energy, in parallel with other low carbon energy sources. The higher penetration of these variable and non-synchronous renewable energy sources in the electricity grid poses several challenges, one of which is system frequency management and reliability in the event of a disturbance. New, faster reserves are needed for this, and these are being researched today and already deployed in some synchronous areas.

Third, through digitalization, people are consuming more and more digital services, causing increasing data processing and storage in data centres. The number and size of data centres is growing, and data centres already consume more than one percent of the world's electricity today and whole ICT sector is responsible for much higher share of electricity use. As such, digitalisation should be performed in the most environmentally friendly way possible, using renewable energy.

Fourth, the data centre power infrastructure includes components that can be utilized to provide flexibility and fast response to the electricity grid, which contributes to the wider utilization of renewable energy. When producing the needed flexibility for low carbon energy system by utilizing existing assets, the need to build dedicated assets for grid support is reducing thus reducing use of natural resources and embodied carbon in the system while bringing economic benefits. This is reducing the socioeconomical cost of the solutions and energy transition.

The research can be expected to be relevant and useful to many parties, as a better understanding of the potential of data centres as an unused resource to support the electricity grid can benefit industry, decision makers and electricity system operators when considering future solutions and making better use of resources today.

3 System balancing and frequency containment

Detailed study of energy and ancillary services markets is not in the scope of this study, but it is useful to go through the general principles of system balancing and frequency containment in electricity grid to help the reader to better understand the role of reserves in the system in case one is not already familiar with topic. The aim of this study is to evaluate the data centres potential to provide fast frequency response, a specific type of frequency containment reserve, and therefore understanding the role and importance of reserves, as well as system balancing in general, supports to form an overall picture on the topic.

The electricity grid in Europe and large part of the world has a nominal frequency of 50 Hz. To maintain the frequency at 50 Hz, the system demand and supply must be in balance i.e., the amount of production of electricity must match the consumption of electricity. The market operators who sell and purchase energy in the electricity market are planning and balancing this for every hour. In practice, some imbalances will occur due to inaccuracies in forecasts, load variations within bidding slots and possible contingency events i.e., major disturbances in the system.

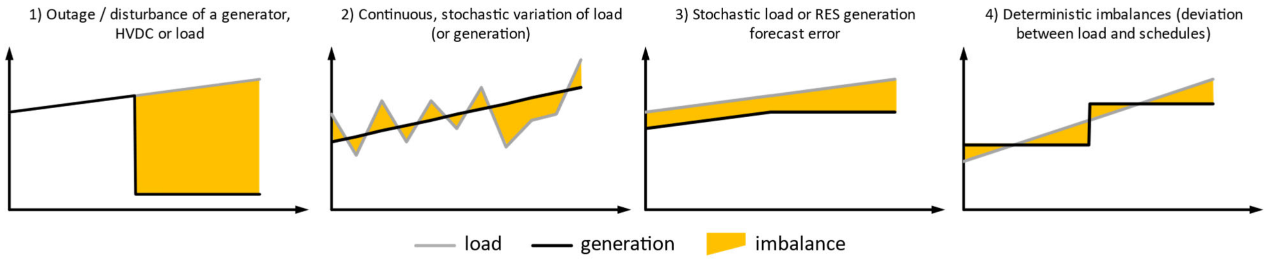

Figure 1. Simplified illustration of imbalance types, modified from (Entso-e, 2013, p. 56)

Transmission system operator (TSO), such as Fingrid in Finland, has the role to ensure system reliability and maintain the power system balance within their load-frequency control area to regulate the system frequency, and to contain frequency inside defined limits. A frequency deviation from nominal 50 Hz is a direct and real-time indication of system imbalance; if production (supply) exceeds consumption (demand) the frequency goes up, and if consumption exceeds the production the frequency goes down.

TSO acquires required capacity of reserves from the ancillary services market to be able to regulate the frequency and to contain frequency within acceptable limits during normal conditions and disturbances, and to be able to restore frequency back to nominal after contingency events.

3.1 Synchronous area and frequency

A synchronous area is an electricity grid that has its parts connected via alternating current transmission lines and shares the same frequency throughout the network, impacted by the balance of demand and supply within the synchronous area. A synchronous area can have a single or multiple transmission system operators and load-frequency control (LFC) areas depending on its size and geographical area.

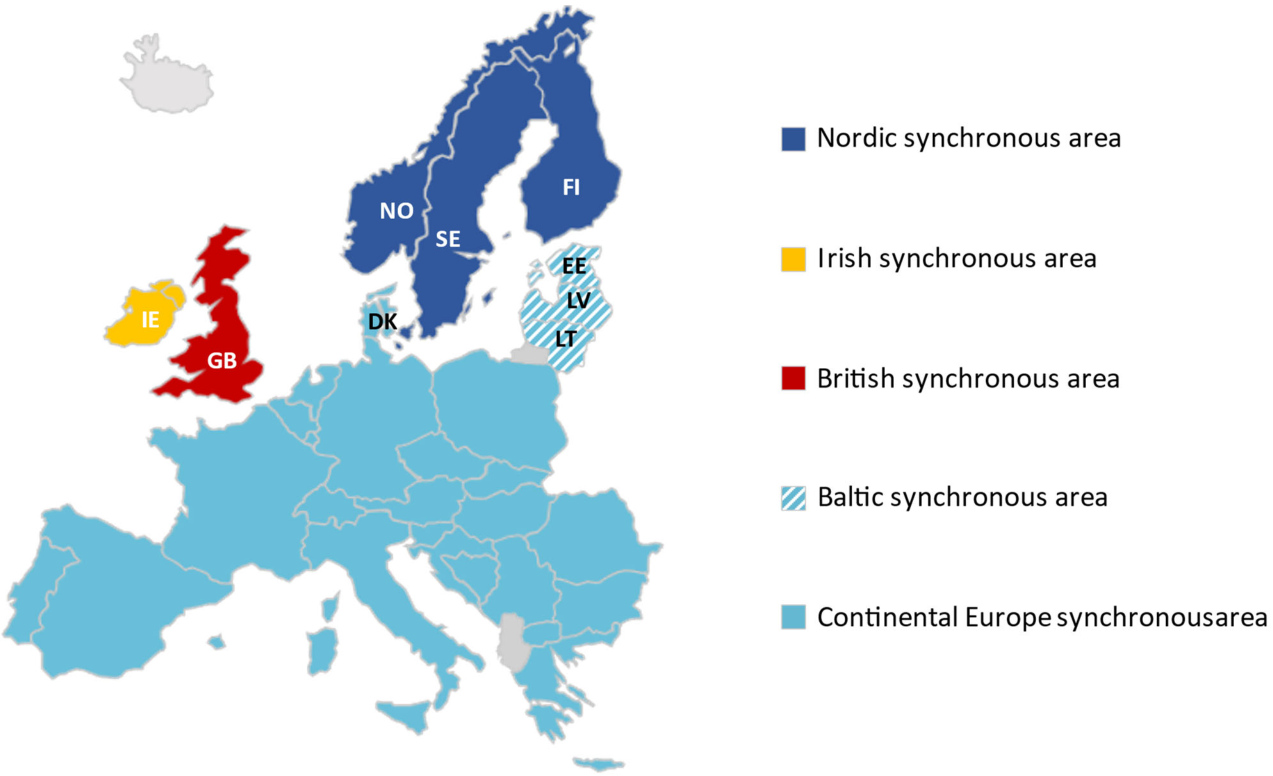

Figure 2. European synchronous areas, modified from (Entso-e, 2015, p. 15)

Transmission of electrical energy between different synchronous areas happens through high voltage direct current (HVDC) systems. System balance in one synchronous area doesn’t impact the frequency or balance of other synchronous areas as long as imported or exported energy through HVDC remains constant.

In this study the focus is on synchronous areas of Great Britain, Ireland and Nordics. British synchronous area is operated by nationalgridESO, Irish by Eirgrid (Republic of Ireland) and SONI (Northern Ireland), and Nordic synchronous area is operated by Energinet (Denmark), Statnett (Norway), Svenska kraftnät (Sweden) and Fingrid (Finland). Eastern part of Denmark is connected to Nordic synchronous area while Western part is connected to Continental Europe synchronous area. Baltic countries shown in Figure 2 are today synchronised with Russian IPS/UPS but will be synchronised to Continental European system in the future (Elering, 2021, p. 1).

As a general principle, in a synchronous area, all connected parts of the electricity grid are synchronized with each other and the frequency is same in all parts of a synchronous area. In reality, there can be small and momentary variations in the frequency between different parts of a synchronous area, but in long-term the frequencies are following same trend.

Figure 3. Local frequencies in Continental Europe Synchronous Area on 12.3.2022

Figure 3 is a snapshot of the Continental Europe Synchronous Area frequencies taken from Swissgrid's (n.d.) website. As shown, there are minor differences in local frequencies that will result a phase shift between areas and over the transmission network. When the synchronous generators operate in parallel connected to same grid, they are synchronised to each other through the system and rotate electrically at same speed, creating approximately 50 cycles per second in 50 Hz system. If there's a momentarily a slight difference in rotational speed resulting slightly different frequency, their outputs will slowly shift apart. As an example, in case of a 100 mHz (0,1 Hz) temporary difference in frequencies between different parts of synchronous area, during one second the area with higher frequency will have its voltage doing 0,1 cycles more, resulting 36° voltage phase (angular) displacement between areas.

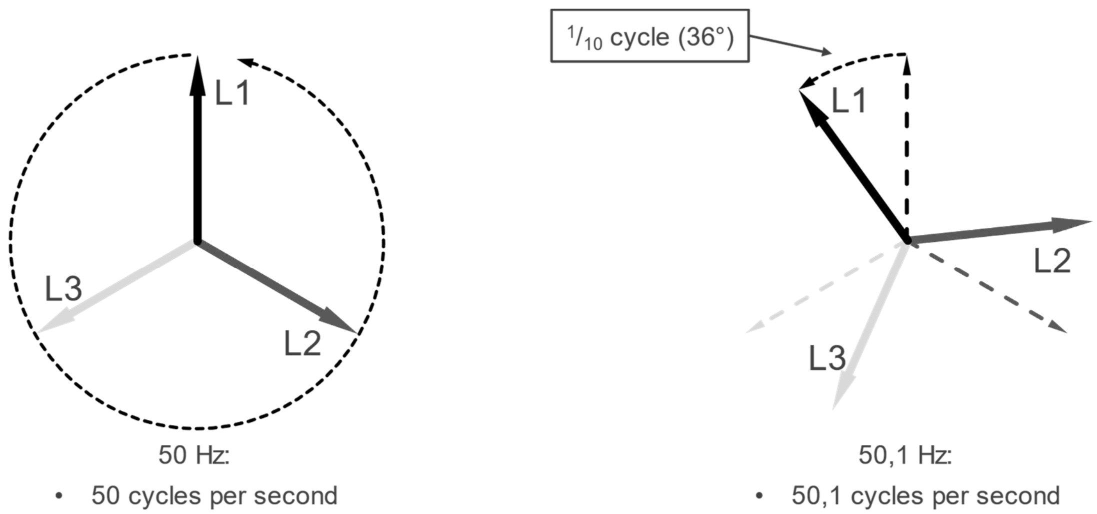

Figure 4. Phase displacement and difference in frequency

During contingency events, resulting large momentary imbalances and frequency transients, the differences between regions can be larger than normally. Nevertheless, the frequencies follow same trend line while momentary differences created by the oscillations between generating groups can cause some temporary phase shifting between areas. Figure 5 shows the measured local frequencies at far ends of Nordic synchronous area during contingency event.

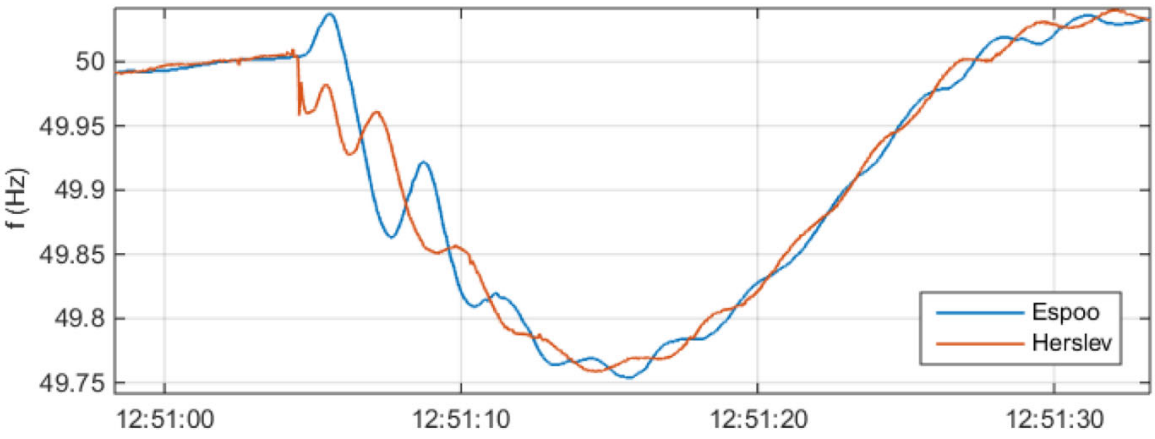

Figure 5. Frequency in Espoo (Finland) and Herslev (Denmark) after a loss of 580 MW (Ørum et al., 2018b, p. 13)

3.2 System balancing through energy markets

Some of the electricity is generated and purchased through long-term bilateral contracts in forward market. Typically, this applies for large generating units, such as nuclear power plants, covering part of the base load on the grid. Additional power generation capacity is offered to market to meet the forecasted demand through day-ahead market. The required generation capacity for each bidding slot (e.g., an hour) of the following day is based on consumption forecasts impacted by outside temperature, day of the week and by variable renewable energy forecasts used to estimate how much renewable power generation capacity is available for each hour. Through intra-day market additional adjustments to production capacities are made within same day based on updated and more accurate forecasts.

As shown in Figure 6, nuclear power generation, that is sourced through long-term bilateral contracts, is constant. Industry cogeneration is providing energy for self-consumption and often heat is the primary product while electricity is a by-product of heat generation, similarly to cogeneration of district heating. Therefore, these production forms are rather constant and partly insensitive to market price variations as primary motive to operate the generating plant is not driven by electricity market prices. Hydro power production is more flexible and is typically used in the Nordic countries to balance the system and adjust production capacity to meet the variations in demand and in other production forms, such as wind and solar. Finally, import and export of power between regions or countries is used to match the supply with demand when regional production capacity is insufficient to cover all the regional consumption.

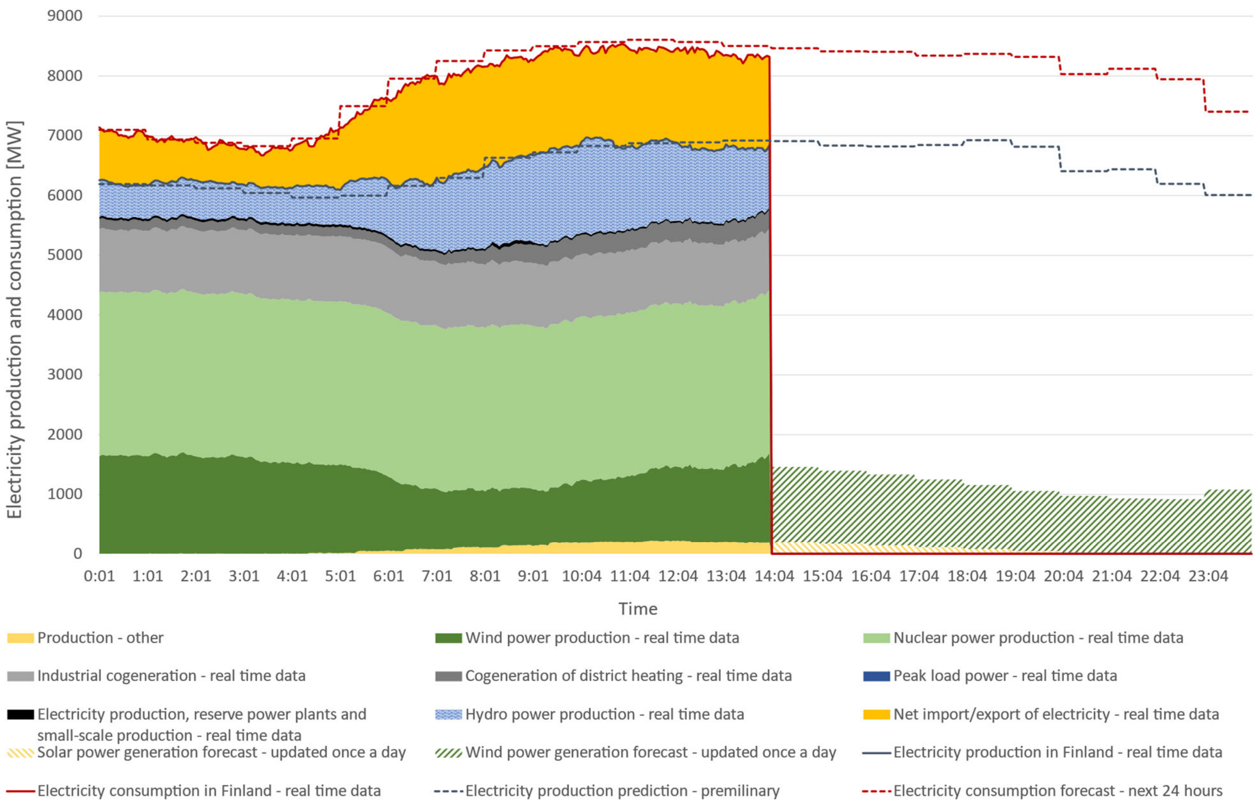

Figure 6. Production and consumption data with forecasts from Finnish national grid on 20 July 2021. Graph based on data available from Fingrid open data portal (Fingrid, n.d.)

As production capacity and energy in the market is traded for certain bidding slots, for example 15 minutes or an hour, it cannot be matched for each minute and address the possible variations within these time slots. These imbalances are result of normal load variations, forecast errors and possible contingency events, such as a failure of a generating plant. See also Figure 1.

The general principle for system balancing is shown in Figure 7. Part of grid’s demand is covered with production capacity acquired through forward market. This is complemented with additional production capacity acquired through day-ahead market to meet the forecasted demand for each bidding slot of a following day, while taking account forecasted wind and solar generation for the same time period. This roughly matches the average production capacity for the bidding slot with average forecasted consumption of the same slot. Where applicable, intra-day market is used with updated forecasts to acquire additional up or down regulation capacity to better match the production and consumption for each slot.

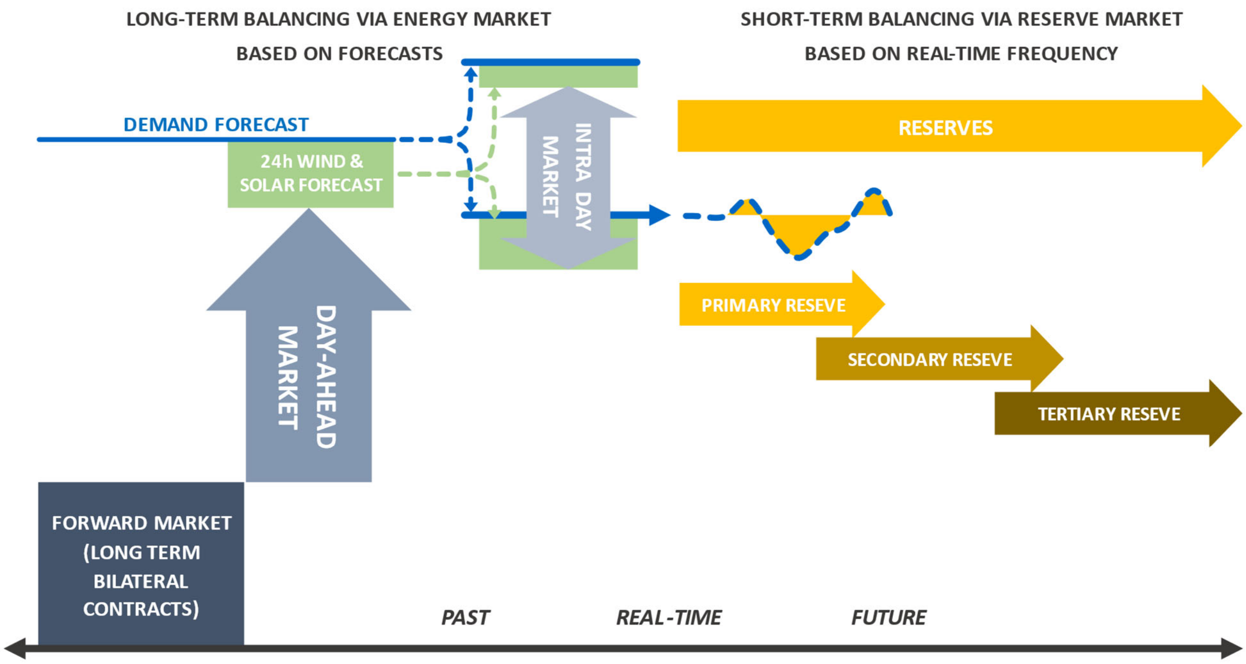

Figure 7. Principle of system balancing

Finally, frequency containment reserves acquired through ancillary services market are used continuously and in real-time to fine tune the system balance to regulate the system frequency during normal conditions and disturbances. The overall reserves are composed from multiple reserves types, each aimed to provide faster or slower response for a shorter or longer period to manage expected imbalances and various fault scenarios in the power system. The activation of frequency containment and restoration reserves is based on real-time system frequency.

Where system balancing through energy market mechanism is a proactive method based on forecasts to maintain the system balance, use of frequency containment reserves is a reactive method based on real-time system frequency to correct existing imbalances.

3.3 System balancing with reserves

Transmission system operators have an obligation to maintain the system reliability and regulate the system frequency. 'Establishing a guideline on electricity transmission system operation'

(Regulation 2017/1485) is giving the requirements for European system operators and is defined by European Parliament and Council. It is giving obligation for each TSO acquires required reserves from the ancillary services (balancing) market for the purpose. Depending on the market, the exact names or abbreviations of the reserves can vary.

Generally, the reserves are divided to three categories according their primary purpose. These are frequency containment reserves (FCR), frequency restoration reserves (FRR) and replacement reserves (RR). These are also often referred as primary, secondary, and tertiary reserves (Ramboll, 2019, p. 15). Figure 8 shows the hierarchy of the frequency control processes and activation of reserves according to Entso-e.

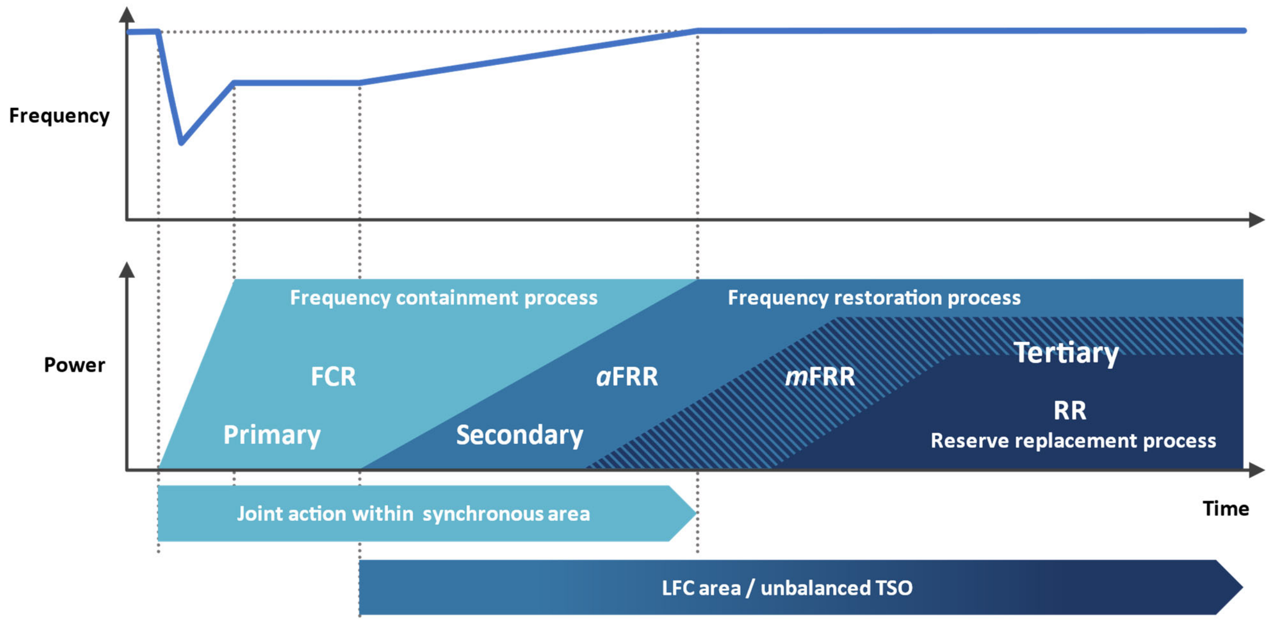

Figure 8. Dynamic hierarchy of frequency control processes, modified from (Entso-e, 2013, p. 38) and (Entso-e, 2018, p. 5)

Frequency Containment Reserves (FCR)

Frequency containment process. The reserves act as active power reserves used to regulate the frequency in normal conditions and to contain and stabilize the frequency inside acceptable limits during and after disturbances. Frequency containment process is a joint action within whole synchronous area (Entso-e, 2018, p. 6) and the frequency containment reserves can physically locate anywhere in the synchronous area. There are different types of frequency containment reserves, with different technical requirements and each aimed for a specific purpose.

Frequency Containment Reserve for Normal (FCR-N) is used to make tiny adjustments to system balance to regulate the frequency during normal conditions. In practice, these operate with minimal frequency dead-band and continuously regulate the frequency up or down.

Frequency Containment Reserves against Disturbances (FCR-D) is used to provide additional regulation capacity and reserve power in case of contingency events. These reserves activate within few seconds after larger deviation from nominal frequency and remain activated as long as frequency is outside defined boundaries or defined maximum response time has been exceeded.

Fast Frequency Response (FFR) is a new type of reserve to mitigate challenges related to low system inertia. FFR provides faster response than FCR-D and is used to contain the frequency during low inertia conditions, as traditional technologies providing FCR-D cannot react fast enough to keep the frequency nadir inside specified limits. The activation time is typically below one second, and maximum response time limited to tens of seconds.

Frequency Restoration Reserves (FRR)

Frequency restoration is a mandatory process and used to restore the frequency back to nominal setpoint after a disturbance. FRR will replace the activated FCR in the system and is typically activated after some minutes. FRR can be activated automatically (aFRR) or dispatched manually (mFRR) upon a request from TSO to restore power balance within their load-frequency control area (Entso-e, 2018, p. 6).

Replacement Reserves (RR)

Reserve replacement is an optional process and is used to replace or complement the activated FRR in the system, so that required level of FRR is available for possible additional disturbances. These are dispatched manually and activated in the disturbed load-frequency control area (Entso-e, 2018, p. 6)

3.4 Dimensioning and reference incident

The frequency containment and restoration reserves are sized to contain and stabilize frequency within defined limits and to restore the system frequency back to setpoint after a disturbance. Required capacity of reserves depends on the size of a contingency event and the reserves are sized against the reference and dimensioning incidents. Reference incident, used for FCR sizing, is the maximum expected instantaneous power imbalance between electricity demand and supply in the synchronous area. Dimensioning incident, used for FRR sizing, is the maximum expected instantaneous power imbalance between electricity demand and supply in the control area. The determination of reference and dimension incidents are based on the power system and its components and design, and typical fault scenarios used for the purpose are disconnection of large power generation units, disconnection of large load groups and interruptions in transmission and HVDC lines between regions or synchronous areas (Entso-e, 2012, p. 2).

Table 1. Largest Infeed and assigned minimum inertia levels (Mehigan et al., 2020, p. 6).

	Largest Infeed [MW] (Reference Incident)	Assigned minimum inertia for RoCoF limit of 1 Hz/s [MWs]	Assigned minimum inertia for RoCoF limit of 0,5 Hz/s [MWs]
CE	3 000	75 000	150 000
Nordic	1 400	35 000	70 000
GB	2 000	50 000	100 000
Baltic	700	17 500	35 000
Ireland	700	17 500	35 000

The reference or dimensioning incidents define the sizing criteria for frequency containment and restoration reserves. The impact of dimensioning incident to a system depends also on the relative size of the expected maximum fault and inertia in the system. Dimensioning incidents of Nordic, Great Britain, Ireland and Central European Synchronous Areas are compared to average generation capacity in the system during summertime, from June to August in 2016 to 2020 (see also Figure 13). Larger the relative size of a disturbance and smaller the system inertia is, faster and further the frequency will deviate from nominal frequency (Ørum et al., 2018a, p. 7).

