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A Closed-loop Renewable Energy Evaluation Framework

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A closed-loop renewable energy evaluation framework

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ABSTRACT

Many businesses that have embraced renewable energy projects as part of their corporate sustainability efforts lack direction concerning how the projects are assessed. This study presents a framework that prescribes the necessary stages that allow a robust project evaluation to take place. The framework should assist practitioners in ascertaining if renewable energy projects, such as wind turbines and hydro-electric generators, contribute to energy cost savings and a reduction in CO_2 emissions. The conceptual framework was developed using empirical data accessed from an 850-kW wind turbine case study and a 40-kW hydro-electric case study and embraced the action research methodology. Both renewable projects are based in Ireland. The 850-kW wind turbine project was found to display disappointing results. As part of the electrical generator power quality measurement, it was found that there was large dispersion in the wind turbine output signal where the coefficient of variation values of between 128% and 939% were recorded. The simple payback period for the wind turbine investment is 7.34 years. The assessment of the 40-kW hydro-electric project found that positive values could be attributed to the environmental, economic, and social aspects of the project. Coefficient of variation values of between 2.8% and 3.9% were calculated for the hydro-electric plant with a simple payback period of fewer than two years. It was found that the dispersion value affects the actual financial and environmental benefits of the project. This is the first time that the short-term dispersion characteristic of a renewable generator power output signal is considered as part of the power quality analysis. Measurement of the quality of renewable power outputs should include the short-term ramping, dispersion, characteristic of the power signal. An implication for stakeholders is that the short-term ramping variation of renewable energy generators must be measured in each evaluation process.

1. Introduction

Sustainable business development can be defined as a business decision-making philosophy that encompasses human, economic, and environmental dimensions. There are interplay and synergy between the three components (Svensson et al., 2018; Ruhnke and Gabriel, 2013). Kuhnen and Hahn (2019) suggest that environmental protection and economic prosperity are a means to an end of ensuring human well-being, i.e., the social dimension of sustainability. The sustainable development concept and its related term Corporate Social Responsibility (Silvestre and Tirca, 2019), belong to the academic discipline of management. Many business managers are currently embracing renewable energy sources to power their production facilities to make the production process cleaner. Renewable energy sources chosen for analysis in this current study are wind turbines and hydro-electric generators. Implementing renewable energy strategies is expected to make savings on electrical energy bills and reduce harmful CO_2 emissions (Vazquez-Hernandez et al., 2019). In the Irish context, wind turbines are very popular but may suffer from the fact that the power output from the wind turbines varies (Lap-Arparat and Leephakpreeda, 2019) although a literature review reveals that the variations have not been measured in extensive detail. The link between measuring and managing has been identified in academic literature as being a vital link (Powell-Jackson et al., 2019). Some measurement of outcomes as a result of businesses embracing renewable energy technologies has provided little evidence of tangible benefits in any of the three sustainability aspects (Kealy, 2017). The three sustainable development dimensions were presented as a Triple-Bottom-Line (TBL) model by Elkington in 1997, and there has been minimal development of the model in an intervening couple of decades. One criticism of the TBL model is that it is difficult to measure the TBL outputs. There are research

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gaps in the published literature regarding the presentation of methods by which economic, environmental, and social sustainability outcomes can be measured. The overall objective of this current study is to address the shortcomings by introducing a novel framework in which the three components of a business investment decision can be measured and evaluated. The framework is developed using empirical case study quantitative data from (i) an 850-kW wind turbine and (ii) a 40-kW hydro-electric generator as well as qualitative/quantitative data from the results of an online survey. Measuring the short-term variation (dispersion) in the renewable generator outputs is part of the criteria by which the power quality is assessed. The online survey allows crucial enablers/inhibitors to be identified that facilitate the integration of the corporate sustainability strategy with the overall business strategy.

2. Literature Background

Sustainable development (SD) received its first significant international recognition at the United Nations (UN) Conference on the Human Environment held in Stockholm, Sweden, in 1972. There have been many UN sustainability conferences since then (e.g., Kyoto in 1997, Rio de Janeiro in 2012, and Paris in 2015). It appears that the sustainable development philosophy has become increasingly influential in civic society. In the corporate arena, corporate social responsibility (CSR) is seen as a vehicle for achieving sustainable development (Weber et al., 2014), and the two terms are used interchangeably in this study. Corporate decision-making now increasingly considers human, economic, and environmental dimensions instead of the traditional metric for the health of a business expressed in purely (financial) bottom-line values.

Several theories underpin SD/CSR literature, namely, legitimacy theory, institutional theory, and stakeholder theory (Susith and Stewart, 2014). Legitimacy theory refers to a contract between society and companies whereby companies require not only economic success but also social acceptance to survive (Saenz, 2019). The link between legitimacy theory and sustainable business practice leads to businesses mainly communicating their positive sustainability behaviour by producing an annual sustainability report (Hummel et al., 2019; Kim, 2019). The report considers resource usage; typically, these include human resources, water, energy, and waste. These factors affect the environmental footprint of a building (Egan, 2019). From a business management perspective, measuring the SD dimensions, particularly the environmental and social aspects, has been problematic (Arjalies and Mundy, 2013). Popowska and Rotkowska (2018) suggest that some of the problems stem from the fact that there appears to be a lack of a simple, universal framework by which to measure and report on a business' overall sustainability actions and decisions. A novel framework is presented in this study, demonstrated graphically in Fig. 1. The framework focuses on renewable energy measurements. Chen et al. (2018) state that the measured data in the reports must be objective and reliable. The quantitative data collected and analysed in this current study is considered as objective and reliable as the Fluke meter, which gathers the data and has an operating error of ± 0.5% (https://www.fluke.com).

