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The missing parameter in renewable energy power quality analysis, i.e., the coefficient of variation: Case study of a 3-MW on-site wind turbine project in Ireland

Tony Kealy

School of Electrical & Electronic Engineering, Technological University Dublin, Ireland

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A B S T R A C T

Businesses are employing distributed generation techniques, such as wind turbines, to decarbonise their electrical energy supply by reducing their dependence on fossil-fuel-generated energy. This study investigates the effectiveness of a company making a €3,500,000 investment in a 3-MW on-site wind turbine to supply some or all of their factory electrical loads. The results should benefit the investing company and other potential investors by evaluating the economic, environmental, and social outcomes of the investment. A case study methodology was used. The study found that the payback period was six and a half years, and the turbine installation benefited the environment by offsetting 3,195 tonnes of CO_2 per annum. As part of the power-quality analysis of the wind-turbine output, the short-term variability of the power output signal was calculated as the coefficient of variation values. The study found that the most stable power output is achieved when the turbine is generating at full output power (i.e., 3-MW). In addition to the existing range of traditional power quality parameters, the coefficient of variation parameter was found to be an essential aspect of electrical power quality and should be included in future practice.

1. Introduction/background

Sustainable (business) development is defined as (corporate) decision-making that considers the economic, environmental, and social aspects of those decisions (Jagerbrand, 2020). Of the plethora of business decisions to be made, one involves the best approach to take when sourcing and making use of electrical energy on-site to power the assortment of machines, processes, and equipment for such a versatile energy source. It is in the context of sourcing electrical power that distributed renewable energy generators, such as wind turbines, have come to the fore of business thinking in recent years (Wacker et al., 2020). However, despite the increased penetration of distributed renewable energy sources deployed by small-to-medium-enterprises (SME), studies on their effect on sustainability and economic performance are scant (Dey et al., 2019).

An important aspect of sourcing electrical power is knowing the quality of the power is up to acceptable standards (Parvez et al., 2019). Much of the modern equipment on the consumer end is highly sensitive to numerous power quality problems. Also, power quality problems produce a negative impact on the generation side. It is necessary to know the root of the disturbance before taking suitable mitigating action to rectify the power quality problems (Parvez et al., 2019). Measuring power quality on the generation side using established traditional parameters appears not to be uncovering any pertinent issues. Kealy (2020) developed a novel framework to evaluate renewable energy projects that included an analysis of the power output quality. The methodology included the measurement of the short-term variations in the generator active power outputs. It is essentially a post-connection evaluation of a distributed energy source. High values of the ramping (short-term variation) phenomenon are known to reduce the expected environmental and economic benefits of renewable generators (Cullen, 2013). 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). The novelty in this current research is the naming of the parameter by which the short-term variations in the active power output of the renewable energy sources can be quantified.

E-mail address: tony.kealy@tudublin.ie.

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Nomenclature

CO_2	Carbon Dioxide
CV	Coefficient of Variation
ESB	Electricity Supply Board
kWh	kilo-Watt-hour
MEC	Maximum Export Capacity
MIC	Maximum Import Capacity
MV	Medium Voltage
MW	Mega-Watt
PP	Payback Period
PQ	Power Quality
PQA	Power Quality Analyser
SCADA	Supervisory Control And Data Acquisition
SEAI	Sustainable Energy Authority of Ireland
SME	Small-to-Medium-Enterprise
SPSS	Statistical Package for Social Science
TBL	Triple Bottom Line
WTG	Wind Turbine Generator
XLPE	Cross-Linked Polyethylene

The parameter is the coefficient of variation (CV), and this research also identifies the method by which the CV can be calculated.

The main tests proposed by Kealy (2020) for evaluating the effectiveness of distributed renewable energy sources were (i) measuring the quality of power (including the coefficient of variation), (ii) measuring the quantity of kWh energy, and (iii) assessing the energy benchmarks that were associated with the project (Fig. 1). These proposed tests are utilised in this current research study. This present case study on the 3-MW wind turbine fills a gap in the literature by assessing its effect on sustainability and economic performance while also implementing a power quality (PQ) assessment on the renewable generator active power output. The PQ assessment includes the calculation of the coefficient of variation values. The main objective of the study is to demonstrate that the coefficient of variation parameter should be included as part of the well-established standard power quality analysis parameters in future renewable energy research.

2. Literature review

It appears that the sustainable development philosophy has become increasingly influential in corporate and civic society (Ferns and Amaeshi, 2019). In the business domain, corporate social responsibility (CSR) is seen as a vehicle for achieving sustainable development (Weber et al., 2014). The United Nations (UN) set up the Bruntland Commission in 1983 to address the social and environmental degradation prevalent at the time and released its first report in 1987 (Bruntland Commission, 1987). The Bruntland Commission (1987, Chapter 1, Section 43) states that environmental problems are linked to underlying social factors. This social/environmental synergy can also be found in some published literature (Svensson et al., 2018; Ruhnke and Gabriel, 2013). Environmental problems such as climate change and global warming may, therefore, be influenced by the current social degradation in Ireland, the host country of this research (USI, 2019; Delargy et al., 2019). This close relationship is due to the interplay and synergy among the three generally accepted dimensions of sustainable development: environmental, social, and financial dimensions (Kealy, 2014a), modelled by Elkington (1997), in the often-cited Triple-Bottom-Line (TBL) framework. The synergy between the financial aspects (including financial risks) and the environmental impact of companies seems to be gaining traction. In the United Kingdom, there is increasing pressure on companies to disclose the financial risks they face because of the climate change crisis, and the annual reports of many publicly listed companies must explain how they plan to measure and manage the threat of a climatic catastrophe. Improved disclosures are expected to enable investors to make more informed choices about allocating capital (Ambrose, 2020).

Institutional theory, one of the theories underpinning sustainable development, is grounded in the idea that businesses conform to similar norms, values, and assumptions about what is generally expected from them and what constitutes appropriate economic behaviour (Susith and Stewart, 2014). One increasingly taken-for-granted premise is that companies make strategic decisions to transition their energy systems towards cleaner production, embracing less carbonised energy models (Vazquez-Hernandez et al., 2019). It is in this context that technological developments and economic opportunities have facilitated the integration of distributed generation (DG) in electricity networks (Rabuzin et al., 2021). DG refers to the generation of electricity in a decentralised manner. The 3-MW wind turbine discussed in this study is an example of DG. The turbine is installed by the small-medium-enterprise (SME) on their factory site, and the power output cables are connected on the customer side of the electrical utility meter. Wind-generated electricity is perceived as an effective alternative to the traditional fossil fuel-generated energy model. By the end of 2018, the installed capacity of wind generation in Ireland reached 3676 MW (SEAI, 2019, p 46), accounting for 28% of the annual electricity generation requirements. However, the variability of wind speed is a disadvantage in utilising wind-generated power (Katzenstein and Apt, 2012). There has been minimal research into assessing the amount of variability inherent in wind turbine active power outputs, particularly short-term variations. Capturing energy from wind requires modern electronic power converter topologies (Xiong et al., 2020). The non-linear dynamic of wind, which is driven by stochastic disturbances, augments the engineering challenge of attempting to sustain a steady electrical power output (Azizi et al., 2019). Two pitch-controlled approaches to this challenge would be to (i) tune the turbine rotor at an optimal

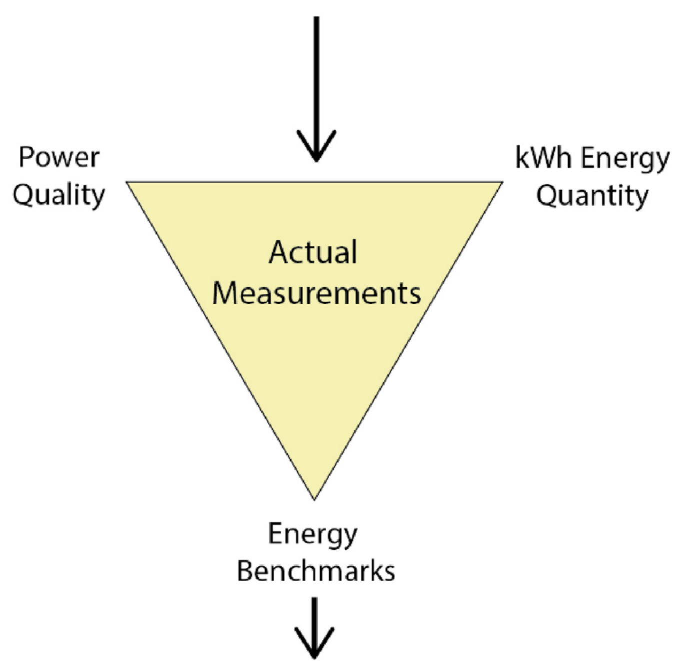

Fig. 1. Closed-loop evaluation framework, stage 3 'actual measurements' (Kealy, 2020).

angular speed while keeping the blade pitch angle constant and (ii) adjust the rotor blades' pitch angle while keeping the rotor speed constant (Azizi et al., 2019). The first solution is designed for low-wind conditions, while the second solution is intended for high-wind conditions. An added complication of providing high-quality power may arise when the wind speed switches rapidly between low- and high-speed conditions, perhaps during turbulence. Pitch control is commonly used in moderate-sized to large-sized wind turbine applications. For smaller output wind turbine applications, the stall-controlled strategy may be used because it is a cheaper and less complicated option (Mohammadi et al., 2018). The quality of power has become a prime factor for the electrical utility sector in recent years. The electrical machines and equipment on the consumer end are highly sensitive to power quality problems (Parvez et al., 2019). Malfunctions in the electrical power system, such as transients, under- and over-voltage, under- and over-frequency, and harmonics, are caused by the poor quality of the power supply. Despite the engineering challenges to supply high-quality power from wind turbines, this study hypothesises that an increase in localised wind speed and, therefore, an increase in wind turbine power output should 'offset' the overall power requirement generated by traditional, mostly fossil fuel, means (Dorsey-Palmateer, 2020).