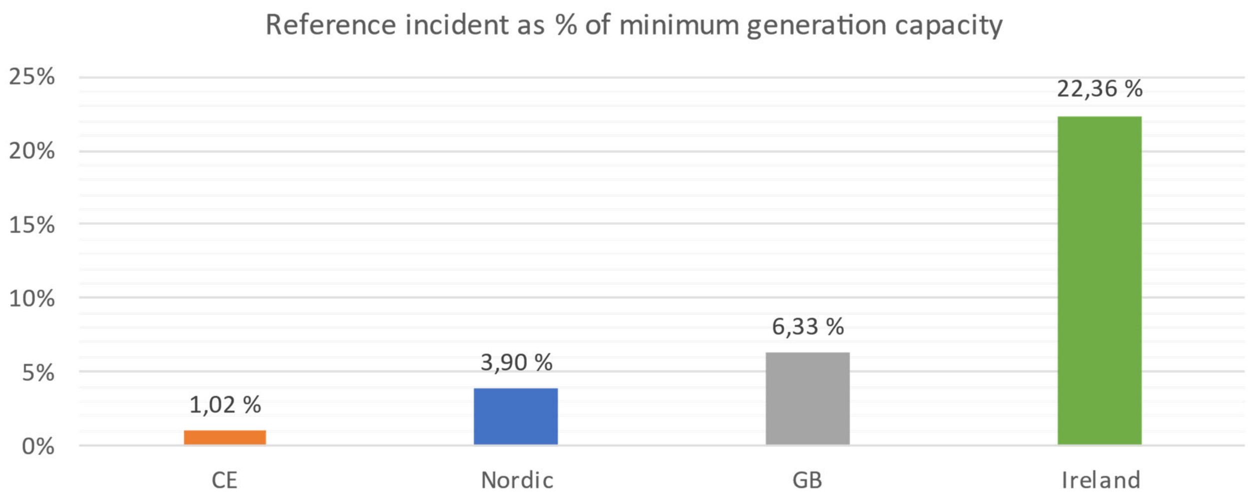

Figure 9. Size of reference incident as % of minimum generation capacity in the grid

4 System inertia

System inertia is a key concept to understand when discussing the future challenges of low carbon electricity grid with high penetration of variable renewable energy (VRE), such as wind and solar. Where traditional power generation technologies are based on synchronous generators having a spinning rotor magnetically coupled to rotating electric field of the stator winding, that is directly coupled to the grid, photo-voltaic (PV) panels and wind turbines are asynchronous and do not have a spinning mass or it is decoupled from the grid with power semiconductor converters.

With synchronous generators the spinning mass and the kinetic energy of the generating set is coupled with the electricity grid frequency and it provides inertia for the grid, while asynchronous generation does not contribute to system inertia. "*Inertia of a power system is defined as the ability of a system to oppose changes in frequency due to resistance provided by kinetic energy of rotating masses in individual turbine-generators"* (Ørum et al., 2018b, p. 8). The share of non-synchronous generation in the system is often referred as System Non-Synchronous Penetration ratio (SNSP, %) (O'Sullivan et al., 2014, p. 5) and defiend as follows:

$$\mathrm{SNSP}[\%] = \frac{P_{\mathrm{VRE}} + P_{\mathrm{HVDC(import)}}}{P_{\mathrm{load}} + P_{\mathrm{HVDC(export)}}} * 100 \qquad (4\text{-}1)$$

Where P_{VRE} is capacity of variable renewable energy, P_{load} is system demand and P_{HVDC} is electricity import and export via high-voltage direct current lines to or from other synchronous areas.

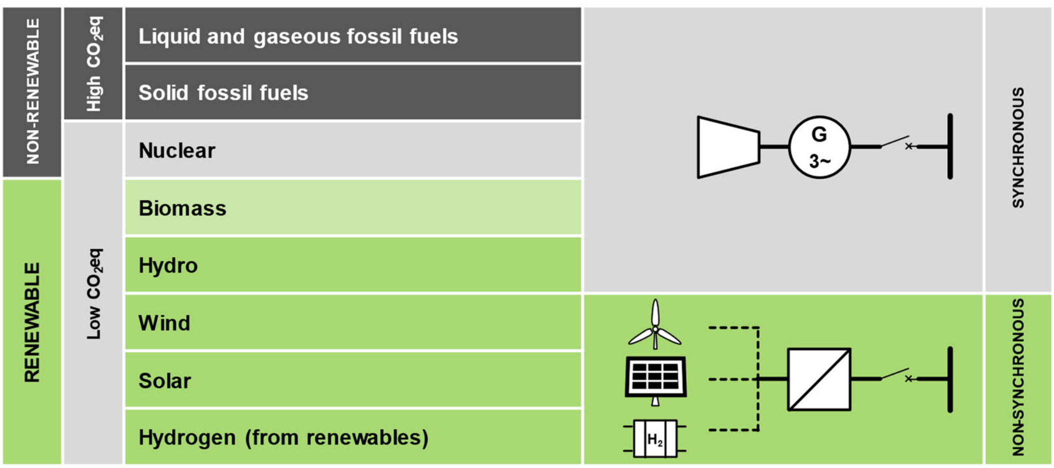

Figure 10. Power generation technologies and their properties

4.1 Inertia and RoCoF

The inertia of individual generator can be described with inertia constant *H* and calculated with Equation 4-2. Inertia constant *H* equals the time in seconds the stored kinetic energy in rotating parts of the generator can supply the rated power of a generator (Ørum et al., 2018b, p. 8).

$$H = \frac{1}{2}\frac{J\omega_{\mathrm{n}}^2}{S_{\mathrm{n}}}\,[\mathrm{s}] \tag{4-2}$$

where J is the moment of inertia of a generating set [kgm^2], ω_n is the rated mechanical angular velocity of the rotor [rad/s] and S_n is the apparent power of the generator [VA].

Typical inertia constant varies between different power generation technologies as the rotational speed and mass per megawatt varies. Typical values for different production types are collected from various sources and listed with calculated averages in Table 2.

Table 2. Production types and their typical inertia constants. Values in *italic* are from mentioned sources.

Production type	*(Ensto-e, 2020, p. 24)*	*(Tielens et al., 2018, p. 61)*	*(Persson & Chen, 2018, p. 1)*			*(Ørum et al., 2018b, p. 52)*	***Average***
			SE	NO	FI		
Nuclear	*5,9*	*6,0*	*6,2*		*6,6*	*6,3*	**6,2**
Thermal	3,9	3,8	*2,9*	*2,5*	*4,4*	*4,0*	**3,6**
Fossil Brown coal/Lignite	*3,8*	*3,9*					
Fossil Hard coal	*4,2*	*4,1*					
Fossil Gas	*4,2*	*4,3*					
Fossil Coal-derived gas	*4,2*						
Fossil Oil	*4,3*	*4,3*					
Fossil Oil shale	*4,3*						
Fossil Peat	*3,8*	*3,7*					
Waste	*3,8*						
Other	*3,8*						
Biomass	*3,3*	*3,3*					
Geothermal	*3,5*						
Solar-thermal & other renewable	*3,5*	*3,0*					
Hydro	3,3	3,6	*4,5*	*2,9*	*2,8*	2,5	**3,3**
Hydro Run-of-river and poundage	*2,7*	*2,7*				*3,0*	
Hydro Water Reservoir	*3,7*	*4,0*				*3,0*	
Hydro Pumped Storage	*3,5*	*4,0*				*3,0*	
Hydro small scale						*1,0*	
Wind	0,0		*0,0*	*0,0*	*0,0*	*0,0*	**0,0**

For a synchronous area the overall kinetic energy and inertia is the sum of kinetic energy of individual generators and their inertia constants. Ørum et al (2018b, pp. 8-9) calculated the system inertia constant H_{sys} with Equation 4-3 and the stored kinetic energy in system's rotating masses in megawatt seconds [MWs] with Equation 4-4.

$$H_{\mathrm{sys}} = \frac{\sum_{i=1}^{\mathrm{N}} S_{\mathrm{n}i} H_i}{S_{\mathrm{n,sys}}} \tag{4-3}$$

$$E_{\mathrm{k},sys} = S_{\mathrm{n},sys} H_{\mathrm{sys}} = \sum_{i=1}^{\mathrm{N}} S_{\mathrm{n}i}\, H_i [\mathrm{MWs}] \tag{4-4}$$

where $S_{n,sys}$ is the sum of apparent power of individual generators [VA] in the system, S_{ni} and H_i are the apparent power [VA] and inertia constants [s] of individual generating sets.

Higher the spinning mass and kinetic energy coupled to system, higher the inertia time constant H is and system ability to resist frequency changes. With increasing level of system non-synchronous penetration (SNSP), the system inertia is reducing and resulting higher and faster frequency variations during contingency events, if nothing else changes to mitigate the impact of reducing inertia.

Rate of Change of Frequency (RoCoF) is a term used to describe the speed the frequency varies. Initial RoCoF is the instantaneous RoCoF immediately after a disconnection of either a generator or load from system before system frequency controls activate (Entso-e, 2017, p. 4). Ørum et al (2018a, p. 123) use Equation 4-5 to calculate the initial RoCoF after a fault.

$$\frac{\mathrm{d}\Delta f}{\mathrm{d}t} = \frac{f_{\mathrm{n}}}{2 S_{\mathrm{n,sys}} H_{\mathrm{sys}}} \Delta P = \frac{f_{\mathrm{n}}}{2} \frac{\Delta P}{E_{\mathrm{k},sys}} \tag{4-5}$$

where f_n is the system nominal frequency, ΔP is the size of disturbance and $E_{k,sys}$ is the kinetic energy stored in the system. $S_{n,sys}$, H_{sys} and $E_{k,sys}$ are the overall values in the power system after disconnection of a generator or load (Entso-e, 2017, p. 4).

The initial RoCoF is therefore impacted by the system inertia H and size of power imbalance ΔP in relation to overall generation capacity $S_{n,sys}$ after a fault. Equation 4-5 can be also written as:

$$\frac{\mathrm{d}\Delta f}{\mathrm{d}t} = \frac{f_\mathrm{n}}{2H_\mathrm{sys}} \frac{\Delta P}{S_\mathrm{n,sys}} \tag{4-6}$$

Using Equation 4-6 the relation between initial RoCoF and size of a fault for various inertia constants have been plotted in a graph in Figure 11.

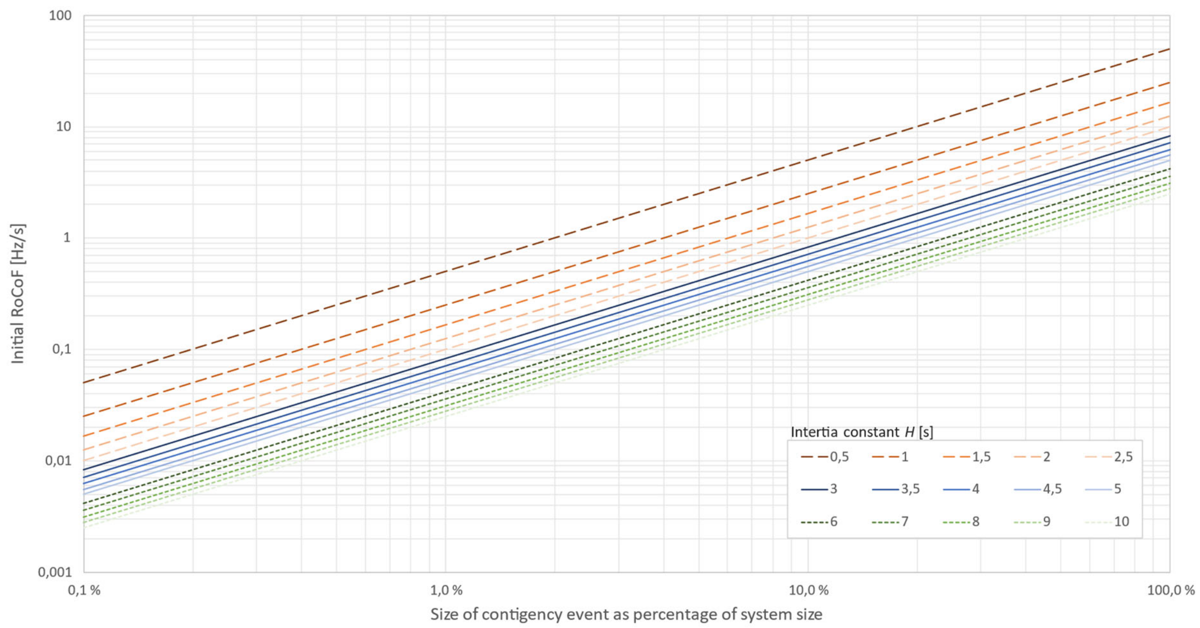

Figure 11. Initial RoCoF as function of intertia constant *H* and size of contingency event

The amount of system inertia is not constant and depends on the amount of connected load and generation and generation mix in the system. It varies according weather, time of day and there's also seasonal variation (Ørum et al., 2018b, pp. 33-35). In some regions the seasonal variation is larger, mainly due to climate. Also, other factors influencing people, businesses and industry can impact the demand in the electrical system, such as Covid-19 in first half of 2020 (Buechler et al., 2022, p. 4). Since the system inertia and size of reference incident in relation to overall generation varies, the amount and type of acquired reserves may vary according the changes in the power system (Entso-e, 2019, p. 19).

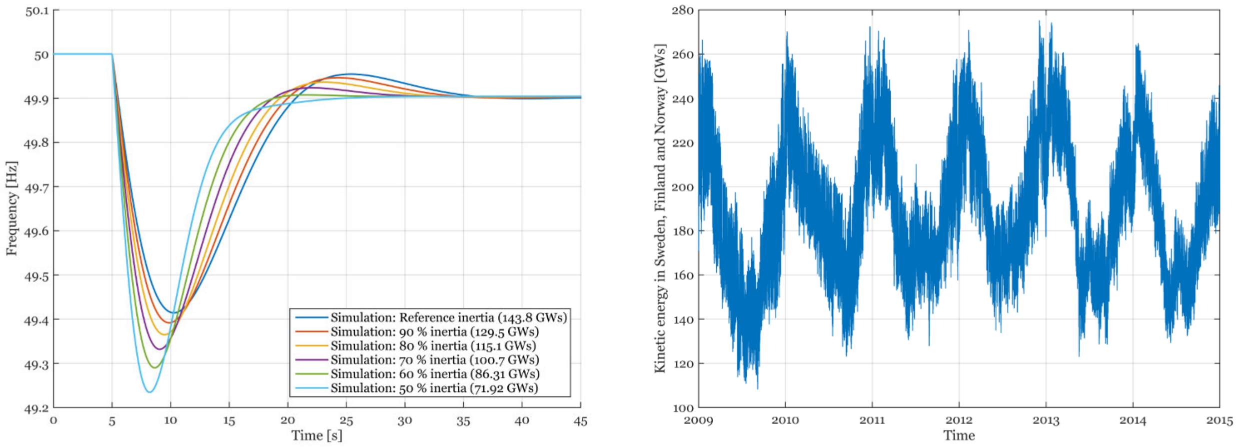

Figure 12. Simulation results for varying inertia (left) and estimated kinetic energy in Sweden, Finland and Norway (right) (Ørum et al., 2018b, pp. 35, 48)

Graphs in Figure 13 are based on net electricity generation monthly data from Eurostat (2021) database. The data provided by Eurostat for each country is allocated to corresponding synchronous area and the data for Denmark is equally split between CE and Nordic synchronous areas. Finally, the provided monthly net generation energy in gigawatt-hours [GWh] is divided by number or hours in each month to get the average monthly generation power in gigawatts [GW].

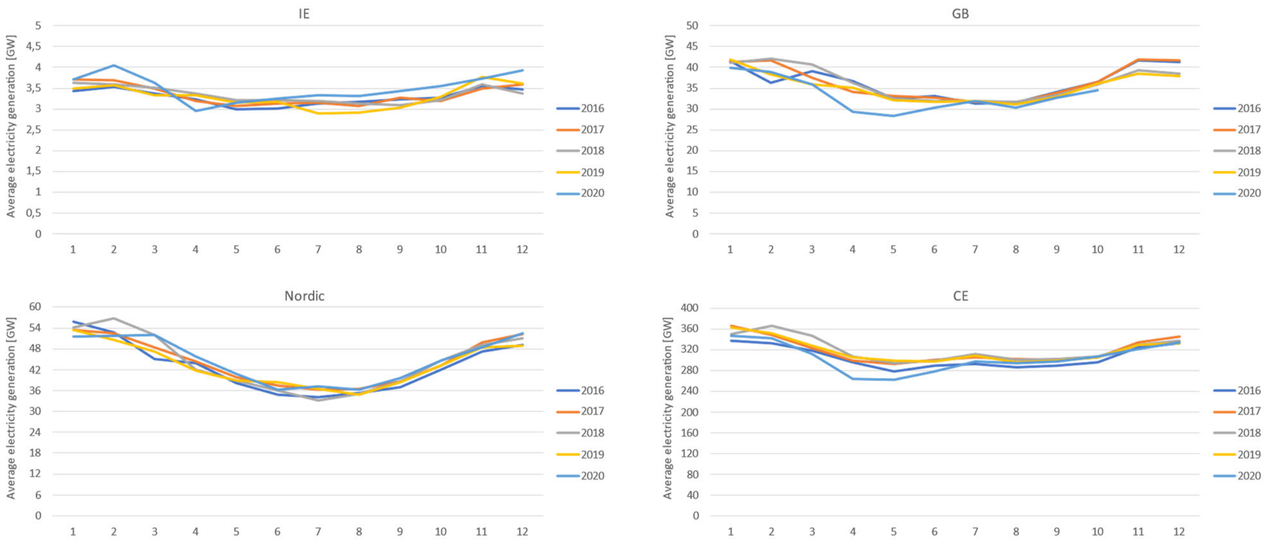

Figure 13. Average generation capacity for Ireland, Great Britain, Nordic and Continental Europe in each month between 2016 and 2020

4.2 Contingency events

As the size of a power system (synchronous area) decreases, typically the size of a maximum fault in relation to system size increases. As such, the frequency variations following a fault are typically faster in smaller power systems and vice versa. Figure 14 has examples of frequency disturbances caused by a contingency event in different size synchronous areas. All graphs are created from numerical data from mentioned sources and are using same timescale on x-axis. The frequency disturbance starts at 10 seconds in each.

Graph a) presents the system frequency in Ireland on 8 May 2019. Frequency data is provided by Enel X and recorded at Eaton global headquarters in Dublin, where an Eaton UPS is used to participate in DS3 market and to provide FFR. The shown frequency disturbance was caused by disconnection of Whitegate power plant and 351 MW of power generation from the grid (EirGrid & SONI, 2020a, p. 53). The power generation (and consumption) in Ireland during the incident (10:14) was about 3,75 GW based on data available from Entso-e (n.d.). As such, the contingency event caused nearly 10% instantaneous reduction in system's generation capacity.

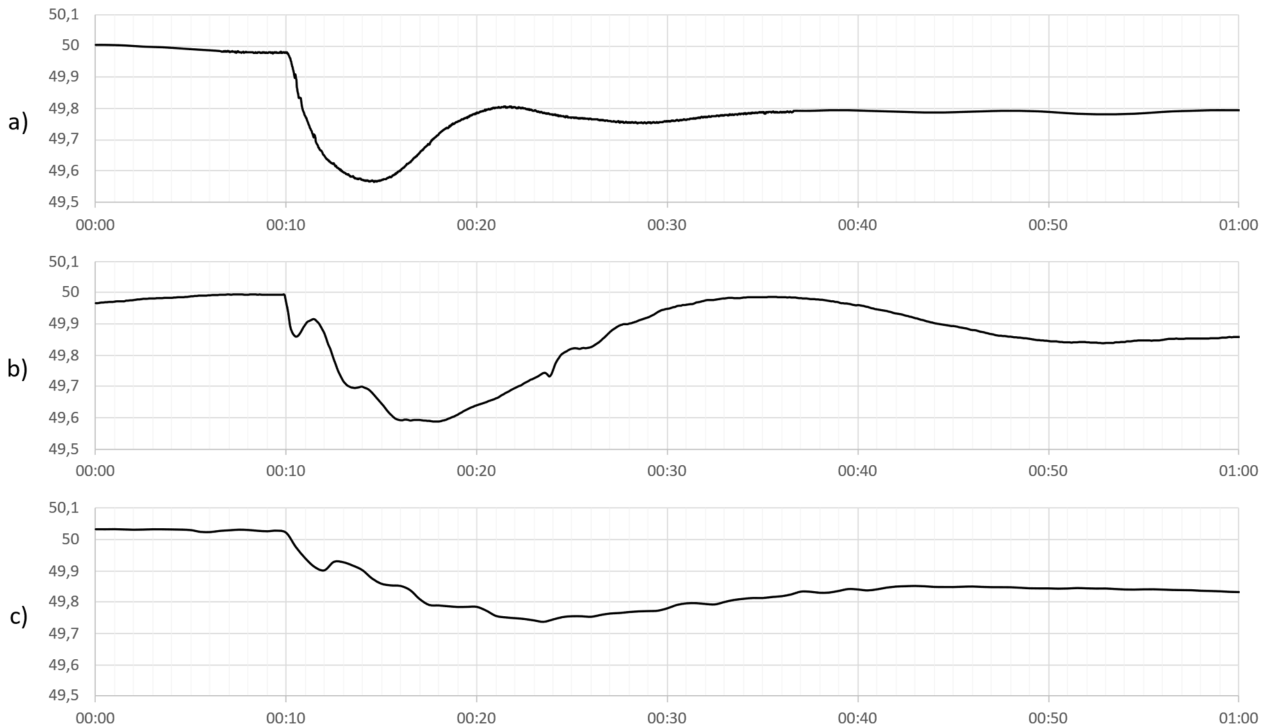

Figure 14. Major frequency disturbances in a) Irish, b) Nordic and c) Continental Europe synchronous areas. Frequency on y-axis [Hz] and time on x-axis [mm:ss]

Graph b) presents the system frequency in Finland on 18 July 2018 when Olkiluoto 2 nuclear power plant and 876 MW of nuclear power generation was disconnected from the grid (Fingrid, n.d.; Pahkin, 2018). According data available on Svenska Kraftnät (n.d.) website, total power generation in Nordics just before the incident was 38 GW and the contingency event therefore equals to 2,3% loss of production capacity.

Graph c) presents the system frequency in Continental Europe synchronous area during the system separation on 9 January 2021. Multiple high voltage transmission lines between North-West and South-East regions disconnected after cascading faults over approximately 30 seconds, removing 5800 MW of power export from South-East to North-West and resulting 1,8% power imbalance in North-West region (Entso-e, 2021, pp. 41, 70). The frequency data is provided by Technical University of Denmark and is measured at Central Jutland, Denmark (Thingvad et al., 2021).

In these 3 examples the frequency deviation was arrested by activation of FCR and dispatchable loads through Low Frequency Demand Disconnection (LFDD) scheme (Entso-e, 2021, pp. 56-57). In cases where primary reserves are not sufficient to arrest the frequency deviation, system operators have other means such as LFDD to contain the frequency and avoid system wide power outages. Exact implementation of LFDD scheme and settings for Under Frequency Load Shedding (UFLS) relays depend on system characteristics and are vary between synchronous areas. General requirements are given in Commission Regulation 'establishing a network code on electricity emergency and restoration' (Regulation 2017/2196) by European Parliament and Council of.

Figure 15 shows a frequency disturbance in UK after disconnection of 1131 MW of power generation from the grid following a lightning strike to a transmission circuit, and additional loss of 350 MW due to RoCoF protection. The total lost generation capacity of 1481 MW was above dimensioning incident of 1000 MW and the frequency fell to 49,1 Hz where it was arrested by activated frequency response. Shortly after the frequency was stabilized at 49,2 Hz, additional 210 MW of generation tripped and the frequency started to decrease again until LFDD activated at 48,8 Hz and disconnected approximately 5% (1 GW) of the demand and about 1,1 million customers (NationalgridESO, 2019, pp. 4-5, 15). The historical frequency data is available on nationalgridESO data portal (NationalgridESO, n.d.).

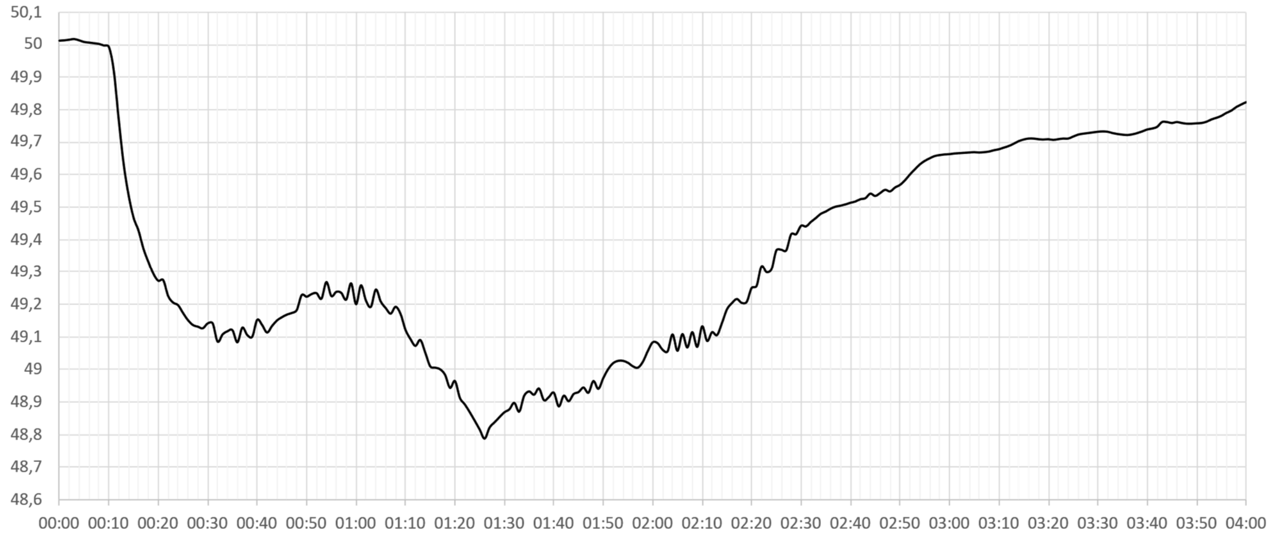

Figure 15. Major frequency disturbance in UK on 9 August 2019. Frequency on y-axis [Hz] and time on x-axis [mm:ss]

There are differences on how quickly the frequency nadir is reached and what is the initial RoCoF following the fault. In a small system with less kinetic energy and bigger relative size of faults, frequency changes faster requiring faster activating frequency containment reserves. In a very large synchronous area, the RoCoF is moderate even in worst case scenarios. Therefore, new fast acting reserves, such as FFR, are taken into use in smaller systems like Ireland, Nordics and GB. Also, reduction in system inertia due to displacement of traditional generation with non-synchronous generation will make the frequency containment even more challenging as the frequency deviations will be larger and faster (Ørum et al., 2018b, pp. 45-48; Tielens et al., 2018, p. 25).

4.3 Mitigation of low system inertia

As the system inertia is decreasing due to increasing penetration of non-synchronous generation and modernization of industrial motor loads, the frequency variations caused by the system imbalances will be faster and higher (Ørum et al., 2018a, p. 7). Therefore, it will be more challenging for system operators to contain the frequency within defined limits as there’s less time for primary reserves to react (Hong et al., 2019, p. 1696).

Ørum et al (2018a, pp. 101-116) studied different mitigation methods to offset the impact of low system inertia in Nordic synchronous area to limit the maximum frequency deviation by 0,1 Hz after a dimensioning incident of 1450 MW in a system having 80 GWs of kinetic energy. The studied methods were use of rotating mass to increase system inertia, reduction of dimensioning incident and use of active power from various sources to contain the frequency. A summary of evaluated mitigation method effectiveness as required volume in power units is presented in Table 3. When a total required value for 20 GWs or 0,1 Hz nadir improvement was not provided, it was calculated and rounded to closest 100 MW or MVA based on provided capacity and kinetic energy values for each technology. Required traditional generation to add 20 GWs into system when curtailing non-synchronous units is achieved using average inertia constant from thermal and hydro power plants in Table 2.

