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Research paper

The need for energy storage on renewable energy generator outputs to lessen the Geeth effect, i.e. short-term variations mainly associated with wind turbine active power output

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ABSTRACT

Many studies investigating the short-term variations associated with the power output from wind turbine generators utilise simulated or modelled data in the analysis. This current study uses short-term empirical data downloaded directly from operational wind turbines via electrical power quality meters. The empirical data shows that the short-term variations (one-second or sub-one-second timeframe) occur continuously over most of the power output range. A novel name is proposed, the *Geeth Effect*, for this variability phenomenon. The Geeth Effect is measured using the coefficient of variation mathematical expression and is likely contributing to (i) lower-than-expected financial and environmental benefits associated with the vast increase in connected wind turbine capacity, (ii) significant challenges faced by the transmission system operator as they seek to deliver a stable electricity grid. Calculated coefficient of variation values include 64% (10-kW wind turbine), 46% (300-kW wind turbine), 30% (3-MW wind turbine), 1.4% (169-kW solar PV), and 3.2% (40-kW hydroelectric plant). Energy storage methods are recommended to minimise the Geeth Effect. Recommendations include the installation of (i) filters (supercapacitors) and (ii) battery energy storage systems, both systems connected to the output stage of the wind turbine generators. Supercapacitors are the preferred choice for wind turbines because of the continuous charge/discharge cycling events, which can be detrimental to battery energy systems. Low coefficient of variation values are desirable and high values undesirable.

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1. Introduction

Despite the vast increase in renewable energy penetration, particularly wind-generated energy, as part of the overall electrical energy mix, there is no universal satisfaction that substantial improvements are being made. Challenges remain regarding the successful integration of renewable and traditional sources of energy into national electricity grids. This study assesses one cause of the dissatisfaction, namely the short-term variability associated with wind turbine power outputs. One of the unique characteristics of this study is that the researcher downloaded experimental data from several renewable energy sources during the duration of the study. High-quality electrical power meters were connected to renewable energy sources and the primary data was utilised in the analysis process.

The basic theory of wind turbine operation is derived from a first-principles approach using the conservation of mass and conservation of energy in a wind stream. The electrical power generated is proportional to the cube of the wind speed and the swept area. Power captured from the wind can be expressed as in Eq. (1):

$$P(t) = 0.5\rho\, A\, C_P\, v_w\ (t)^3 \tag{1}$$

where – ρ is the air density in kg/m^3, A is the swept area of the wind turbine blades in m^2, C_P is the coefficient of power conversion, and v_w is the instantaneous wind speed value in m s^{-1}. C_P is a value based on an interference factor, the interference caused by the rotor blades obstructing and removing some of the kinetic energy from the wind. This causes the turbine speed to reduce. The reduction in turbine speed reduces the turbine power output.

While wind turbines are increasingly used to harvest electrical energy from a renewable energy source, the turbines operate in a turbulent flow environment. Turbulence is likely to cause highly varying electrical power fed into either (i) the national electricity grid or (ii) directly to on-site localised connected loads. Turbulence is manifested by differences in the wind's speed and the wind's direction. The reason for turbulence is down to two factors, namely (i) friction with the earth's surface, and (ii) thermal effects which can cause air masses to move vertically as a

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Nomenclature

BESS	Battery Energy Storage System
BM	Balancing Mechanism
CEN	(French) Comite Europeen de Normalisation (English) European Committee for Standardisation
CENELEC	(French) Comite Europeen de Normalisation Electrotechnique, (English) European Committee for Electrotechnical Standardisation
CV	Coefficient of Variation
DC	Direct Current
EN	European Standards
ESO	European Standards Organisations
ESS	Energy Storage Systems
ETSI	European Telecommunication Standards Institute
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
MW	MegaWatt
MWh	MegaWatt hour
NGESO	National Grid Electricity System Operator
PMSG	Permanent Magnet Synchronous Generator
PP	Payback Period
SCADA	Supervisory Control And Data Acquisition
SEMO	Single Energy Market Operator
SNSP	System Non-Synchronous Penetration
SoC	State of Charge
TPD	Total Power Distortion
TSO	Transmission System Operators
UK	United Kingdom
WTG	Wind Turbine Generator

result of variations of temperature and hence in the density of the air (Jenkins et al., 2021). Milan et al. (2013) show that the complex structure of turbulence dominates the spectral characteristics of the wind turbine power output. The limited efficiency of a wind turbine is caused by the braking of the wind from its upstream speed to its downstream speed while allowing a continuation of the flow regime (Ragheb and Ragheb, 2011). We may express wind turbulence using Reynold's number system, with high Reynold's numbers showing a turbulent wind flow.

Increased variations in renewable energy power outputs (mainly wind turbine generators) and turbine loads can have a significant effect on the stability of the electricity grid in some situations. The quality of electrical power and its related term electrical energy are essential in the narrative surrounding national electricity markets. Many modern appliances and loads connected to the national grid are increasingly sensitive to power quality issues. There are well-established power quality standards and grid codes that must be adhered to when electrical generating companies install new generators and export power to the national electricity grid or use the generated energy on private sites. However, the established metrics used for power quality analysis of traditional, mainly fossil-fuel, generating plants may not capture some phenomena associated with renewable generating plants. The relatively recent increase in renewable energy generators supplying parallel-connected loads has brought the power, energy, and quality facet to the fore. Wind turbine generators (WTG) are deemed a significant perpetrator in the 'greening' of electrical power sources. This study proposes a new expression, termed the 'Geeth Effect' and is the name applied to the short-term, i.e. one second or less, variations in the active power output from renewable electricity generators, notably wind turbines. Gaoth (pronounced Geeth) is the Gaelic word for '*Wind*'. The terms power quality and energy quality are used interchangeably in this current study. Power quality is primarily concerned with the quality of voltage and current waveforms. In contrast, energy quality is concerned mainly with the quality of power or power flow waveforms over specific periods. The quality of power integrated onto the national electricity grid, from every source, must comply with national power quality standards and grid codes.

Standards, including power quality standards, provide rules, guidelines, or characteristics for activities or their results, for common and repeated use. Stakeholders that help create and develop standards include regulators, manufacturers, end-users, non-profit organisations, and academic institutions. The IEEE SA (Institute of Electrical and Electronics Engineers Standards Association, www.standards.ieee.org) is a consensus-building organisation that develops standards in various industries, including power and energy. The IEC (International Electrotechnical Commission, www.iec.ch) is an international standards organisation that prepares and publishes international standards for all electrical, electronic, and related technologies, collectively known as *electrotechnology*. EN (European Standards) are documents that have been ratified by one of the three European Standards Organisations, CEN, CENELEC, or ETSI. All the standards are produced and developed by collaborating with interested stakeholders through a transparent, open, and consensus-based process. Referring to the IEEE, IEC, and EN standards throughout this review study.