A real-time online power quality monitoring and assurance device connected to the turbine power output circuit is one method by which the root of any power quality issues are known (Parvez et al., 2019). International standards for measuring and assessing the power quality in grid-connected wind turbines consider voltage fluctuations, current harmonics, active and reactive power control, grid protection, and reconnection time (Redondo et al., 2019). Grid protection of distributed renewable energy sources is typically afforded 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 generators. The EGIP relay is demonstrated in Fig. A4 of a research study carried out on a 300-kW wind turbine (Kealy, 2017). The EGIP is designed to disconnect the renewable generator from the electricity utility network should any of the wind turbine power output parameters exceed any of the predefined programmable 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 functions of the EGIP relay is to ensure that the power quality of the wind turbine is up to the same high standard of the power quality in the network distribution system. This comparison allows the synchronisation of the two supplies (Mastromauro, 2020). The EGIP tests the following power quality parameters (ESB Networks, 2016):

- Over voltage
- Under voltage
- Over frequency
- Under frequency
- Directional overcurrent protection
- Loss-Of-Mains protection (Rate-Of-Change-Of-Frequency)

The EN 50438 standard outlines the requirements for micro-generating distributed renewable energy sources that are connected in parallel with public low-voltage distribution networks. The standard is adhered to in the Irish case study of an embedded 10-kW wind turbine (Kealy, 2014b). All installed micro-generators must comply with EN 50438 with the specific Irish protection settings (ESB Networks, 2018, p 3). The 5-kW inverters linking the wind turbine to the main distribution board are EN 50438-compliant. The Irish settings for direct current (DC) to alternating current (AC) electronic devices (inverters) are as follows:

- Over voltage (230-V + 10%) − clearance time 0.5 s
- Under voltage (230-V − 10%) − clearance time 0.5 s
- Over frequency (52 Hz) − clearance time 0.5 s
- Under frequency (47 Hz) − clearance time 20 s
- Loss-Of-Mains (LOM) functionality − rate-of-change-of-frequency, 1.0 Hz/s, clearance time 0.6 s
- Automatic reconnection time − 20 s minimum

Kealy (2020) raised concerns about the quality of some of the power generated using parallel-connected (embedded/distributed) wind turbine technology in Irish-based SME's. In particular, the short-term active power variations, measured as CV values, were causes for concern. The active power output CV parameter is not generally considered in international power quality standards. High CV values detected in the wind turbine power output were deemed to negate the renewable systems' effectiveness. For example, disappointing results were found to be associated with the 300-kW DFIG wind turbine installation by an SME (CV average was 0.426; Kealy, 2020, Table A1) and the 10-kW three-phase synchronous wind turbine installation (CV average was 0.611; Kealy, 2020, Table A2). In contrast, very positive outcomes were deemed to be linked to the low CV values of the 40-kW hydroelectric installation, in which the CV average was 0.034 (Kealy, 2020, Table 4). The 40-kW distributed hydroelectric generator supplied the SME with 100% of its electrical energy requirements during the 10-day test period, from September 5, 2017 to September 15, 2017. Zero kWh electrical units were imported from the parallel-connected national grid during this period (Kealy, 2020, Table 5). Another relevant parameter that represents the effectiveness of renewable energy generators is the capacity factor parameter. Capacity factors for Irish-based wind turbines lie in the range of 30%−32% (Henaghan, 2013). The capacity factor for the 40-kW hydroelectric plant was calculated at 54% (Kealy, 2020, Table 5). Despite the positive hydroelectric results, hydroelectric generation accounts for only 2.2% of the electricity generated in 2018 (SEAI, 2019, p 32, Table 12).

The 'Actual Measurements' stage of the framework presented by Kealy (2020), utilised in this current research, is demonstrated in Fig. 1.

3. Research methodology

A case-study methodology is utilised in this research and is suited to gathering data from the wind turbine in the context of its normal operations. The turbine electrical power output is proportional to the (cube of the) localised wind speed. Wind energy sources can be characterised by a high degree of uncertainty because of the randomness of wind resources (D'Amico et al., 2020). As managers have no control over wind speed and direction during normal operations, the turbine power output is highly influenced by the local wind speed. One of this study's hypotheses is that an increase in (local) wind speed leads to an increase in the quantity of kWh energy units produced by the wind turbine over a defined period. Many of the published research studies on wind turbines obtained output data under ideal test conditions (Han et al., 2018), or the output was modelled using computer software (Yang et al., 2020; Syahputra and Seosanti, 2019; Mohammadi et al., 2018).

The research methodology for this current study included the implementation of a power quality assessment of the wind turbine output by an independent third-party power quality expert. The assessment was carried out on data downloaded from the turbine for the period between February 17, 2020 and June 2, 2020. The turbine data was downloaded via the ethernet connection at the rear of the Janitza Power Quality Analyser connected to the turbine power output cables. The assessment was performed primarily according to the EN61000-2-4: 2002 and the EN50160 standards.

3.1. Plant overview and data collection & analysis methods

The wind turbine generator (WTG) evaluated in the current study is an Enercon E−101 type with a maximum export capacity (MEC) of 3 MW and was installed by the SME in October 2017. The turbine cost is €1,100,000 per MW output (total cost €3,300,000), with a further charge of €200,000 for work to accommodate the turbine wiring in the main switch-room. There are currently six similar turbines installed in Ireland. Both the E−101 wind turbine's output and the Electricity Supply Board (ESB) 10-kV supply (either supply 1 or supply 2) are fed in parallel to the main factory busbars in MV Substation 1 (Fig. 2). Therefore, the entire site load's electrical energy demand is provided by a combination of the wind turbine generator (WTG) and the ESB Grid supply. There is a WTG power quality analyser (PQA) installed on the 10-kV supply cables between the wind turbine and the factory medium-voltage (MV) busbars in MV Substation 1 (Fig. 2). The PQA is a Janitza UMG 512 PRO device. The 'Gridvis' software is used in conjunction with the Janitza PQA. The current transformer (CT) ratio on the 10-kV supply cables is 200/5, and the voltage transformer (VT) ratio is 10,000/100. The turbine generates electrical power at 400 V, four-wire (phase to neutral), variable frequency output (690 V, phase to phase). A rectifier converts the alternating current (AC) to direct current (DC) at a DC voltage level between 600 V and 700 V. The DC output supplies twelve 300-kW three-inverters to convert the DC back to grid-frequency (50-Hz) AC. The AC output from the inverters is connected to the primary winding of a 3500-kVA-rated power transformer. The inverters and transformer are situated in the base of the turbine tower (Fig. 2). The secondary side of the power transformer is rated at 10-kV. The XLPE aluminium cables are routed underground to connect as one of the two main inputs to MV Substation 1 busbars in parallel with the other primary input, the ESB 10-kV supply cables in MV Substation 1 from the overhead distribution system. The 10-kV output cables from the main switch-room in Substation 1 are fed to five on-site 10-kV/400-V step-down transformers via Substations 2, 3, and 4 within the factory premises (Fig. 2). A supervisory control and data acquisition (SCADA) system monitor the WTG energy quantity values.

A schematic diagram of the electrical system on site is shown in Fig. 2.

Many electrical generator installations include a proprietary power quality analyser (PQA) inserted in the power output cables. Power quality analysers, such as the Janitza, utilised in this case study routinely collect data to measure the following parameters:

- Voltage (under-voltage and over-voltage)
- Current (value and direction)
- Power (active, reactive, and apparent power)
- Energy
- Frequency (under frequency and over frequency)
- Power factor
- Harmonic distortion (voltage and current)
- Transients
- Flicker

Analysis of the data to appraise the above power quality parameter values may also be used to ascertain if any of the measured values violate pre-set power quality threshold standards. The threshold values are set as a percentage of the rated values. Some of the common standards are EN 50160 and the IEC 61000-2-4 standards. EN 50160 is the standard for the voltage characteristics of electricity supplied by public electricity networks. IEC 61000-2-4 specifies compatibility levels for low frequency conducted disturbances in industrial plants. Should the measured values fall outside the predefined values in either of the common standards, the power quality analyser can trigger an 'event' to inform the user of the power quality anomaly. The nominal values of, for example, voltage and frequency must be configured in the PQA before such events will be activated. Events can be threshold value violations of effective voltage and current values or rapid frequency or rapid voltage changes. The Janitza PQA will not give an automatic warning that an event occurred place unless the facility is set up in the alarm-management section of the Gridvis software. Events can be accessed and analysed in the 'historical data' folder's event list. Transients are short-lived pulsed electrical phenomena. To detect and record transients, it is necessary to use high-quality digital analysers with high sampling rates. Flicker values can be measured as per EN 61000-4-15:2011, which is the standard for functional flickermeters and contains specifications for their design. Voltage and frequency variations can cause flicker that can be experienced from a practical perspective — for example, light density changes in lamps. The maximum tolerance level of flicker interference is based on the human perception of the disturbance. It considers the interference sensitivity of the human eye regarding its perception of light fluctuations. Both short-term and long-term flicker can be measured. Information from the PQA is communicated to the data analysis software on PCs or other digital devices. The PQA data analysis software allows some or all the following reports to be generated as a PDF or Excel document:

- Event and transient report
- Power Quality Report according to EN 50160 2011 (or 2016)
- Power Quality Report according to EN 61000-2-4
- Voltage reports

4. Results — Power quality (Actual Measurements, Fig. 1)

The power quality assessment undertaken by a third-party expert found that no international power quality parameter was breached. The complete report can be viewed by downloading the power quality report in the supplemental data file - 'Supplemental data'. The total harmonic distortion of the voltage reached only half the maximum limit, i.e., 4%, during the measurement period. The measured value of the voltages was found to lie continuously within the required range. There were no voltage events detected which violated the limit value specifications. The harmonic current pollution was very low since the current levels of each harmonic are negligibly low compared to the Root-Mean-Square (RMS) value of current supplied by the turbine. The same positive results were found with the primary turbine frequency, which continuously stayed within the nominal range, i.e., 50 Hz. During the total test period, only two relevant flicker values exceeded the EN50160 threshold. This event was caused by the turbine switching off and on. The temporary flicker was due to the high gradient of $dI/dt \approx 170$ Amps. None of the other measured flicker values caused problems, which can be linked to the turbine. The calculated power factor of the active power output was a very desirable value of almost 1. Overall, it was concluded that the wind turbine feeds the electrical power grid (and the factory) with high-quality power, based on the EN61000-2-4: 2002 and the EN50160 standards.