Table 3. Low inertia mitigation methods (Ørum et al 2018a, 101 – 116). Values provided in source document are in *italic*.

Mitigation method	*Capacity*	*E_{kin}* [GWs]	*Volume needed for* 20 GWs *or* 0,1 Hz *nadir improvement*	*Units*	*Notes*
Rotating mass					
Synchronous condensers	*1 475*	*2,8*	10 400	MVA	
Gas turbines	*1 233*	*6,2*	4 000	MVA	
Hydro (Pelton) turbines	*5 500*	*18*	6 100	MW	
Pumped hydro	*1 000*	*3*	6 700	MW	
Curtail non-synchronous units		*20*	5 800	MVA	20 GWs from traditional generation
Dimensioning incident					
Reduce output of DI (Nuclear)			*120*	MW	
Reduce import via HVDC			*121*	MW	
Active power					
EPC (HVDC link)			*155*	MW	min. 100 MW/s ramp rate
Extra FCR-D			*340*	MW	
Synthetic Inertia		*20*	*337,5*	MW	peak power at df/dt = -0,404 Hz/s
FFR proportional			*148*	MW	peak power at Δf = -1,072 Hz
FFR static			*130*	MW	duration of 10 s
Reduce load (incl. hydro pumps)			*130*	MW	

When comparing different mitigation methods, it is obvious that increasing the system inertia by using rotating mass and traditional generation technologies requires much higher capacity than reducing the dimensioning incident or using FFR and dispatchable loads. As such, the effectiveness of latter methods to mitigate the impacts of low inertia to system frequency, and to improve system reliability during large disturbances, is much higher.

Also, the availability of rotating mass from various sources to provide inertia was limited in the Nordic power system, except for use of Pelton turbines (Ørum et al., 2018a, p. 116). The associated operating cost relating to use of gas turbines is high with estimated value of 3500 €/GWs,h, resulting 70000 €/h cost to mitigate lack of 20 GWs in the system.

Similarly limiting the dimensioning incident (DI), output of largest generating units that is typically a nuclear power plant, has a cost. Curtailing the Sizewell nuclear power plant by 600 MW in UK between May 7 and September 24, 2020 was estimated to cost between 53 and 73 million pounds (GBP) for the system operator (NationalgridESO, 2020; Twidale, 2020). Calculated cost per hour is approximately 26 – 36 £/MW,h. In the Nordic synchronous area, output of Oskarshamn 3 nuclear power station has been reduced during low inertia conditions. In summer 2018 the output power of Oskarshamn 3 was reduced by 100 MW during 3 weekends, and the redispatch cost was a result of 49 kr/MWh compensation for lost revenue in energy sales, 50000 kr fixed fee per activation, and cost of purchasing substitute power from regulating market. Overall cost for reducing DI by 100 MW for 166 hours was estimated to be 988000 € (Tosatto et al., 2020, pp. 484-491). This equals 60 €/MW,h. Assuming 120 MW is needed to mitigate lack of 20 GWs in the system, the overall cost to would be in range 3800 – 7200 €/h based on these two examples.

When curtailing non-synchronous sources, such as import via HVDC link, wind or PV, the missing energy needs to be replaced by enough traditional generation to provide required additional inertia. As shown in Table 3, the required quantities are high. Besides the operational cost, replacing low carbon sources with traditional fossil-based generation increases the emissions in the system. Using HVDC link for Emergency Power Control (EPC) can be cost efficient and the required quantities are similar to reduction of DI according Tosatto et al (2020, pp. 491-492) and Ørum et al (2018a, p. 116).

4.3.1 Fast Frequency Response

FFR is a promising mitigation measure for low inertia situations as several technologies can provide fast active power response. This is evaluated to happen with low socio-economic costs, either by using disconnection of loads or fast response from power semiconductor converters. Also, FFR is estimated to be more cost-efficient mitigation method than reduction of dimensioning incident (Entso-e, 2019, p. 6).

Required quantities, presented in Table 3, to mitigate low inertia with FFR are similar as reduction of DI and considerably less than solutions based on rotating mass. The effectiveness of FFR to contain frequency nadir depends on reaction speed and ramp-up rate. Short response time and fast ramp, or step-like response, improves the frequency control and therefore converter-based solutions are better fit to provide FFR than traditional synchronous generators which cannot ramp up their output fast enough (Hong et al., 2019, pp. 1699-1702).

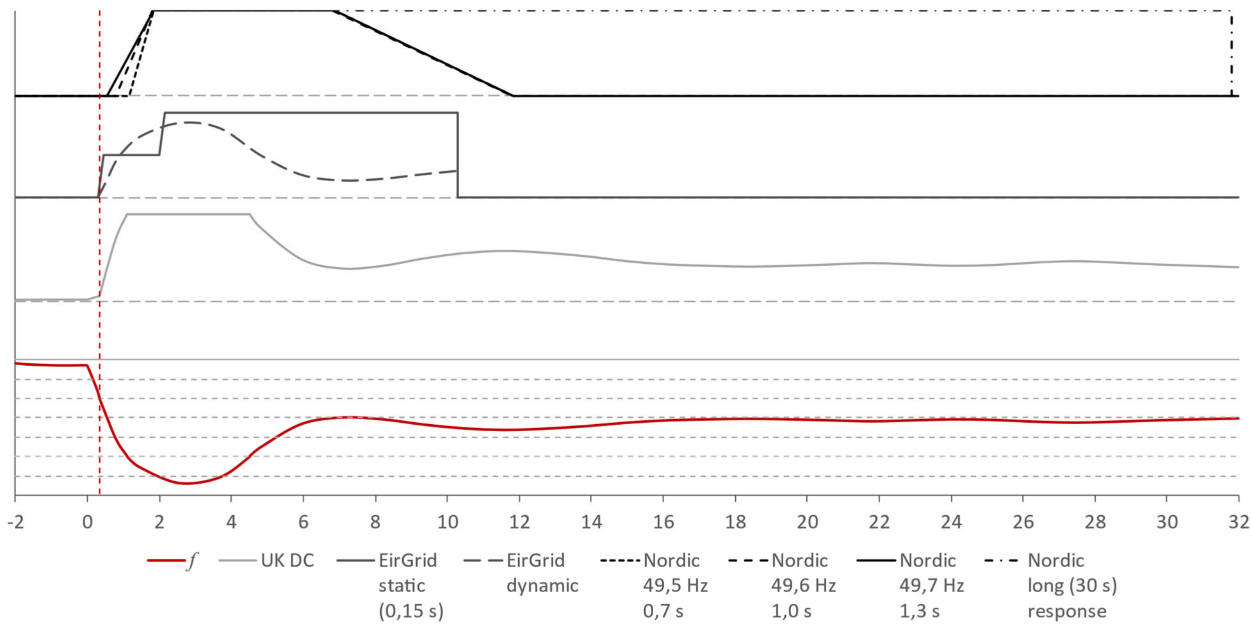

Figure 16. Examples of fast frequency response in Nordics, Ireland and UK

The FFR response in Nordics is static, and the activation time in Nordic market depends on the trigger frequency. The three options are shown in Figure 16. The expected active power response needs to be provided within specified time and response is sustained either for 5 s and followed by a ramp reducing response maximum 20% per second, or response is sustained for 30 s and can be switched off without a ramp (Entso-e, 2019, p. 8).

In Ireland the response is either static or dynamic. Static response anyhow needs to have at least two discrete steps with separate trigger frequencies, and the dynamic response is proportional to frequency deviation. Trigger frequency range is between 49,8 and 49,3 Hz for static response and 49,985 and 49,8 Hz for dynamic response. Activation time must be less than 2 s, but not faster than 0,15 s, and the expected active power response needs to be delivered within specified time. Response duration is limited to 10 s from beginning of the frequency event. Faster response is rewarded with higher market value that is calculated using specific scalars (EirGrid & SONI, 2017, pp. 19-24).

In UK the new fast acting reserve is Dynamic Containment (DC). FFR shall not be mixed with Firm Frequency Response, that has been previously used in UK ancillary services market. DC is using ±15 mHz dead-band frequency and the response is symmetrical, providing up (DCL) and down (DCH) regulation. Response is dynamic i.e., proportional to frequency deviation consisting two regulation ranges. Between dead-band frequency and 0,2 Hz deviation, the active power response increases linearly from 0 to 5 %. Between 0,2 and 0,5 Hz deviation, the response grows linearly from 5 to 100 %. Full response shall be delivered within 1 s, but not faster than 0,5 s and maximum response shall be sustained for 15 minutes when needed (NationalgridESO, 2021, pp. 4, 11).

4.3.2 FFR markets

Since the assets used for FFR are additional to the system, they do not use existing generation capacity from the system that would need to be substituted through regulating market. The associated cost comes from purchasing cost via ancillary services market and varies between markets. Table 4 summarizes FFR prices, volumes and costs in Nordic, UK and Irish markets. Table is generated from the hourly market data from Fingrid (n.d.), Svenska Kraftnät (2022) and Energinet (n.d.), and a summary market report for Norwegian market 2021 (Statnett, 2021). Numbers for UK are based on market data from nationalgridESO (n.d.) and the gate procurement summary reports available on EirGrid Web site (n.d.) are used for Irish market. Since 16 September 2021, dynamic containment in UK has been purchased in 4 hour EFA blocks separately for DC-L and DC-H. Only numbers for up regulation (DC-L) are shown in Table 4.

Table 4. Average and total price, volume and cost of Nordic and Irish FFR markets, and UK dynamic containment (DC-L).

	Hours acquired	*Price* (€/MW,h)		*Volume* (MW,h)		*Cost / h* (€)	
		Average, acq. hours	***Total***	*Average, acq. hours*	***Total***	*Average, acq. hours*	***Total***
Fingrid [1]	1 408	40,42	**56 918**	18,44	**25 958**	837	**1 177 904**
Svenska Kraftnät [2]	1 335	132,33	**176 666**	27,68	**36 953**	5 896	**7 871 068**
Energinet [3]	1 568	303,52	**475 926**	7,11	**11 149**	2 721	**4 269 640**
Statnett Profil [4]	1 581	11,74	**18 561**	51,18	**80 916**	601	**2 900 000**
Statnett Flex [5]	400	51,89	**20 755**	88,50	**35 400**	4 592	
Nordic FFR total					**190 375**		**16 218 611**
nationalgridESO (DCL) [6]	4 688	19,10	**90 322 (168 775)**	487,80	**2 306 180 (4 309 330)**	10 240	**48 006 887 (89 705 702)**
EirGrid (DS3 FFR) [7]	8 760	4,45	**38 982**	713,76	**6 252 576**	3 174	**27 800 000**

1) 5 April to 31 October 2021; 2) 27 April to 25 October 2021; 3) 26 April to 31 October 2021; 4) 17 May to 12 September 2021; 5) 3 May to 3 October 2021; 6) 15 September 2021 to 31 March 2022; 7) October 2020 to September 2021

Hours acquired indicates the number of hours each TSO purchased fast response from the market i.e. hours when volume was > 0. *Price* (€/MW,h) is the market price in Euros per megawatt for an hour, *Volume* (MW,h) is the amount of capacity in megawatts purchased from the market in bidding slot and *Cost / h* indicates cost for per hour that is the product of price and volume. Averages are calculated for the hours when FFR was acquired from the market. *Total* field represents the total cumulative sum for specified time period.

Based on the used market reports and data, the estimated cost for FFR in Nordic synchronous area was 85,19 €/MW,h. Value is calculated by dividing the overall annual cost by overall FFR volume acquired by the transmission system operators during sample period. Equivalent cost in UK was 20,82 €/MW,h and 4,45 €/MW,h in Ireland. FFR and DC are mainly acquired through hourly market, and the volumes and prices vary from hour to hour according actual need and availability of reserves. For comparison with other mitigation methods and to get average cost of mitigating low inertia with fast frequency response, the overall cost was divided by number of overall hours in the sample. Number of hours in the sample were 4099 for Nordics (average of all system operators), 4728 for UK and 8760 for Ireland. The resulting average overall costs per hour for FFR are 3957 €/h in Nordics, 10154 €/h in UK and 3174 €/h in Ireland. There is a large difference in costs, but also the acquired volumes are very different in the markets. In the Nordics FFR is acquired when inertia is low, with varying volumes according the need, while in UK and Ireland FFR (DC) is purchased constantly in higher volumes.

The hourly variation in FFR prices and volumes in the Nordic can be seen in Figure 17. The chart is based on the hourly market data (Fingrid, n.d.; Svenska Kraftnät, 2022; Energinet, n.d.). Average cost per hour for a system operator is not same as average price since highest prices occur on same hours as highest volumes. Most capacity is acquired when prices are high, pushing the cost up for a TSO. In the Nordics, the FFR volumes are highest during weekends and night-time when system inertia is low. FFR in the Nordics is used mainly between April and October (Fingrid, n.d.).

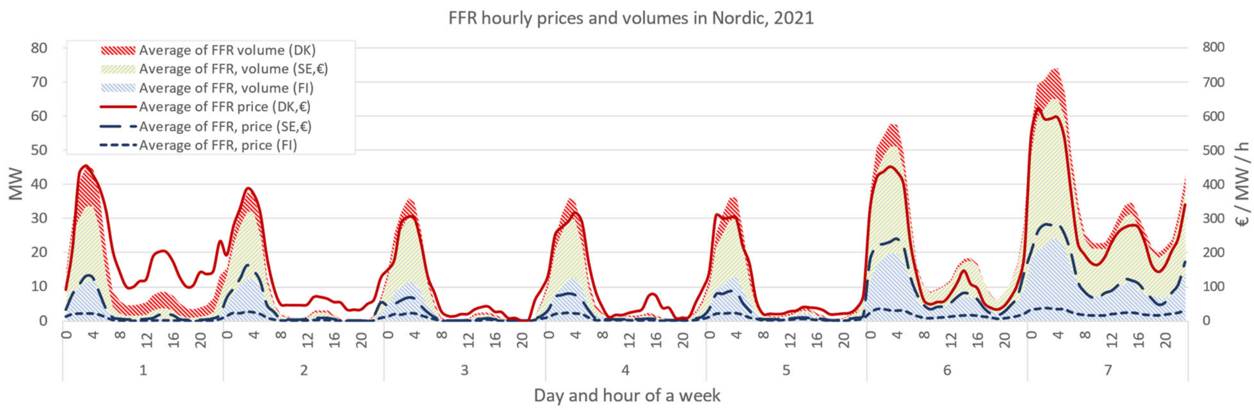

Figure 17. Variation in Nordic FFR prices and volumes according day and hour of a week

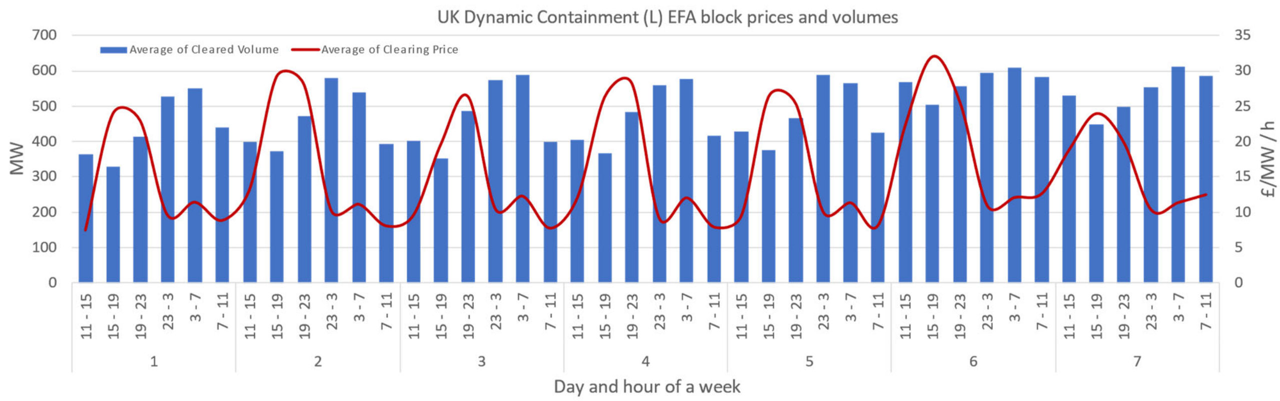

Figure 18. Hourly (4 h EFA blocks) variation in UK DC-L prices and volumes

UK market price and volume variation throughout a week between September 2021 and March 2022 is shown in Figure 18. Prices are highest in the evening time and highest volumes occur with lowest prices. This is different from Nordics, probably impacted by availability of reserve units to provide DC in the market as higher volumes in offers are resulting lower clearing price.

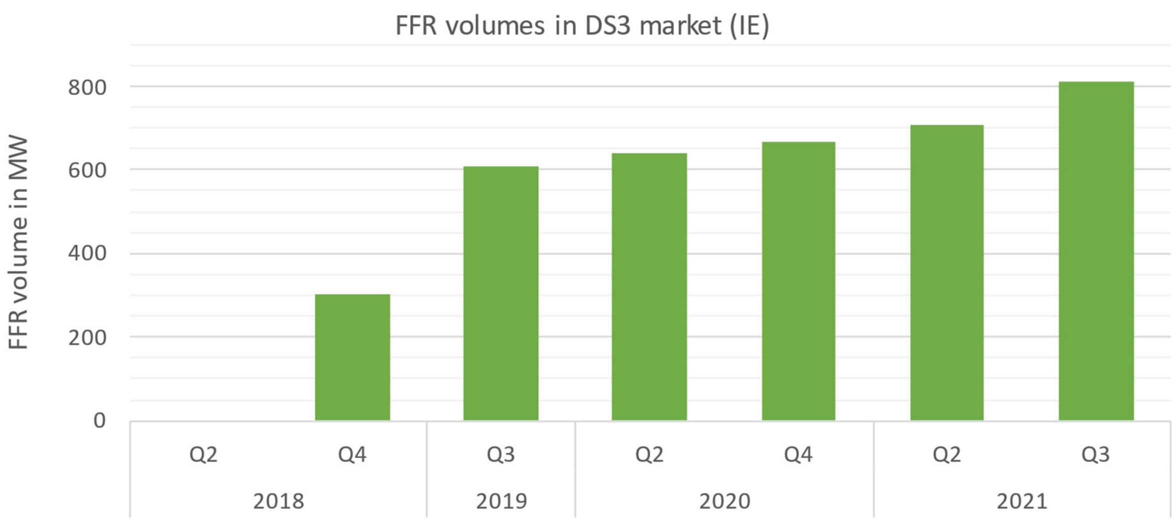

Figure 19. Irish DS3 market FFR volumes

Ireland has different bidding mechanism and EirGrid is using “gates” for tender process where service providers are bidding for a longer period. There is no hourly market or data, even the payments are calculated on hourly basis using scarcity scalars according non-synchronous system penetration (SNSP%). Instead, gate procurement summary reports with contracted reserve volumes and forecasted expenditures are published after each gate on EirGrid (n.d.) Web site. The costs and volumes of FFR in Irish DS3 market are presented in Figure 19 and Table 4.

5 Data centres and UPS as a source of fast frequency response

The growth of digital services is creating a demand to build more data processing facilities, known as data centres, that is contributing to growing energy use of ICT sector (Hintemann & Hinterholzer, 2019, p. 5; Andrae, 2019, p. 8). The estimates on global energy use of data centres by IEA is 200 – 250 TWh per year, about one percent of global electricity consumption (IEA, 2021). The annual energy consumption of data centres within Europe has been also studied, but these show some level of uncertainty in the results (Koronen et al., 2019, p. 3).

The growth of global electricity consumption of selected large data centre companies is presented in Figure 20. The graph is using the annual electricity usage data published by companies in their annual environmental and sustainability reports for given years. These reports are available for download at corporate websites and not listed here individually. The annual growth rate is between 20 and 40%, highest among companies providing video streaming and social media.

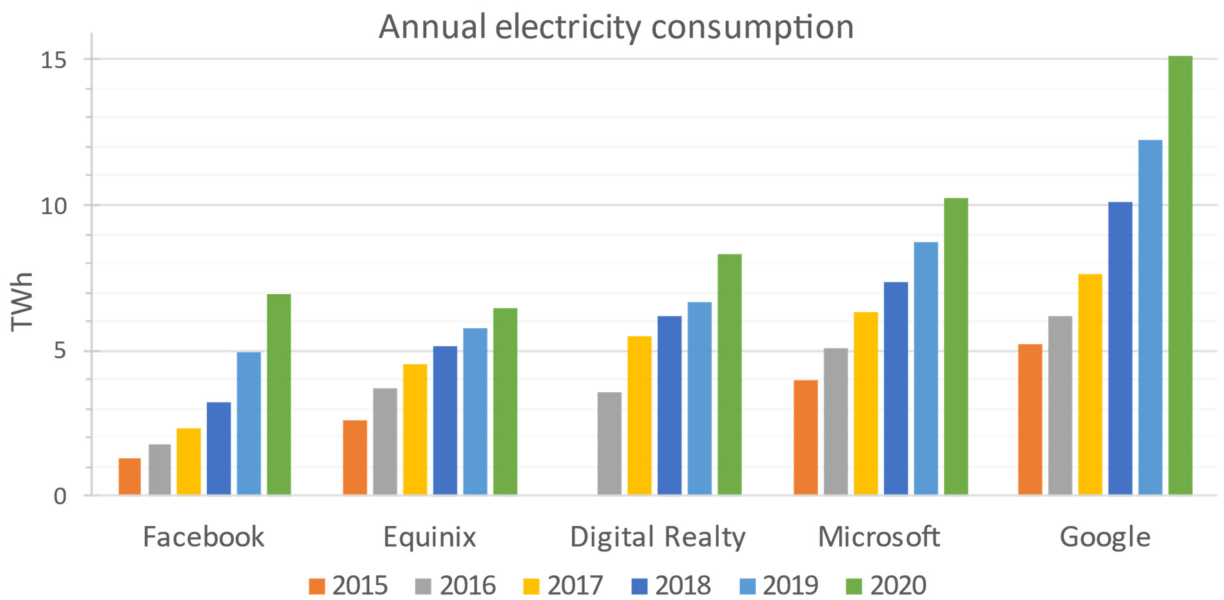

Figure 20. Growth of global annual electricity consumption of large data centre companies

Information technology and data traffic is mostly used for our entertainment. During past years the growth of video services has been dominating the growth of data traffic, while online gaming share of data traffic has started to increase. The annual growth rate of global data traffic is estimated to be 26% and video streaming will contribute even 70 to 80% of all internet traffic (Barnett et al., 2018, p. 67). According latest Global Internet Phenomena Report, the four categories having largest share of internet traffic are video streaming (53,72%), social media (23,69%), Web browsing (9,86%) and on-line gaming (5,67%) (Sandvine, 2022, p. 13).

As the energy usage is expected to multiply in future, it will be more difficult to reduce the net greenhouse gas (GHG) emissions globally, unless this growth is based on use of renewable energy (Andrae & Edler, 2015, p. 133). As part of corporate social responsibility actions, large data centre operators aim to be more sustainable and become carbon neutral, or even carbon negative (Smith, 2020), by using renewable energy for their operations. Data centre industry is also demanding higher use of renewable energy sources for electricity generation by local utilities (Greenpeace, 2019), while some of them are already largest corporate purchasers of renewable energy (IEA, 2021).

A grid-interactive data centre can support higher penetration of renewable energy and reduce the emissions of the electrical system. It can reduce carbon footprint of others by providing system services, a concept called as carbon handprint (Pajula et al., 2021). For example, a grid-interactive UPS can reduce need for additional purpose-built reserve systems, replacing spinning reserves and supporting higher penetration of renewable energy to replace sources based on fossil fuels. All this helps to reduce emissions outside the data centre, either embodied in built assets or resulting from operation of generators based on fossil fuels.

A grid-interactive UPS and data centre is already reality. Microsoft is suggesting using data centre UPS units and batteries for grid support and balancing to further help penetration of renewable energy sources to power system (Paananen & Nasr, 2021). In the Nordic, a data centre operator in Sweden has been using their UPS systems to provide system services and to participate in frequency regulation market (Eaton, 2021). Also, recently another data centre started to provide FFR in Finnish market (Fortum, 2022).

Large data centres are often connected to high voltage grid, due to high power demand, in a location selected to have good grid reliability and firm connections. As such, they are well suited to provide grid-support for the transmission system. Those are also very power dense facilities, with lots of power infrastructure built-in that can be potentially leveraged for grid support.

Technical suitability of modern uninterruptible power supplies and data centre electrical infrastructure for the purpose has been studied in pilot projects conducted with transmission system operators (Alaperä et al., 2019; Svenska Kraftnät, 2018). Also, a recent study about Irish synchronous area and data centres as a provider of fast frequency response supports these findings (Al Kez et al., 2021, pp. 19-20). The economic benefits of leveraging data centre's electrical infrastructure for ancillary services have been studied by Alaperä et al (2019, p. 5065) and this supports the conclusions made by Nursimulu (2016, p. 11).

5.1 Demand side response and ancillary services

Today residential, commercial, and industrial consumers can provide flexibility for the electrical system by adjusting their consumption according the needs of the grid. This can happen through demand (side) response or ancillary services such as frequency regulation and it is useful to understand the general differences between the two. Demand response is performed inside consumer facilities, or 'behind-the-meter', and is done to generate savings by smarter use of energy and leveraging market price signals for the purpose. It can also include remotely activated dispatchable loads, consumer allowing the control of their loads against incentives from network operator (U.S. DoE, n.d.).

Categorising something as demand response or ancillary service depends on definition. U.S. Department of Energy (n.d.) defines demand response as:

> *"Methods of engaging customers in demand response efforts include offering time-based rates such as time-of-use pricing, critical peak pricing, variable peak pricing, real time pricing, and critical peak rebates. It also includes direct load control programs which provide the ability for power companies to cycle air conditioners and water heaters on and off during periods of peak demand in exchange for a financial incentive and lower electric bills."*

Ancillary services in other hand are provided to system operators through market participation. Provider is offering services with a selected price and has an obligation to deliver promised services when his bid is accepted. When talking about frequency regulation, a service provider is getting compensated for market participation and generating revenue regardless of actual usage (activation) of reserve units, especially when talking about reserves used against disturbances (FFR, FCR-D). These differences are summarized in Figure 21.

There is some overlapping between the two for example when talking about the dispatchable loads that can be used for both, demand response and ancillary services. Here the allocation to correct bucket depends on activation mechanism, is it voluntary and self-motivated action to create savings, or is it activated remotely or automatically to provide services to balance the system e.g., frequency regulation, etc. Demand response is a preventative method to avoid system congestion while ancillary services and frequency regulation are a reactive method to correct existing imbalances in the system and to regulate the system frequency in real-time.

Type	Demand Response			Ancillary Services	
Purpose	Proactive / Preventative			Reactive / Corrective	
Motivation	Savings in energy cost, tariffs and tax		Incentives	Revenue generation	
Control of use	User Control - €/kWh, €/kW		Remote control	Market obligation, following remote signal or grid frequency	
Application	Time-of-Use	Peak shaving	Direct Load Control, Dispatchable loads		Balancing services, frequency regulation
Compensation	Creating savings as used		Paid for market participation / availability		

Figure 21. Differences between demand response and ancillary (system) services (Paananen J. , 2019a, p. 7)

5.2 UPS technology

As defined in a standard IEC 62040-3:2021, an Uninterruptible Power System or Supply (UPS) is a combination of converters, switches, and energy storage devices, and it is used to protect critical loads by providing continuity of power in case of a power failure (IEC, 2021, p. 11). The standard refers to and is covering static UPS technology based on power semiconductor converters. These UPS equipment can have several topologies, such as off-line, line-interactive, and double conversion (IEC, 2021, pp. 64-66). Simplified schematic diagrams of these topologies are shown in Figure 22.