Institutional theory is grounded in the idea that businesses conform to similar norms, values, and taken-for-granted assumptions about what is generally expected from them and what constitutes appropriate economic behaviour. One of the increasingly taken-for-granted premises is that companies make strategic decisions that are intended to transition their current energy system towards a cleaner, more decarbonised model (Vazquez-Hernandez et al., 2019). It is expected that this goal can be achieved by acquiring electrical energy from renewable energy sources such as wind turbines and hydro-electric generators. Several countries have developed highly successful renewable energy strategies; for example, 100 per cent of Iceland's electricity needs are supplied by either geothermal or hydro-electric power, and 97 per cent of Norway's electrical generation is hydro-electric power (Kroposki et al., 2017). Ireland has focused much of its renewable energy efforts on wind technology (Eirgrid, 2018). It is expected that the deployment of embedded renewable energy sources, such as wind and hydro, reduces (offsets) the amount of harmful CO_2 emissions that occur when traditional fossil-fuel driven electrical generators are solely deployed (Cullen, 2013). However, the variability in the output power of an embedded wind turbine generator presents compensating challenges for the parallel-connected traditional generators (Katzenstein and Apt, 2012). Traditional, fossil-fuel driven, electrical generators tend to be heavy machines with considerable built-in inertia (momentum) associated with such large-scale plant. Indeed, Kealy (2019) found that the significant increase in wind turbine installed capacity between 2014 and 2017 failed to produce an equivalent impact on the Irish energy benchmarks for the same period. Embedded generators must include an interface protection system to disconnect the generator from the electrical network if the voltage, frequency, or synchronisation violate acceptable pre-set bands. They must also include a loss-of-mains (LOM) function (Bignucolo et al. 2017). Separately, proprietary power quality analysers (PQA) may be installed to analyse renewable power quality (Viciana et al., 2019). While PQA devices monitor power quality events, voltage, and current waveforms (along with other advanced features) following the specifications given by international standards such as IEC 61000-4-30 and EN -50160, they do not routinely measure the dispersion in the renewable generator power output signal as part of the standard suite of measurements. This current study hypothesises that wind turbine power outputs under tightly controlled test conditions (Fig. A.4) display different characteristics than power outputs in real-world situations. The high-resolution (1-s and 500 milli-second) real-world empirical wind turbine (and hydro-electric) data presented in this study contributes valuable insight into renewable energy research. Much of the published literature in the wind turbine area presents either modelled/simulated data (Bandi and Apt, 2016) or test results under ideal test conditions in controlled environments (Arteaga-Lopez et al., 2019; Karassin and Bar-Haim, 2016; Sedaghatizadeh et al., 2018; Zhang et al., 2013). Some of the previous studies present findings using hourly data (Kaffine et al., 2013), half-hourly data (Di Cosmo and Malaguzzi Valeri, 2018), 15-min data (Katzenstein and Apt, 2012), and 10-min averaged data (Shoaib et al., 2019), although Apt (2007) used 1-s turbine power output data to estimate the power spectrum of several wind farms. The power quality measuring stage in the new framework produces a measure of the short-term dispersion in the power output signals, hence the need for the 1-s and 500 milli-second data sampling. The study does not assess the long-term averaged variation effects. Kealy (2017) and Kealy (2014) used empirical real-time (1-s and 500 milli-second) data obtained from the output of a 300-kW on-site wind turbine for a manufacturing facility and a 10-kW on-site wind turbine on an agricultural installation, respectively. Using (the majority of) electrical energy locally on-site reduces transmission and distribution losses (Sgobba and Meskell, 2019), contributing to businesses incorporating the cleaner production concept. As part of the power quality analysis of the 300-kW and 10-kW wind turbines, the coefficient of variation (CV) values was calculated. There was a significant variance in the power output, and the expected CO_2 savings and economic assessment of the allegedly clean technology were disappointing (Kealy, 2014, 2017). While hydro-electric power currently accounts