Grid codes are technical regulations for transmission system operators (TSO) and power plants to follow. The codes aim to ensure compliance to provide a reliable electricity grid. Each national authority may have different grid codes specific to its transmission requirements.

2. Methodology

The multiple case study research methodology is utilised in this study. The four wind turbine case studies analyse the variations in the active power output from four differently sized wind turbine generators, namely a 10-kW, a 300-kW, an 850-kW, and a 3-MW wind turbine. Experimental data was used in two separate case studies to generate Fig. 6 (169-kW Solar PV system) and Fig. 7 (40-kW Hydroelectric generator). The data was gained directly at each individual site, following permission granted by the site owners. The researcher visited the site on several occasions between 2014 and 2020. The power output plots presented in Figs. 1 to 7 utilise data from non-controlled real-life conditions. Case studies are a commonly employed empirical strategy in research (Hughes and McDonagh, 2017). Publications that present real-time, short-term, power output data are reviewed (Kealy, 2020, 2017, 2014). Primary, experimental data for the case studies (Kealy, 2020, 2017, 2014) were gained from the wind turbines/Solar PV/Hydroelectric plant by connecting a FLUKE 1735 Power Logger on the output cables from the turbine and setting the resolution to the desired value, i.e. half-second intervals. The data was downloaded from the power logger to the researcher's PC, where SPSS was used to analyse and present it. The Coefficient of Variation (CV) statistical value was used to quantify the dispersion of power output values around the mean. The CV value shows the severity of the Geeth Effect. The CV value is found by dividing the standard deviation (SD), symbol σ, by the mean, symbol μ, demonstrated in Eq. (2):

$$CV = \frac{\sigma}{\mu} \tag{2}$$

The CV is a valuable and appropriate statistic for comparing variation from different renewable energy sources, even if the means are radically different from each other.

3. Literature review

3.1. Problems associated with renewable energy variability and intermittency

There is a significant increase in the global capacity of operational wind turbine installations. In Ireland, there is an exponential growth in the connected capacity of wind turbine installations. Irelands Climate Action Plan (2021) is significantly driven by this increase and its aim of reaching a target of 70% of its electricity generated by renewable sources by 2030. However, the variability and intermittency associated with renewable sources have presented some challenges for the Transmission System Operator (TSO). To ensure a stable electricity grid, the TSO (in Ireland, the company is named Eirgrid) has put a limit of 65% on the amount of renewable energy sources supplying the grid at any one time. This limit is termed the System Non-Synchronous Penetration (SNSP) limit. The TSO are the guardians of this limit and can reduce the output of connected wind farms when the 65% SNSP limit is exceeded. This reduction is called 'Dispatch Down', and the two principal components of dispatch down are (i) curtailment and (ii) constraints. Conventional generators provide the remaining power requirement, such as Combined-Cycle-Gas-Turbines (CCGT), which provide proven stability to the national electricity grid. Curtailment occurs typically during periods of high wind energy generation. In EirGrid's 'All Island Quarterly Wind Dispatch Down Report' 2020 (page 1, Quarter 4), we can see that 12.1% of lost generation was down to TSO dispatch down restrictions.

In the fifteen months between July 2020 and September 2021, the Single Energy Market Operator (SEMO) issued seven system alerts to warn of capacity shortages on the Irish electricity grid, compared with just 11 alerts over the previous 10 years. One criterion by which the amber alert is activated is that the margin between the electricity supply and the electricity demand is so small that losing one large generation set would give rise to a reasonable possibility of failure to meet the system demand (SEMO, 2021). The increase in amber alerts coincided with the closure of two peat-power generating plants. The decommissioned plants were the 135-MW Lanesboro plant in County Longford and the 100-MW plant in Shannonbridge in County Offaly.

The curtailments and constraints associated with the variability and intermittency of renewable energy generators are likely to be contributing to the less than obvious financial and environmental benefits expected from the exponential growth in wind turbine installations. The simplistic consensus is that wind energy is free. However, integrating wind energy onto the national electricity grid is not free. For example, In the UK, the National Grid paid wind farms £1.8 m over three days (week beginning 20th September 2021) to shut down 38 wind farms as constraint payments to help balance supply and demand across the electricity network (Mendick, 2021). The affected wind farms were all situated in Scotland and the constraint decision was taken because the generated electricity that would have been produced could not have reached the regions that needed it. Unsurprisingly, the financial cost of electricity to customers has risen over the past number of years. One reason for this increase is that additional operational and infrastructural projects that need to be undertaken because of the increase in renewable energy penetration are passed on to the consumer. While the cost per unit of electrical energy to the customer (domestic, commercial, industrial) reduces a complex metric with an array of technical issues into a much simpler one, it shows how effective and efficient the production of electricity is in that country. From an environmental viewpoint, Kealy (2019) found that an increase of 43% in connected wind turbine capacity in Ireland between 2014 and 2017 resulted in a much smaller energy benchmark improvement (g CO_2 per kWh) of just 5% for the same period. The disappointing benchmark results may be linked to studies by Herp et al. (2015) and Morales et al. (2012), who show that wind flow variability affects the power output of wind turbines. Variability affects the power quality of the turbines. Power quality literature focuses mainly on variations and distortions of voltage and current waveforms. The relatively recent step-change in renewable energy generators supplying the electricity grid has highlighted the significance of the variability and intermittency from these renewable sources. Variability is short-term dispersion, while intermittency is considered a longer-term issue in renewable energy generators' power output signals. It is in this context that energy quality is perceived as a significantly important issue. Power quality mainly considers voltage and current waveforms, while energy quality is primarily concerned with the quality of power or power flow waveforms over time (Zhang and Yan, 2020). The increase in distributed generation (DG) has posed problems for distribution system operators (DSO) in that the quality of the renewable output power and energy must be of the same high standard associated with traditional, mainly thermal, generators (Jasinski et al., 2020). Conventional power systems have traditionally generated consistent, steady, and extremely controllable active power outputs (Zhang and Yan, 2020). A good-quality, stable output is essential to supply the plethora of connected loads, many of which are sensitive to irregularities in electrical power quality (Gaikwad and Reddy, 2020). One problem with traditional power quality standards is that they do not routinely consider the short-term (one-second or sub-second) active power output variations as part of their power quality assessment criteria (Kealy, 2021). The increase in renewable energy penetration may force power quality companies to consider adding this parameter to the suite of conventional parameters established over many years. Traditional, fossil-fuel, driven electrical generators had steady outputs that did not require one-second or sub-second analysis.