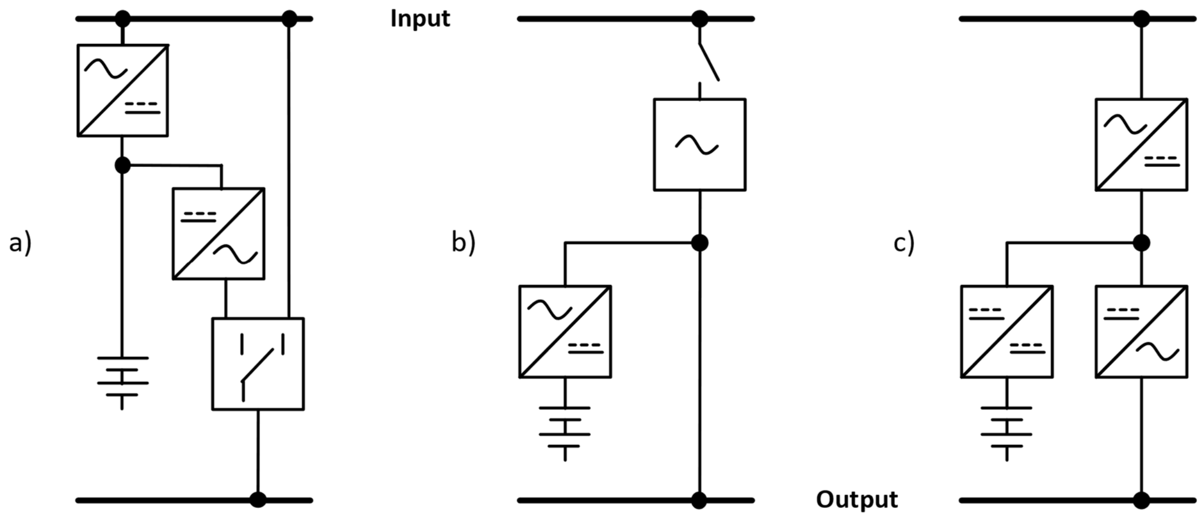

Figure 22. Static UPS topologies: a) off-line, b) line-interactive, and c) double conversion

Double conversion topology, that is rectifying the incoming mains voltage and creating new clean sinusoidal voltage for the output and critical loads, is providing best protection for the loads and is the most used topology in the data centres. It also represents the topology used by UPS products with recent development to provide grid support and perform energy management.

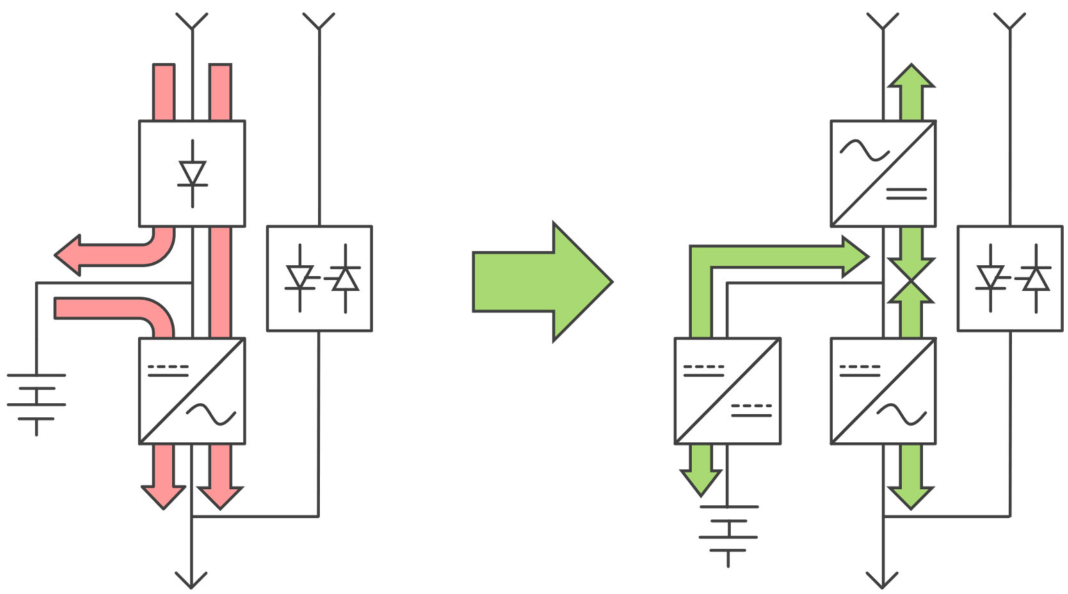

Figure 23. Uni-directional and bidirectional power flow through a UPS (Paananen et al., 2017, p. 5)

Technological development during past 20 years has resulted higher efficiency and reduced losses, higher power density and smaller footprint, and improved input power quality due to reduced rectifier current harmonics and improved power factor. Besides these improvements, modern modular UPS units can have additional operating modes to improve efficiencies even further, especially at low load levels. Introduction of bi-directional rectifier into a UPS has enabled more flexibility to manage stored energy in batteries, that can be leveraged for various power and energy management purposes as well as to provide system services for grid operators (Paananen et al., 2017, pp. 2-6).

The power flow and main parts of a double conversion UPS are shown in Figure 24 on the left (a). In normal operation mode (green) the rectifier (1) draws power from mains to feed required energy for the inverter (2), needed to provide conditioned power for the loads, and additional power for battery (5) charging (green). The power is supplied to loads through two conversions hence the name double conversion topology. The dc-dc converter (3) is charging and discharging batteries and converting the voltage in dc-link to suitable level for the batteries and vice versa. Static bypass switch (4) is used to power the load during overload and fault conditions (red dotted line), when the inverter is unable to feed and protect loads. During a mains failure (orange) the batteries are discharged to provide uninterrupted power for inverter and loads.

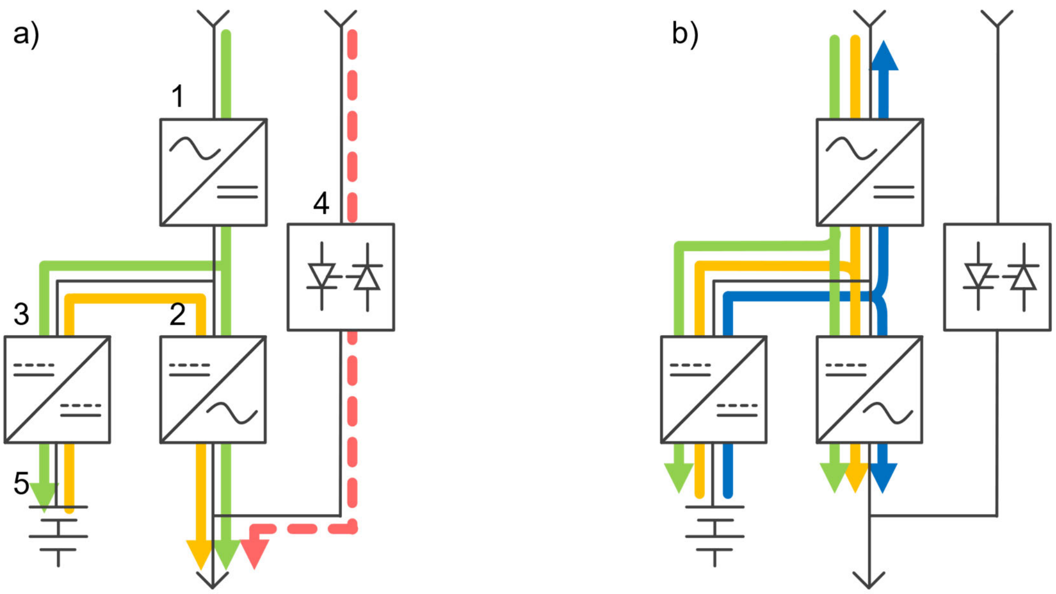

Figure 24. a) double conversion UPS main components and power flows, b) grid-interactive UPS energy management

5.3 Grid-interactive UPS

A grid-interactive UPS is leveraging its capabilities to manage the stored energy and power i.e., flow of energy, to interact with local electrical system and grid and to provide additional benefits to asset holder, for example a data centre. With correct control algorithms the stored energy in batteries can be seamlessly controlled in parallel with mains by power sharing with a rectifier to support the loads, or even feeding energy back to grid with a bidirectional rectifier, which enables to use the batteries independent of UPS load level as maximum discharge power is not limited by UPS load (Paananen & Nasr, 2021, p. 3). Figure 24 on the right (b) shows the flow of power when performing energy management. UPS can increase the demand and store energy by charging batteries while supporting load (green). UPS can decrease demand by discharging the batteries and sharing power between batteries and mains (orange). And finally, UPS can feed energy to back to its mains supplies while supporting the load (blue), enabling load independent use of batteries. This opens possibilities for various applications such as local energy management, demand response, investment deferral and to provide ancillary services such as frequency regulation.

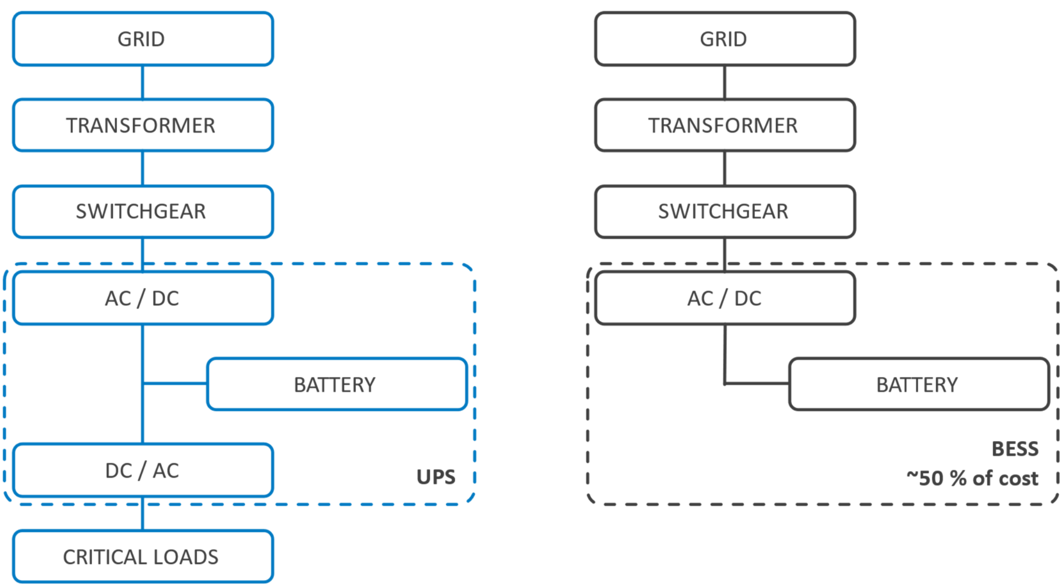

Figure 25. Similarities of a data centre UPS system and BESS, modified from (Paananen & Nasr, 2021, p. 4)

Previous studies about data centre loads and batteries (UPS) for demand response and frequency regulation have focused on applications with high number of discharge cycles using energy storage lithium-ion batteries (Wierman et al., 2014; Cupelli et al., 2018) and optimization of battery usage from financial aspects (Shi et al., 2018; Zhang & Nasr, 2021). Technical and economic feasibility of data centre UPS systems with lead-acid batteries for primary regulation was studied by Alaperä, Honkapuro & Paananen (2018) showing promising results. A business case analysis comparing a data centre and purpose-built Battery Energy Storage System (BESS) use case showed great savings, when leveraging existing power infrastructure of a data centre for frequency regulation (Alaperä et al., 2019, pp. 5065-5066). Besides reducing the cost, leveraging existing assets also reduces use of natural resources and embodied carbon.

To perform frequency regulation, a grid-interactive UPS could measure the frequency and provide a power response autonomously or follow an external signal from site or aggregation controller. Latter is the more common method even the autonomous frequency regulation was tested with good results in Svenska Kraftnät pilot (Svenska Kraftnät, 2018, p. 23). Using UPS internal measurements and algorithms eliminates the possible delays in external communication links but creating the power response in local site aggregation controller based on local frequency sensing and sending it to a UPS can still typically meet response time requirements for FFR.

In a typical grid-interactive UPS system you have a UPS itself and the local site controller that is generating the power reference for a UPS based on measured frequency. It also stores grid measurement data such as voltages, currents, frequency and power, and provides a link to aggregation platform often referred as a virtual power plant (VPP). The aggregation controller can perform measurements itself or read the data from a digital power meter. In some markets outside Europe the response power for frequency regulation is not based on local frequency measurement but instead the primary reserves are following a regulation signal created and sent by transmission system operator (PJM, 2022, pp. 37-40). In those cases, site controller acts as interface between TSO system and local assets.

Similarly, when performing demand response and local energy management, UPS is typically connected to a local energy management controller providing the power reference. Some grid-interactive UPS products, like ones from Eaton, also support activation of power response with a dry-contact i.e., a relay signal, and UPS performs the regulation autonomously. This allows to create simplistic energy management, demand response and frequency regulation schemes.

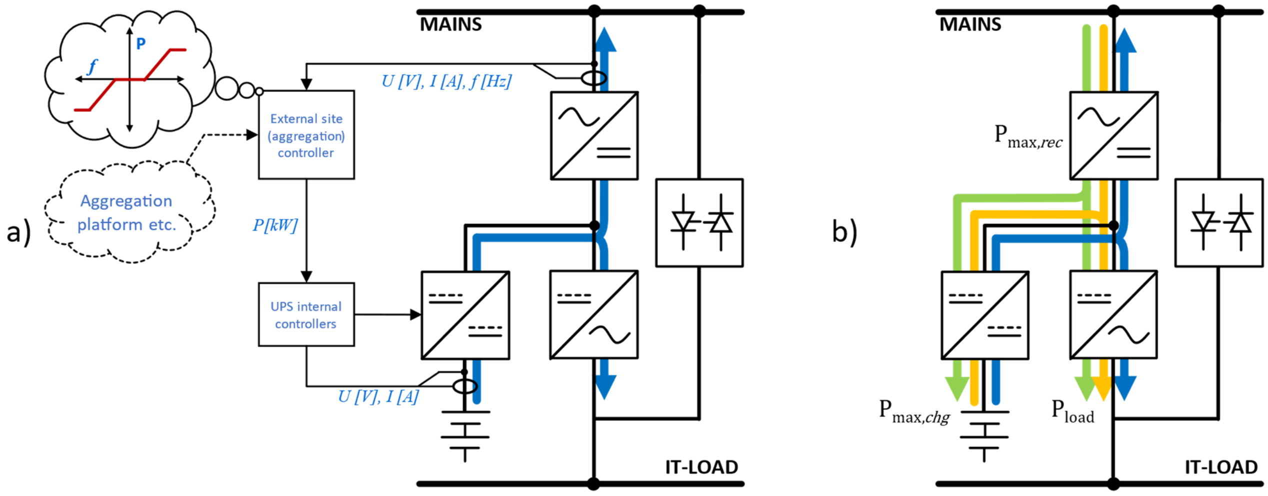

Figure 26. a) Grid-interactive UPS and control principle modified from (Paananen J. , 2019b, p. 12) and b) power flow in down-regulation (green), up-regulation with no export (orange), up-regulation with power export (blue)

A grid-interactive UPS is feeding the loads connected to its output while performing the grid support and the required energy is drawn from mains with a rectifier. When increasing demand from the grid by charging batteries to perform down-regulation (regulating frequency down), the additional power is added on top of the power drawn from mains by rectifier to support the load. The rectifier has a limit for maximum power it can continuously draw from mains, and total power used for load support and down-regulation cannot exceed this. Also, depending on a UPS model, the battery charger can have limits for maximum current defining limits for maximum response for down-regulation. The general principle for down-regulation power limit is as follows (see also Figure 26b):

$$P_{\mathrm{down}} \leq \min\{\mathrm{a},\mathrm{b}\} \qquad \mathrm{a} = P_{\mathrm{max,rec}} - P_{\mathrm{load}} \qquad \mathrm{b} = P_{\mathrm{max,chg}} \tag{5-1}$$

When performing up-regulation (regulating frequency up) by reducing the demand from grid by discharging the batteries, the response is limited by nominal power of a UPS or by actual amount of load connected to a UPS if power export to mains input is not desired.

$$P_{\mathrm{up}} \leq P_{\mathrm{N,UPS}} \qquad P_{\mathrm{up(no\ exp)}} \leq P_{\mathrm{load}} \tag{5-2}$$

This means that a power response capability of a grid-interactive UPS is asymmetrical; increasing the demand is limited by rectifier (and upstream power distribution infrastructure) maximum power (current) and is impacted by load level of a UPS, while reducing demand is not limited below UPS nominal rating, unless exporting power upstream is not allowed. This has importance when estimating the size of power response a UPS can provide, especially for down-regulation.

The use of UPS technology for frequency regulation (FCR-D) was tested in Sweden by Svenska Kraftnät (2018) with good results. In Norway, Stattnet piloted fast frequency response (FFR) for the Nordic synchronous area by leveraging a data centre UPS units in a live data centre. This pilot also confirmed the suitability of UPS technology for the frequency regulation (Alaperä et al., 2019, pp. 3-5). UPS response to frequency deviations during the pilots are shown in Figure 27. In the Swedish pilot for FCR-D the UPS was set to provide a power response (red) when frequency (blue) fell below 49,9 Hz with a proportional response, and UPS response followed the incoming mains frequency accurately. In the Norwegian pilot the UPS units were set to activate at 49,67 Hz using a slight ramp and providing full response at 49,6 Hz. Plot in Figure 27 (right) is using data logged from Eaton UPS units during pilot and provided by an aggregator. Frequency data for Finland (FI) is from Fingrid (n.d.) Open Data portal. Based on the pilot, UPS units can provide a fast, and load independent, response once trigger frequency is exceeded. Data from UPS units was logged with 1 second sample rate therefore having limited resolution for the fast frequency event.

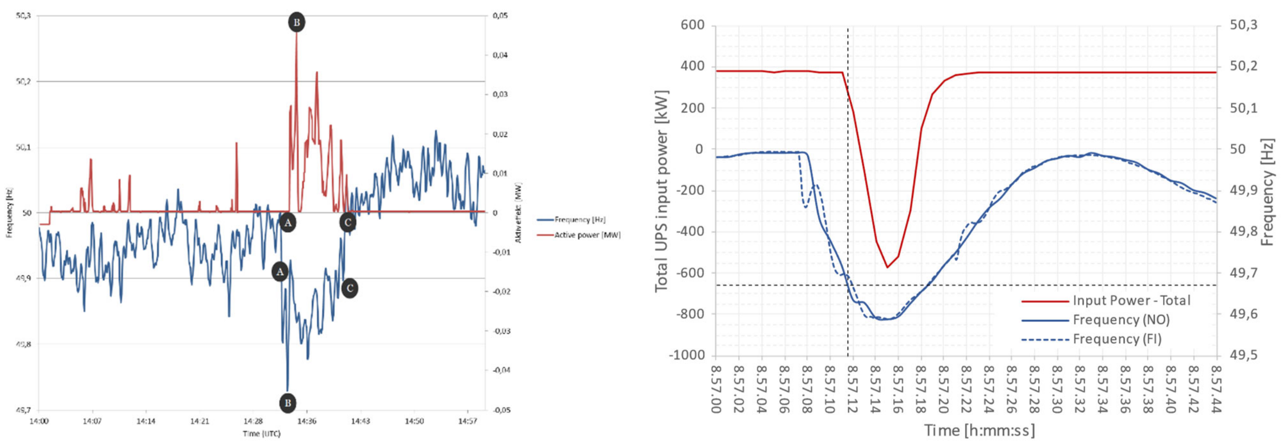

Figure 27. UPS technology pilots for frequency regulation: SvK pilot for FCR-D on the left (Svenska Kraftnät, 2018, p. 23), Statnett pilot for Nordic FFR on the right

5.4 Data centre power distribution topologies

Data centres can use different power distribution topologies, and these vary according companies and size of a data centre. Selected topology can have significant impact on how much redundant power infrastructure is installed in the system, and to number and capacity of overall UPS units.

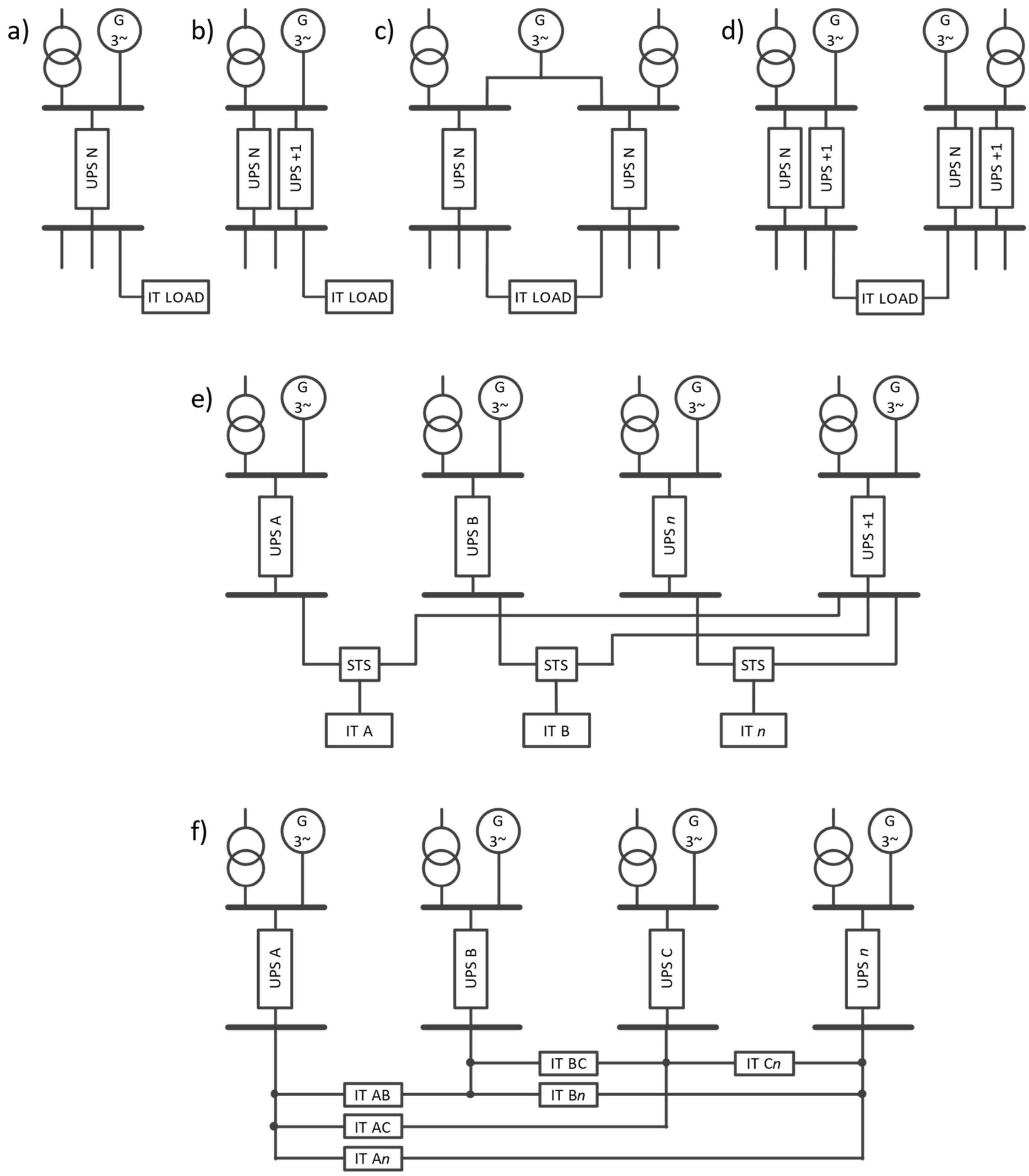

Figure 28. Data centre power distribution topologies: a) single path no redundancy (Tier I), b) single path redundant (Tier II), c) dual path 2N (Tier III), d) dual path 2(N+1) (Tier IV), e) block redundant and f) distributed redundant

Tier classification has been traditionally used to categorise the topologies; a higher Tier provides higher availability of power for the critical IT systems. Actual Tier classification depends on design of whole data centre infrastructure including back-up generators, cooling, power distribution and UPS systems (Stansberry, 2014). The aim here is not to explain details of Tier classification or power distribution topologies, but to show different options in high level focusing on the potential impact to UPS content in the data centre and to maximum expected load level on a UPS. As the number of streams (paths) increases, the amount of overhead in the infrastructure reduces and average loading of a UPS increases.

The required overall capacity of UPS units for each case showed in Figure 28 can be calculated using following equations, assuming equal size of load in each stream:

$$\sum_{i=1}^{\mathrm{n}} P_{\mathrm{UPS}i} \geq \sum_{j=1}^{\mathrm{n}} P_{\mathrm{IT}j} \times k \tag{5-3}$$

Single non-redundant power stream (Tier I). P_{UPSi} is the power rating of an individual UPS unit in a power stream, P_{ITi} is power rating of individual IT load and k is a design margin multiplier.

$$\sum_{i=1}^{\mathrm{n}-1} P_{\mathrm{UPS}i} \geq \sum_{j=1}^{\mathrm{n}} P_{\mathrm{IT}j} \times k \tag{5-4}$$

Single redundant power stream (Tier II). P_{UPSi} is the power rating of an individual UPS unit in a power stream, P_{ITi} is power rating of individual IT load and k is a design margin multiplier.

$$2\left(\sum_{i=1}^{\mathrm{n}} P_{\mathrm{UPS}i} \geq \sum_{j=1}^{\mathrm{n}} P_{\mathrm{IT}j} \times k\right) \tag{5-5}$$

Dual non-redundant power stream (Tier III). P_{UPSi} is the power rating of an individual UPS unit in a power stream, P_{ITi} is power rating of individual IT load and k is a design margin multiplier.

$$2\left(\sum_{i=1}^{\mathrm{n}-1} P_{\mathrm{UPS}i} \geq \sum_{j=1}^{\mathrm{n}} P_{\mathrm{IT}j} \times k\right) \tag{5-6}$$

Dual redundant power stream (Tier IV). P_{UPSi} is the power rating of an individual UPS unit in a power stream, P_{ITi} is power rating of individual IT load and k is a design margin multiplier.

$$(N+1)\left(\sum_{i=1}^{n} P_{\mathrm{UPS}i} \geq \sum_{j=1}^{n} P_{\mathrm{IT}j} \times k\right) \tag{5-7}$$

Block redundant system. P_{UPSi} is the power rating of an individual UPS unit in a power stream, P_{ITi} is power rating of individual IT load is a stream, k is a design margin multiplier and N denotes the number of active streams.

$$N\left(\sum_{i=1}^{n} P_{\mathrm{UPS}i} \geq \frac{\sum_{j=1}^{n} P_{\mathrm{IT}j} \times k}{N-1}\right) \tag{5-8}$$

Distributed redundant system. P_{UPSi} is the power rating of an individual UPS unit in a power stream, P_{ITi} is power rating of individual IT loads shared between all power streams, k is a design margin multiplier and N denotes the number of overall power streams.

The maximum loading of active power streams and overall UPS system capacity in relation to overall IT load for block and distributed redundant systems is shown in Figure 29. As the number of streams grows the overhead in power infrastructure reduces, but gains become marginal after 4 or 5 streams while adding system complexity, especially in distributed redundant configuration. Note: Distributed redundant with 2 streams is same as dual path non-redundant system (Tier III).

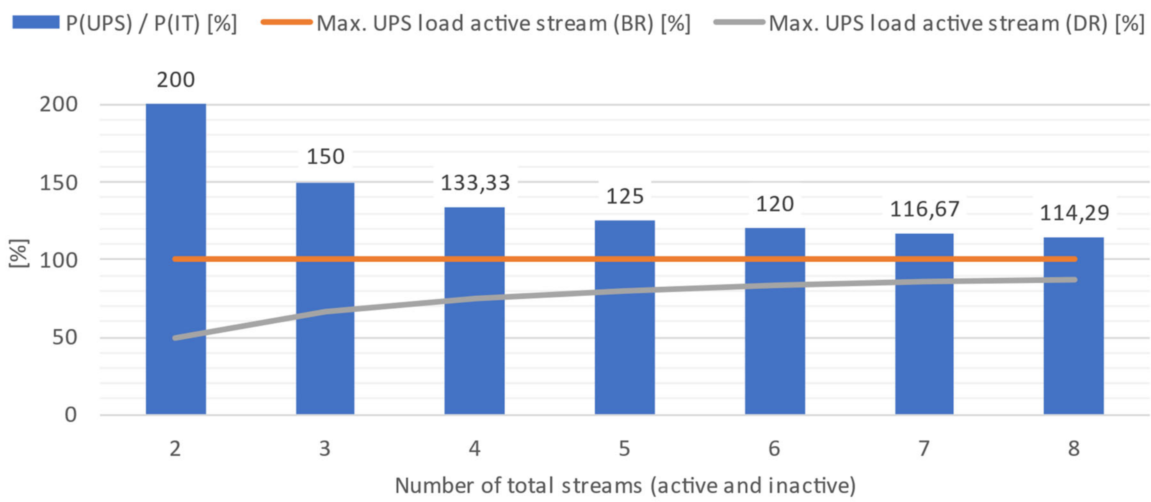

Figure 29. Amount of UPS capacity as percentage of IT load and maximum loading of active UPS systems in block and distributed redundant configurations

5.5 Battery technologies

The grid-interactive UPS is leveraging stored energy in batteries to perform demand response or to frequency regulation to support the grid, that will cause additional discharge cycles and usage of the batteries. Impact to battery degradation depends on battery type and on the number and depth of discharge (DoD) cycles. Traditionally, Valve Regulated Lead Acid (VRLA) batteries have been the most common type in the data centres, but lithium-ion batteries have become more common and preferred solution during past years due to expected longer lifetime and higher power and energy density. The basic characteristics and differences between lead acid and lithium-ion batteries are explained here for battery types used in a data centre application.