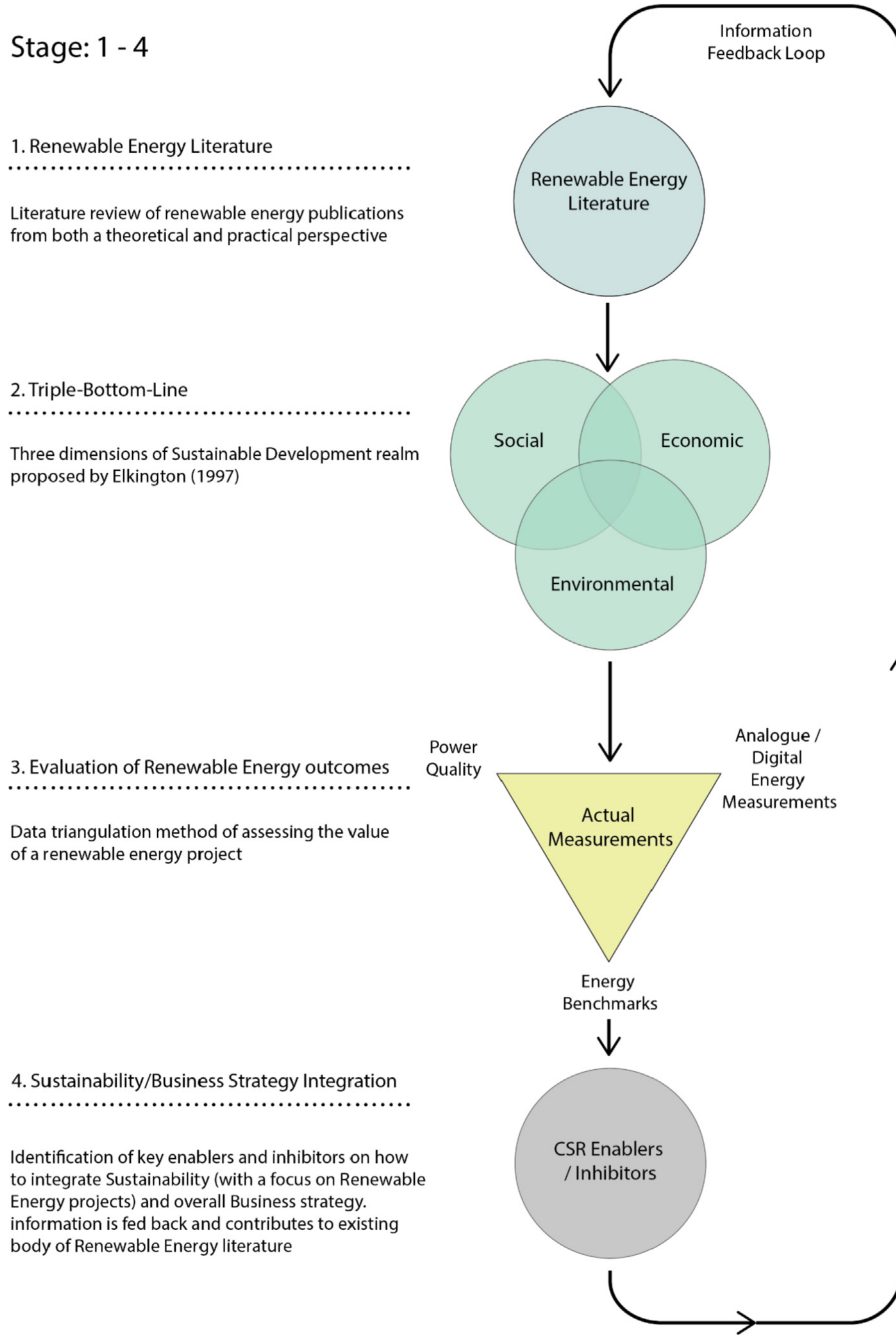

Fig. 1. Closed-loop renewable energy evaluation framework.

for only 2.4% of national, Irish, energy requirements (SEAI, 2018, p. 34), it is chosen for analysis in this study because (i) there is minimal human opposition to hydro-electric projects, and (ii) hydro-electric power was traditionally a significant factor in the development of the Irish electricity system. In the early stage, the Shannon hydro-electric scheme (referred to as Ardnacrusha) provided 100% of national energy needs, making Ireland's energy sector 100% renewable (Gaffney et al., 2017).

Another theory underpinning the sustainable development concept is stakeholder theory. Stakeholder theory holds that a business has an effect on, and is affected by, a range of groups and individuals as it goes about its efforts to achieve its business objectives (Freudenreich et al., 2019). In this context, different stakeholders may have diverse and sometimes conflicting expectations (Susith and Stewart, 2014). Academic institutions are stakeholders in the sustainability arena (Lopez-Perez et al., 2017), and their input is considered in this study when critical enablers to sustainability/strategy integration are discussed in stage four of the development of the evaluation framework. The transdisciplinary aspect of sustainability is presented in an article by Chareonpanich et al. (2017), who focused on research outputs, policies, and technologies to make Asian society more sustainable through cleaner production. Hussain et al. (2018) identified 'training' and 'knowledge' as critical parameters in effective sustainability measurement and reporting. While the social dimension of sustainable development includes simple metrics such as employee training, employee turnover, and time lost due to workplace incidents (Hummel et al., 2019), community members are also stakeholders in local businesses and may express opposition to renewable energy installations, particularly wind turbine installations (Cashmore et al., 2019).

3. Material and methods

In this study, a mixed methodology approach is utilised that combines an action research methodology and a case study methodology. The action research methodology offers an opportunity to bridge the divide between research and practice (Zhang et al., 2015), and the researcher is required to engage the process of evaluating renewable energy projects practically. This practical aspect of the methodology involves the design and connection of electrical power/energy meters on the cables linking the renewable generators to the electricity supply system. Analogue electrical energy meters and a digital power logger (Fluke 1735 Power Logger) are used in this longitudinal study. The digital meter has an operating error of ± 0.5% (https://www.fluke.com). Also, the Schneider ION™ power meter and SCADA device generate 1-s interval data that is used to plot the 15-min graph in Fig. 4. Quantitative data has been downloaded from the Fluke meter and the Schneider ION meter to the researcher's PC. The SPSS (Statistical Package for Social Science) software was used to analyse the quantitative data statistically.