One of the main contributions from this current study is the measurement of a parameter that is generally outside the scope of traditional power quality standards, namely the active power output short-term variations. Significant short-term fluctuations reduce the effectiveness of wind turbine performance. The short-term fluctuations are expressed as coefficient of variation values,

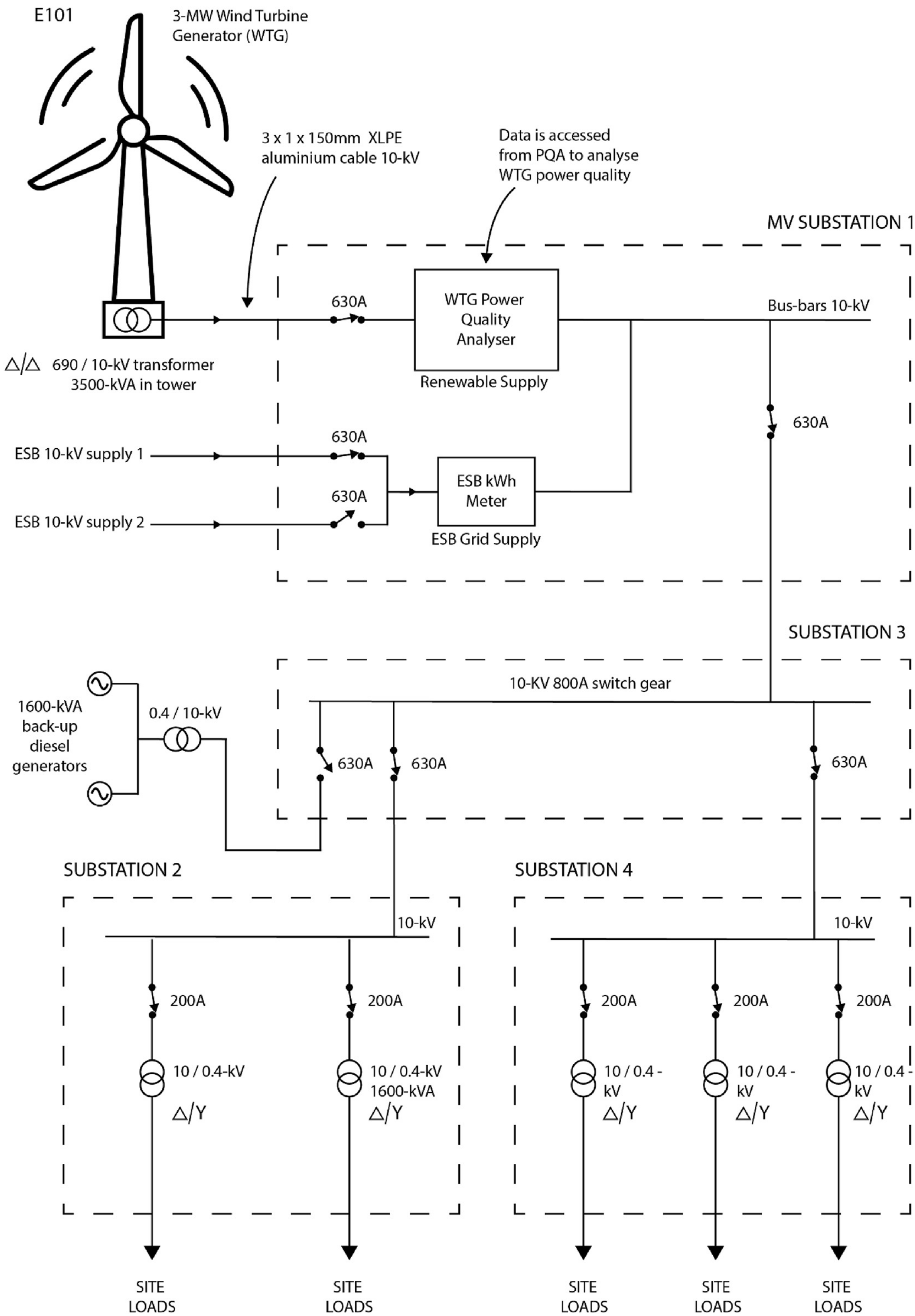

Fig. 2. Main schematic diagram.

with low numerical values most beneficial. Coefficient of Variation (CV) = Standard Deviation (σ) ÷ Mean (μ). Short-term data (at 1-s and half-second intervals) were downloaded from the wind turbine generator (WTG) PQA (Fig. 2) to the researcher's PC. The data were subsequently analysed using the SPSS software to calculate the active power output variations in the wind turbine signal. The resulting time-varying plots and statistical analysis are now presented. The graphical representation of the short-term, 3-MW wind turbine data taken on June 12, 2019 is demonstrated in Fig. 3 and identified as Test 1 [T1]. Subsequent time-varying tests are carried out from [T2] to [T7].

The average daily wind speed recorded at the Irish

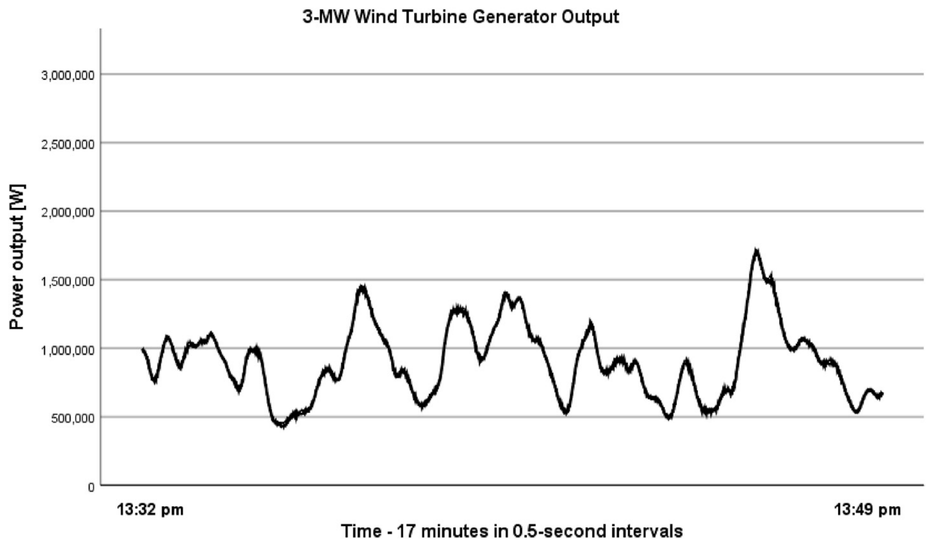

Fig. 3. Total three-phase active power output on Wednesday, June 12, 2019 [T1].

Meteorological Service weather station closest to the factory, i.e., Ballyhaise, Co. Cavan (see Fig. A14), on June 12, 2019 was 3.7 m/s, with the highest gusts recorded at 10.8 m/s (https://www.met.ie). The average hourly wind speed between 13:00 and 14:00 (during the T1 test period) was recorded at 5 m/s; between 14:00 and 15:00, it was recorded at 4.6 m/s. The average monthly wind speed at Ballyhaise for June 2019 was 2.9 m/s. The highest recorded gust for the month was 21.6 m/s.

The average daily wind speed on Tuesday, June 18, 2019, recorded near Ballyhaise, was 3 m/s, with gusts up to 8.7 m/s. The average hourly wind speed recorded between 10:00 and 11:00 (during the T2 test period) was 3 m/s; between 11:00 and 12:00, it was 4 m/s. The average monthly wind speed was 2.9 m/s. The power output for the 16-min test period shown in Fig. 4, which had an average localised daily wind speed of 3 m/s, was lower than the wind turbine power output on June 12, 2019 (Fig. 3). This result is expected, as the wind turbine power output is proportional to the (cube of the) localised wind speed. The average daily wind speed for June 12, 2019 was 3.7 m/s.

Another power quality test was carried out on Monday, February 17, 2020 [T5 and T6]. The day was exceptionally windy due to Storm Dennis. The day's average wind speed was 6.2 m/s, and the 3-MW wind turbine was at full power output (≈3 MW) during some of the high wind speeds (all data shown in Fig. A9 and Fig. A10). The CV was calculated at 0.005. During the test period shown in Fig. A9, the factory did not import any kWh units from the ESB supply. The 3-MW WTG was able to supply 100% of the electrical load to the factory while exporting approximately 1 MW of instantaneous, high-quality power back to the ESB supply. The wind speed then decreased, and the WTG power output reduced and fluctuated, as shown in Fig. A10. The CV value calculated for this comparatively lower wind speed was 0.355. The wind turbine ran for approximately 16% of the external power quality test period (February 17, 2020 to June 2, 2020) at its rated output, 3-MW.

From the data presented in Table 1, it is observed that the lowest (and most desirable) value of CV occur when the wind turbine is producing its maximum output, i.e. ≈ 3-MW [T5 and T7].