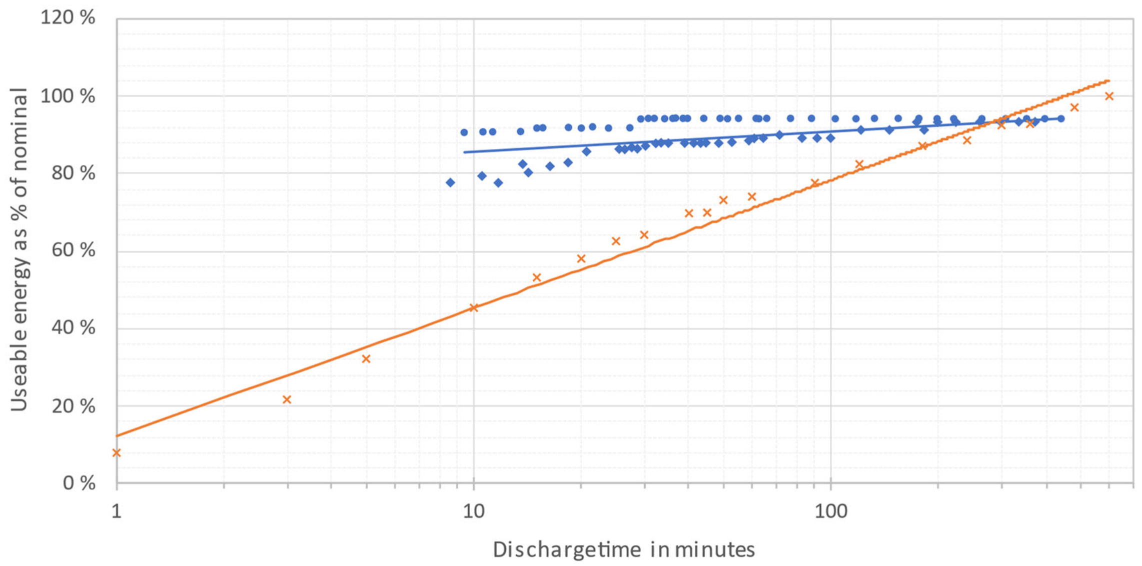

Figure 30. Useable energy from VRLA and lithium power battery (6C) vs discharge time. Lead acid in orange and lithium in blue

Ragone plot is used often to compare different energy storage technologies and their power and energy densities (Kularatna & Gunawardane, 2021, pp. 62-63). Typically, comparison is done at cell level for core technology, but it can be also useful to illustrate differences between complete systems. Here the power and energy densities of complete battery systems installed in open battery stands (lead acid) or cabinets (Li-ion) are plotted for a comparison in Figure 31. The Ragone plot has both, gravimetric and volumetric densities.

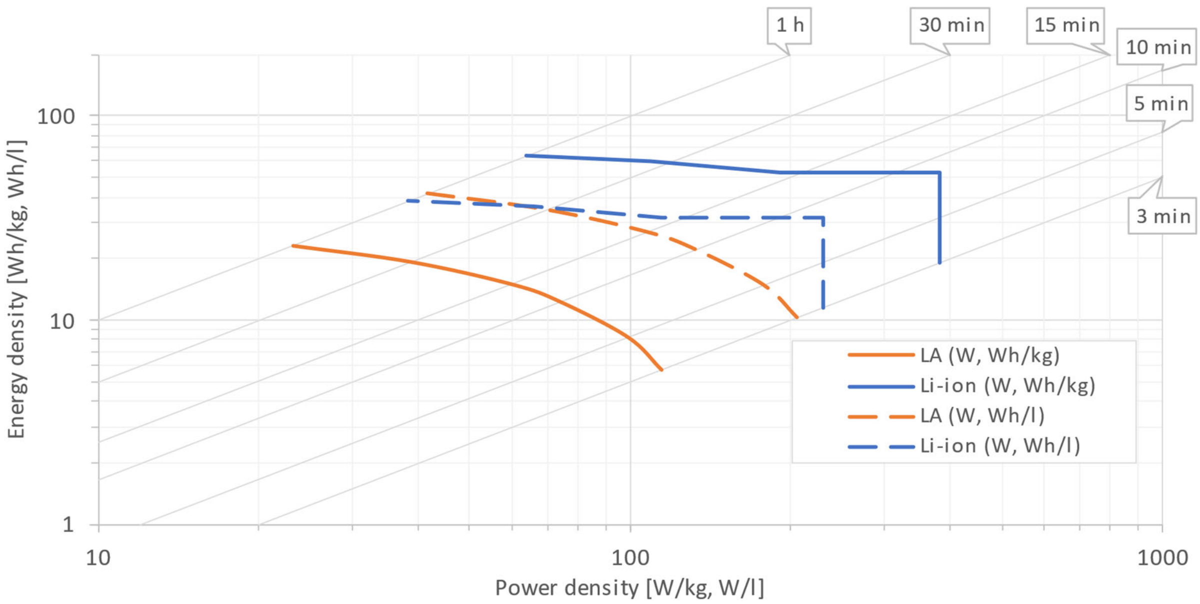

Figure 31. Volumetric and gravimetric power and energy densities of complete lead acid (LA) and lithium-ion battery systems in Ragone plot for a back-up time range from 3 minutes to 1 hour

Example curves in the Ragone plot are based on constant power discharge performance data published by lead acid battery manufacturers for selected products (3 pcs) having data available for below 5 minutes discharge rates. Lithium-ion high discharge rate power battery curves are based on confidential performance data received from the supplier for a commonly used lithium-ion battery. Lithium-ion solution is using weight and volume of a complete cabinet while lead acid solution is using average volume, weight, and performance of selected battery blocks. Weight of open battery stand is added to complete lead acid battery solution, as well as adding 60% volume on top of battery blocks to get overall space required by a battery stand with batteries.

5.5.1 Lithium-ion

Lithium batteries are not all the same and they have variability on their characteristics depending on cell chemistry and other factors (IRENA, 2017, pp. 124-125). For example, the physical design of modules and racks can impact the thermal behaviour of the overall battery system and maximum charge and discharge currents. It is important to acknowledge that general information about lithium-ion batteries and chemistries in research articles and other publications is focusing on battery energy storage (BES) and electrical vehicle (EV) batteries, while typically in a data centre and UPS application the used batteries are a different type. BES and EV applications are using 'energy cells' with low discharge rate, while UPS application is using 'power cells' designed for a high discharge rate. Challenge is the limited availability of the research data about power batteries, that would reflect the true limitations and capabilities instead of marketing materials that are often 'picking the raisins from the bun'. Here the focus is on the power batteries and products typically used in the data centre UPS applications.

Table 5. Comparison of lithium-ion energy storage and UPS application power batteries with high discharge rate (6C – 10C). Power battery data for a complete assembled cabinet

		(IRENA, 2017, pp. 124-125)		*Li-ion power battery, internal data*
Technology		*LFP*	*NMC/LMO*	*Various*
Calendar life (yrs.)	Reference	12	12	14
Cycle-life (eq. full-cycles)	Worst	1 000	500	48
	Reference	2 500	2 000	77
	Best	10000	4000	5 000*
Energy density (Wh/l)	Worst	200	200	21,9
	Best	620	735	48,9
Power density (W/l)	Worst	100	100	192,2
	Best	10000	10000	402,7
Energy installation cost (€/kWh)	Worst	773 €	773 €	1 265 €
	Reference	526 €	386 €	636 €
	Best	184 €	184 €	559 €

The lithium power batteries used for UPS application differ a lot from batteries used BES and EV, especially the cycle life differs from typical values presented in public due to battery system design, warranty terms and conditions, and load profiles. The values for UPS application are summarised into a single line in Table 5, based on confidential information received from battery suppliers. As such the details of individual products cannot be shown. This information is based on limited number of products and in-depth information from battery supplier engineering wasn't available for all products. In that case data from public information was used and marked with asterisk. These lithium power batteries present some of the typical lithium-ion products in the market used for data centre UPS applications and are having high discharge rate ranging approximately from 6C to 10C for practical back-up times. The data is here used to highlight the fundamental differences between general information about lithium-ion batteries and real-life power products when delivering actual systems to customers. Besides the limited number of products, when designing a complete system for a specific customer and application, system size, load profile and other conditions can have considerable impact to project specific values. As such, caution should be used if referring to any stated values that are used here only for indicative purposes to demonstrate the differences between BES and Li-ion power battery products.

Useable energy, power and energy density

The discharge rate has only a limited impact to useable energy from lithium-ion battery. Even with short back-up times and using maximum continuous discharge rate, major portion of the energy can be drained from the battery as indicated in the Figure 30. The data is created from constant power discharge performance tables received from two lithium-ion power battery suppliers.

The power and energy densities are higher than with lead acid batteries, especially with typical runtimes in UPS applications. Anyhow, with very short back-up times, lithium-ion batteries need to be sized according maximum discharge power and rate, forcing to oversize the system beyond needed energy. Consequently, the solution will be physically larger, and power and energy density can be similar to optimized lead acid solution as can be seen in Figure 31.

Cycle-life

Lithium batteries are known for high cycle-life, as indicated for example in the report from IRENA (2017, pp. 124-125). The evaluated batteries are typically aimed for BES or EV applications. The lithium-ion power batteries commonly used in UPS applications are very different in this respect. Data in Table 5 shows this very well. Generally, used lithium chemistries allow high number of discharge cycles, whereas the battery systems designed for high power discharge applications do not. High power discharge is causing more heat generation in batteries accelerating the aging. The UPS batteries are also charged differently and kept at 100% State of Charge (SoC), potentially accelerating battery aging. Also, as the battery lifetime is impacted by discharge cycles and DoD, battery suppliers may state cycle limits in relation to product performance warranty. Exceeding the maximum cycle count and used energy (throughput) can void the warranty, and as such, this can become a limiting factor when selecting and designing a battery solution for a specific project.

Discharge rate

Lithium power batteries available in the market for UPS applications have a typical maximum discharge rate from 6C to 10C. This means that maximum continuous discharge power is about 6 to 10 times the nominal kWh rating, resulting approximately 10 to 6 minutes of back-up time for a UPS and critical loads. When less back-up time is needed, the maximum continuous discharge power becomes the limiting factor and batteries are sized to not to exceed the maximum C-rate. In Figure 31 this can be seen as a constant power density and straight line downward after the maximum discharge rate has been exceeded. The power density cannot increase as the discharge power per lithium-ion battery cabinet is limited to maximum value. Beyond this point, overall energy in batteries is exceeding needed amount, but overall maximum allowed discharge power is enough for maximum load of a UPS. This is also the reason why batteries aimed for BES and EV applications are not used with a UPS. Those have typically 1C continuous discharge rating, and this would result a system with 1 hour back-up time with UPS maximum load, when only few minutes is needed. As such, the systems would have plenty of extra cost and require a lot of extra space.

If the maximum discharge current in a battery cabinet or module is exceeded, Battery Monitoring System (BMS) inside lithium battery cabinet will disconnect the battery to protect battery cells and modules from overheating and potential fire hazard. When lithium battery system is sized to be just enough to support maximum load, losing one faulty cabinet can also trip protective devices in other cabinets due to increased discharge power exceeding the maximum current, and there is no redundancy between strings at design load.

Scalability

Lithium batteries have limited options for modules sizes and typically the batteries come as complete cabinets from manufacturer. As such, the scalability is in steps of tens of kWh. The average nominal energy for lithium-ion power battery cabinets used in Table 5 is 31,3 kWh, that can provide approximately 10 minutes of back-up time for 160 – 170 kW of UPS load. With very large UPS units this is not a problem, but for small and medium size 3-phase UPS products the module size can be rather coarse for cost optimization. Most battery suppliers support options to equip cabinets with different number of battery modules in series to provide some (very) limited scalability, assuming the UPS system allows some variation in the nominal battery string voltage.

5.5.2 Lead Acid

Useable energy and densities

Lead acid battery follows Peukert's Law and useable energy depends strongly on discharge current and time (Cugnet et al., 2010, p. 2). Figure 30 shows the relation between discharge time and useable energy for lead acid and lithium power battery while Figure 32 shows lead acid battery useable energy vs discharge power and time. Graphs are using data from constant power discharge performance tables of 59 different commercially available VRLA batteries for UPS application, published by battery manufacturers. As the discharge current (power) increases, useable energy reduces. The batteries in a typical data centre application are sized for some minutes of back-up time for the design load. This means that Depth of Discharge (DoD) for lead acid batteries in a UPS application is almost never 100% due to high discharge rates, even when using all useable energy from batteries. Also, when operating at typical partial load levels, the useable energy from batteries increases. Reducing the load to half almost triples the discharge time and increases the useable energy over 40%. This has significance for the grid-interactive UPS application and the extra energy available in a UPS operating at partial load level.

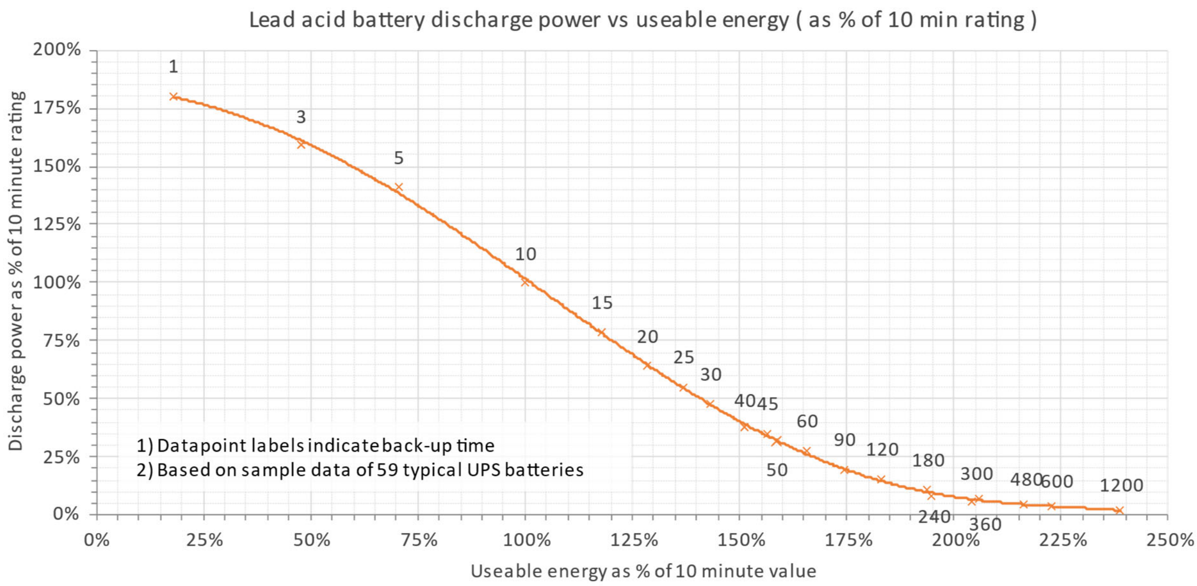

Figure 32. Valve regulated lead acid battery useable energy vs discharge power, 10 minute values as a reference point (Paananen & Rantanen, 2016, p. 18)

Power and energy densities can be compared according nominal capacity, based on ten (C_{10}) or twenty (C_{20}) hour discharge rates. As discharge rate has significant impact on useable energy, these are not meaningful to use for a specific system design in a project. With extremely short back-up times the power density of lead acid can be close to lithium-ion as lead acid batteries can be better optimized for high discharge rates while lithium-ion solution is limited by maximum discharge rate hence using more batteries requiring extra space. With long back-up times more energy can be drawn from lead acid battery improving the energy density as seen in the Ragone plot. Therefore, comparison between products and technologies shall be done based on specific project parameters and by comparing commercially available, and feasible, products.

Cycle-life

Lead acid batteries have limited cycle life mainly due to corrosion in battery (positive) electrodes caused by the chemical reactions occurring in the battery (Jafari & Rahimpour, 2020, pp. 34-36). Higher DoD is causing higher stress on active material and requires stronger recharging. Therefore, the cycle-life of a battery depends strongly on the DoD (GNB, 2016, pp. 34-36). Batteries in UPS application do not normally see 100% DoD, but much shallower cycles. As such, the battery lifetime is not normally limited by cycle-life, especially in European countries with reasonable mains power quality and seldom power outages. Even without discharge cycles, there is degradation in the battery caused by charging and the calendar life for a typical VRLA battery is 6 to 8 years in normal operating conditions.

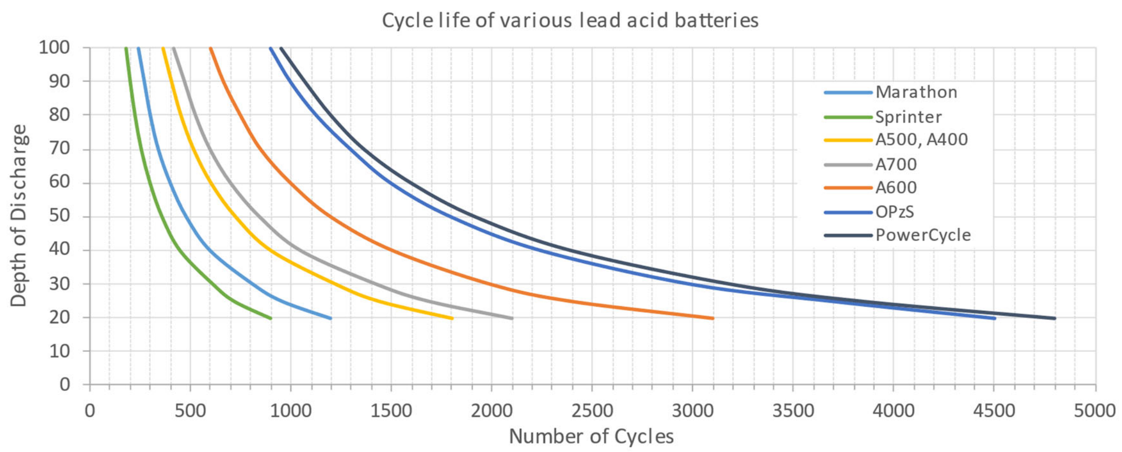

Figure 33. Cycle life for various types of lead acid batteries. Graph compiled from data published for stated individual battery types by GNB Industrial Power

Discharge rate

In a typical UPS application, lead acid batteries are discharged with high current, and a typical back-up time in a data centre is between 5 and 15 minutes, but even as low as 1-minute (End of Life) designs have been used. There are multiple lead acid batteries from major suppliers capable to very high discharge rates. In a system with multiple battery strings, typically remaining strings can still provide some back-up if one string fails, as long as string protection fuses or breakers are not tripped.

Scalability

As the lead acid batteries are old technology, there's a wide range of products and size of individual battery blocks. This allows to optimize the battery system design by choosing from different size of battery blocks, number of battery strings and blocks per string to minimize overhead, cost, space, and to add create redundancy between battery strings with marginal cost when needed.

5.6 Grid-interactive Data centre

5.6.1 Securing loads in mission critical environment

Data centres with their assets can provide flexibility and fast response for electricity grid, and the technical capability of a grid-interactive UPS has been proven in various pilots while first data centres already participate in the ancillary services market providing frequency regulation for the electricity grid system operators (Eaton, 2021; Fortum, 2022). It is also important to acknowledge that data centres are also mission critical facilities providing power, cooling and space for data processing hardware typically used for business-critical applications. Therefore, primary task for a UPS equipment shall be always protection of critical loads, while grid support is a secondary task, and certain principles must be followed to ensure this.

Possible impact to UPS primary operation to protect critical loads and secure business continuity i.e., perceived risks, are biggest obstacles for adaptation of grid-interactive UPS technology in a data centre. This has become obvious during numerous discussions with data centre companies and designers, especially with data centre operations personnel, in past years. This is supported by a recent study done by Omdia (Levy & Galabov, 2022).

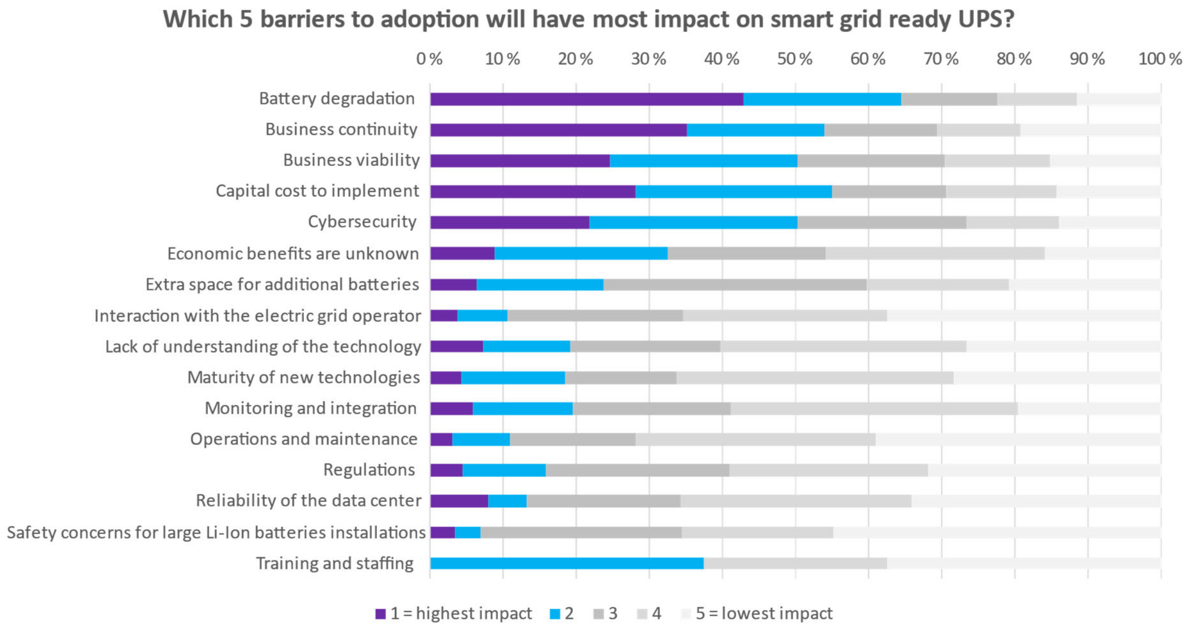

Figure 34. Barriers to adoption of grid-interactive UPS in a data centre (Levy & Galabov, 2022)

Fail safe response

A power response should never be performed by opening an electromechanical device such as a contactor or a circuit breaker, or any other method that doesn't allow parallel use of rectifier and batteries. If demand reduction is done by switching the mains power off, a failure in battery circuit can result a load loss. Therefore, a seamless transfer of power from rectifier to batteries while operating both sources in parallel (power sharing) is more secure and fault resistant, as load can be reverted to either source instantaneously if other source would fail.

Abnormal conditions and local control of use

A data centre operations personnel is making sure everything operates as expected and the 'keep the lights on' in the data centre. As a data centres are complex systems, there are numerous abnormal conditions and ways for systems and sub-systems to fail. Also, regular preventative maintenance must be performed for critical infrastructure. Therefore, there shall be a possibility for a data centre operations team to manually disable the grid-interactive operation mode and turn off the aggregation controller, preferably with a mechanical switch, if required due to site conditions and based on their judgement. The operations team shall have the final decision if and when a UPS supporting critical loads is allowed to perform additional tasks besides critical load protection, such as grid support.

Similarly, if there would be any alarm condition in the UPS itself, that could impact the normal operation and load protection, a UPS shall automatically by own decision revert to basic operation mode to maximize the load protection. Any alarm in a UPS protecting critical loads should engage site operations personnel to inspect the cause of the alarm and start corrective actions. Once the cause of the alarm is rectified by a site personnel or suppliers service organisation, and UPS system is restored to normal state, grid support operation can be enabled.

Control interface

There shall be a watchdog or handshaking signal and timeout between UPS and the external aggregation controller to cease the grid-interactive operation mode when communication to controller is lost. This is to prevent a grid-interactive UPS from keeping following potentially high discharge power reference 'indefinitely' and from depleting the batteries in case of controller or communication line failure. For same reason, the control commands and power references shall not be 'sticky' and remain active after communication to aggregation controller is lost, as such could cause a UPS to unnecessarily deplete the battery.

Also, a UPS shall perform a sanity check for external power reference to verify those are within specified range and safe to use. In general, a grid-interactive UPS that manages the protection of critical loads with its own control firmware shall decide when to follow external 'requests', rather than commands, and to what extent, to always prioritize the critical load protection.

Caution shall be used when implementing various control commands to grid-interactive UPS interface for aggregation and energy management controllers. A control interface supporting any commands allowing directly to control operation states of a UPS, such as transferring to bypass or turning UPS off, can be considered as a high risk as such commands could be activated accidentally or purposely by a malicious attacker penetrating the system from outside data centre by using communication lines. Therefore, it is better to keep the aggregation control interface, that has a connection to aggregators Virtual Power Plant (VPP) outside a data centre, isolated from other control and monitoring systems inside a data centre, and to limit the supported control commands to ones truly necessary for a grid-interactive operation.

Allocation of the battery energy

An obvious concern is how to make sure that UPS units have always enough stored energy in the batteries to provide required back-up time for critical loads, as grid support is using energy from batteries. To ensure this, the State of Charge (SoC) of the batteries is constantly monitored and calculated, and a specified portion of energy is reserved for critical loads. The SoC calculation and monitoring can be done in additional controllers outside of a UPS itself, or within a UPS as often preferred by data centre operators. Lithium battery systems always have a sophisticated Battery Management System (BMS) that can tell the SoC of batteries, while lead acid batteries do not and this has to be calculated from battery performance data, discharged energy, load levels, etc. As useable energy from lead acid battery is heavily load dependent following Peukert's Law, this is a bit more complex than with lithium battery.

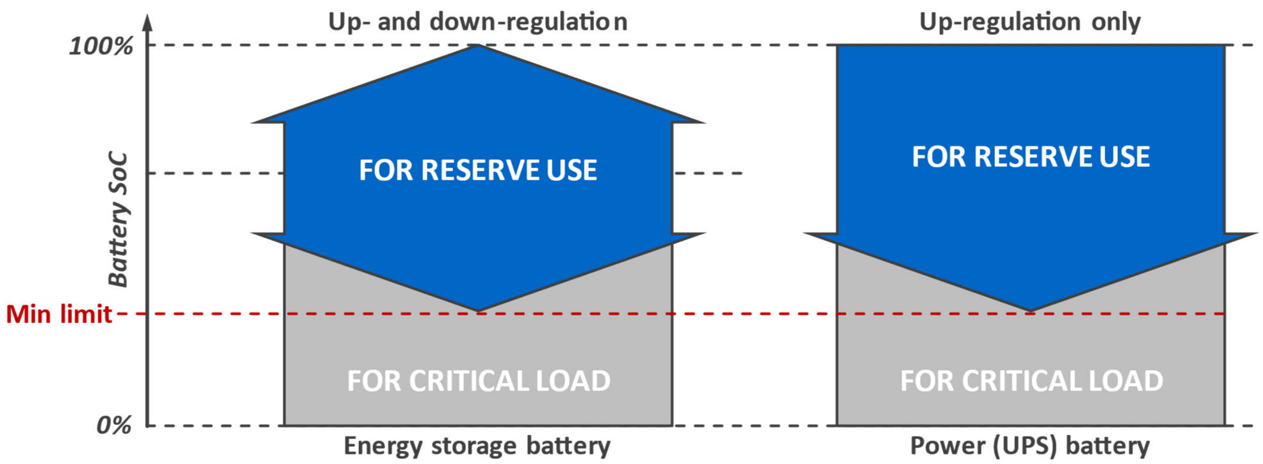

Figure 35. Battery SoC and allocation of energy for up- and down-regulation

In practice, a specific amount of stored energy in batteries is allocated for critical load support, and excess energy is available for grid support, demand response, local energy management, etc. When battery SoC and remaining energy in batteries reaches defined limit, grid support etc. activities are cancelled to preserve enough energy in batteries for critical load support to meet the required back-up time in case of mains outage. When managed in UPS itself, it declines to follow external discharge commands.