The case study investigates a contemporary phenomenon in depth and within its real-world context. The case study is a suitable methodology in this piece of research as there appears to be a shortage of real-world renewable energy data in context, especially concerning wind turbine projects. Many publications present renewable energy modelled data or renewable energy data under ideal test conditions (Arteaga-Lopez et al., 2019), but these methods may not represent what is happening in the real-world context. The 36-min, 500 milli-second, test data (and the 15-min 1-s data in Fig. 4) allows enough time in the case study to analyse and quantify the short-term variability in the generator electrical power output. It has been suggested (Cullen, 2013) that short-term variation has a significant impact on the effectiveness of the installation. The mean, standard deviation, and coefficient of variation (CV) descriptive statistics are used to quantify the short-term fluctuations in the sampled data. The CV is commonly used in engineering applications and is a valid measure of dispersion (Teoh et al., 2017). The 'Run-Sum' method (Teoh et al., 2017) is utilised whereby time-series analysis is carried out on several partitioned regions of the test data (at specified intervals) overlapping by quantified intervals (Tables 1–4). Triangulated data measurement methods are encompassed using analogue/digital energy measurements, power quality measurements, and energy benchmarks. By developing converging evidence, data triangulation helps to strengthen the construct validity of the case study (Yin, 2018).

The energy benchmarking method involves a quantitative analysis for performance evaluation over several years (Petrovic et al., 2018). The 850-kW wind turbine case study uses the Carbon Intensity of Electricity Benchmarks expressed as the number of grammes of CO_2 emitted for every kWh unit of electrical energy generated (SEAI, 2018). The methodology for calculating the carbon intensity benchmark is explained in Section 4.1. The energy benchmark utilised for the 40-kW hydro-electric case study accounts for the number of kWh units imported from the electrical utility provider when (i) the hydro-electric generator was switched ON and (ii) the hydro-electric generator was switched OFF (section 4.2).

4. Results

4.1. Vestas 850-kW wind turbine case study

This case study is carried out on an 850-kW Double-Fed-Induction-Generator V52 Vestas wind turbine installation. The turbine output is connected directly to the national electricity grid in the west of Ireland. The single wind turbine is one part of a multi-turbine wind farm owned and maintained by a leading Irish utility established in the 1920s. The large corporation employs approximately 7000 personnel and perceives wind energy to be a core component of the company's sustainability strategy. The corporation employs people across a broad range of disciplines, including engineering, finance, IT, business, and marketing. The cost of the Vestas 850-kW turbine is €1,300,000. The annual revenue is €177,066 based on a 29% capacity factor (actual values obtained from SCADA indicating 83,148 kWh units produced in 14 days). The unit price is €0.082 per kWh (Kealy et al., 2015, Table-5). The simple payback period for this investment is 7.34 years. There are approximately 308 similar turbines installed in the Republic of Ireland. The case study measures the TBL value of the project. The environmental dimension focuses on three energy metrics, namely the analogue/digital energy measurements, power quality measurement, and energy benchmarks.

Analogue/Digital Energy Measurements (Wind Turbine) - This part of the triangulated data measuring stage is to verify the quantity of kWh electrical energy units allegedly produced by the alternative energy generator. In this current case study on the 850-kW wind turbine, the amounts of the analogue-measured and digitally measured energy units were compared over 14 days (17th July 2017 to 31st July 2017). During this period, the analogue (rotating-disc-meter) recorded a total of 84,416 kWh units. During the same period, the digital energy output (from the SCADA instrument in the central control room) recorded 83,148 kWh energy units. The accuracy of the two readings is 98.5% (83,148/84,416). The 1.5% error value is deemed to be sufficiently low and, therefore, is acceptable in this case.

Power Quality (Wind Turbine) – In addition to validating the quantity of kWh electrical energy units produced by the wind turbine, this part of the data measurement stage also analyses the

Table 1
Descriptive statistics for 850-kW wind turbine power output on 7th June 2017, using the run-sum method when calculating the coefficient of variation.

Data Points (Split into Six Time Zones)	Mean Power Output [W]	Standard Deviation [W]	Coefficient of Variation (%)
1–1200 (0–10 Minutes)	20,885	26,766	128
600–1800 (5–15 Minutes)	14,979	24,276	162
1200–2400 (10–20 Minutes)	1,995	18,747	939
1800–3000 (15–25 Minutes)	8,265	17,959	217
2400–3600 (20–30 Minutes)	12,429	19,707	158
3000–4200 (25–35 Minutes)	25,426	35,957	141

Table 2
Descriptive statistics for 850-kW wind turbine power output on 14th May 2018, using the run-sum method when calculating the coefficient of variation.