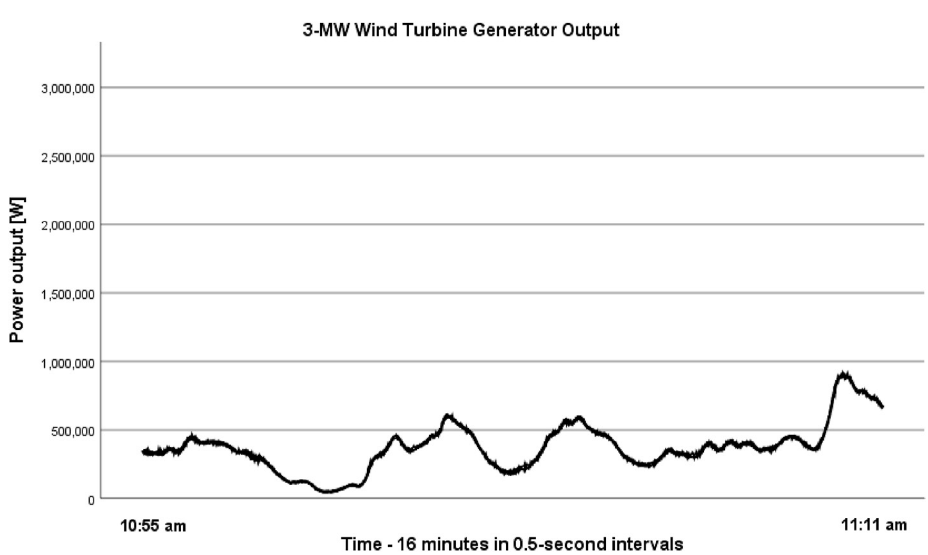

Fig. 4. Active power output on Tuesday, June 18, 2019, approx. 16 minutes (calm day) [T2].

Table 1
Coefficient of variation values for 3-MW wind turbine under different wind conditions, [T1] to [T7].

Time & Date [Test Number]	Mean [Watts]	Standard Deviation [Watts]	Coefficient of Variation
0–5 min (12-06-19) [T1]	852,918	229,068	0.268
4–9 min (12-06-19) [T1]	1,034,947	241,908	0.233
8–13 min (12-06-19) [T1]	858,950	252,058	0.293
11–16 min (12-06-19) [T1]	899,289	314,079	0.349
0–5 min (18-06-19) [T2]	249,893	133,985	0.536
4–9 min (18-06-19) [T2]	301,987	157,351	0.521
8–13 min (18-06-19) [T2]	357,224	113,461	0.317
11–16 min (18-06-19) [T2]	414,211	161,485	0.389
0–5 min (18-06-19) [T3]	192,698	51,417	0.266
4–9 min (18-06-19) [T3]	159,058	42,520	0.267
8–13 min (18-06-19 [T3]	390,757	216,053	0.552
11–16 min (18-06-19) [T3]	491,838	173,190	0.352
0–5 min (18-06-19) [T4]	487,172	111,807	0.229
4–9 min (18-06-19) [T4]	292,554	89,078	0.304
8–13 min (18-06-19) [T4]	159,690	114,447	0.716
11–16 min (18-06-19) [T4]	248,861	143,558	0.576
0–2 min (17-02-20) [T5]	3,053,541	15,278	**0.005**
2–15 min (17-02-20) [T6]	1,874,887	666,713	0.355
09:00–18:40 (02-03-19) [T7]	3,013,941	79,482	**0.026**

5. Results – kWh energy quantity (Actual Measurements, Fig. 1)

The monthly kWh output from the 3-MW wind turbine generator for 2018 and 2019 can be accessed from the SCADA system and are shown in Fig. 5. The lowest number of kWh units were generated during the summer period. This finding is in line with the lowest monthly-average wind speed occurring during summertime, as demonstrated in Fig. A4. The (negative) correlation between the two variables, i.e. the localised wind speed in metres per second and the number of kWh units IMPORTED by the SME from the national grid, is shown in Fig. A3.

Fig. 6 indicates the number of kWh electrical units imported by the SME to the site for production operations from the ESB grid supply (Fig. 2). The years 2016 and 2017 show the level of import before the turbine was installed, while the years 2018 and 2019 indicate the reduced number of kWhs imported after the turbine was installed.

One of the stand-out values in Fig. 6 is the small number of kWh units imported in February 2019. It is assumed that the WTG supplied the additional kWh units required to carry out plant operations (Fig. 2). This positive result can be attributed to the fact that February had the highest recorded monthly average wind speed in 2019, 4.2 m/s, with recorded gusts of up to 25 m/s. The 2018/2019 summer months showed an increase in imported kWh units. This finding is to be expected, as the summer months have the lowest average recorded wind speeds (Fig. A4).

6. Results – Energy benchmarks (Actual Measurements, Fig. 1)

The SME connected the turbine during the latter part of 2017 and, thus, would have influenced the number of kilowatt-hour (kWh) units imported from the ESB Grid Supply from 2018 onwards. There was a decrease of 5,711,539 kWh units from the ESB Grid Supply throughout 2019 compared to 2016. The renewable on-site wind-turbine generator produced these (offset) units. This offsetting represents a decrease of 42% in imported ESB energy unit quantity. The annual monetary savings for the same period of comparison were €361,194. The monetary savings expressed as a percentage are 26%. The WTG produced 8,522,005 kWh units of electrical energy in 2019. Of these, 2,145,818 units were exported to

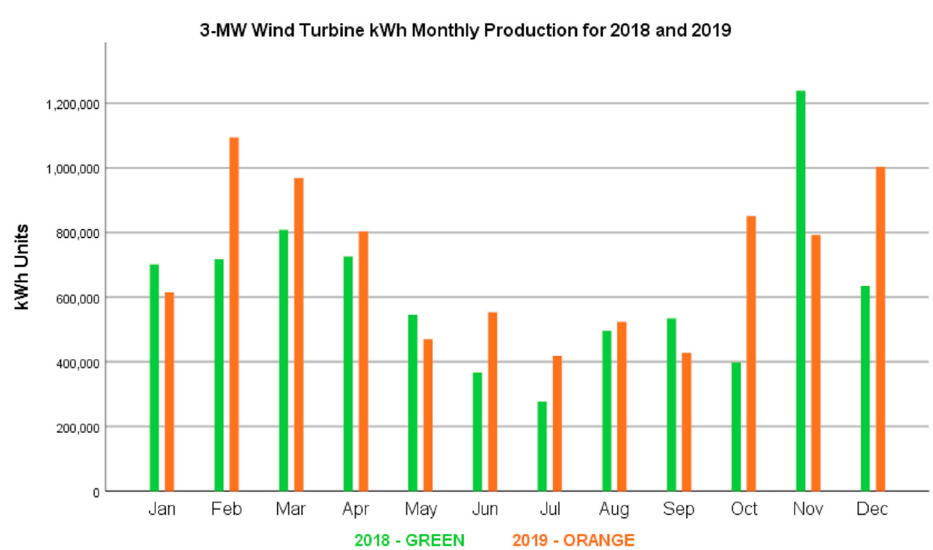

Fig. 5. Wind Turbine kWh Output 2018/2019.

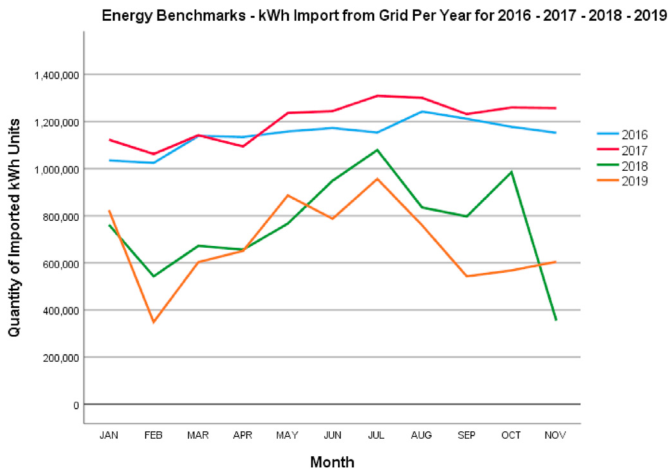

Fig. 6. Quantity of imported kWh units pre-installation (2016/2017) from the National Electricity Grid, compared with post-installation (2018/2019).

the national grid, and the remaining units were used on-site. The 2,145,818 exported units received a price of €0.045/kWh or annual revenue of €96,561. The annual savings on the 6,376,187 kWh units used on-site is €446,333 (average Day/Night charges in Fig. A5 = €0.07/kWh). Based on these figures, the simple payback period (PP) is 3,500,000 ÷ (96,561 + 446,333) ≈ 6.5 years. From an environmental perspective, there is an annual (2019) reduction of 3195 tonnes of CO_2 being emitted into the atmosphere as a result of the carbon-neutral WTG supplying the 8,522,005 energy units (SEAI, 2019, p 34).

There is a significant improvement in the kWh/Unit energy benchmarks pre-connection (2016/2017) and post-connection (2018/2019), as shown in Table 2. It required 157 kWh units of imported electrical energy to process each unit in the factory. To process the same unit in 2019, it required the much-reduced figure of 88 kWh units of imported electrical energy, contributing to the cleaner production philosophy.

The yearly cost of the imported electric units from the ESB grid (Fig. 2) was as follows:

- €1,368,646 (2016, with 13,703,584 kWh imported units)
- €1,495,657 (2017, with 13,979,080 kWh imported units)
- €1,275,491 (2018, with 9,124,564 kWh imported units)
- €1,007,453 (2019, with 7,992,045 kWh imported units)

Considering the significant differences in the number of kWh units imported in 2017 compared with the value in 2018 (Fig. 6), there appears to be a smaller percentage difference in the actual monetary savings between the two years. The difference in monetary terms is €1,495,657 − €1,275,491 = €220,166. The percentage of monetary savings is €220,166 ÷ €1,495,657 = 15%. The percentage of reduction in imported kWh electrical units for the same period is (13,979,080−9,124,564) ÷ 13,979,080 = 35%. Further analysis is needed to determine the cause(s) of the significant difference between these two benchmark values.