Two of the most common DG renewable energy sources are solar photovoltaic (PV) systems and wind turbine generators (WTG). With solar PV systems, passing clouds induce short-term variability in their electrical output. Brinkel et al. (2020) claim that the major problems caused by this PV phenomenon are voltage fluctuations and light flicker, and in their study, they used 20-second resolution. However, it is unlikely that PV output fluctuations will violate any of the parameters associated with the flicker standards in the EN-50160, as cloud transients take a few seconds. A PV study by Marcos et al. (2011) utilised a short-term resolution, namely one second, and found output fluctuations of 80% of the installed PV capacity. Energy storage systems (ESS) may be utilised to counteract the short-term variations. ESS is characterised by its power capacity (MW), energy capacity (MWh), ramping capabilities (or response speed), and lifetime efficiency. The operation of energy storage may also be limited by cycle-life efficiency (Makarov et al., 2012). Two of the established ESS solutions are (i) battery energy storage systems (BESS) (Xia et al., 2015; Yang et al., 2020) and the use of filters (capacitors/supercapacitors) (Ammar and Joos, 2014). The short-term variations in wind turbine power outputs (less than one second) mean that BESS's short charge/discharge cycles negatively affect battery performance. This issue can lead to battery wear and lifetime reduction (Mohammadi et al., 2020). One strategy that can counteract battery microcycles is to use a hybrid combination of BESS and supercapacitors.

The presence of the supercapacitor extends the lifetime of the battery unit (Ammar and Joos, 2014). ESS used on Double Fed Induction Generator (DFIG) wind turbines positively influence power control, power dispatch, energy management, and power quality (Dosoglu and Arsoy, 2016). Supercapacitors regulate the electrical torque and inertia of the DFIG by providing short-term frequency support (Hao et al., 2015). Peguelores-Queralt et al. (2015) claim that it is essential to maintain a 50% State-of-Charge (SoC) to maximise the smoothing capability of a supercapacitor energy storage (SCES) system. Any values below the 50% SoC value limit the system to deliver the energy to the load/grid. SoC's high values would not allow the supercapacitors to absorb the energy needed for power smoothing. Zakeri and Syri (2015) claim that (super)capacitors are the most direct method to store electricity, offering a fast response to life cycles of tens of thousands and very high efficiency.

For overall grid frequency control, batteries, combined with PV systems, need to provide an equal response in both a positive and negative direction. This means that the battery SoC must be kept at a nominal percentage of its rated voltage, perhaps 60%, to have the capacity to be charged and discharged at an equal rate and for a similar time (EFCC, 2015). Pairing renewable electricity generation with battery storage works exceptionally well with solar energy, which follows a predictable daily pattern. This combination would help with a 'levelling out' between supply and demand and replace fossil-fuel 'peaker' plants that kick in for a few hours when energy demand rises.

Similarly, it is well established that variations in WTG's 'active power outputs have been problematic for parallel-connected thermal, mainly fossil-fuel driven generators (Cullen, 2013). While some conventional double-conversion wind turbines have electrolytic capacitors connected to the DC link, these capacitors only filter any voltage ripple on the DC link and cannot store significant amounts of energy produced by the turbine (Mandic et al., 2013). Cullen (2013) claims that short-term variations in the wind turbine outputs reduce renewable generators' expected environmental and economic benefits. An added challenge brought about by the increase in grid penetration of renewable energy is the flexibility required of the parallel-connected thermal power generating plant to adapt to the ramp rates and variations of the renewable sources (Witkowski et al., 2020). Thermal power generating plants comprise heavy-duty, weighty machines (Slawinski et al., 2020) and may not, on their own, cope with the variability inherent in renewable energy systems. Back-up thermal generators increase the infrastructural and operational costs which, ultimately, are borne by the consumer. In a study by Okazaki (2020), the author presents a workable solution and claims that energy storage is essential to cope with renewables' intermittency and suggests a synchronous rotating heater as a valid remedy. While this may be a reasonable proposal, it focuses on the longer-term energy storage issue in the multiple hour range. In contrast, this current study is focused on the short-term, sub-second variability in the turbine power output.

Zhang and Yan (2020) claim that variations and intermittencies from renewable energy generators have increased balancing market costs. Balancing the level of supply, i.e. inputs to the national electricity grid, and level of demand on a moment-by-moment basis, i.e. loads connected to the grid, constitute a significant challenge to the grid operators. One solution to the balancing challenge is battery energy storage systems (BESS). BESS systems are connected to the grid using rectifiers and inverters. The value of the grid frequency can detect the supply/demand imbalance. The BESS system imports energy to the battery pack when the system frequency is above a nominal value and exports power/energy back into the grid when it is below the nominal value. Also, BESS helps improve short-term power quality, e.g. smooth power fluctuations and frequency regulation, and longer-term energy management benefits, e.g. energy arbitrage and peak shaving (Mantar Gundogdu et al., 2019). BESS are capable of fast response to import/export demands in the millisecond time range. Businesses can apply to provide some of the balancing mechanisms on national electricity market tendering schemes. The Balancing Mechanism (BM) is a tool used by the UK's National Grid to balance electricity supply and demand in real-time. The UK has a peak demand of approximately 80-GW (compared to 6-GW in Ireland). When electricity generation and consumption are not in balance, the National Grid uses the BM to purchase generation and consumption changes to correct the mismatch. The increase in variable and intermittent energy from renewable sources, such as wind turbine generators and PV installations, coming onto the grid is making it more challenging to balance the network. In the UK, the National Grid Electricity System Operator (NGESO) had a balancing cost that was 39% higher than expected in the spring and summer of 2020 (NGESO, 2020).

While 10-minute intervals for data collection are the norm in many supervisory-control-and-data-acquisition (SCADA) monitored wind turbine applications, shorter-term resolution data are not generally analysed in the one-second or half-second range. Power quality analysers measure at sub-second intervals, but the resulting data is averaged over ten minutes and stored for external evaluation. Wind farm operators seem keener to get averaged data than instantaneous data. Averaged data may be easier to cultivate a monetised model than instantaneous data. Kealy (2020, 2017) used proprietary power logging tools to generate real-time, half-second interval data from WTG autoproducers. The data logger was connected to the cables wired to the WTG output, and the empirical half-second data was used in the study. The empirical data was downloaded during normal operating conditions and led to significant findings regarding the power output signal dispersion. The empirical data was beneficial in that much of the previously published literature made use of either (i) modelled/simulated turbine power output data generated under stringently controlled test conditions which may not reflect the power output data under normal operating conditions (Bandi and Apt, 2016) or (ii) lower-resolution averaged data. Previous studies present findings using hourly data (Kaffine et al., 2012), half-hourly data (Di Cosmo and Malaguzzi Valeri, 2018), 15-minute data (Katzenstein and Apt, 2012) and 10-minute averaged data (Shoaib et al., 2019). However, Apt (2007) used 1-second turbine power output data to estimate the power quality and estimate several wind farms' power spectrum. Wind farms compliant with relevant grid codes require basic SCADA information to be exchanged with the Transmission System Operator (TSO) (Nycander and Soder, 2018).