Data Points (Split into Six Time Zones)	Mean Power Output [W]	Standard Deviation [W]	Coefficient of Variation (%)
11.04–11.14 (0–10 Minutes)	50,514	27,166	54
11.09–11.19 (5–15 Minutes)	26,119	10,178	39
11.14–11.24 (10–20 Minutes)	21,005	10,808	51
11.19–11.29 (15–25 Minutes)	9,706	14,200	146
11.24–11.34 (20–30 Minutes)	Turbine shut down	No wind	OFF
11.29–11.39 (25–35 Minutes)	Turbine shut down	No wind	OFF

Table 3
Descriptive Statistics for 850-kW data shown in Fig. 4 on 14th May 2018.

Data Points (Split into Seven Time Zones)	Mean Power Output [W]	Standard Deviation [W]	Coefficient of Variation (%)
10.44–10.47 (0–3 Minutes)	186,670	84,600	45
10.46–10.49 (2–5 Minutes)	250,010	41,934	17
10.48–10.51 (4–7 Minutes)	283,180	61,504	22
10.50–10.53 (6–9 Minutes)	177,300	67,708	38
10.52–10.55 (8–11 Minutes)	77,060	30,914	40
10.54–10.57 (10–13 Minutes)	54,310	21,352	39
10.56–10.59 (12–15 Minutes)	66,440	18,869	28

Table 4
Descriptive statistics for 40-kW Hydro-Electric power output on 5th Sept 2017 using the Run-Sum method when calculating the Coefficient of Variation.

Data Points (Split into Six Time Zones)	Mean Power Output [W]	Standard Deviation [W]	Coefficient of Variation (%)
11.09–11.19 (0–10 Minutes)	27,735	966	3.5
11.14–11.24 (5–15 Minutes)	27,130	757	2.8
11.19–11.29 (10–20 Minutes)	26,848	876	3.3
11.24–11.34 (15–25 Minutes)	26,644	943	3.5
11.29–11.39 (20–30 Minutes)	26,581	999	3.8
11.34–11.44 (25–35 Minutes)	26,943	1,041	3.9

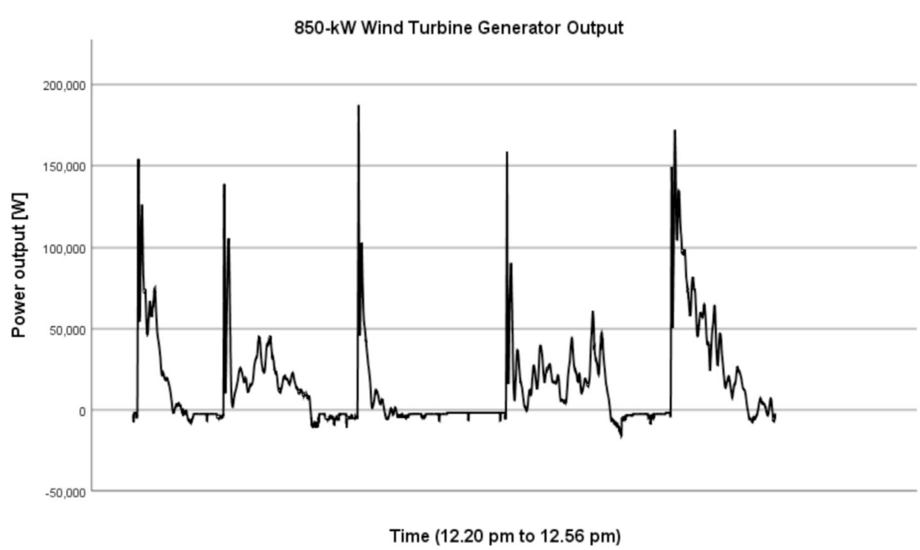

Fig. 2. Power Output from 850-kW Wind Turbine on 7th June 2017, 500-ms data (calm day).

quality of the power produced. The quality of the output power was examined using the high-resolution Fluke 1735 Power Logger and the Power Log V4.3.2 software for Fig. 2 and Fig. 3. Fig. 4 utilises 1-s data downloaded from the SCADA software. The power quality is focused on short-term dispersion in the generator output signal and is expressed numerically as a coefficient of variation value. The time-series analysis of the 850-kW power output data involved sampling the power output at 1-s (Figs. 4) and 500 ms time intervals (Figs. 2 and 3). The graphical representation demonstrated in Fig. 2 illustrates a plot of the data over a 36-min test period. A 'run-sum' method of dividing the plot into zones (10-min zone intervals) and calculating the coefficient of variation for each zone allows the measure of dispersion in the generator power output signal to be monitored. There is a 5-min overlap in the boundaries