Table 2
Energy benchmarks.

Year	Units Processed in Factory	Total kWh Electrical Import	Energy Benchmark (kWh/Unit)
2019	90,637	7,992,045	88
2018	94,064	9,124,514	97
2017	87,872	13,979,080	159
2016	87,192	13,703,584	157

A detailed bill analysis was carried out on the electric utility bill for May 2018 (random selection). The total cost of the monthly bill is €103,584.16 (including VAT). A breakdown of the bill is as follows:

The figures in Table 3 indicate that the non-energy-related items on the electricity bill account for 38% of the overall monthly cost. Such items include standing charges, levies, and management fees. Therefore, the energy-related savings as a result of the distributed renewable energy source (wind turbine) is not wholly reflected in monetary savings on the electric utility bill.

It required approximately 14,000,000 kWh units (13,979,080 in 2017 and 13,703,584 in 2016) to power the SME production annually. The wind turbine contributed a significant amount of those units in 2018 and 2019 (Fig. 7). In addition to providing a significant number of units used on-site, 2,145,818 kWh units are generated by the wind turbine and are surplus to on-site requirements. They were *exported* to the national grid in 2019 via the ESB grid connection (and similarly, 1,967,000 units were exported in 2018). The excess exported units provided an added revenue of €96,561 in 2019.

7. Discussion

From the line graph in Fig. 6, it is plain to see the reduction in imported kWh electrical units (from the ESB grid supply) from 2018 onwards, i.e., after the turbine was installed. While factory output remained reasonably steady from 2016 to 2019 (Table 2), the reduced ESB grid-supplied kWh imported units confirmed that the turbine 'offset' a significant number of units by generating carbon-neutral kWh units consumed in the factory, the hypotheses stated in the literature review holds. Any excess units produced by the turbine above and beyond what was required on-site were exported to the national grid. The wind turbine generated a significant quantity of kWh energy units during the two years after it was installed (Fig. 5). In 2019, the WTG produced 8,522,005 kWh units of electrical energy. These units supplied by the carbon-neutral WTG would otherwise have to be provided by traditional means of electricity generation, including fossil-fuel-driven generators. The WTG contributed to a carbon emission reduction of 3195 tonnes for 2019 for the SME. This CO_2 emission reduction contributes significantly to the environmental dimension of the TBL concept (Elkington, 1997). The capacity factor values of 28% in 2018 and 32% in 2019 (Table A2) are in line with expected values (Henaghan, 2013). The six-and-a-half-year payback period is an improvement on previous wind turbine research results (Kealy, 2014b), and the findings indicate positive sustainability and economic performance.

While the kWh quantity of electrical units offset by the wind turbine display positive results, the monetary savings are slightly

Table 3
Breakdown of May 2018 electricity bill.

kWh Electrical-Energy Related	Non-Energy Related
€56,245.82 (Day and night units)	€151.15 (Standing charge)
€2860.85 (DUoS energy rates)	€3039.55 (DUoS capacity charge)
€5304.21 (TUos rates)	€479.11 (Low power factor surcharge)
	€3530.79 (TUoS capacity charge)
	€0.06 (Capacity margin charge)
	€11,361.35 (PSO levy)
	€4766.02 (Market operator charge)
	€13,241.13 (System capacity charge)
	€2176.34 (Vayu management fee)
	€435.27 (Electricity tax)
	€7.48 (Capacity charge refund)
Total €64,410.88 [62%]	**Total €39,173.30 [38%]**

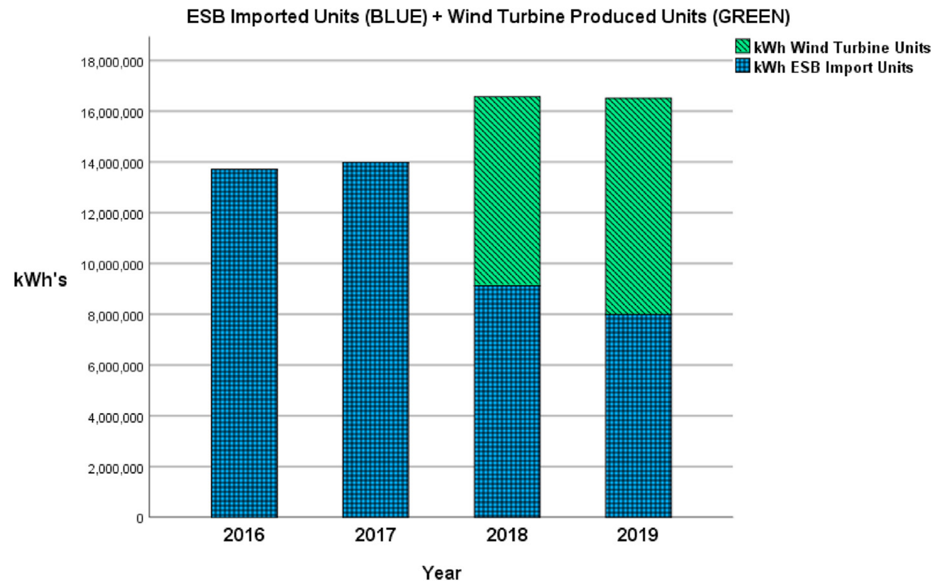

Fig. 7. Total Number of kWh Electricity Units Over Four Years.

disappointing. This finding is due to several factors, one of which is that the electricity bill for May 2018 (Table 3) indicates that only 62% of the total bill, €64,410.88, goes towards the cost of the kWh day and night imported energy units. The remaining cost includes standing and management charges (Table 3) and accounts for 38% of the total cost for May 2018. The day unit cost is 7.9 cents/kWh, and the night unit cost is 6.1 cents/kWh (VAT included). These day/night rates are quite competitive. If these costs per kWh were to increase, the economic dimension of the project would become even more appealing. Note that the maximum import capacity (MIC) for the industrial facility is 2750 kVA. This MIC value is unlikely to be reduced despite the WTG installation as it seems evident that the 3-MW wind turbine has a low power output value at some stage every month due to moderate wind conditions. The monthly kVA maximum demand is measured over 15 min (averaged), and the highest 15-min maximum demand value is recorded for billing purposes. At times of low wind speeds, the ESB grid must supply most or all of the electrical energy necessary to power the site loads (Fig. 2). Therefore, despite the positive outcomes associated with the 3-MW wind turbine installation, the factory premises still need to be connected to the national electricity grid to operate continuously. At specific points every month, the grid supplies all the kWh units, generated by a combination of traditional and renewable sources that includes a significant element of fossil fuels.

The power quality of the 3-MW wind turbine is much improved, compared to the 300-kW DFIG wind turbine and the 10-kW three-phase synchronous wind turbine discussed earlier. This finding is based not just on the power quality assessment undertaken by the external third-party experts (Supplementary Data), but the CV values associated with the 3-MW wind turbine. It is not enough to solely measure the traditional parameters of power quality without measuring the CV value. The EGIP measurements inherent in the 300-kW turbine and the compliance with EN 50428 on the 10-kW wind turbine did not indicate any 'red flag' issues, despite both installations being disappointingly ineffective. Both installations recorded high CV values. A range of CV values for the 3-MW wind turbine depending on wind speed, and, therefore, active power output, is shown in Table 1. While these values show some sporadic, very positive results for the 3-MW turbine installation, there is still room for improvement before the installation reaches the consistently low hydroelectric CV value of 0.034. The CV value is comparable to the hydroelectric value during very high wind speeds, leading to the turbine operating at full capacity 3-MW output. In these high-wind speed conditions, the CV values for the 3-MW WTG are 0.005 (0.5%) [T5] and 0.026 (2.6%) [T7] (Table 1). The wind turbine ran for approximately 16% of the power quality test period (February 17, 2020 to June 2, 2020) at its rated output, 3-MW. It is a recommendation, based on the findings from this current study, to investigate the effect that smoothing capacitors would have on the turbine power output signal because this would help consistently lower the CV value at all wind speeds.

While it is encouraging to see a reduction in the number of imported kWh units as the wind's speed increases (Fig. A3), the scatter plot also shows a significant scatter around the 4 m/s wind speed. Wind speed values, both below and above the 4 m/s value, follow a consistently negative correlation pattern. The correlation coefficient is calculated as −0.766, which indicates a strong negative correlation between the two variables. The negative correlation coefficient describes the extent to which the wind speed variable and the imported energy unit's variable move in opposite directions, (i.e., the higher the wind speed, the lower the number of units imported to the factory). This hypothesis, stated in the research methodology section, holds.

8. Conclusions

The study concludes by verifying the investing SME reduced their amount of CO_2 emissions by 3195 tonnes in 2019, and they saved money on their electricity bills as a result of installing a 3-MW wind turbine on their factory site. The payback period for the turbine is 6.5 years. Positive outcomes can be attributed to environmental, economic, and social spheres, so it is a beneficial, sustainability-focused project. While there are many studies carried out using modelled or simulated results, there are fewer empirical studies, such as this one, that examine actual cases using real data. A novel contribution is the identification of a parameter that is imperative in renewable energy power quality analysis, namely the coefficient of variation of the turbine active power output. The short-term fluctuations of the turbine power output influence the overall effectiveness of the project. The missing parameter is expressed as the coefficient of variation values, and this new characteristic is measured in addition to the traditional suite of power quality parameters usually associated with renewable energy technologies. Low CV values indicates good quality power and is an important indication as to the effectiveness of the wind turbine installation. CV values of 2.6% and below were measured during the study. In power quality measurements for future research, the measurement process should calculate the power output CV parameter in real-time. Future research work is recommended in the area of power quality analysis of solar PV electrical systems and importantly, the additional power quality parameter presented in this current research, i.e. the CV parameter, must be included in the suite of power quality measurements.