An operational BESS/WTG hybrid system is the Tullahennel Wind Farm in the South-East of Ireland. The wind farm comprises 13 wind turbine generators, each with a power output of 2.85-MW. Each turbine has a separate lithium-ion battery at the base of the tower. The batteries can store 69-kWh units of electrical energy. Under a 15-year purchase agreement, all of Tullahennel's power generation will go to Microsoft Corporation data centres. The BESS is expected to reduce the amount of fossil-fuel plants idling in the background to meet electrical energy demand, should the load change or the wind speed drop.

3.2. International power quality standards for all electrical power generators

One method of ensuring that renewable energy generators produce good quality power/energy is for each electrical generator output to conform to international power quality standards. The power quality standards have pre-defined parameter settings, and when the settings are not violated, the power quality is deemed a 'gold' standard. Power quality parameters typically include voltage characteristics, frequency stability, harmonics, and flicker. Flicker is a common short-term power quality issue in wind turbine generators, whereby the output voltage varies between 90% and 110% of the nominal voltage (Shiddiq Yunus et al., 2020). Continuous variations in the amount of connected power (electrical loads) can cause this flicker phenomenon. The human eye can see flicker as changes to light sources' illumination intensity, caused by voltage fluctuations (Saadat et al., 2020). The traditional power quality standards do not include a parameter to show the short-term (sub-second) variations in the active power output over time, i.e., energy quality (Kealy, 2021). The measure/indices proposed here to characterise the short-term variations are the coefficient of variation, showing the Geeth Effect's severity. Some researchers (Zhang and Yan, 2020) claim that the coefficient of variation characteristic is the same as Total Power Distortion (TPD). Previous studies (Kealy, 2020) found that the short-term variations are an essential power/energy quality component, particularly in wind turbine generator outputs. Short-term variations significantly influence renewable energy sources' overall effectiveness and contribute to less-than-expected economic and environmental benefits. Kealy (2019), using national energy benchmarks, found that, while there was a 43% increase in the country's installed wind turbine capacity between 2014 and 2017, there was a corresponding carbon emission benchmark improvement of just 5% for the same period.

Some of the common power quality standards considered in this research include:

- IEC/EN 61000-4-30 (Testing and measurement techniques — Power quality measurement methods)
- IEC 61000-4-15 (Specifications of flickermeter for Voltage fluctuation measurement)
- EN 50160 (Voltage characteristics in Public Distribution Systems)
- IEC/EN 61000-2-4 (Electromagnetic compatibility (EMC): Ambient conditions, compatibility level for low frequency, conducted interferences in industrial plants)
- IEEE 519 (Recommended practices and requirements for Harmonics Control in Electrical Power Systems)

Based on international standards for measuring and assessing the power quality in grid-connected wind turbines, some measured parameters include voltage fluctuations, current harmonics, active and reactive power control, grid protection, and reconnection time (Redondo et al., 2019). Grid protection, under the guidance of grid codes, of distributed renewable energy sources is typically provided by either the installation of an embedded generation interface protection (EGIP) relay on the output stage of the larger generators or compliance with the EN-50438 standard on the inverter stage of the smaller renewable micro-generators. The EGIP disconnects the renewable generator from the electricity utility network should any wind turbine power output parameters stray outside the programmed pre-set limits. It is a dedicated circuit breaker or recloser and is located as close as possible to the interface between the wind turbine and the utility distribution network. One of the EGIP relay functions is to ensure that the wind turbine's power quality is up to the same high standard as the power quality in the network distribution system. This comparison allows synchronising the two supplies, i.e. the utility electricity supply, with the renewable electricity supply (Mastromauro, 2020). The EGIP scrutinises over-voltage and under-voltage, over-frequency and under-frequency, over-current protection, and Loss-Of-Mains protection (ESB Networks, 2016).

The EN 50438 standard outlines the requirements for micro-generating distributed renewable energy sources connected in parallel with public low-voltage distribution networks. The standard is adhered to in an embedded 10-kW wind turbine (Kealy, 2014). All installed micro-generators must comply with EN 50438 with the specific Irish protection settings (ESB Networks, 2018).

3.3. Grid codes for all electrical generators connected to the electricity grid

Companies that plan to connect their renewable energy generators to the electricity grid must comply with local or national grid codes. Compliance with grid codes imposes minimum technical requirements and ensures a reliable and stable power system (Nycander and Soder, 2018). We must adopt grid codes to ensure that the increased wind turbine capacity does not endanger the power system's reliability. Grid codes are concerned with voltage and frequency tolerances, active power and frequency control, reactive power and voltage control, data and communications, and requirements under disturbances. The key requirement under grid disturbances is the low voltage ride through, so a wind farm should not disconnect from the grid under a temporary voltage drop before a fault is cleared and the voltage restored (Nycander and Soder, 2018). Additional grid code requirements, such as power forecasting, ramp rate, and offshore wind power, are discussed in other studies (Wu et al., 2019).

4. Results

4.1. Wind turbine energy variations — Experimental data

Energy quality is concerned with power, or power flow, waveforms over time. To visually reveal the short-term variations in wind turbine active power outputs over time, i.e. the Geeth Effect, the following graphical representation of the downloaded data utilises the SPSS software. Figs. 1 through to 5 displays the short-term dispersion aspect of the active power output signals from four different wind turbine generators. Figs. 4 and 5 displays data from the 3-MW DFIG wind turbine under different local wind conditions on different days. The sampling time for the data is a half-second sampling time. Visually, the Geeth Effect can be observed by plotting and analysing the data for Figs. 1 through to 5. The 10-kW, 300-kW, and 3-MW turbine installations discussed here are termed autoproducers, whereby the investing company consumes and generates electricity on a single premise. The generated units are wholly or partly for their own use to support their primary activity on site. Excess electrical units may be exported to the grid with a guarantee of a minimum price for each unit exported. The price depends on current government policy and market conditions.

Fig. 1 demonstrates the 10-kW-rated turbine active power output as a function of time, 35 min total. The WTG is a permanent magnet synchronous generator (PMSG) type. The turbine cost €26,620 in 2013 and, based on the number of kWh units produced annually, had a simple payback period (PP) of 23 years. The 10-kW turbine produced 7269 kWh units annually, giving it a capacity factor of 9.5%. The investor had an annual electric load requirement for the premise of 76,338 kWh's and was disappointed with the investment outcomes (Kealy, 2014).