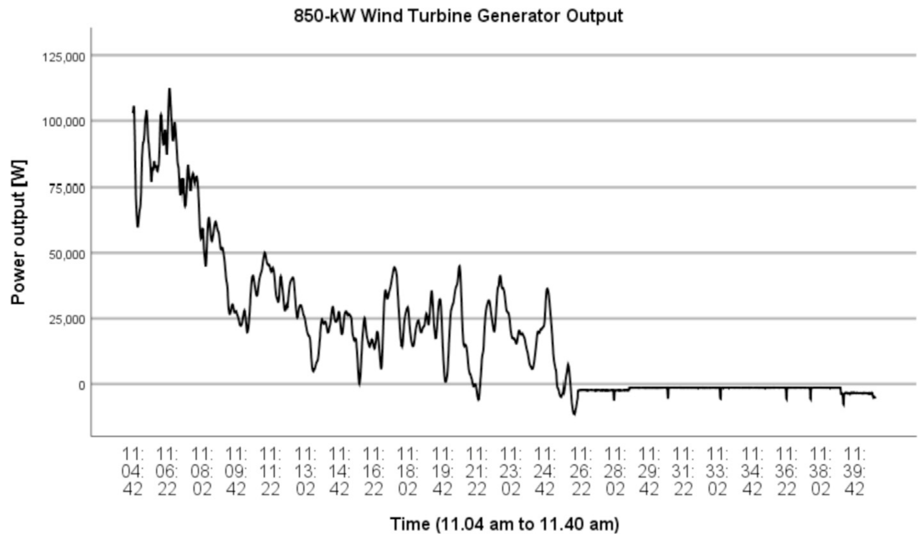

Fig. 3. Power Output from 850-kW Wind Turbine on 14th May 2018, 500-ms data.

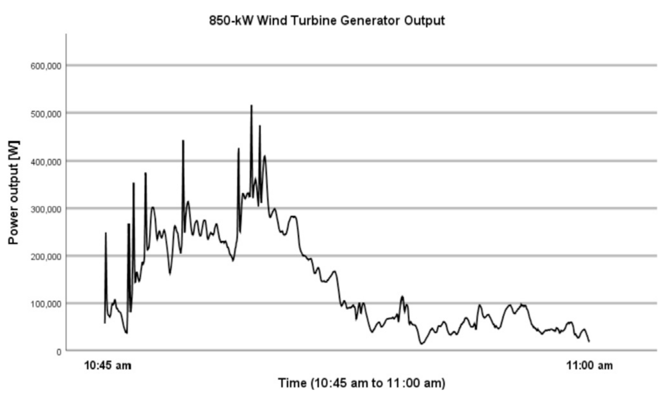

Fig. 4. Power Output from 850-kW Wind Turbine on 14th May 2018, 1-s interval data from Schneider ION™ Meter in Local Sub-Station.

of the designated zones, as demonstrated in Tables 1, 2 and 4 (and Tables A1, A2, and A3). There is a shortage of empirical data by which to compare the power quality results of this current study with other studies.

There was a considerable short-term variation in the 850-kW power output signal, demonstrated in Fig. 2. A study comparing turbine output power curves under strictly controlled test conditions and actual power curves under operating conditions in context found that instantaneous values of wind speed and wind power exhibit significant scattering about the mean profile (Bandi and Apt, 2016). Factors that contribute to this variability include turbulent fluctuations, wind shear, directional shear, and directional fluctuations. Shoaib et al. (2019) claim that environmental factors such as air temperature and pressure differences produce continuous and rapid variations in wind speeds, resulting in the non-linear behaviour of wind energy systems. There are constant and rapid variations of the 850-kW wind turbine power output demonstrated graphically in Fig. 2. The ramping phenomenon shown in Fig. 2 displays a similar profile to that shown in a comparison test carried out on a 300-kW wind turbine (Kealy, 2017). The dispersion and variability effect can be seen in Fig. 2 of this study and is quantified using the mean, standard variation, and coefficient of variation (expressed as a percentage) statistical parameters demonstrated in Table 1:

Energy Benchmarks (Wind Turbine) - The energy benchmarks component of the measurement stage gives a general indication if the decision to invest in the wind turbine installation is helping the stakeholders reach their objectives, i.e., to reduce CO_2 emissions and save money on energy costs. Benchmarking is not an exact science, as many variables can affect the benchmark values, but it indicates whether further investigations need to be carried out (Petrovic et al., 2018). The energy benchmark values used in this study were taken from the SEAI's national energy benchmarks from 2018. The carbon intensity of electricity benchmarks (CO_2 g/kWh) for 11 years is shown in Fig. 5. The carbon intensity benchmark is calculated by (i) summing up the total fuel quantities used nationally to drive all the electrical generators, (ii) multiplying each of the different fuel quantities by their emission factors to calculate the total amount of CO_2 produced, and (iii) dividing the total

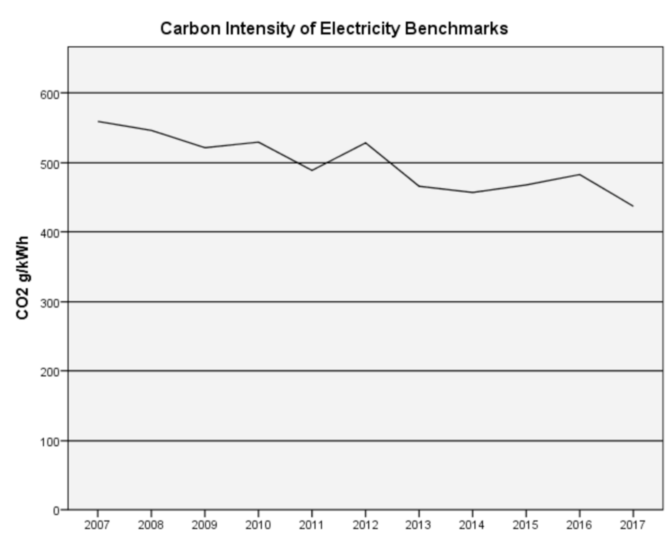

Fig. 5. Carbon Intensity of Electricity Benchmarks in CO_2 g/kWh (SEAI, 2018).

amount of CO_2 produced by the total number of kWh energy units produced nationally. Part of the reason for the reduction in the 2017 CO_2 g/kWh value (from the 2016 value) was the reduction in the quantity of coal and peat used in electricity generators (SEAI, 2018).