Needed useable energy from batteries can be calculated with equations below where $E_{bat(up/up\text{-}down)}$ is the required battery energy for critical load and for up, or up-and down-regulation. $P_{load,max}$ is maximum expected critical load and $t_{back\text{-}up}$ is required back-up time. $P_{up/down,max}$ and $t_{up/down,max}$ are the maximum power and time for up- and down-regulation.

$$E_{\mathrm{bat(up-down)}} \geq P_{\mathrm{down,max}} * t_{\mathrm{down,max}} + P_{\mathrm{up,max}} * t_{\mathrm{up,max}} + P_{\mathrm{load,max}} * t_{\mathrm{back-up}} \quad (5\text{-}9)$$

$$E_{\mathrm{bat(up)}} \geq P_{\mathrm{up,max}} * t_{\mathrm{up,max}} + P_{\mathrm{load,max}} * t_{\mathrm{back-up}} \quad (5\text{-}10)$$

When using a grid-interactive only for up-regulation, such as FFR, normal UPS batteries can be used assuming resulting cycles are within reasonable limits for the technology. These can be either lead acid or lithium-ion power batteries. Up-regulation is performed by reducing the demand on the grid by discharging the batteries and batteries can be held at 100% SoC. Amount of excess energy available for grid support depends on UPS load level and how much energy needs to be allocated for critical load support. Amount of energy required for grid support depends on how much power is used for grid support, that is adjustable, and what is the required maximum duration of response. In Nordic synchronous area FFR activation is between 10 and 30 seconds using very limited energy, while in UK the response shall be sustained for 15 minutes if needed. See also section 4.3.1.

When performing up- and down-regulation, the batteries need to be held at partial State of Charge (pSoC) to allow to charge the batteries to increase demand from the grid and to regulate the frequency down. Typically, frequency regulation schemes requiring up-and down-regulation are also creating high number of cycles exceeding capabilities of commonly used power batteries, also causing a need to use energy cells i.e., similar or same batteries as used for energy storage applications. General principle for allocating the battery energy is shown in Figure 35.

The required battery design is also impacted by other battery and system characteristics and for example by load profile. As such, allocation and calculation of required energy is only one piece of overall design and product selection process.

Battery degradation

Battery degradation is another obvious concern when leveraging a data centre UPS for grid support. Additional cycles can increase degradation and shorten battery life and have a negative impact on system reliability (Jafari & Rahimpour, 2020, pp. 34-36). Therefore, it is important to understand the potential impact of grid support to batteries and select a battery technology suitable for application or use the existing batteries for an application suitable for batteries. Number of cycles and Depth of Discharge (DoD) are typical parameters to evaluate. Some use cases, such as peak-shaving or Time-of Use demand response applications, are energy intensive using batteries frequently and for long durations. Fast Frequency Response is power intensive as it uses batteries seldomly (with high power) and only for some seconds at a time.

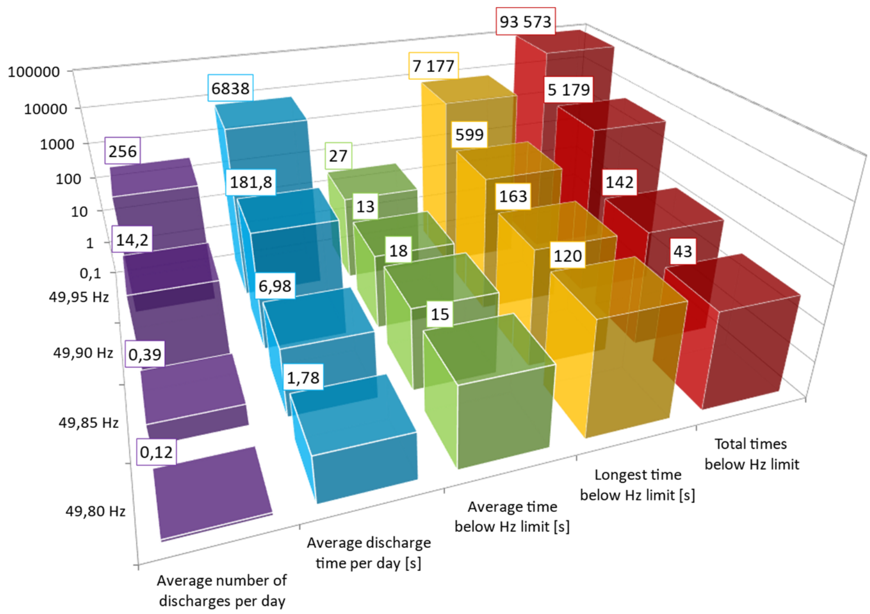

Figure 36. Frequency statistic of Ireland in 2016 and resulting battery discharges in dynamic regulation, modified from (Paananen J. , 2019a, p. 10)

When using a grid-interactive UPS for frequency regulation, the mains frequency quality and participation parameters, trigger frequency and window, have a big impact to resulting number of discharge cycles and DoD. Historical frequency data is made available by some transmission system operators, such as Fingrid (n.d.) for Nordic synchronous area (SA), nationalgridESO (n.d.) for Great Britain SA and Elia (n.d.) for Central European SA. Combining this with defined parameters for frequency regulation, the expected number of cycles, maximum power and DoD and annual throughput (overall used energy) can be estimated with correct algorithms. The grid frequency remains close to nominal most of the time. Further the trigger frequency is from 50 Hz, less activations there will be and for a shorter time. Especially with dynamic regulation, where response follows the actual frequency deviation, used energy reduces drastically with low trigger frequencies (up regulation). Figure 36 shows how many times and for how long frequency has deviated outside specific limits in Ireland in 2016, based on historical frequency data.

Based on expected number of discharge cycles and throughput, a suitable battery or participation parameters are chosen to make sure battery is not stressed too much to impact the reliability of the systems. Frequency containment reserves aimed to protect the system against large contingency events, such as FFR and FCR-D with correct parameters, will result only occasional cycles and are easily suitable for standard lead acid or Li-ion power batteries. Reserve types aimed to contribute to frequency regulation during normal conditions with a small dead-band around nominal frequency, or performing up- and down-regulation, would need to rely on more cyclable energy storage batteries. In that case the C-rating can become a defining factor for battery sizing.

Power export

Depending on a UPS manufacturer and model, a grid-interactive UPS may be capable to discharge batteries with a power level exceeding the load connected to UPS output as explained in section 5.3. In some case this not desired or may be restricted by the connection to an electricity grid. Typically, exporting power would not impact the system reliability unless reverse power protection relays are used, that could be tripped in case of accidental power feedback.

Exporting power to distribution network would typically require an export license (permit) and requires use of specified protective devices etc. While some facilities may have export licenses in place and are for example using generators for ancillary services, others may not. Also, a grid-interactive UPS feeding power back to its own mains connection, when used to provide ancillary services, may be considered as a generating unit and needs to comply with applicable 'grid codes'. Systems having nominal export power below 0,8 kW are excluded from these requirements (Regulation 2016/631, Article 5). A grid-interactive UPS used only to share the power (load) between rectifier and batteries, and not exporting power, can be seen as a relay connected load doing demand reduction, or as 'a group of relay connected loads' with an adjustable response.

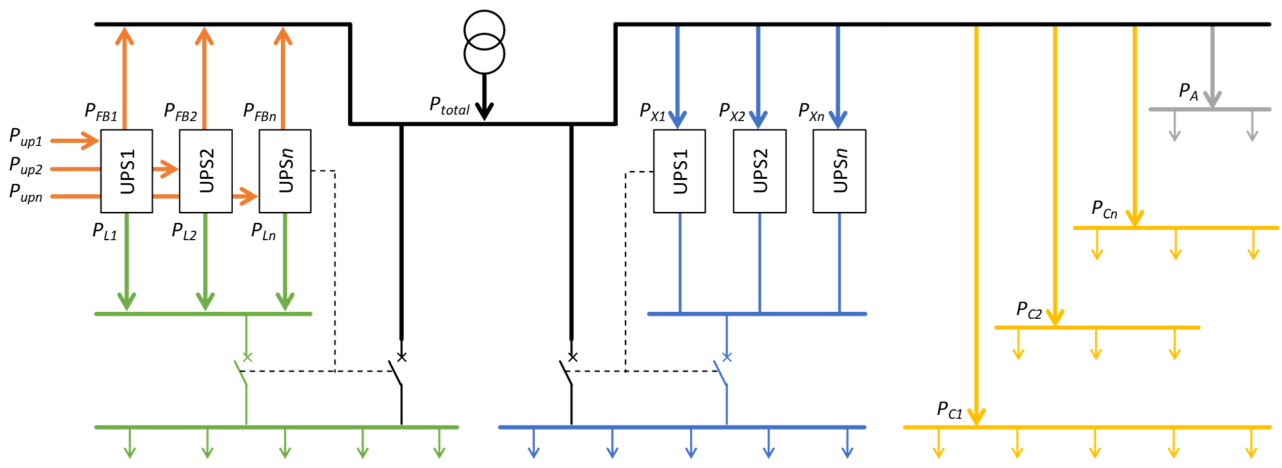

Figure 37. System level power flows in a data centre with grid-interactive UPS units

For a complete system the power can be managed on data centre facility level by taking account the overall power response provided by participating UPS units and all other loads in the building (Alaperä et al., 2019, p. 3). When power export to grid is not desired or allowed, the overall response from participating units shall not exceed the total sum of loads in the building consisting of loads of UPS system providing the response, loads of other UPS units not participating in frequency regulation, cooling and auxiliary loads.

$$\sum_{i=1}^{n} P_{\mathrm{up}_i} \leq \sum_{j=1}^{n} P_{\mathrm{L}j} + \sum_{k=1}^{n} P_{\mathrm{X}k} + \sum_{m=1}^{n} P_{\mathrm{C}m} + P_{\mathrm{A}} \tag{5-11}$$

P_{up} is the power (response) used for up-regulation, P_L is the load connected to UPS providing the response, P_X is the load connected to UPS units not used for frequency regulation, P_C is the power consumed by cooling and P_A stands for auxiliary loads in the data centre.

$$\sum_{i=1}^{n} P_{\mathrm{FB}i} = \sum_{j=1}^{n} P_{\mathrm{L}j} - \sum_{k=1}^{n} P_{\mathrm{up}_k} \tag{5-12}$$

To calculate the input power of a UPS system (or unit) providing a response for up-regulation, the response power P_{up} is deducted from UPS output load P_L. When response power is higher than UPS load (result is negative), some power P_{FB} is fed back to mains.

Possible power fed back from units providing frequency regulation will be consumed by other loads in the low voltage electrical system (building). When the overall power taken from batteries exceeds the overall demand in low voltage electrical system (building), excess power is exported to grid. The maximum response power can be adjusted to avoid power export from individual UPS or complete system, as needed. A grid-interactive UPS can also have a paramater to inhibit power export. In that case UPS itself prevents it regardless of load level and this may be useful with varying load levels, and especially to avoid to accidentally trip the reverse power protection relays.

5.6.2 Data centre operator motives

Reasons to be interested or to operate a data centre as a grid-interactive can be various. Here I divide these to three general categories: sustainability, financial gains, and company image and reputation. First two are the ones generally talked about and common topic coming up around discussion about grid-interactive UPS and data centre.

Company image and reputation

A data centre is a highly technical facility filled with latest technology. On power infrastructure side, basic topologies and solutions still typically follow ‘good old principles’, and for a good reason. Nevertheless, some companies are continuously exploring new concepts and designs to improve efficiency and find cost reductions or other gains. Being innovative and pioneering new technologies can be also leveraged for marketing purposes on building a brand image (Hanysha et al., 2014, p. 2). For a colocation data centre, whom product is the facility and the infrastructure to support their customer’s critical loads, using innovative solutions can be a way to differentiate from competition and improve competitiveness.

Using grid interactive technology can be deemed as innovative and could as such have a positive impact on company brand and reputation. This has not been typically the primary motivation for interest towards grid-interactive UPS, based on discussion with data centre operators during past years, but recent Omdia Smart Grid Ready UPS Survey (Levy & Galabov, 2022) shows a different result. Technology innovation and pioneering, and company image, were clearly one of the top adoption drivers for grid-interactive technology among 380 respondents. 42% of respondents were from UK, Ireland and Nordic countries that are in scope of this study.

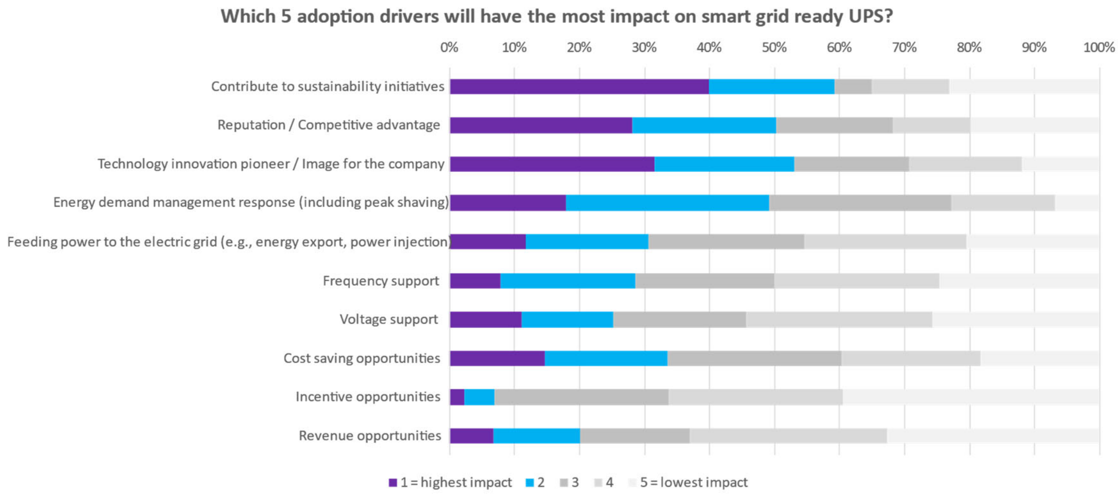

Figure 38. Grid-interactive UPS adoption drivers (Levy & Galabov, 2022)

Financial gains

A grid-interactive UPS can create savings through demand response by optimizing overall cost of energy. A typical suggested approach is energy arbitrage (time-of-use), where energy from batteries is discharged when cost of electricity is high, and recharged when electricity is cheap. In this case generated savings depend on daily variations in price and on the difference between cheapest and most expensive hour, assuming the data centre would be paying for electricity based on spot prices and not protecting itself against high price variations with a long-term power purchase agreement (PPA) etc.

Using batteries for energy arbitrage creates high discharge cycles, even every day, and is therefore requiring use of lithium-ion energy cells. Business case study for a demand response is comparing the cost of extra battery capacity vs generated savings through energy arbitrage and other possible peak charge avoidance. As an example, discharging 1 MWh during most expensive hour, and recharging 1 MWh during cheapest hour, would have resulted in Nordics annual savings close to 16000 € during 2021 (excluding losses). With an average cost of Li-ion energy cells presented in Table 5, 1 MWh of extra battery capacity would cost 456000 €. As such, business case for energy arbitrage is weak unless other significant savings besides cost of energy can be created. Spodniak, Bertsch & Devine (2021, pp. 15-16) came to same conclusion when analysing profitability of energy storages in European market. Price volatility can be higher in other markets with possible peak time tariffs etc. enabling higher savings. This is always a case-by-case evaluation. Example is used here to highlight the cost vs savings, as much better results are often assumed before having a closer look into actual numbers. Plot in Figure 39 is based on hourly market price historical data (NordPool, 2022).

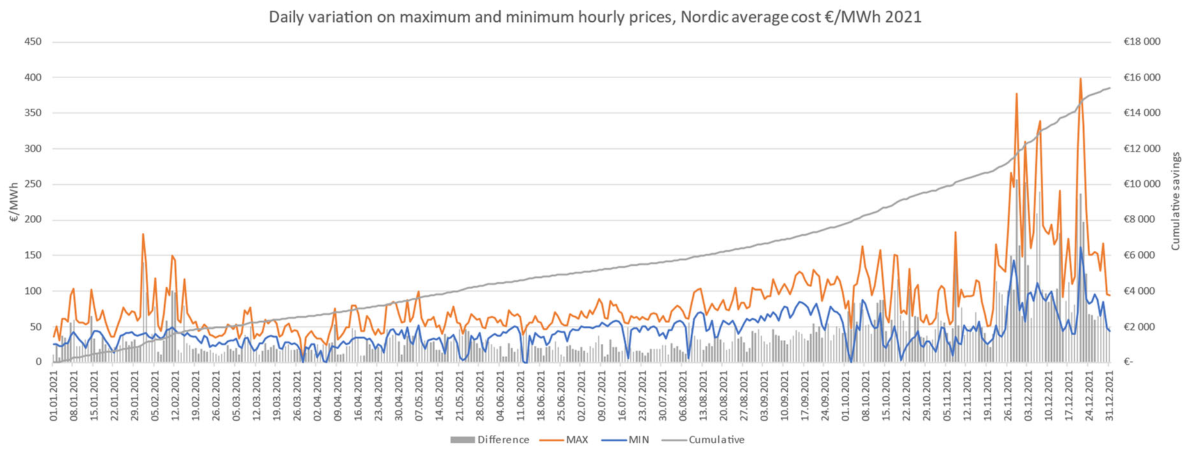

Figure 39. Daily MAX and MIN of Nordic average electricity spot price [€/MWh], the difference and cumulative price difference for 2021.

When using a grid-interactive UPS for ancillary services, and to provide frequency regulation, the generated financial gains can be much higher. Possible revenues and required extra investments are market specific, depending on type of the reserve, technical requirements, frequency quality of the grid and design of a UPS system. The evaluations shall be done case by case.

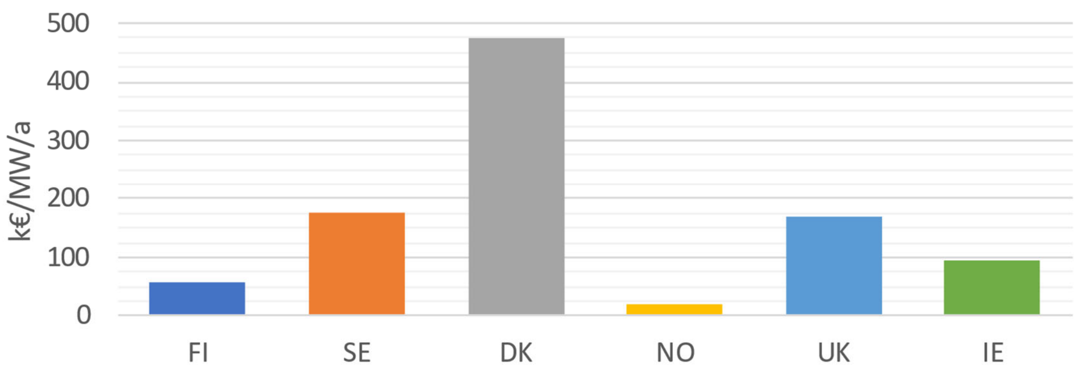

Figure 40. Potential revenue from FFR (DC-L) market with a grid-interactive UPS

Alaperä, Honkapuro, Tikka & Paananen (2019, pp. 5065-5066) estimated potential annual earnings between 70 and 135 k€/MW for up- and down-regulation (FCR-N or similar) resulting in some cases positive results for required extra investment in energy storage batteries. Potential earnings from FFR market with a grid-interactive UPS are shown in Figure 40, based on the market data presented in Table 4. Market value for Ireland was adjusted to expected level by taking account scalars when providing a fast, dynamic and longer provision (FFR – TOR1, up to 5 minutes) of response (EirGrid & SONI, 2017, pp. 19-32) while assuming similar System Non-Synchronous Penetration (SNSP) and scarcity scalars as in 2021. In Ireland, FFR revenues are paid for hours when SNSP is above 50% (scarcity scalar = 1) and payment increase when SNSP exceeds 60 % (4,7) and 70% (6,3) (EirGrid & SONI, 2017, p. 44). This means that potential revenues are increasing during high wind years.

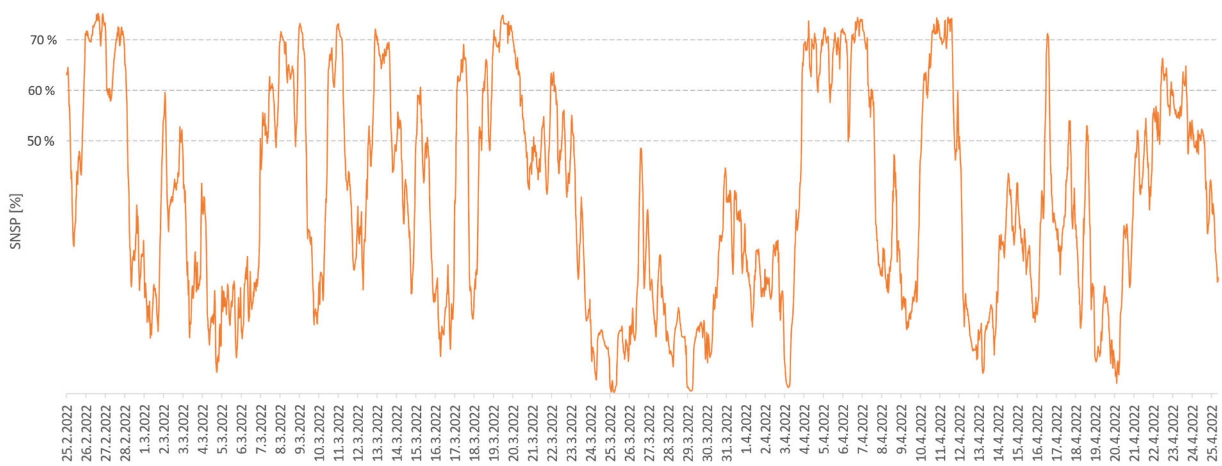

Figure 41. System Non-Synchronous Penetration in Ireland synchronous area between 25 February and 25 April 2022

When providing FFR, with limited activation time and occasional cycles, existing or standard battery solutions can be used. Extra investment in batteries, if any, is low. As such, from financial perspective this can be more interesting when compared to other possible use cases of a grid-interactive UPS.

Data centre operators generally find this potential extra revenue from ancillary services tempting. Even the additional savings or revenue may not be highest adoption driver for grid-interactive technology, according a study by Omdia (Levy & Galabov, 2022), a fact that a solution supporting other adoption drivers (sustainability, image, and reputation) also presents a good business case is a win-win scenario and supporting adoption of new technology. In same study the possible capitol cost of solution was one of the highest barriers (see Figure 34 and 38) and therefore importance of positive financial outcome is an important enabler for the grid-interactive UPS in data centres. Eventually, financial gains and extra revenue can be more important to some data centre companies than others, as the business models and decision to invest can be very different.

Sustainability

Sustainability and supporting energy transition and higher penetration of renewable energy is the biggest adoption driver for a grid-interactive UPS (Levy & Galabov, 2022). This is supported by personal experience and numerous discussions with data centre operators during past years. Many of the data centre companies have 'net zero' goals. For example, large number of data centre operators have signed the Climate Neutral Data Centre Pact and pledged to have data centre electricity demand matched with 100% renewable energy by end of 2030, among other sustainability drivers (Climate Neutral Data Centre Pact, n.d.).

Grid support and grid-interactive UPS are related with energy transition and higher penetration of non-synchronous variable renewable energy sources, and these are helping to mitigate the challenges seen by the electricity grid and supporting higher use of renewable energy. While doing so, they can reduce the carbon footprint of others and create a carbon handprint to offset their own emissions.

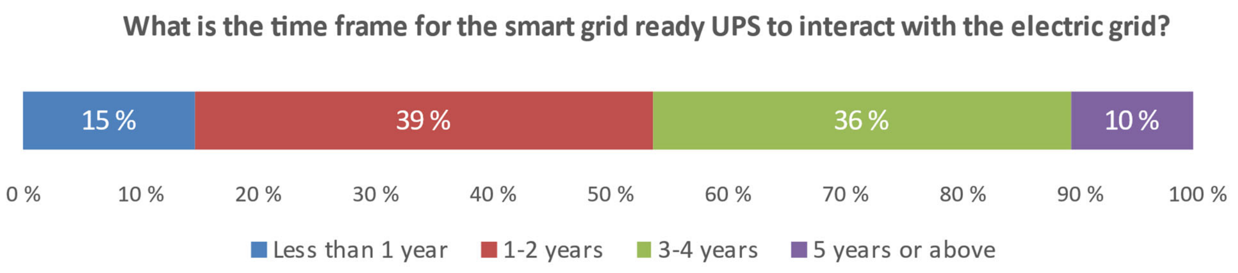

Figure 42. Expected time frame before grid interactive UPS is in operation (Levy & Galabov, 2022)

Data centre operators are top corporate purchasers of renewable energy (IEA, 2020), and therefore it is not surprising that sustainability aspect of grid-interactive UPS solution is found to be the most important adoption driver. Sustainability is strongly linked to positive company image and reputation, but importance of financial gains should not be under-estimated, as positive return on possible extra investment can be a requirement for implementation of the grid-interactive UPS solution. Data centre professional are expecting wider adoption of grid-interactive UPS in near future according Omdia survey (Levy & Galabov, 2022).

6 Fast frequency response in UK, IRE and Nordics

When evaluating the potential of UPS units to provide dynamic flexibility and fast response for the electricity grid and to protect the system against large frequency deviations caused by contingency events, the comparison is not done against the overall size of a synchronous system (area), but against the required amount of fast acting reserves acquired by transmission systems operators. The size of reserves used by a TSO is dimensioned against dimensioning or reference incident i.e., the biggest expected fault in the system (Entso-e, 2013, p. 57).

Since the synchronous areas can be very different in size and composition of power generating assets and resulting system inertia, the overall quantity of fast acting reserves is unique for each synchronous area and the comparison has to be done for each synchronous area separately.

6.1 Nordic Synchronous Area

In the Nordic synchronous area Fast Frequency Reserve (FFR) has been in use during spring, summer and autumn since May 2020 (Fingrid, n.d.). The acquired FFR volume varies by an hour depending on the actual needed volume is determined by system inertia.

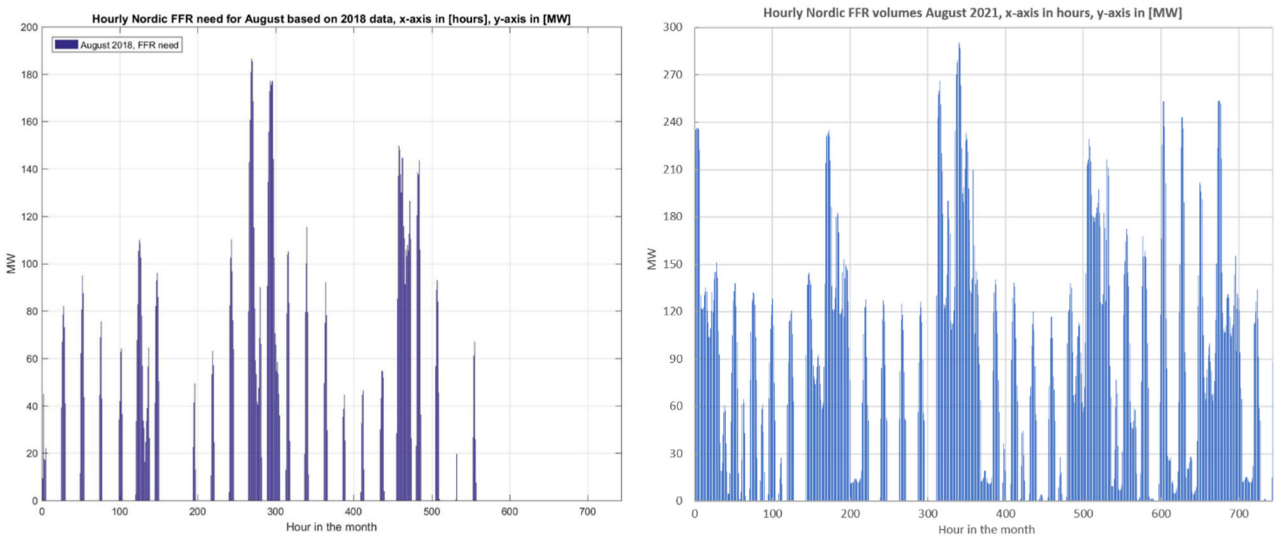

Figure 43. Need for FFR in the Nordics, estimated need (Entso-e, 2019, p. 17) on the left and actual volumes on the right (based on historical hourly data)

Highest volume is expected to be around 300 MW. The obligation to source FFR from the market is divided between four Nordic transmission system operators according defined criteria and the shares for 2022 are: Energinet (DK) 8%, Fingrid (FI) 18%, Statnett (NO) 39% and Svenska Kraftnät (SE) 35% (Modig et al., 2022, p. 10). Maximum volumes are acquired from market rarely, based on 2021 hourly data. Average volume for hours when any FFR was purchased was 71,5 MW for whole Nordics and average volumes for individual TSO are shown in Table 4 (Statnett values based on summary report). During the season from April to October, over 50% of time the volume was zero. Nevertheless, the maximum estimated required volume is 300 MW, and there should be assets (potential reserves) available equal or greater amount for the FFR markets, so that each TSO can fulfil their obligations. As such, 300 MW will be used as reference FFR volume for the Nordic SA.