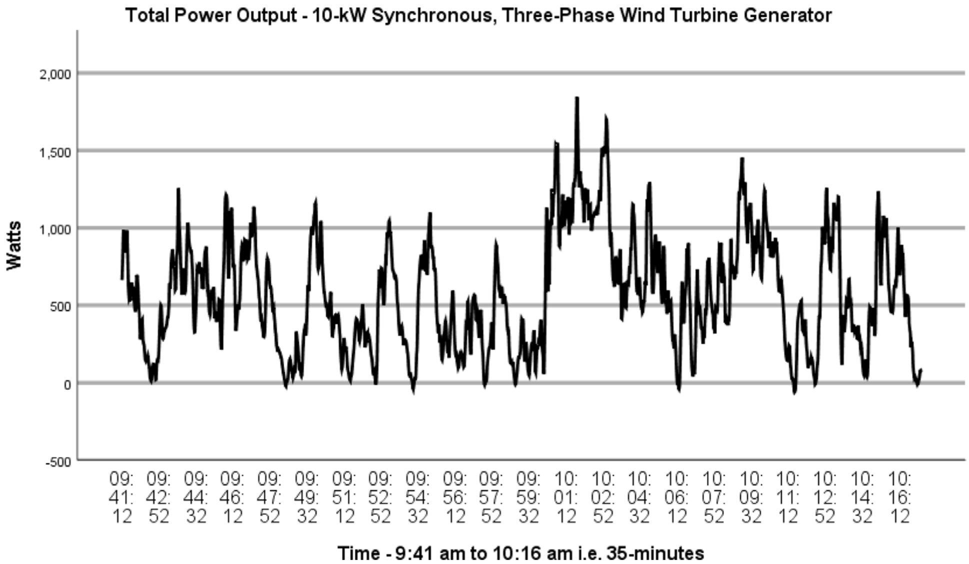

Fig. 1. 10-kW PMSG WTG power output over 35-min, Half-second sampling time (Kealy, 2014).

The statistically calculated CV value for the power output data presented in Fig. 1 is 0.64 (64%). This measure of power output variability shows the amount of 'lost' energy borne by the system. The 10-kW WTG is connected in parallel (embedded) with the national electrical grid. The installed connected loads are supplied by either, or both, of these two sources. The national electricity grid sources are unable to respond to such fast dynamics demonstrated in Fig. 1. Therefore, the benefits are 'lost' to the consumer. The 'lost' energy is due to poor power quality, observed as the highly variable signal plotted over a 35-minute test period (Fig. 1). If there had been a stable power output signal from the (autoproducer) wind turbine, this would lead to an offsetting (improvement) of 64% in the number of kWh units imported from the national electrical grid to supply the connected loads. Note that every unit generated and imported from the grid has a carbon intensity of 324 grammes of CO_2 per kWh (Energy in Ireland, 2020). A 64% improvement in the number of carbon-neutral kWh units produced annually by the 10-kW PMSG, i.e. 7260, would generate an extra 4646 kWh units. At the cost of €0.17/kWh, this financially benefits the investor by €790 annually. This outcome is besides the environmental benefits of reducing approximately 1.5 tonnes of CO_2 emitted annually (1,505,304 g).

The CV for the 300-kW WTG data shown in Fig. 2 is 46%. The company made the €280,000 investment decision based on a predicted energy output of 600,000 kWh units produced annually. The turbine produced 346,698 kWh units in 2018. A 46% increase in production because of smoothing on the power output signal equates to a rise of 159,481 kWh units produced annually. At the cost of €0.13/kWh, the company saves a further €20,732 annually if the power output signal employs a smoothing mechanism to deliver a stable output. An increase of 159,481 kWh carbon-neutral units would benefit the environment by reducing approximately 51.67 tonnes of CO_2 emitted into the atmosphere because of the factory electrical load requirements (Energy in Ireland, 2020).

The time-domain power output plot shown in Fig. 3 is generated using data from the DFIG-type, double-conversion WTG. The turbine is Vestas manufactured, 850-kW V52 with a nominal generator three-phase voltage output of 690-Volts, four-wire. It can deliver 711 Amps. The 850-kW turbine is part of a 3,2-MW wind farm based in the West of Ireland. The day on which the data was downloaded was calm, with the peak output values shown in Fig. 3 corresponding to a local wind speed of 5.7 m/s. The trough values correspond to a local wind speed of just 1.7 m/s. A 25% capacity factor is recorded during the summer, up to 34% in the winter.

The 850-kW turbine power output discussed in this section is fed directly into the National Grid via a local substation. Therefore, it is expected to contribute positively to the overall national energy benchmarks used by the Sustainable Energy Authority of Ireland (SEAI). The SEAI use a benchmark for the amount of CO_2 emitted into the atmosphere due to generating one kWh unit of electrical energy. This benchmark is identified as the carbon intensity of electricity, and the value for 2019 was 324 g CO_2/kWh (Energy in Ireland, 2020).

The primary data used to generate the plots shown in Figs. 4 and 5 is downloaded from a DFIG, three-phase, double-conversion, 3-MW WTG.

The 3-MW autoproducer wind turbine is installed on a factory site, connected in parallel with the 10-kV supply from the national grid (Kealy, 2021, Fig. 2). Should there be any excess kWh electrical units generated by the turbine and not required in the factory, the surplus units are exported to the national grid and the private company is reimbursed for supplying their excess energy. The 3-MW turbine produced 8,522,005 kWh units in 2019. There was a significant improvement in the factory energy benchmarks after the turbine was installed (Kealy, 2021, Table 2). While the Geeth Effect is observable for much of the data shown in Fig. 5 (and Fig. 4), the output shows stability at its full rated power value, i.e. 3-MW. This stability occurs twice in Fig. 5. A power quality analysis carried out on the 3-MW wind turbine output between 17th February 2020 and 2nd June 2020 calculated that the turbine produced its full rated value of 3-MW for 16% of the time. The CV value for the data presented in Fig. 4 is 30%, and for Fig. 5, it is 36%. These CV values are an improvement on the previous case study results, but there is still room for more improvement. If the 8,522,005 kWh value for 2019 were improved by 30%, this would lead to a further offsetting of 2,556,600 kWh carbon-neutral units effectively produced by the turbine. At a kWh unit cost of €0.072, the annual savings would increase by €184,075.

With each of the five graphs (Figs. 1 to 5) shown, the 'Coefficient of Variation' (CV) metrics (2) were calculated to show the short-term variability (Geeth Effect) in the active power output signal. In Table 1, the CV values are also presented as percentages and highlighted (last column in Table 1). The CV values range from 0.30 (30%) to 1.76 (176%).