CRediT authorship contribution statement

Tony Kealy: There is only one author associated with the article, namely Tony Kealy. All the work is carried out by Tony Kealy for this article.

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.

Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.124699.

Appendix

USI (2019) report — A survey methodology was used in the study, and data were coded and analysed using the Statistical Package for Social Sciences (SPSS) software. Some key findings of the USI (2019) report:

- Students are experiencing extremely severe levels of anxiety (38.4%), depression (29.9%), and stress (17.3%),
- Close to a third (32.2%) of students had a formal diagnosis of a mental health difficulty at some point in their lives,
- A fifth (20.9%) of students did not have someone to talk to about personal and emotional difficulties.

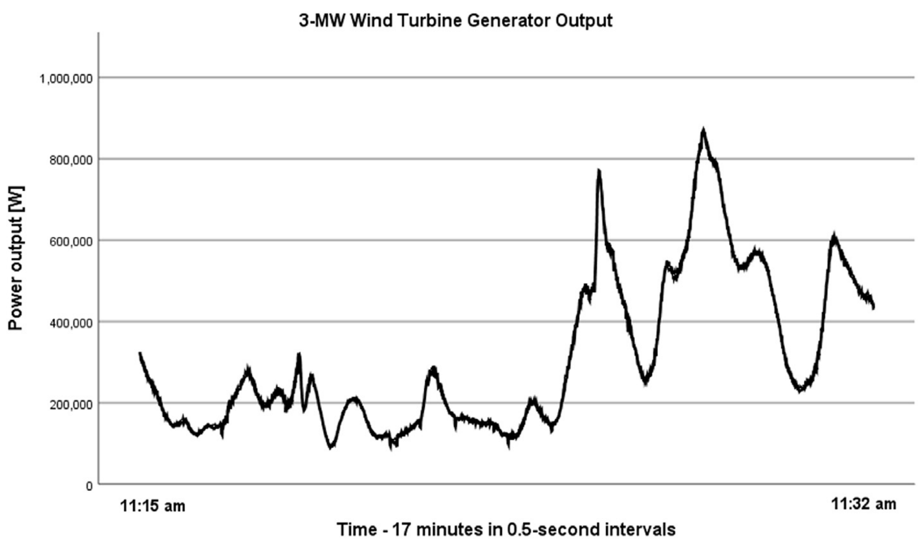

Fig. A1. Active Power Output on Tuesday June 18, 2019, approx. 17 mins [T3].

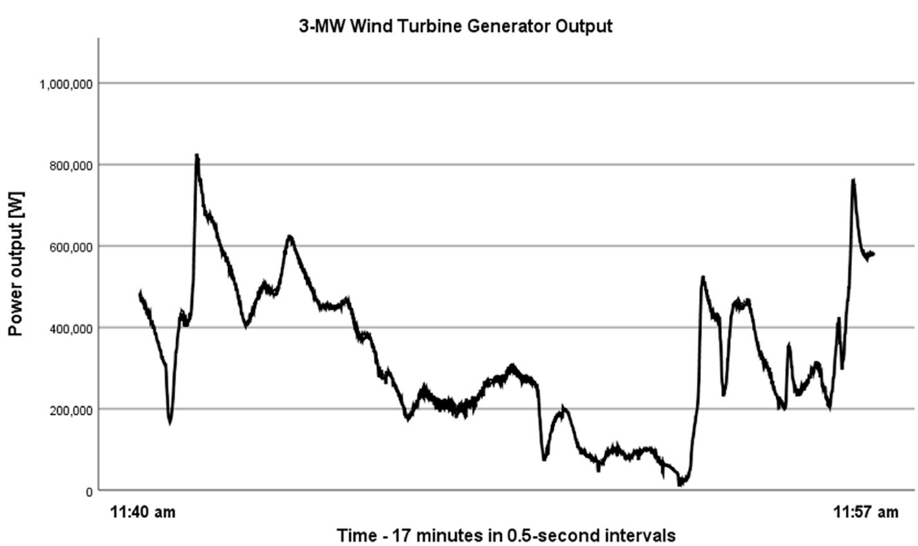

Fig. A2. Active Power Output on Tuesday June 18, 2019, approx. 17 mins [T4].

Statistical, bivariate correlation, analysis was carried out on the downloaded wind turbine data, and energy data, using the SPSS software package. The analytical techniques utilised was the correlation test which measures the strength and direction of two variables on a scatterplot. The two variables were (i) the wind speed and (ii) the number of kWh electrical units imported from the national electricity grid. The resulting correlation coefficient, r, value is always between +1 and −1. The +1 value means a perfect positive linear relationship, while the −1 value means a perfect negative linear relationship.

A second correlation analysis was carried out on the same two variables, but only one day (Thursday) every week was analysed. The data inform us that, before the wind turbine installation, there was a consistent number of kWh electrical energy units imported on that day, as is demonstrated in Fig. A6. For this test, the correlation coefficient was calculated as −0.766. A scatter plot of the two variables is shown in Fig. A3. The r-value of −0.766 indicates a strong negative relationship.

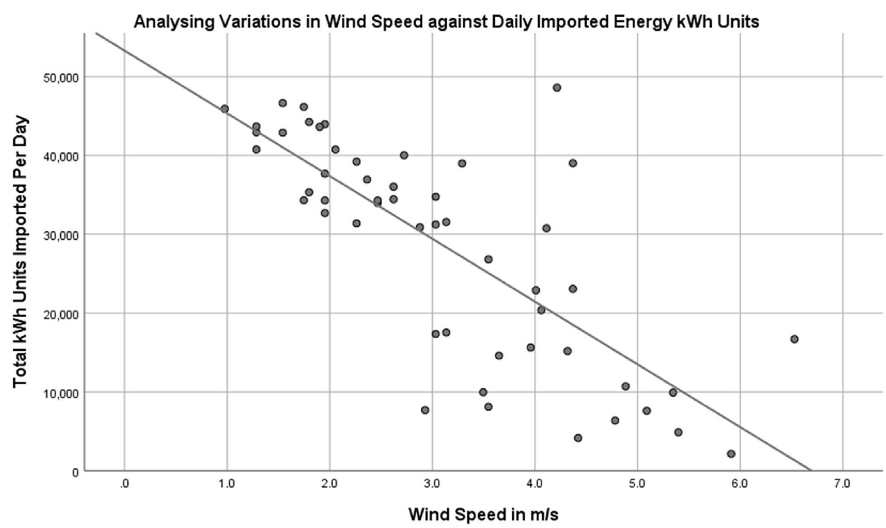

Fig. A3. Scatter Plot – One-year Data, Thursday-only (52 Thursdays between June 7, 2018 and May 30, 2019).

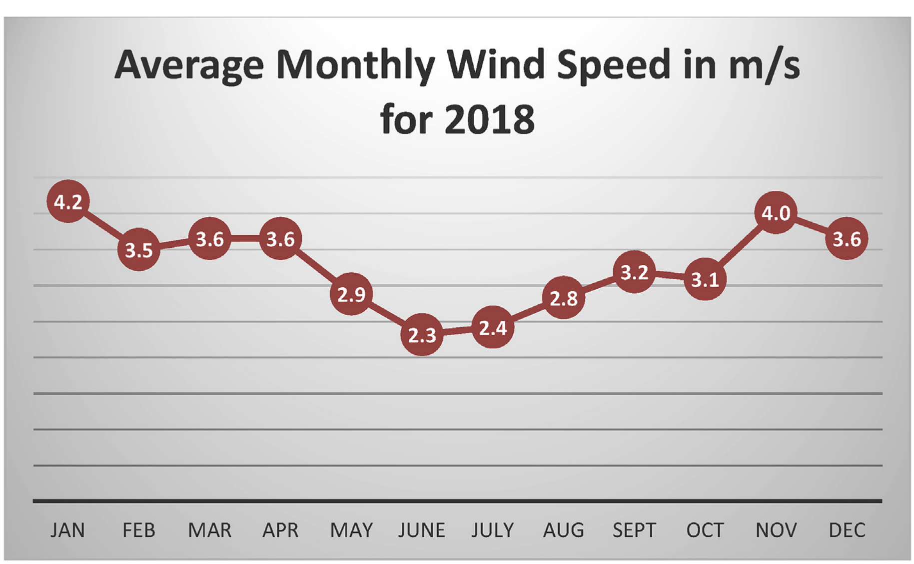

Fig. A4. Ballyhaise Co. Cavan Wind Data for 2018.