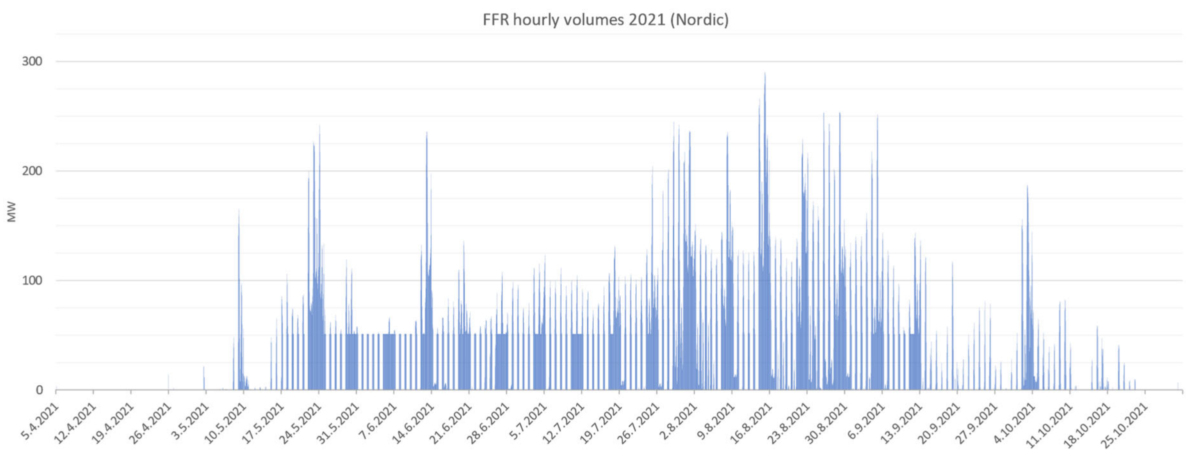

Figure 44. Nordic FFR hourly volumes 2021

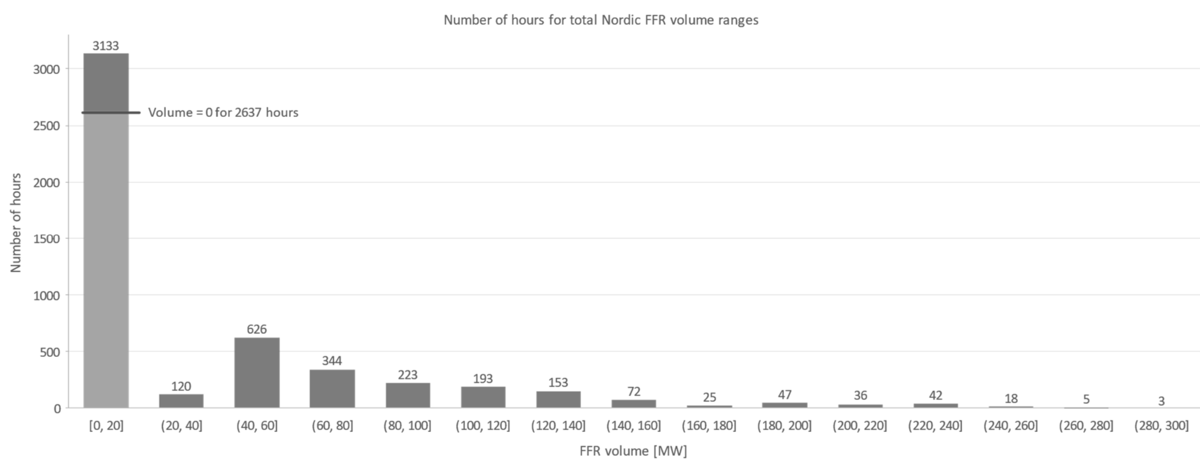

Figure 45. Histogram of Nordic FFR volumes

6.2 Great Britain Synchronous Area

In UK the Dynamic Containment (DC) reserve is sourced from market for each EFA block (4 hours). According nationalgridESO (n.d.), volumes are expected to raise up to 1000 MW in future. Volume variation between EFA blocks during January – March 2022 are shown in Figure 46. There were changes for auction rules in September - October 2021 impacting the volumes. Therefore, market data from 2022 indicates better the existing situation and is used here. The maximum DC-L volume procured from market was 771 MW, averaging 430 MW and some DC-L was sourced on all hours. Maximum expected volume is 1000 MW and used as a reference when evaluating potential of data centre assets for Dynamic Containment.

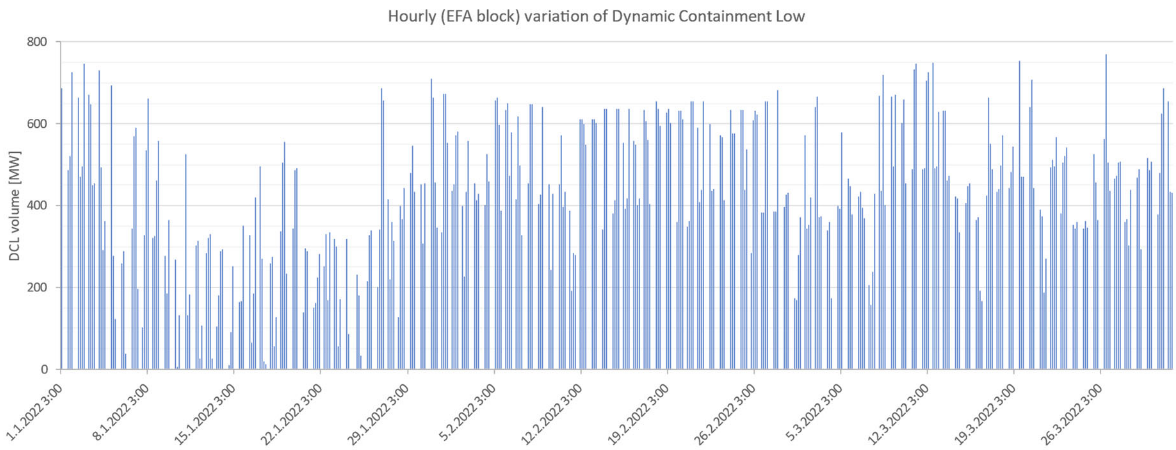

Figure 46. Variation of DC-L volumes from January to March 2022

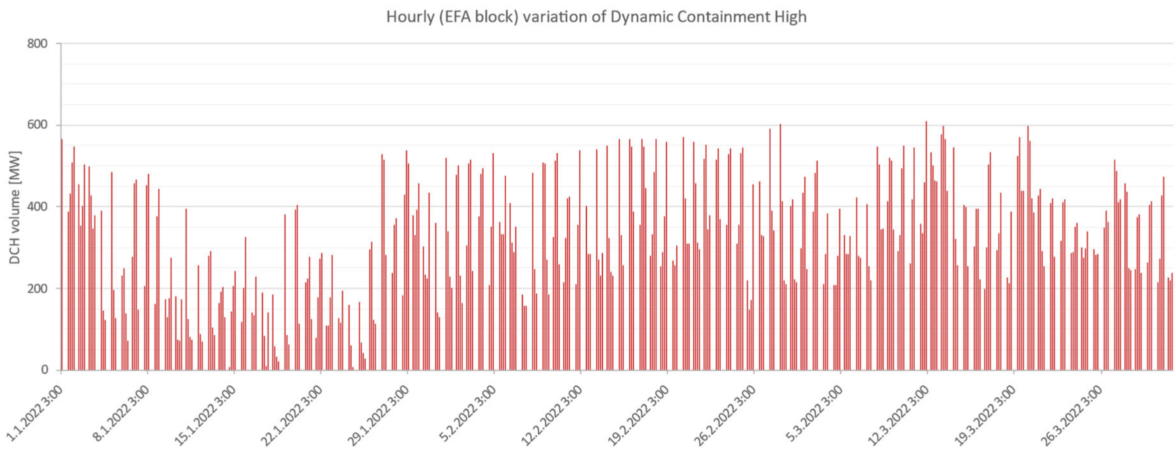

Figure 47. Variation of DC-H volumes from January to March 2022

Dynamic Containment has also down-regulation part (DC-H), sourced from market separately and having different volumes, but these can be provided by same assets. Maximum procured volume from market between January and March 2022 was 623 MW, averaging 327 MW and also DC-H was sourced on all hours. Distribution of volumes is very different from Nordics, and majority of EFA blocks had mid-range volumes for both, DC-L and DC-H.

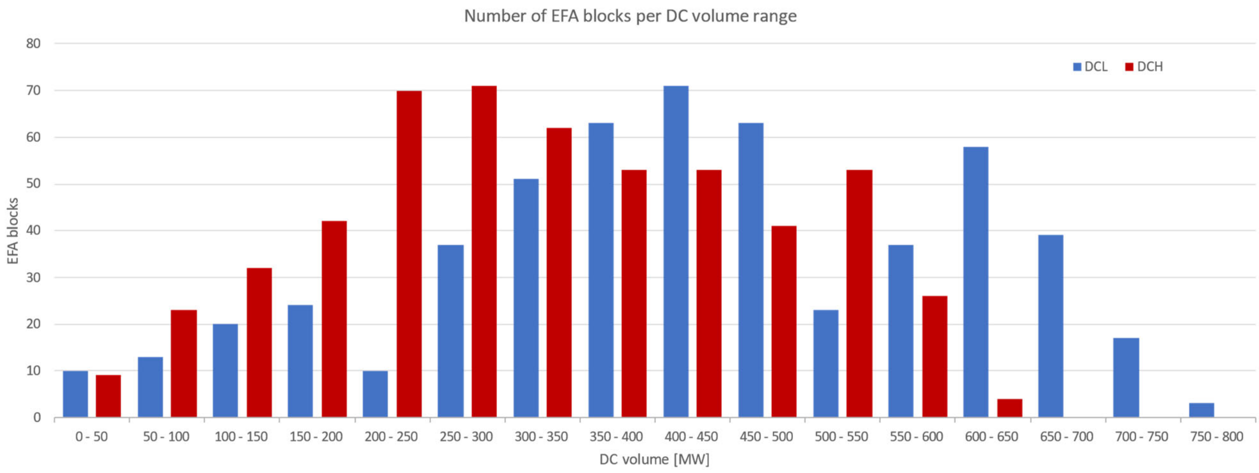

Figure 48. Histogram of Dynamic Containment volumes (January – March 2022)

6.3 Ireland Synchronous Area

EirGrid in Ireland is procuring reserves from market using bi-annual gates and there is no hourly market or variation in volumes. Development of FFR volumes in Ireland is shown in Figure 19, and existing procured volume is 810 MW (1073 MW for IE & NI). The size of market has grown since it opened in 2018. The maximum Largest Single Infeed (LSI), same as Dimensioning Incident (DI) elsewhere in this document, is 700 MW and FFR sized for 75% of LSI (525 MW). For the procured volume, TSO applies availability factors based on type of asset providing the FFR. Expectation is that LSI would not grow in upcoming years (EirGrid & SONI, 2021, pp. 15-18).

Availability of assets to provide FFR in 2030 vs. required volume is presented in Figure 49. These are shown for three different scenarios (portfolios) depending on approach taken to manage the expected future demand. Based on presented results the expectation is that there will be enough assets to provide required FFR in all scenarios. When estimating the reference FFR volume for Ireland synchronous area, for the comparison against UPS install base in data centres, 75% of the

LSI is used after corrected with average Availability Factor (52 – 53%) in 'System Services - 2030 Volumes, Indicative Portfolio Capability Analysis' document (EirGrid & SONI, 2021, pp. 23-29). Resulting FFR reference volume is 1000 MW.

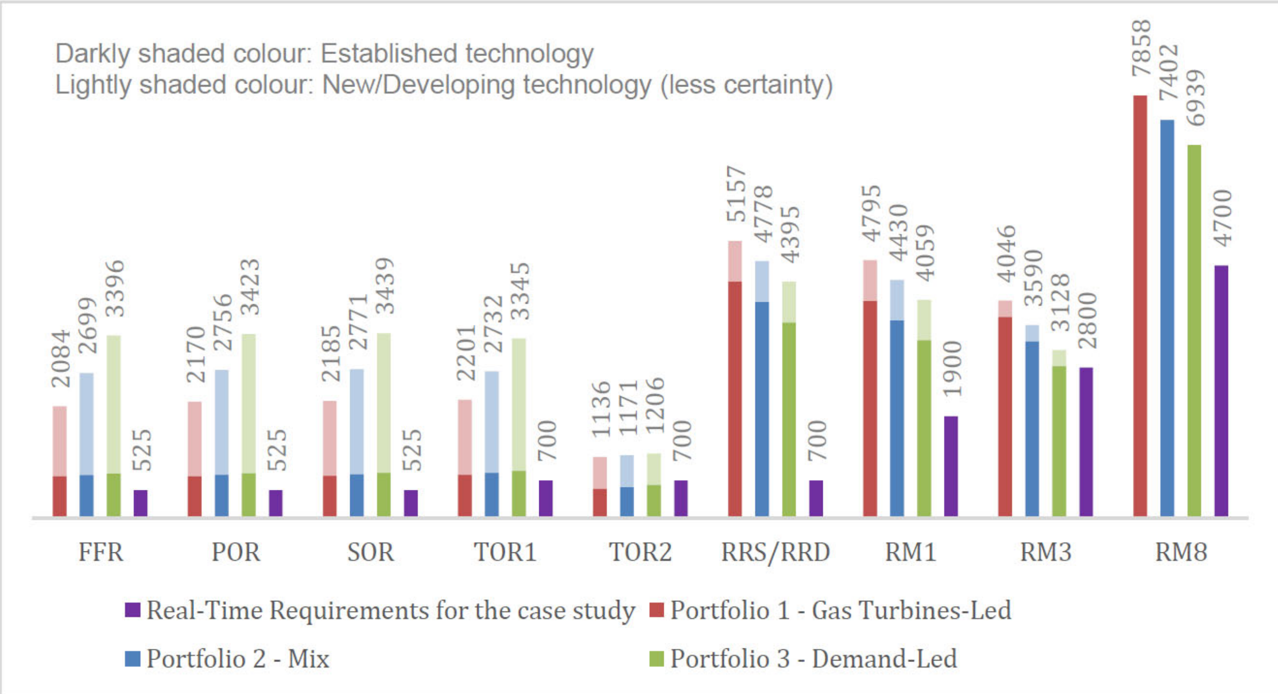

Figure 49. Available Volume vs Real-Time requirements per service (in MW) (EirGrid & SONI, 2021, p. 18)

7 Data centre capacity to provide Fast Frequency Response

7.1 Principles to estimate UPS capacity in data centres

When estimating the potential of data centres to provide Fast Frequency Response, and available power capacity from grid-interactive UPS units for frequency regulation, different approaches can be used. Selected approach for a specific country or region depends on available information.

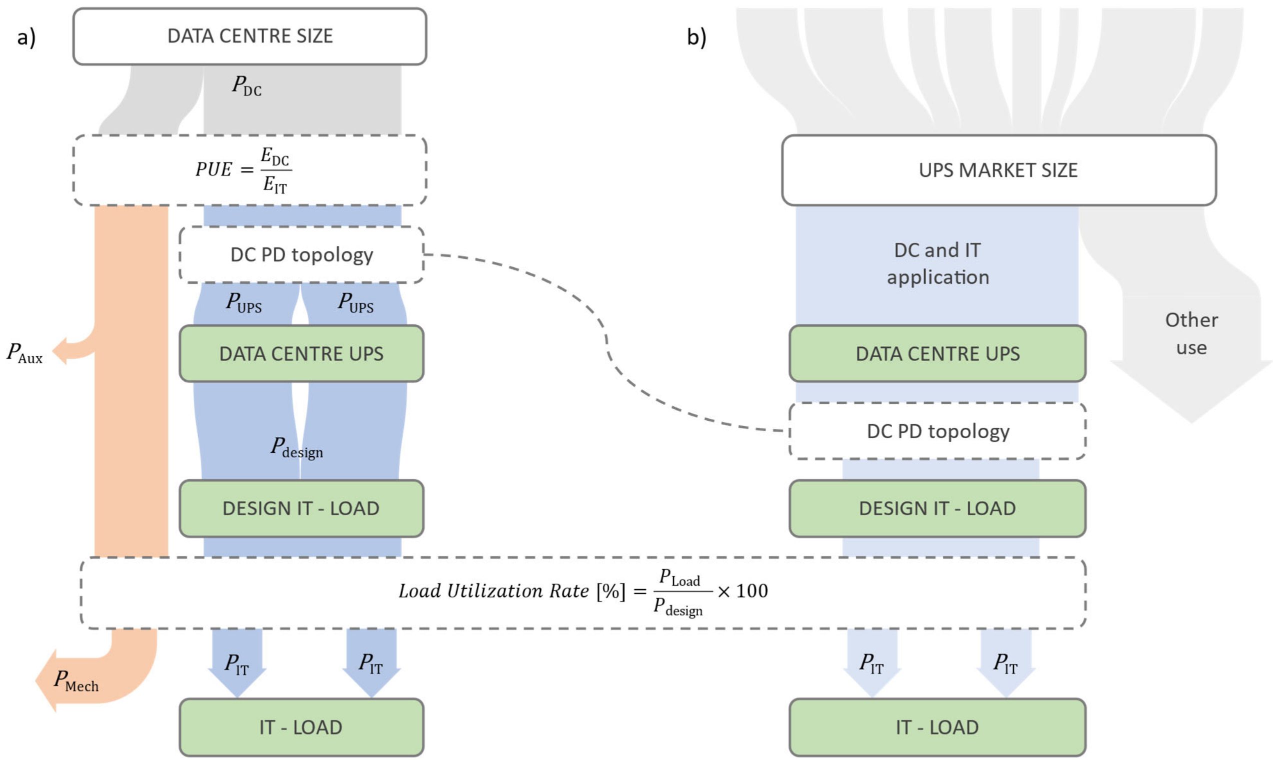

Figure 50. Correlation of various inputs and metrics to UPS and IT-load content in a data centre

First option is to use the estimated data centre energy consumption to derive the average data centre power. The overall power drawn by data centre(s) can be allocated between IT loads and auxiliary and cooling loads according estimated (average) Power Usage Effectiveness (PUE). After the estimated IT load is known, design IT load can be estimated by using an average or known load utilization rate. The overall UPS capacity can be estimated from design load based on data centre power distribution topology. Simplified diagram is shown in Figure 50 (a) to illustrate the power flow, PUE and load utilization rate.

Alternatively, if the data centre design power capacity is known, using the design PUE and power distribution topology the amount of UPS equipment can be estimated. Applying utilization rate to design load gives the actual load estimation. This can impact the available regulation capacity depending if exporting power to the grid is allowed or not. If a starting point is design IT load instead of data centre design power capacity, same principles are followed but applied in reverse order.

Lastly, the UPS equipment install base in data centres can be estimated from UPS market and supplier data by allocating correct share of the UPS equipment delivered to market into data centres. Using same principles, design IT load and final demand of a data centre can be estimated based on power distribution topology, utilization rate and PUE estimates as illustrated in Figure 50 (b).

7.2 PUE, load utilization rate and UPS to design load ratio

PUE

Based on reported data from 289 European data centres facilities participating in the European Code of Conduct for Data Centre Energy Efficiency, the average PUE is 1,80 with a downward trend. Average PUE reported on 2016 was 1,64 (Bertoldi et al., 2017, pp. 15-17). This means that for every 100 kW of power used by IT equipment, additional 64 kW is used by cooling and auxiliary loads in the data centre.

Design PUE refers to value that is a goal for Power Usage Effectiveness when designing a data centre. This is typically lower than actual PUE when operating at partial load levels. Design PUE is here applied when estimating the ratio between design capacities within a data centre. A typical value for design PUE in a modern data centre is 1,30 (Lawrence, 2020). Cloudscene (n.d.) states 1,36 as a typical value for on data centre in UK.

Load Utilization Rate

Since IT Equipment Utilization for servers (ITEUsv) is not typically 100%, meaning the data centre servers do not operate at maximum processing capacity, and IT space and cabinets (racks) may not be fully populated, the actual load on data centre is typically less than its design value. The average annual IT electricity consumption in Bertoldi et al (2017, p. 15) was 7871 MWh while average rated (design) IT load was 1956 kW. The average load (infrastructure) utilization rate can be calculated as follows:

$$P_{\mathrm{IT}} = \frac{E_{\mathrm{IT(year)}}}{8760\ \mathrm{h}} = \frac{7871000\ \mathrm{kWh}}{8760\ \mathrm{h}} = 899\ \mathrm{kW} \tag{7-1}$$

$$Load\ Utilization\ Rate\ [\%] = \frac{P_{\mathrm{IT}}}{P_{\mathrm{design}}} \times 100 = \frac{899\ \mathrm{kW}}{1956\ \mathrm{kW}} \times 100 = 46\% \tag{7-2}$$

The calculated IT load utilization rate is 46%, meaning the actual IT load is 46% of its design value. In a study conducted by National Energy Agency of Singapore (2012, pp. 53-54), the UPS utilization rate of 23 data centres was 27,4% and the load utilization rate was approximately 51%. In a 2N topology, the load is equally shared by two streams and UPS utilization rate is half of the load utilization rate. In a recent study by BloombergNEF (2021, pp. 15-19) the estimated live (actual) data centre power was 43,5% of designed power capacity. Load utilization rate used here is 45%, if no other information is available, that is average from the two European studies.

UPS to design load ratio according power distribution topology

The used topologies and system sizes in various data centre projects were reviewed from available data of 125 projects between 2013 and 2022. System size refers to overall size of back-up system used for the topology, and one back-up system can consist one or more individual UPS systems as shown in Figure 28. The cloud and large colocation data centres are over-presented in the sample as data was available mainly for projects of larger data centre companies. Therefore, the data does not necessarily reflect accurately the whole data centre market and segments even large hyperscale data centres do present a major and growing share of the data centre market and energy consumption (IEA, 2017, pp. 105-106; Montevecchi et al., 2020, p. 60). Also, they should present major share of the new data centre capacity coming to market potentially leveraging new technologies.

Based on the sample data, traditional in-house i.e., corporate data centres are using basic single or dual path designs while large colocation and cloud providers (hyperscale) data centres use mainly distributed and block redundant designs. The average UPS system overhead for each topologies and data centre segments are shown in Figure 52. Overall average UPS capacity was 136,8% of design IT load across all sample data.

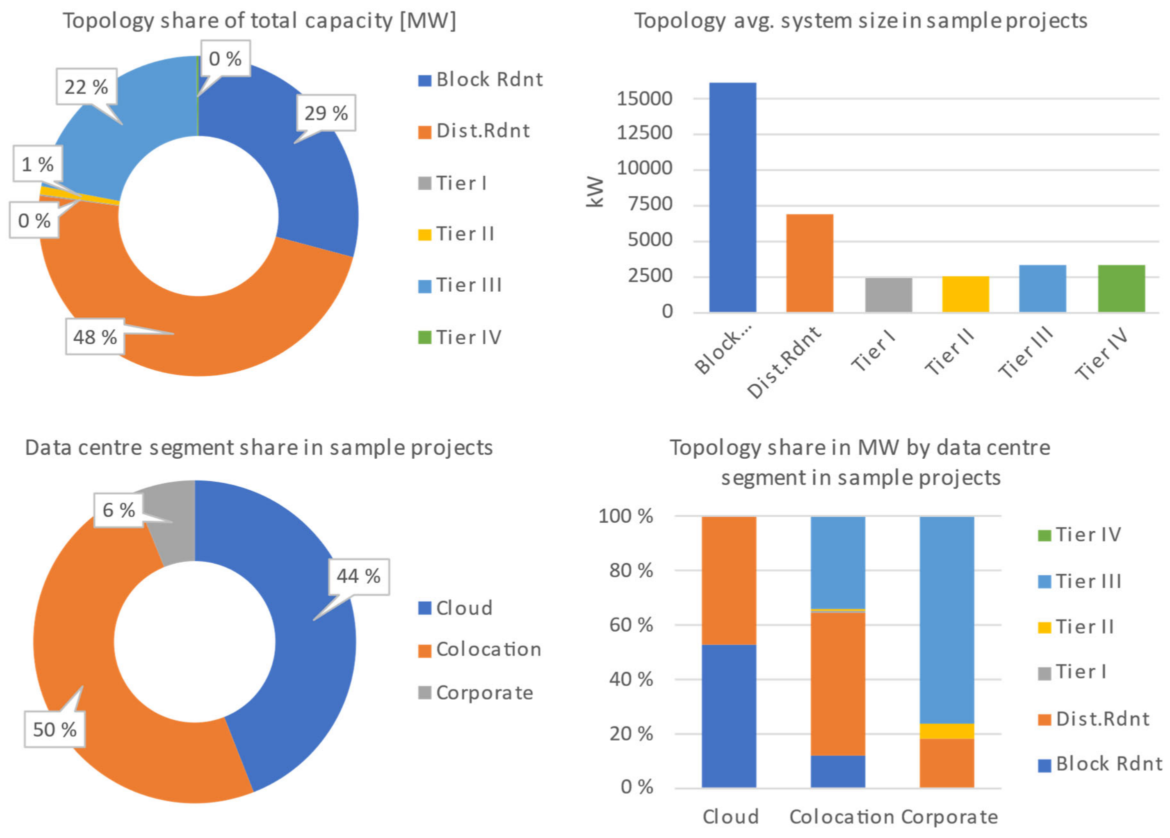

Figure 51. Share of topologies and data centre segments in sample projects

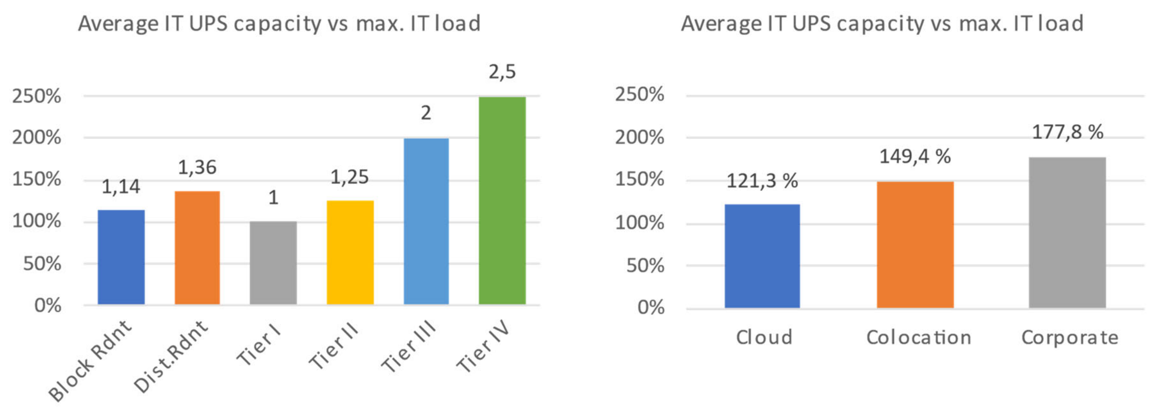

Figure 52. Average IT UPS capacity vs maximum IT load in the system

Tier II and Tier IV system overhead depends strongly on granularity of the system. A 4+1 configuration with 25% overhead was used here, but overhead could be higher depending on number of individual UPS units used in parallel. These topologies anyhow present about one percent of overall sample and therefore this possible inaccuracy has limited impact to overall results. The UPS system design overhead is lower with cloud service providers and colocation data centres when compared to traditional corporate data centres. This is expected as cloud segment almost exclusively uses block and distributed redundant topologies, and these present also a large share of used power distribution topology in colocation segment.