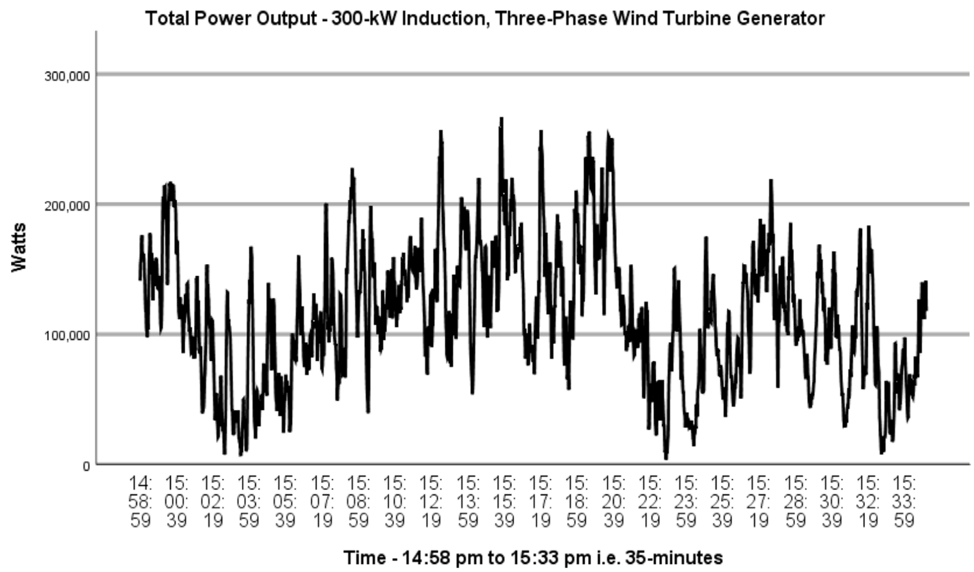

Fig. 2. 300-kW WTG power output over 35-min, Half-second sampling time (Kealy, 2017).

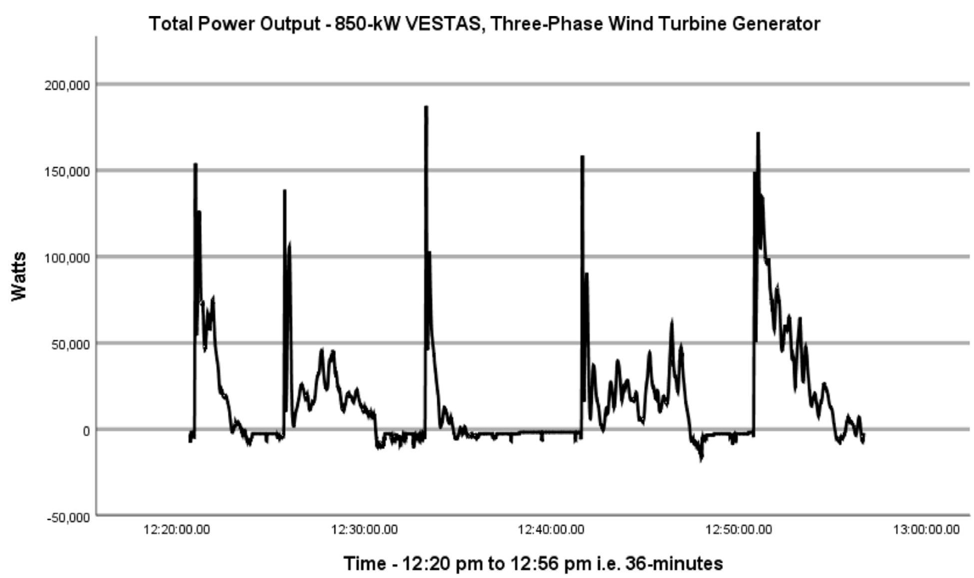

Fig. 3. 850-kW DFIG WTG power output over 36-min, Half-second sampling time (Kealy, 2020).

Table 1
Coefficient of variation of active power outputs from wind turbine generators (WTG).

	Type	Average (W)	SD (W)	CV (%)
Fig. 1	10-kW	572	365	0.64 (**64%**)
Fig. 2	300-kW	114,141	52,500	0.46 (**46%**)
Fig. 3	850-kW	16,108	28,400	1.76 (**176%**)
Fig. 4	3-MW	904,464	266,836	0.30 (**30%**)
Fig. 5	3-MW	1,972,764	716,541	0.36 (**36%**)

4.2. Solar PV and hydroelectric plots

The CV values for the four different wind turbines are compared to CV values from solar PV and hydroelectric renewable energy power outputs. The following two graphical representations show, first in Fig. 6, a 169-kW Solar PV three-phase output and, secondly in Fig. 7, a 40-kW hydroelectric three-phase induction-type generator. The Fluke 1735 Power Logger tool was used to download ALL the data, and the identical sampling time was used in all the graphs. Positive economic, environmental, and social outcomes are attributed to the installations to which the hydroelectric and solar PV are utilised (Kealy, 2020). The low CV values for the active power outputs are likely to have played a significant role in achieving these positive outcomes. Note that the localised weather conditions for the factory location where the PV system was connected, shown in Fig. 6, were clear skies throughout the day.

The 169-kW solar array produced 127,630 kWh electrical units in the 12 months between July 2019 and June 2020. The capacity factor was, therefore, 8.6%. The simple PP was calculated as approximately eight years.

On a test carried out on the 40-kW hydroelectric generator between 5th September 2017 to 15th September 2017, the generator could supply 100% of the hotel's (owner) electrical requirement while also exporting 4590 kWh's back to the national grid as excess units. The simple PP is calculated at less than two years (Kealy, 2020).