Description	Units	Unit Price	TOTAL
Energy Charges			
(a) Day Energy	517,279 kWh	*6.9841 c/kWh*	€36,127.33
(b) Night Energy	249,712 kWh	*5.3776 c/kWh*	€13,428.46
Distribution Charges (DUoS)			
(a) Standing Charge		*1,568.00 €/year*	€133.17
(b) Capacity Charge		*€11.47 KVA MIC year*	€2,678.02
(c) Unit Rates			
Day	517,279 kWh	*0.004530 €/kWh*	€2,343.27
Night	249,712 kWh	*0.000710 €/kWh*	€177.30
(d) Low Power Factor Surcharge	51,542 kVrh	*0.008190 €/kWh*	€422.12
(e) Excess kVa Surcharge	0 KVA	*€57.33 KVA MIC year*	€0.00
Transmision Charges (TUoS)			
(a) Network Capacity Charge	2.519 MW	*1234.9471 €/MWh*	€3,110.83
(b) Network Transfer Charge	794.388 MWh	*2.2924 €/MWh*	€1,821.06
(c) System Services Charge	794.388 MWh	*3.5905 €/MWh*	€2,852.25
(d) Capacity Margin Charge	536.935 MWh	*0.0001 €/MWh*	€0.05
Market Operator Charge			
(a) Variable Market Operator Charge (VMOPy)	794.388 MWh	*0.286 €/MWh*	€227.20
(b) Imperfections Charge (IMPy)	794.388 MWh	*5.0000 €/MWh*	€3,971.94
System Capacity Charges (based on estimates)	794.388 MWh	*14.6858 €/MWh*	€11,666.19
System Capacity Charges (Reconcillation from previous month)			-€6.59
Vayu Management fee	766,991 kWh	*0.250 c/kWh*	€1,917.48
Electricity Tax	766.991 MWh	*50.00 c/MWh*	€383.50
PSO Levy		*€3.64per kVa of MIC per month*	€10,010.00
Subtotal			€91,263.58
VAT @13.5%			€12,320.58
Total			€103,584.16

Fig. A5. Electricity Bill for May 2018.

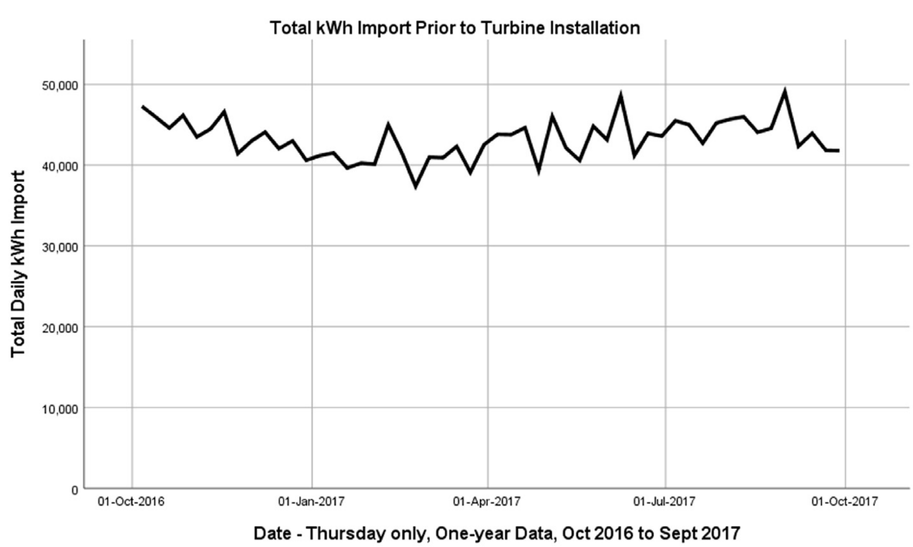

Fig. A6. Graph showing consistent kWh Energy Imported Unit Values – Thursday only, before WTG Installed.

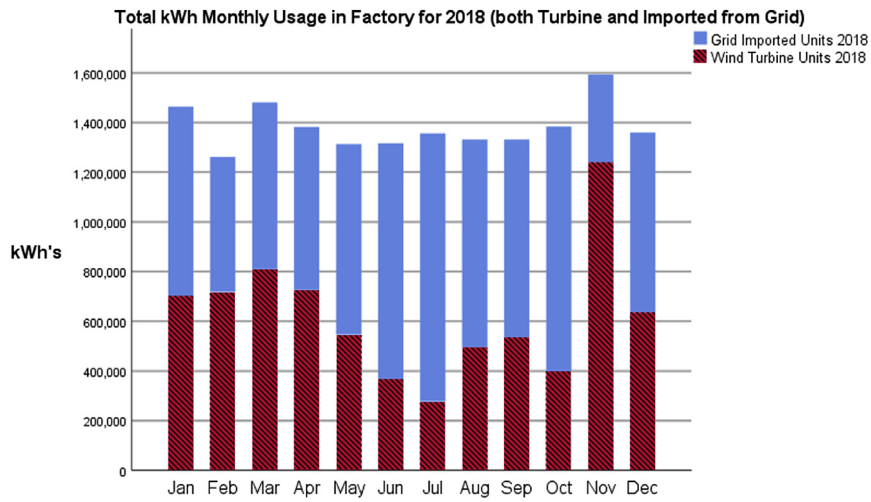

Fig. A7. Total Number of kWh Energy Units Used on-site in 2018 (addition of turbine units and imported units).

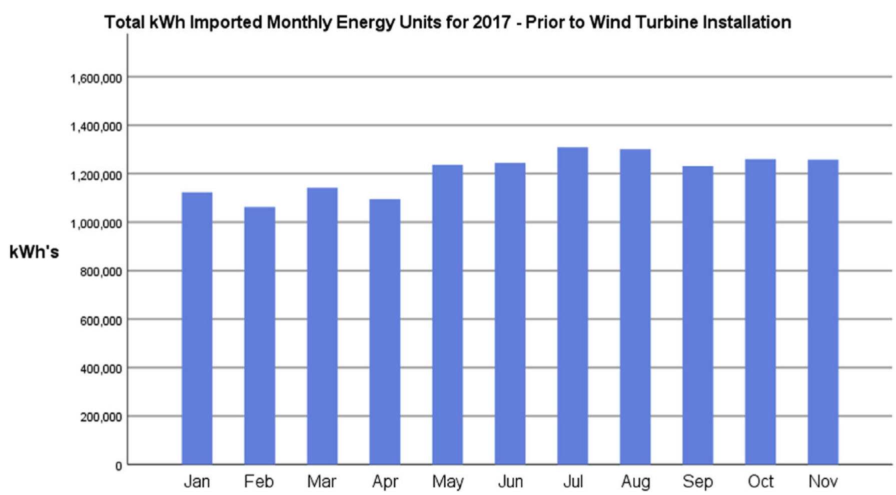

Fig. A8. Number of Imported Energy Units in 2017, before the turbine was in production.

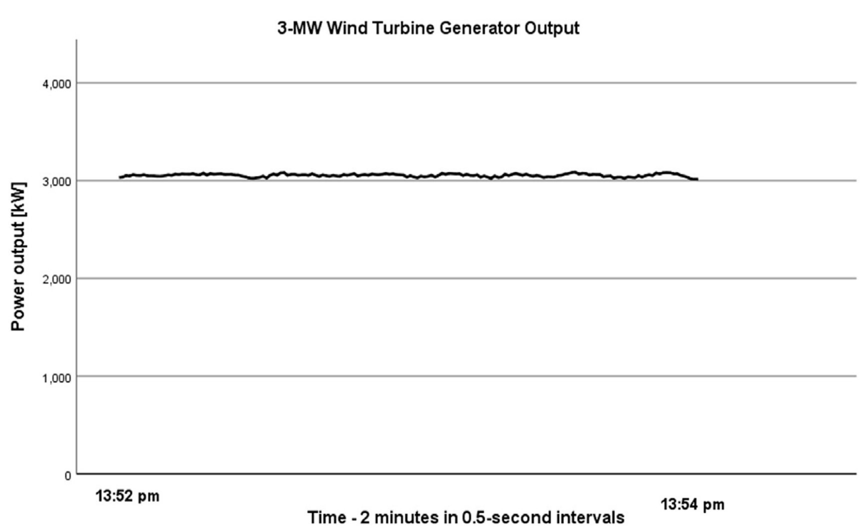

Fig. A9. 3-MW Turbine Power Output on Monday February 17, 2020, 13:52 to 13:54 [T5].

There were substantial wind speeds recorded on February 17, 2020 (Storm Dennis). The CV value for the data shown in Fig. A9 is 0.005. The average daily wind speed in Ballyhaise for February 17, 2020 was 6.2 m/s. The researcher observed that the power output was steady for 30 min before the recorded output starting at 13:52 p.m.

WTG supplies the majority of the power during the high wind conditions on that day.

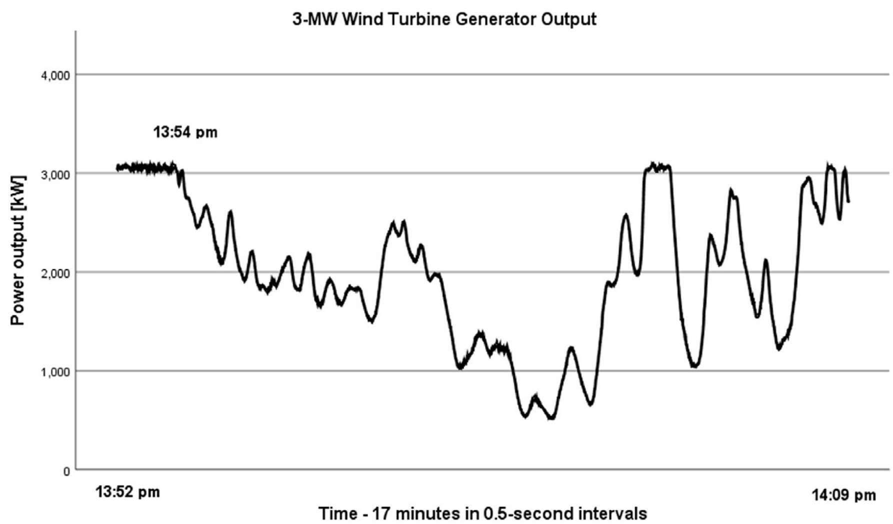

Fig. A10. 3-MW Turbine Power Output on Monday February 17, 2020, 13:52 to 14:09 [T6].

The wind speed abated after 13:54, and the wind turbine power output dropped at that stage. The steady period between 13:52 and 13:54 is shown in Fig. A9. The CV value for the WTG power output between 13:54 and 14:09 was 0.36.