Based on the data centre segments presented in different countries (BloombergNEF, 2021, p. 19), the estimated UPS to design load ratio used here is 136,8% for the Nordics (average of all projects in the sample), 149,4% for the UK due to dominance of colocation data centres in the market, and 135% for Ireland that is a mix of hyperscale cloud and colocation.

Data centre share of UPS market

Most common application for a UPS is a data centre or other application where a UPS is protecting ICT equipment. According a recent market research report, Data Centre and IT applications have 78% share of 3-phase UPS market in Western Europe (Levy, 2021). The UPS units used to protect ICT equipment typically locate in a data centre or other facility dedicated for data processing, telecommunications and digital content delivery (media & entertainment), or they can be used in various other type of facilities protecting in-house ICT equipment, such as hospitals, education, etc. The share of UPS market vertical dedicated to data processing, communication and content delivery is lower, about 52% in Western Europe according the Omdia report (Levy, 2021).

As large >100 kVA static UPS units are predominantly used in data centres, the share of these from 3-phase UPS market is also an indicator of the share of UPS going to data centres. Some process industries would be an exception also using higher quantities of large UPS units. Here the reported 52% share is used for the Nordics and was adjusted to 57% for UK and to 75% for Ireland based on UPS market data (Eaton, 2022b).

7.3 Data centre capacity and UPS volumes

Available UPS market research data was compared to Eaton internal data on UPS unit shipments and sales figures for the countries, and there were major inconsistencies between data sets. As Eaton internal data is available for each individual order of a UPS equipment and can be pinpointed to a specific country with good accuracy, it was deemed more reliable. Instead of using external market research data to estimate the market size and UPS volumes, Eaton internal data and analysis based on market knowledge and using various data sources, complemented with detailed products shipment data, were used for the purpose. As this is strictly confidential information, only the final conclusions based on available data are shared here.

When evaluating the UPS capacity that could provide grid support, the UPS products with these capabilities were introduced to market on 2018 (pilots done in Nordics) and have been used since 2019. Not all UPS suppliers support grid-interactive features yet, but there's a clear trend to this direction. There are already more than one UPS supplier with grid-support capabilities built into products, and all are present in the markets. Depending on products, existing UPS products on data centre sites could be updated to enable grid-interactive capabilities. As such, the potential is more than new UPS units delivered since 2018.

To estimate the potential of added UPS capacity to provide Fast Frequency Response, the actual IT load supplied by a share of UPS assumed to have grid support capabilities has to be calculated. For example, assuming 50% of added UPS capacity into data centres can be leveraged for grid-support this capacity is divided by UPS to design load ratio and then multiplied with load utilization rate. Further assuming the 50% equals 100 MW, UPS to design load ration is 149,4% and load utilization rate is 45%, calculation goes as follows:

$$P_{\mathrm{up(no-exp)}} = \frac{P_{\mathrm{G-UPS}}}{149{,}4\%} * 45\% = \frac{100\ \mathrm{MW}}{1{,}494} * 0{,}45 = 30\ \mathrm{MW} \qquad (7\text{-}3)$$

Above example assumes that grid-interactive UPS units do not leverage the bi-directional capabilities and export power to their mains feed hence having the response limited to actual load level. When power export is allowed, even full capacity of the UPS can be leveraged for grid support and maximum response from UPS is same as their nominal capacity, 100 MW in above.

Table 6. Data centre capacities in UK, Ireland and Nordics

		Data Centre capacity [MW]	*Overall consumption* [MW]	*PUE*	*UPS capacity* [MW]	*UPS to design load ratio*	*IT design load* [MW]	*Utilization rate*	*IT load* [MW]
Nordics	(Tilastokeskus, n.d.) [2] (a)	98	**44**	*1,64*	82	*137 %*	60	*45 %*	27
	(DCByte, 2022) (b)	**900**	405	*1,3*	947	*137 %*	692	*45 %*	312
	(Saunavaara et al., 2022) (c)	**600**	270	*1,3*	631	*137 %*	462	*45 %*	208
	(Eaton, 2022) [1] (d)	**719**	324	**1,3**	757	*137 %*	**553**	*45 %*	249
	AVERAGE (b, c and d)	740	333	1,3	778	*137 %*	569	45 %	256
Ireland	(EirGrid & SONI, 2020d)	**625**	**256**	*1,3*	649	*135 %*	481	41 %	197
	(EirGrid & SONI, 2021)	**961**	**400**	*1,3*	998	*135 %*	739	42 %	308
	Derived from (CSO, 2022)	1071	*450*	*1,3*	1113	*135 %*	824	*42 %*	346
	(BloombergNEF, 2021)	**980**	**540**	*1,3*	1018	*135 %*	754	55 %	415
	AVERAGE (4Q-21)	1026	495	1,3	1065	*135 %*	789	48 %	381
UK	(Cloudscene, n.d.)	2387	1074	**1,36**	2622	*149 %*	**1755**	*45 %*	790
	(BloombergNEF, 2021)	**2100**	**830**	*1,36*	2307	*149 %*	1544	40 %	610
	AVERAGE	2243	952	1,36	2464	*149 %*	1650	42 %	700

1) Eaton internal DC market data
2) Values for Finland only
Values in **bold** from sources and in *italic* defined by author, rest calculated

Nordics

With limited amount of information available about data centre projects and industry, the estimates about Nordic data centre market vary. The existing power capacity of Nordic data centres is estimated to be 600 MW according Saunavaara, Laine & Salo (2022, p. 1). DC Byte (2022) stated 900 MW as existing data centre power capacity and over 200 MW annual growth since 2017. Earlier studies have estimated as high as 280 – 580 MW annual growth between 2018 and 2025 (Christensen et al., 2018, p. 36), while final use of electrical energy for ‘62-63 Computer and information service activities’ in Statistics Finland database is 1384 TJ (384 GWh) in 2019 (Tilastokeskus, n.d.). Using Eaton internal database, the Nordic market was estimated to be 719 MW.

The data from Tilastokeskus translates to 44 MW as average power drawn by data centres in Finland, that is a low value when comparing to number and size of data centres, such as Google, Yandex, Equinix, TietoEvry, Telia, Hertzner and CSC. Therefore, it is excluded from overall estimate.

Assuming 52% share of UPS products for data centre facilities, approximately 500 MW of UPS units (> 100 kVA) have been delivered into data centres between 2018 and 2021 (Eaton, 2022b). The growth in data centre capacity, which are using UPS units for load protection, is approximately 480 MW during the period when applying 136,8% as an average UPS to design load ratio and design PUE of 1,30.

The growth rate is lower than estimated by Christensen et al (2018, p. 36) and DCByte (2022). Probable explanation is that many data centre operators do not invest and install all infrastructure capacity on day-one. Instead, the approach is to pay-as-you-grow, and therefore the UPS market growth is not same as data centre design capacity growth. Also, part of data centre capacity does not use UPS units to protect IT servers.

UK

Data centre IT power (demand) in UK is estimated to be 830 MW and connection power capacity around 2100 MW according BloombergNEF (2021, pp. 19-21). Cloudscene (n.d.) mentions 1755 MW as the power capacity of 461 data centres in UK. This value refers to power available for IT loads. After applying mentioned PUE of 1,36 the overall capacity becomes 2387 MW. The IT load power consumption is 790 MW when applying load utilization rate of 45%.

If 57% share of >100 kVA 3-phase UPS products is going to data centres in UK, 1290 MW of UPS capacity has been added into data centres between 2018 and 2021 (Eaton, 2022b). Data centre design load capacity has increased approximately 860 MW during the period when applying 149,4% as an average UPS to design load ratio.

Ireland

Energy statistics provided by Sustainable Energy Authority of Ireland (n.d.) indicate 173 ktoe (thousand tonnes of oil equivalent) as annual electricity consumption for 'Information and

Communication' commercial services (NACE 58-63) in 2019. This translates to 2015 GWh and 230 MW as average power drawn from the electricity grid. EirGrid (2020d, p. 47) stated 256 MVA as power demand by data centres in Ireland synchronous area, and 625 MVA as connection power capacity in January 2019 (freeze date for report). There was a significant increase in a following year assessment (EirGrid & SONI, 2021, p. 45), that indicated 400 MVA as demand and 961 MVA as connection power capacity in January 2020. BloombergNEF study (2021, p. 19) indicates similar connection power capacity as EirGrid and 35% higher estimated power demand in December 2021.

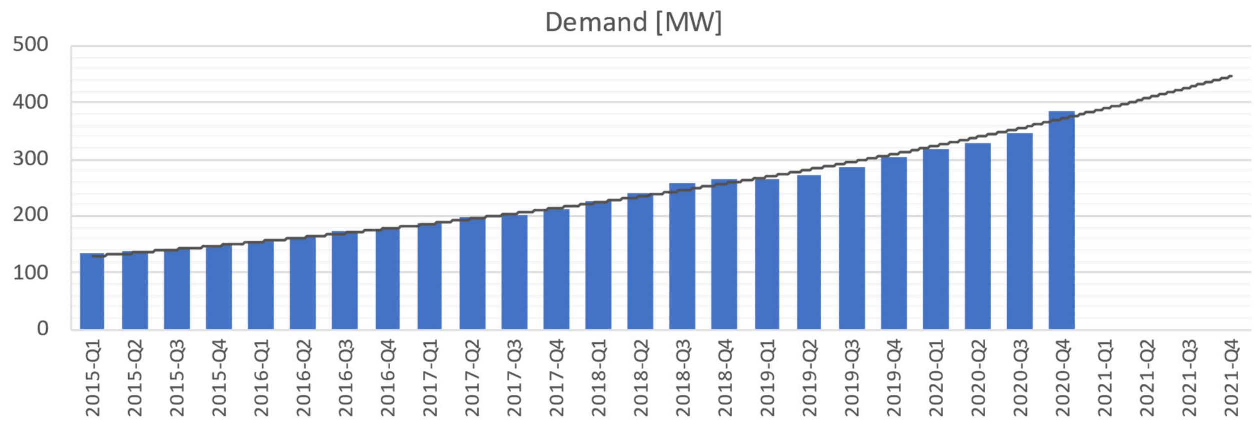

Figure 53. Growth of data centre power demand in Ireland

Central Statistics Office of Ireland (CSO, 2022) reports quarterly metered data centre electricity consumption data between 2015 and 2020. Using the data, average power demand can be calculated and plotted with a trend line. Resulting expected data centre power demand at end of 2021 would be 450 MW.

Based on EirGrid estimations on actual demand and connection capacities, load utilization rate in Ireland is 41% while BloombergNEF estimated 55%. Irish data centre market is dominated by hyperscale cloud and colocation data centres. Average UPS to design load ratio for these two data centre segments is 135% and 1,30 is applied as a typical design PUE. Calculated IT load power consumption in end of 2021 is 381 MW and design IT load is 789 MW. Estimated UPS capacity in data centres is 1065 MW.

Assuming 75% share of >100 kVA 3-phase UPS products is going to data centre facilities in Ireland, 530 MW of UPS capacity has been added into data centres between 2018 and 2021 (Eaton, 2022b). Based on UPS market data, data centre design load capacity has increased approximately 390 MW during the period when applying 135% as an UPS to design load ratio. This translates to 245 MW of added data centre demand when using defined ratios for PUE and load utilization, that is close to an estimate generated from quarterly data centre electricity use data provided by CSO.

7.4 Potential for Fast Frequency Response

To estimate the potential of grid-interactive UPS and data centres to provide FFR, the data centre capacities, demand and grid-interactive UPS potential response was compared to maximum and average FFR (DC-L) volumes in the market. The results are shown in Figure 54. It was assumed that 50% of static UPS capacity (>100 kVA) added to data centres in 4 years, between 2018 and 2021, would be upgradable to a grid-interactive UPS. This is excluding similar UPS units and capacity outside data centres. Maximum market volumes for FFR (DC-L) are specified as 300 MW for the Nordics, 810 MW for Ireland and 1000 MW for UK.

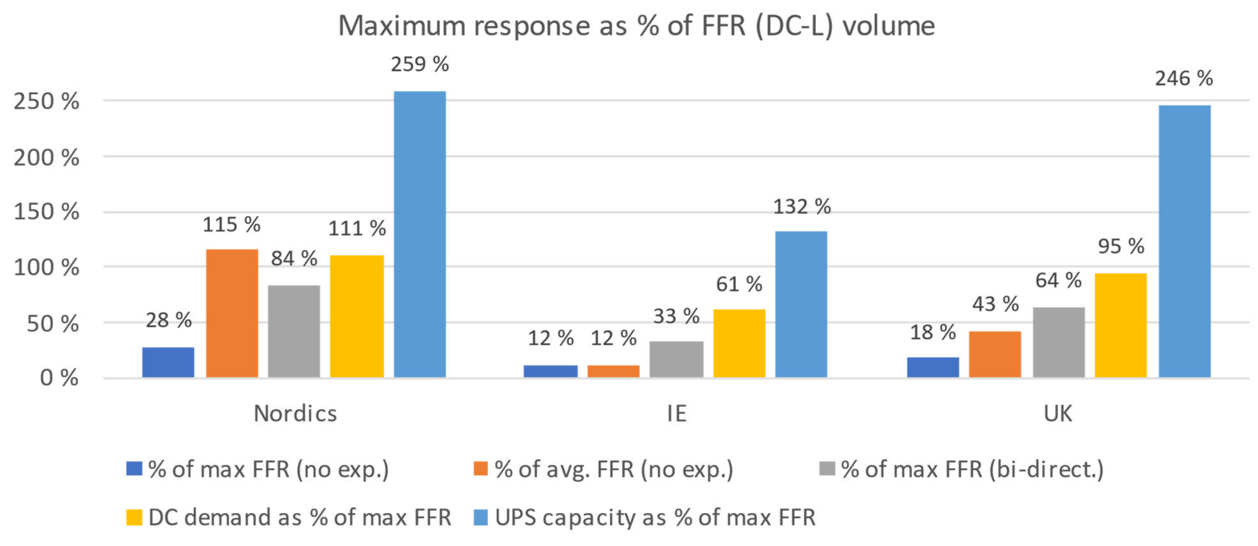

Figure 54. Grid-interactive UPS capacity and potential response as % of FFR (DC-L) volumes

When the response from a UPS is limited by the load connected to a UPS, without leveraging the bi-directional capability and to avoid injecting power back to UPS mains connection, the resulting response is lowest as expected. The potential amount of response is between 12% (Ireland) and

28% (Nordic) of maximum FFR (DC-L) volumes. In comparison to average market volumes the ratios are higher. Average volumes are calculated for hours FFR (DC-L) was acquired from the market, volume being higher than zero, during 2021 for Nordics and January – March 2022 for UK. In the Nordic potential response from UPS systems is exceeding the average acquired FFR volume, and in UK it presents 43% of average volume. In Ireland average and maximum volumes are the same.

When the bi-directional capabilities of grid-interactive UPS are used to provide load independent response, the size of maximum response from the grid-interactive UPS units is limited by their nominal capacity. These are 84% (Nordics), 33% (IE) and 64% (UK) of maximum FFR (DC-L) volume purchased from the market. As some UPS products can become grid-interactive by updating the control firmware, the UPS volume potentially providing grid support is not limited to shipments from past four years as assumed in calculations. In case of Eaton for example, most of products shipped during past 8 years could be updated to grid-interactive operation. As such, Eaton UPS install base alone could cover major part of, or completely, the needed FFR volumes.

Also, comparison between estimated data centre power demand and FFR market volumes was made. In UK and Nordic, the power drawn by data centres is similar to fast response market volumes, and about 60% in Ireland. When evaluating the overall installed UPS capacity in the data centres, this greatly exceeds the required fast response.

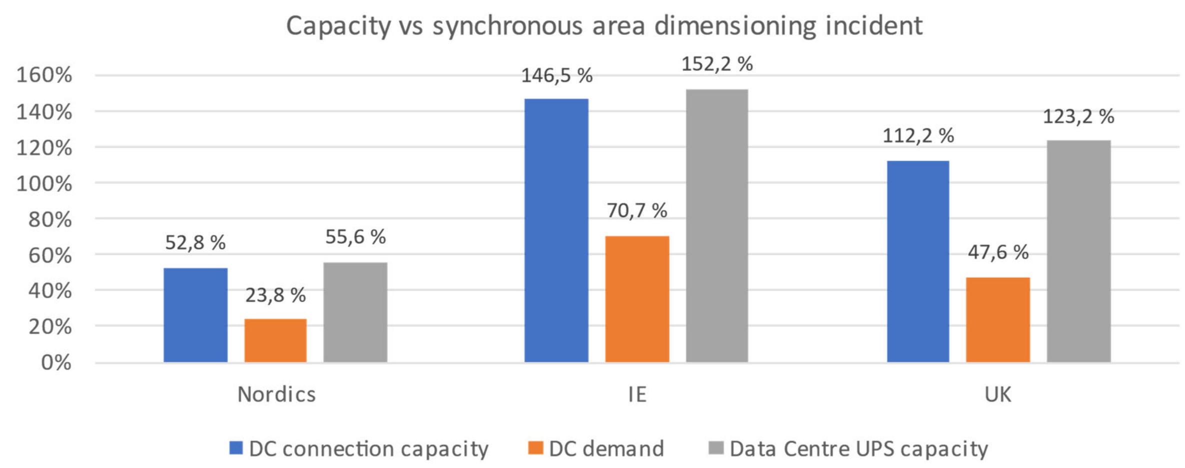

Figure 55. Comparison of data centre capacities against dimensioning incidents

Purpose of FFR is to provide a fast response in case of a large contingency event i.e., disconnection of a large(st) single infeed (LSI) that is typically a large power plant or offshore wind farm, or an HVDC line importing power from other synchronous area. As data centres can provide fast response to help to tackle the consequences after disturbance, it can be meaningful to compare the data centre capacities against dimensioning incidents in synchronous areas. The sizes of dimensioning incidents are 700 MW for Ireland, 1400 MW for Nordic and 2000 MW for UK. As the data centre demand is significant in comparison to dimensioning incident, it means that data centres can have an important role to provide fast response in case of large contingency events. This can be via participation in Fast Frequency Response, or by providing Under Frequency Load Shedding (UFLS) as a last resort to restore balance to system if primary reserves failed to do so.

8 Results

Fast frequency response is a new type reserve in frequency regulation markets aimed to mitigate challenges with low system inertia and to help manage contingency events. In Nordic and Ireland, the required energy is minimal due to very short response time. As such, those are well suited for a data centre UPS, even with traditional lead acid batteries, that doesn't typically have stored energy in the batteries for more than few minutes but can provide a fast response with semiconductor power converters.

Grid-interactive UPS technology has been piloted with transmission system operators and the technology is already in use in FFR markets in Ireland (Eaton, 2019) and Nordics (Eaton, 2021). The technical suitability of the solution was proven in the pilots in Sweden (Svenska Kraftnät, 2018) and Norway (Statnett, 2021) and the results are explained in more details by Alaperä, Paananen, Dalen & Honkapuro (2019). Also, the new UPS technology is no longer limited to Eaton products and other UPS manufacturers have similar capabilities and their products are used on FFR market as well (Fortum, 2022). Data centres are seen as potential provider of flexibility for the grid by system operators (EirGrid & SONI, 2021, p. 21) and the data centre potential for fast response is also supported by other studies (Al Kez et al., 2021).

According a survey with 380 respondents, 90% of data centre professionals are expecting adoption of grid-interactive UPS technology within next 4 years (Levy & Galabov, 2022). This indicates wide acceptance for the solutions in the market, also among large data centre operators, such as Microsoft, who actively promotes grid-interactive data centre as a future solution (Paananen & Nasr, 2021). Sustainability and corporate image are highest drivers for the adoption of grid-interactive UPS technology (Levy & Galabov, 2022). Also, the financial compensation received from participation in ancillary services markets is increasing the willingness to adopt the new grid-interactive UPS technology.

The feedback about grid-interactive UPS in Omdia survey was more positive than expected, based on scepticism observed personally among many data centre professionals during past years. Same time more and more data centre professionals and associations are talking about the concept, and more suppliers are coming with solutions to market while early adopters are already doing it. All this probably drives acceptance in the market, that can be seen in the Omdia survey (Levy & Galabov, 2022).

Results on potential to provide fast response were mostly as expected, and the data centres can have a significant contribution on stabilizing the grid during low inertia. Considering the size of large data centres, their central location in the grid, and very high power density, they are optimally suited to provide system services and flexibility for the grid with their existing power infrastructure. Another important aspect of using grid-interactive UPS vs other industrial loads, is the capability to perform load shedding without interrupting the main process (production) by temporarily moving the loads on batteries. Also, dual purposing the existing data centre assets, primarily used to support digital society, reduces need to build dedicated reserves into the system. This reduces cost of system balancing, use of natural resources and embodied carbon in the system. All this is reducing the socioeconomical cost of the grid balancing and is smarter use of assets.

The large impact of data centre utilization rates to maximum response was not expected, even logical, when the response is limited to actual load level of a UPS. This becomes a limiting factor in data centres operating at lower load levels when exporting power is not allowed or wanted. It highlights the importance of bi-directional capabilities and load independent response of a grid-interactive UPS, as this allows to leverage installed UPS capacity much more efficiently for grid support. In other hand, hyperscale cloud providers operate at much higher utilization rates hence having less limitations for maximum provided response, also when not exporting the power. In a long-term, grid-interactive UPS shall have bi-directional capabilities while fulfilling the grid code requirements when injecting power to grid.

9 Discussion

Challenges in this study related to scattered information to high number of publications from different sources, and in some aspects lack of accurate measured data or variation of it between different sources. Also, some of the data needed to derive the results and answer the research questions was not available requiring some supporting research to be done, increasing the amount of required work. Some of the sources used had to be company internal confidential data hence reducing the transparency of the work in some parts as an unwanted consequence. The results are reported following a good practice and used principles were explained where detailed data couldn't be shown.

Results we're mainly as expected highlighting the importance of similar and future studies to estimate the potential of existing assets in the system to provide the required flexibility for future energy system. As we are creating emissions by consuming and manufacturing goods and materials, the solution to problem is not manufacturing more goods and materials or moving production to other side of world. Smarter use of resources is needed to reduce the overall burden on environment and more research is needed to find resource efficient solutions for our future needs.

Amount of data centres, to support digitalization and use of digital services, is growing rapidly. As a consequence, also the energy consumption of data centres is growing and in some areas data centres can consumer significant share of electricity and there has been publicity around the data centre energy consumption, often in negative light. It is good to remember that these digital factories provide the services for consumers, to all of us. The energy efficiency of data centres has improved in past years, and especially the largest digital factories provide the services with much less energy while being largest corporate purchasers or renewable energy and using innovative technologies to meet their sustainability goals.

In Ireland the estimated 500 MW of power demand equals 16% of the grid demand (3,1 GW) during summertime, same numbers are 1% for Nordics and 3% for UK. When adding fixed and mobile telecommunication networks to overall electricity consumption of ICT, the share of global energy consumption is significant. Therefore, more transparency is needed on reporting the energy consumption of this sector, to support the future policy making. Largest global data centre companies already publish their annual energy use in environmental & sustainability reports, some even for each data centre site separately. Reliable ICT sector energy consumption reporting is important also in national and European level, but today these ICT is not listed as its own sector among other industries or services in the statistics.

Understanding the potential of data centres to provide flexibility and fast response for the grid, highlights also the importance of policy making in relation to grid balancing and frequency regulation. Data centres today are an underutilized asset filled with expensive power infrastructure, that with recent technological development can be a useful and substantial asset for the grid. The policies and practices around grid balancing are still often based on old power generation technologies, not driving the adoption of new technologies and especially helping to leverage existing demand side assets in the system.

There seems to be market acceptance and first data centres are already grid-interactive, while large global companies are planning to do it. Future for grid-interactive UPS and data centre looks promising, as long as it can be economically feasible and market rules allow to efficiently leverage data centre assets. Especially when also adding the potential to reuse of data centre waste heat for district heating into picture, a modern data centre can have an important role in a modern society and future energy system to help to reduce greenhouse gas emissions. Therefore, when creating the market rules, these new possibilities shall be considered as this can reduce the environmental impact and socioeconomical cost of the solutions used to support the energy transition and path towards a cleaner electricity grid. Also, policies could be applied to further encourage large energy user to participate in grid support activities, such as energy tax and tariff reductions for grid-interactive energy user, who help to achieve our common sustainability goals. Eventually, smarter use of assets saves environment and makes the energy transition more affordable to all of us.

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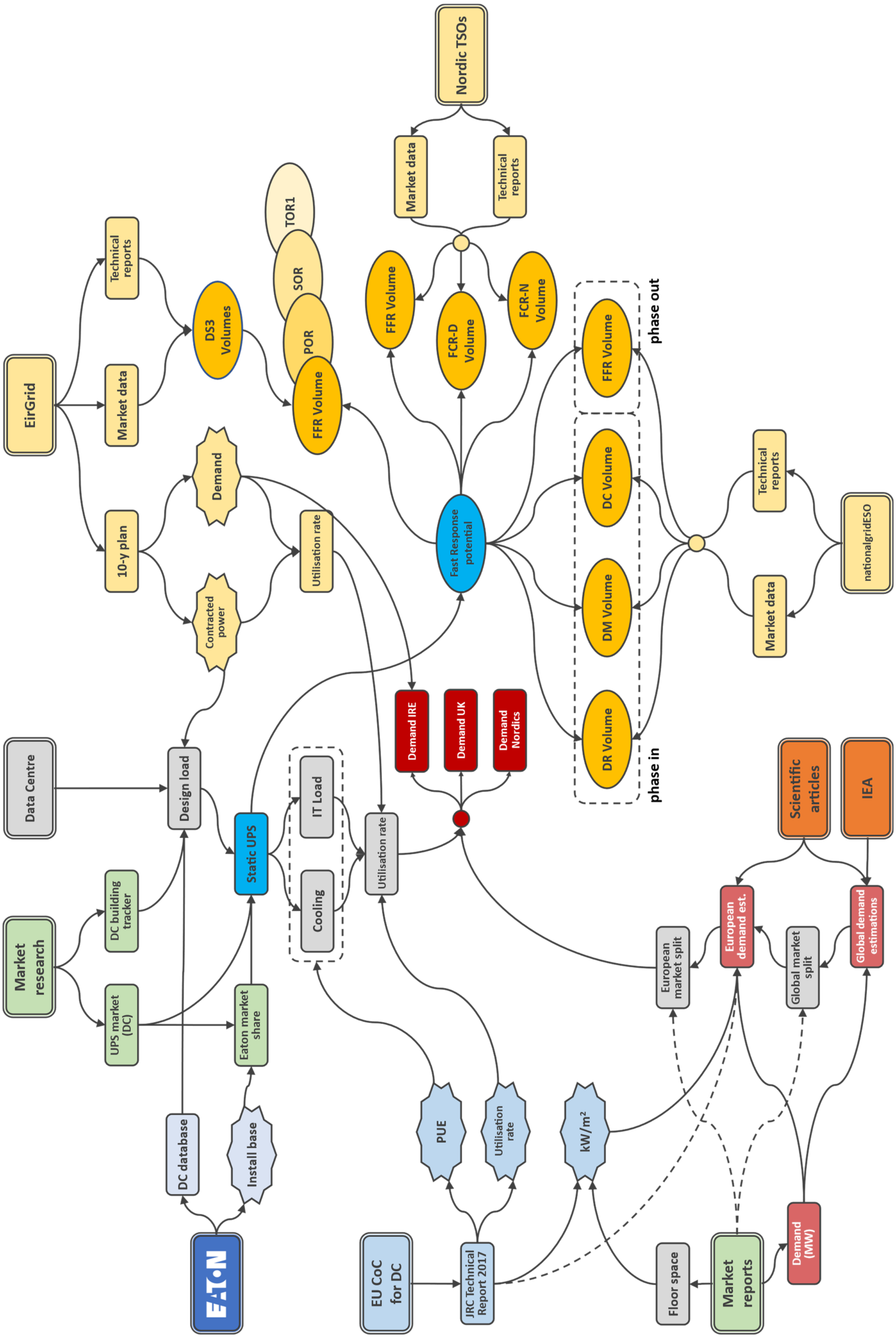
Appendices

Appendix 1. Mindmap – correlation of various data and sources



Appendix 2. Mindmap – data centres, grid and frequency containment