The final consumption of electricity increased in 2017 by 1.1% over the previous year to a value of 25,850 GWh. The SEAI report (2018, p22) states that the size of the final electricity consumption compared with the energy lost in transformation and transmission is striking. These losses represent 50% of the energy inputs (2387 ktoe/4753 ktoe, Figure 10, SEAI, 2018). There has been a fivefold increase in the volume of renewable electricity generated from 1873 GWh in 2005 to 8877 GWh in 2017 (SEAI, 2018, p. 34). Wind-generated power accounted for 25.2% of Ireland's gross electricity consumption, while hydro-electric generated power accounted for 2.4% in 2017 (SEAI, 2018, p. 34). By the end of 2017, the installed capacity of wind generation reached 3318 MW; this value included the 532 MW of wind capacity installed in 2017 (SEAI, 2018, p. 35). The SEAI (2018, p. 39) report states that the calculations for CO_2 displacement due to renewable energy generation used a refined methodological approach in 2017 to consider the effects of ramping and cycling fossil-fuel plants (Holttinen et al., 2014). Note that the conventional generation capacity in Ireland is 7400 MW (Eirgrid, 2018, p. 32). Bearing in mind the environmental dimension of the TBL (Fig. 1), in theory, the 850-kW wind turbine saved (offset) 36,335,676g CO_2 (approximately 36 tonnes) during the 14 days over which the longitudinal case study was carried out. The 83,148 carbon-neutral kWh units would otherwise have been generated using a mix of traditional, fossil-fuel-driven generators and other renewable energy sources connected to the national electricity grid at an SEAI-calculated, emission rate of 437 g of CO_2 for every kWh produced (SEAI, 2018). However, considering that there is a significant number of similar wind turbine installations connected to the grid (3318 MW), the environmental benefits are not apparent based on the data presented in Fig. 5.

Considering the social (human) dimension of sustainable development (Fig. 1), the year-on-year increase in installed capacity of wind turbines has not averted the Irish government from being potentially forced to pay substantial monetary fines to the European Union because it is unlikely to meet its renewable energy targets (O'Neill, 2019). Therefore, the social dimension of the wind turbine decision is not satisfied.

4.2. 40-kW hydro-electric case study

The second case study is carried out on a small-scale 40-kW hydro-electric investment where the generator output is embedded with the electricity utility provider in supplying a three-phase electrical supply to an SME in rural Ireland. Any generated electrical units that are over and above the instantaneous SME load requirement are exported onto the national grid. The generator is a squirrel-cage induction type in the micro-hydro range, i.e., between 5-kW and 100-kW power output (Zhou and Deng, 2017). The squirrel-cage induction generator is attractive in this case because of its low cost, robustness, simple start-up, and little maintenance mainly because of its rugged and straightforward brushless rotor construction, although a modern controller was installed in August 2017 to regulate the voltage and frequency. The total cost of the upgrade for the hydro-electric investment was €40,000. The SME owner spends between €25,000 and €30,000 per year on imported electricity units, depending on the number of hospitality bookings throughout the year. The simple payback period for the investment is less than two years, providing the generator can supply 100% of the load requirement. It is estimated that there are approximately 22-MW of small-scale hydro-electric capacity installed in rivers and streams across Ireland (Commission for Regulation of Utilities, 2018). The same three parameters are analysed in the actual measurement stage as in the wind turbine case study, namely: analogue/digital energy measurements, power quality measurement, and energy benchmarks.

Analogue/Digital Energy Measurements (Hydro-Electric) - The hydro-electric installation had been in situ for many years before the upgrade in 2017, and the analogue rotating-disc-meter (RDM) was still in use at the central electricity supply intake. The number of kWh energy units recorded on the RDM was compared with the number of kWh energy units registered on the digital-type energy meter installed on the front door of the newly designed hydro-electric control panel. The meter readings were recorded over several months on many different occasions. The analogue and digital meters recorded similar values, so the accuracy and validity were assured.

Power Quality (Hydro-Electric) - The time series analysis technique is utilised for this part of the case study. The power output was represented graphically using the Fluke 1735 Power Logger, and the result of the 36-min test period is shown in Fig. 6. There were 4319 'Watts Output' data points recorded during the 36-min test period and used to generate Fig. 6. The embedded generator interface protection (EGIP) device ensures that the standard power quality parameters (Volts, Frequency, Current, Synchronisation) are within pre-set limits. However, the EGIP device does not analyse the dispersion aspect of the power output signal.

Statistical analysis is carried out on the data shown graphically in Fig. 6 to give the following descriptive results to measure the dispersion aspect of the power output signal (CV expressed as a percentage) presented in Table 4.

The stable (non-ramping) output shown in Fig. 6 is replicated on another test on the hydro-electric plant on a different day; the resulting plot is shown in Fig. A.3 and associated data in Table A.3.

Energy Benchmarks (Hydro-Electric) – The energy benchmarks stage shown in Table 5 accounts for the number of kWh units imported from the electrical utility provider when (i) the hydro-electric generator was switched ON and (ii) the hydro-electric generator was switched OFF for maintenance purposes.