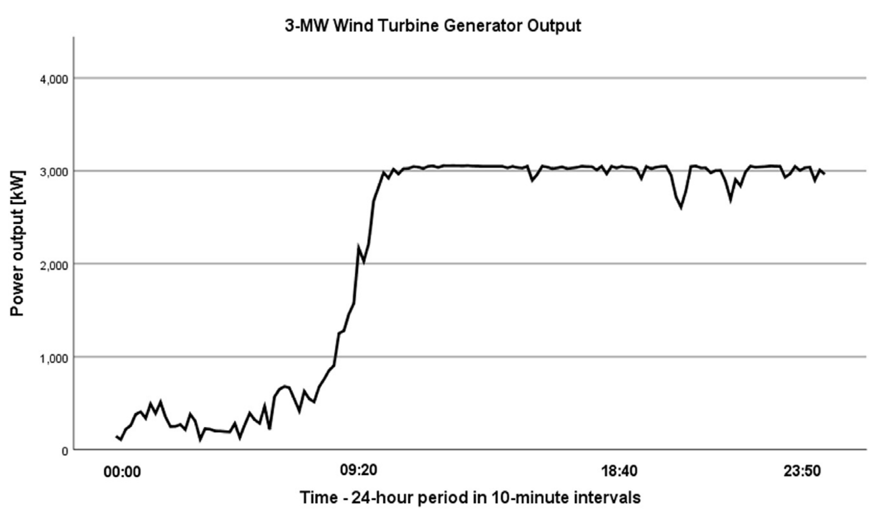

Fig. A11. 3-MW Turbine Power Output on Saturday March 2, 2019, 24 h in 10-min sampling intervals [T7].

The CV value for the power output during the time between 09:20 and 18:40 is 0.026. This low CV value coincides with very high wind speeds (Fig. A12) where the WTG is producing its maximum power output, i.e. 3-MW. The low wind speeds between 00:00 and 09:20 are manifested in the ESB Supply quantity of imported Night Units (9432 kWh) shown in Table A1 for 02-March-2019. Conversely, the amount of Day Units is only 53 kWh as the

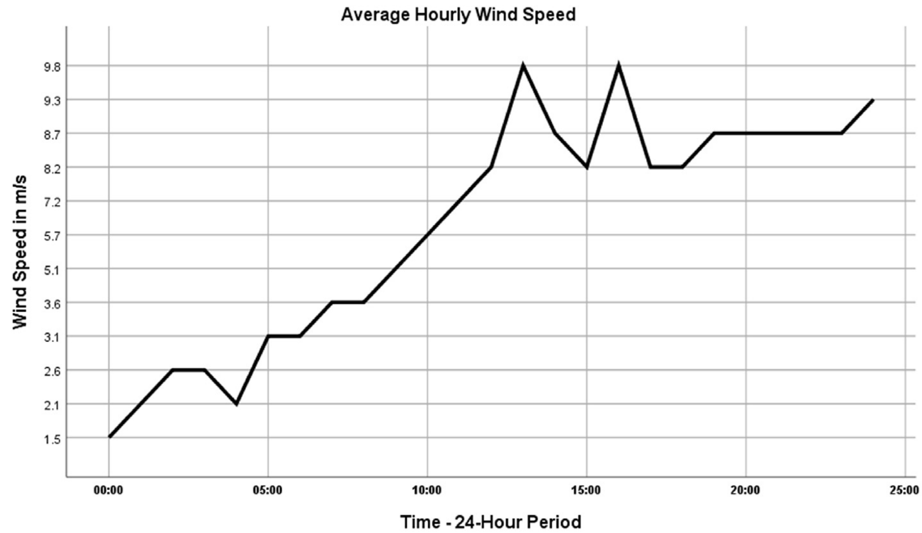

Fig. A12. Average Hourly Wind Speed on Saturday March 2, 2019 in Ballyhaise.

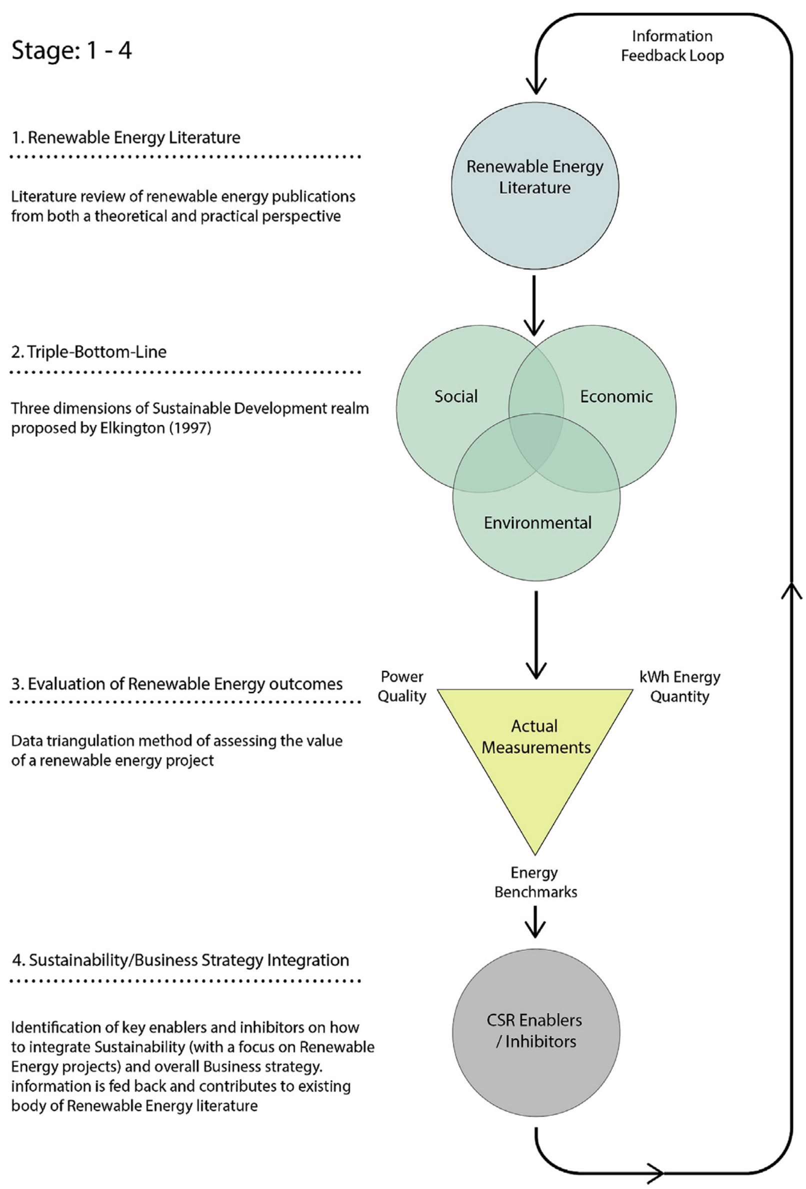

Fig. A13. Closed-loop Evaluation Framework (Kealy, 2020).

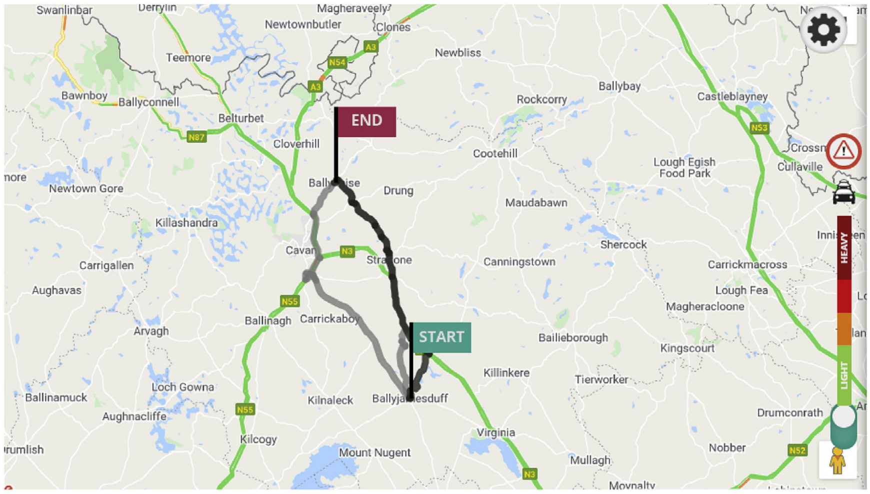

Fig. A14. Distance between Case Study site and Nearest Meteorological Weather Station in Ballyhaise (26-km), both in County Cavan, Ireland (http://www.theaa.ie).

Table A1
Benchmark for Quantity of Imported kWh Energy Units

Date	Day Units (kWh)	Night Units (kWh)	Total Units (kWh)
01-March-2019	27,246 kWh	13,272 kWh	40,518 kWh
02-March-2019	53 kWh	9432 kWh	9485 kWh
03-March-2019	10,165 kWh	1000 kWh	11,165 kWh
04-March-2019	14,859 kWh	7967 kWh	22,826 kWh
09-March-2019	9370 kWh	3281 kWh	12,651 kWh

Table A2
Four-Year Energy Values

	2016	2017	2018	2019
Total Yearly Electricity Bill Cost	€1,368,648	€1,495,657	€1,275,491	€1,007,453
Max. Demand Monthly Average	2.648 MW	2.646 MW	2.627 MW	2.539 MW
Total Yearly kWh Units Import	13,703,584 kWh	13,979,080 kWh	9,124,514 kWh	7,992,045 kWh
Total Yearly kVArh Units Import	4,750,405 kVArh	5,736,415 kVArh	3,671,672 kVArh	3,581,271 kVArh
Average Yearly Power Factor	0.94	0.925	0.927	0.913
3-MW Wind Turbine Production	0	0	7,449,101 kWh	8,522,005 kWh
3-MW Turbine Capacity Factor	N/A	N/A	28%	32%

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