The extremely low CV values for the solar PV and hydroelectric turbine presented in the last column of Table 2 (expressed as a

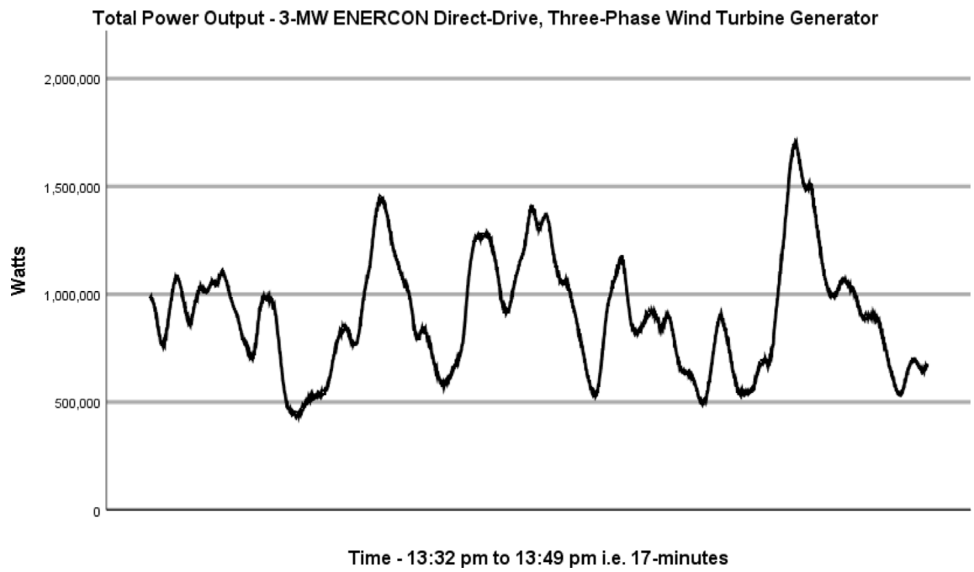

Fig. 4. 3-MW WTG power output over 17-min, half-second sampling time (Kealy, 2021).

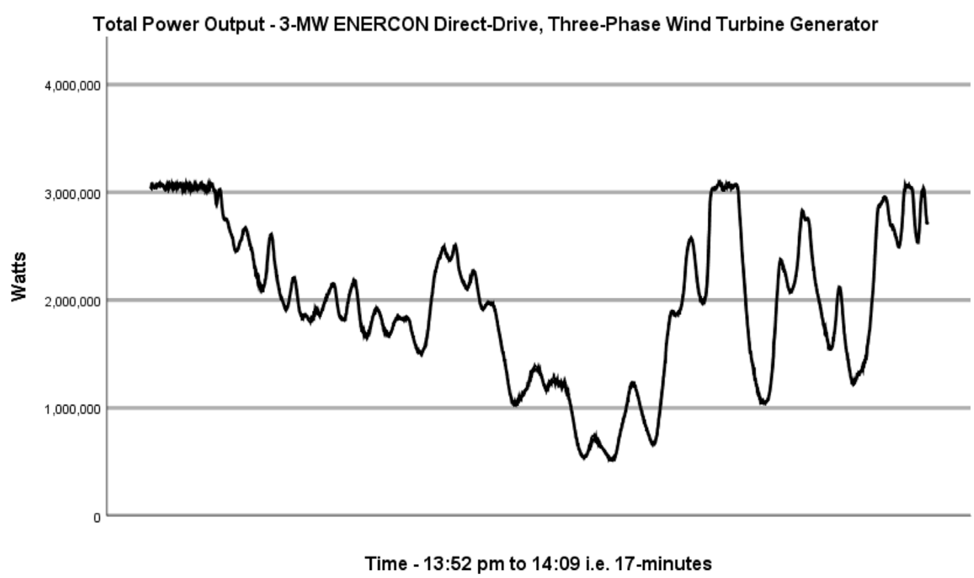

Fig. 5. 3-MW WTG power output over 17-min, half-second sampling time (Kealy, 2021).

Table 2
Coefficient of variation for solar PV and hydroelectric generators.

	Type	Mean (W)	SD (W)	CV (%)
Fig. 6	169-kW PV	48,545	677	0.014 (**1.4%**)
Fig. 7	40-kW hydro	18,165	574	0.032 (**3.2%**)

percentage and highlighted) can be compared to the significantly higher wind turbine dispersion values in Table 1.

5. Discussion

Based on the values in the last column of Table 1, the dispersion level present in the WTG's, measured as CV values and showing the Geeth Effect, shows the need for energy storage to offset the negative effect of the short-term variability associated with the power output signal. Each of the WTG's discussed in this review study were connected in parallel with traditional, thermal, power-generating plants. Problems arise in the balance of power systems when large-scale energy sources' power level changes too fast (Zhang and Yan, 2020). Traditional thermal generating plants must adjust their outputs in unison with renewable generator outputs to supply the instantaneous loading connected to the grid. However, thermal generators are heavy-duty, weighty machines and would not be classified as agile operators. Therefore, it is unlikely that the thermal generators have the flexibility required to adjust to the short-term variations of renewable generators shown in Figs. 1 through to 5.

From the visual evidence provided in the wind turbine graphs (Figs. 1 to 5), energy 'smoothing' (energy filters) or energy storage (batteries) are needed to overcome the variability problem. In deciding which is the best option for a particular application, it is worth noting that the persistent, frequent charging/discharging of battery energy storage systems degrades the batteries over time. Supercapacitors can cope with the continuous charge/discharge cycles needed to stabilise the outputs shown in Figs. 1 through to 5. However, research also suggests that supercapacitors are ideal smoothing devices for WTG outputs in the kW range rather than the MW range and are potentially a viable option for the

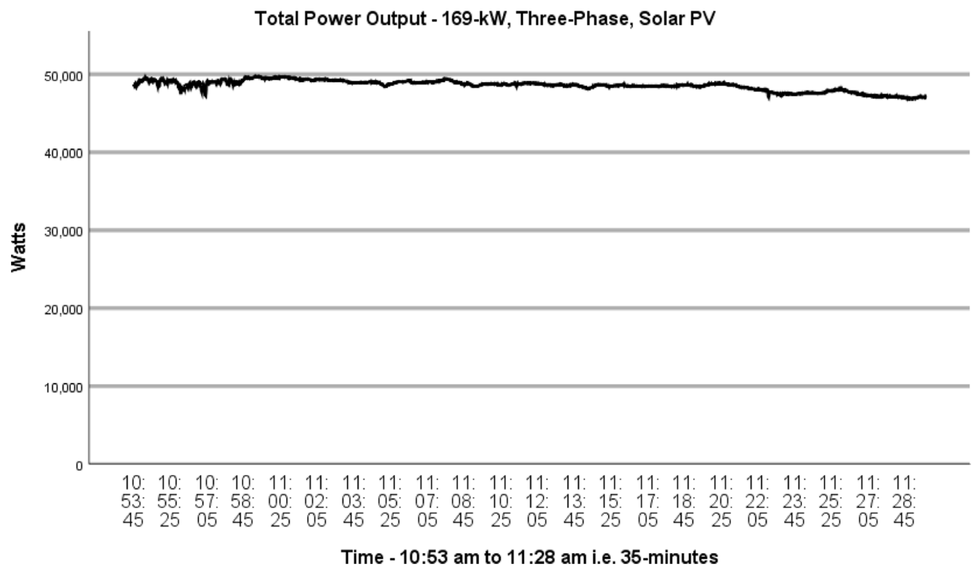

Fig. 6. Solar PV power output over 35-min, half-second sampling time.

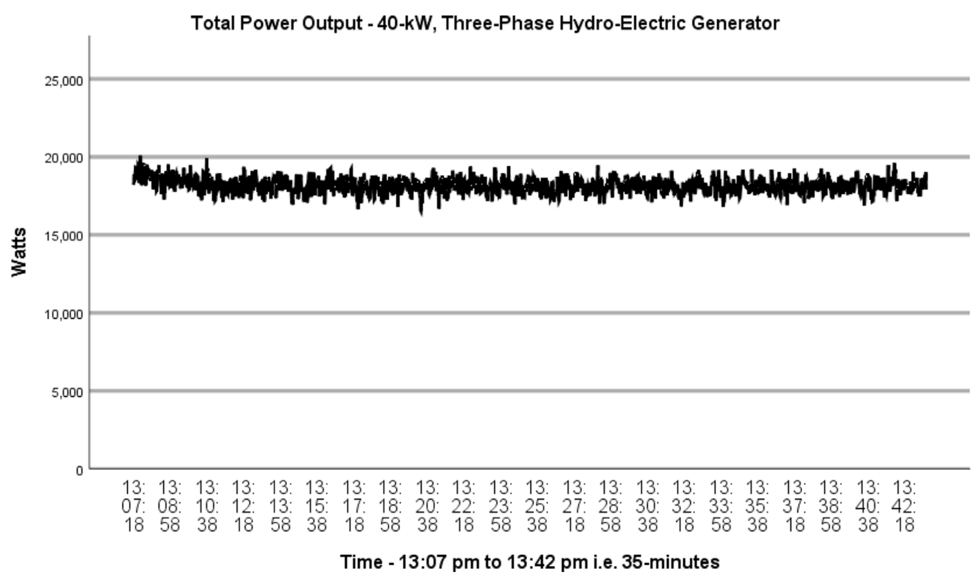

Fig. 7. Hydroelectric power output over 35-min, half-second sampling time (Kealy, 2020).

DFIG turbines presented in Figs. 1–3. The output of the 3-MW turbine may need a hybrid approach to improve power quality, i.e. a Supercapacitor/Battery combination.

Investors in wind turbine technology are losing money because of the short-term active power output variations. The investor of the 10-kW wind turbine (Fig. 1) is losing €790 per year, the 300-kW investor (Fig. 2) is losing €20,732 per year, and the 3-MW autoproducing investor (Figs. 4 and 5) could benefit to the tune of €184,075 per year, all linked to the short-term variations of the turbine power output signals. Contrast these losses with the positive outcomes of the *stable* 169-kW PV system and the 40-kW hydroelectric generator outputs. Supercapacitors may be connected as a smoothing device to mitigate the Geeth Effect in wind turbine installations. Supercapacitors are not prone to problems associated with the constant charge/discharge cycles associated with wind turbine power outputs. Batteries are also an option, but caution must be adhered to because short-term cycling may degrade the battery lifetime. Hybrid solutions (Supercapacitor/Battery) are more suitable for the wind turbines in the MW range, where further research is being carried out on supercapacitors and their energy capabilities. Further research is also recommended into the type of applications that may be suitable for wind turbine projects that do not have a supercapacitor smoothing system on the power output signal. One such application is likely to be wind turbines functioning as the electrical power source to drive an electrical current through water to generate hydrogen (electrolysis).

Proposed method of calculating CV values using existing power quality tools – Currently SCADA-monitored wind turbine installations produce a numerical power value every ten minutes. This ten-minute value is an average mean value of several power output values, measured over a shorter sub-second timeframe. Therefore, the electronic device already has access to the data required to calculate the CV value. The calculation method involves an additional algorithm to compute the standard deviation (SD) associated with the available short-term measured data. The CV value is established by dividing the standard deviation by the mean (2). The CV metric is a means of naming and ordering a problem associated with wind turbine generators, i.e. the Geeth Effect.

6. Conclusions

The advantages due to the stability and certainty associated with traditional fossil-fuel-driven (mainly gas as the energy source) electrical generators cannot be overstated. Introducing large-scale renewable energy generators, particularly wind turbine generators, onto the electrical grid had presented some distinct challenges (operational and infrastructural) than in previous times when the historical predominant primary source of power was fossil-fuel-driven generators. Balancing mechanisms, power capacity alerts, curtailments, and constraints have become essential terms that the TSO must consider in their effort to ensure a stable electrical supply to the plethora of connected loads. The increased attention to these terms is driven by the variability and intermittency phenomena associated with renewable energy sources, not generally encountered in fossil-fuel-driven machines.

The (short-term) variability aspect of renewable energy power sources is the primary focus of this research study. Traditional power quality tests do not capture short-term, one-second or sub-second variations as these established methods utilise 10-minute averaged data in the assessment process. A new label is presented to denote the short-term (one-second or sub-second timeframe) variations in the active power output from wind turbine generators. The 'Geeth Effect' is the name given to this phenomenon. The Geeth Effect can be defined in a mathematical expression as the Coefficient of Variation to quantitatively assess the energy quality, i.e. the power output over time, with low CV desirable values, larger values undesirable. The Geeth Effect phenomenon is prevalent in wind turbines across all localised wind conditions, with one exception. The exception is when the localised wind speed is high enough to drive the WTG to its maximum fully rated output. This is clear with the 3-MW ENERCON, direct-drive, WTG discussed in this current study. At this maximum value, the power output displayed a steady 3-MW value, with low dispersion values during those conditions. The CV value, the first two minutes in Fig. 5, was calculated as 0.01 (1%) during these two minutes. Ironically, the TSO are most likely to apply curtailment restrictions on wind energy generators during periods of high wind energy output, precisely when the Geeth Effect is at its lowest, i.e. most desirable, values. The only situations that solar PV systems might be susceptible to the Geeth Effect are during incredibly high wind and cloudy conditions.

The second main problem associated with renewable energy generators such as solar PV systems or wind turbine generators, i.e. the intermittency problem is likely to be somewhat corrected using utility-scale batteries, boosted mainly by (i) advances in lithium-ion battery chemistry, and (ii) a significant reduction in the cost of utility-scale batteries. However, fossil-fuel electricity generating plants remain essential components to energy security and energy provision within countries.

In renewable energy power output smoothing, a compromise must be reached between the attenuation of the high-speed, short-term variations in the active power outputs and the control/regulation of the state-of-charge. The effective control/regulation of the state-of-charge is necessary to maximise the capability of absorbing and delivering energy, thus ensuring good power smoothing. Future research is also recommended into the cost/benefit analysis of the two corrective systems, namely supercapacitor storage and battery energy storage.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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