It should also be noted that during the test period, when the hydro-electric generator was running (turbine ON between 5th September 2017 to 15th September 2017), there were 1884 Day kWh units *exported* to the electrical network and 2706 night kWh units *exported* to the electrical grid. Therefore, in addition to providing the total energy requirement during these ten days (i.e., approximately 552 kWh electrical energy units), the hydro-electric generator also produced 4590 kWh units over and above what was required to provide electrical power to the SME. Considering the environmental dimension of the TBL concept (Fig. 1), these 5142 carbon-neutral-generated kWh units saved (offset) 2,247,054 g CO_2 that would have been emitted into the atmosphere had they been produced using a mix of traditional fossil-fuel generators and renewable generators. Approximately 2.2 tonnes of CO_2 savings (2017 values, SEAI, 2018) are due to the hydro-electric generator over the course of only ten days. Therefore, there are significant environmental benefits associated with this project.

This hydro-electric project contributed positively to the social (human) dimension of the sustainable development TBL model. The hotel owner was very content with the investment, as it reduced costs and contributed to a cleaner production concept because of increased efficiencies in the local use of renewable electrical energy. Society has the potential to benefit because savings can be passed on to hotel customers. On a national level, society benefits because the hydro-electric project reduces the amount of money that (Irish) society must pay as a penalty for failing to reach EU emission reduction targets.

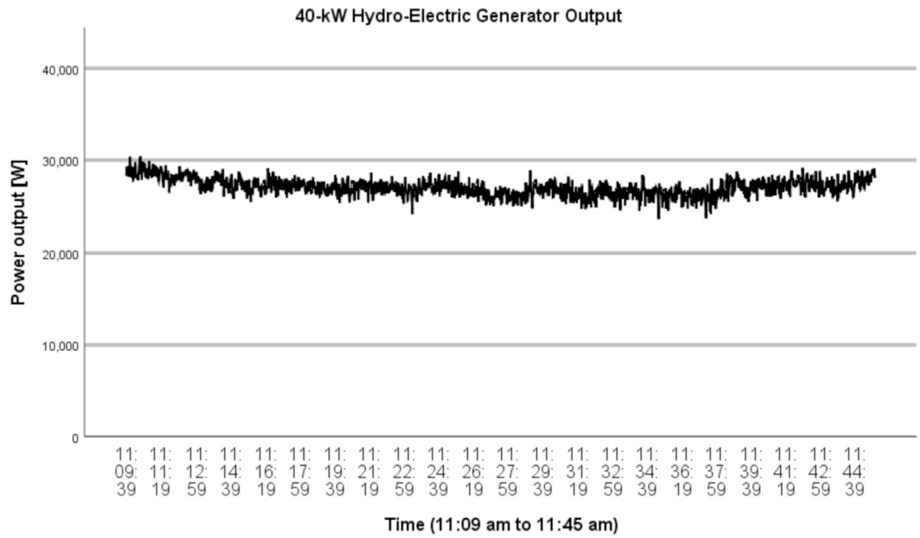

Fig. 6. Power output on 5th September 2017, 500-ms interval data.

Table 5
Energy benchmarks for hydro-electric generator.

Hydro-Electric Turbine	Number of kWh Units Imported from Utility Provider by SME	Time period between:
Turbine ON	0 kWh Units	5th September 2017 to 15th September 2017
Turbine OFF	Total of 552 kWh Units (336 Day kWh Units and 216 Night kWh Units)	22nd September 2017 to 2nd October 2017

4.3. Sustainability/strategy integration

Strategic SD/CSR Decisions - In both cases studied as part of this current analysis, there were significant financial resources assigned by senior business personnel to mitigate the human effect on climate change and to benefit financially from such investments. A total of €1,300,000 was invested in the 850-kW wind turbine project, and €40,000 was spent on the hydro-electric installation upgrade. An important matter is that company personnel (senior, middle, and lower level) must possess the knowledge/education to interpret the results of the (two) case studies. The researcher in this current study explained the significance of the results to the SME owner. Such sharing of knowledge allows for reflective and cyclic learning in the SME environment and increases sustainable management practices (Stewart and Gapp, 2014). Academics and practitioners need to know the significance of the electrical energy values presented in Table 5 as well as the generator power output values in Figs. 2–4 and 6.

Sustainability Enablers/Inhibitors - Firstly, in terms of enablers, an interdisciplinary SD/CSR education enables a range of methods to be employed to assess and evaluate SD/CSR investment decisions. This interdisciplinary nature includes electrical engineering, business management, and economic disciplines. Interdisciplinary SD/CSR education is considered a key enabler in business management (Lopez-Perez et al., 2017). Knowledge of electrical meters and the information that can be obtained from them is a vital component in evaluating the decision to invest in alternative energy sources, based on the findings of this current study. Business managers must be able to manage *all* their resources effectively, including their financial resources, to reach company goals (Nijhof et al., 2019). Decisions to invest in wind turbine and hydro-electric technology must benefit the economic, social, and environmental aspects of a business (Cubas-Diaz and Martinez Sedano, 2018). In addition to the engineering and business management academic disciplines, a thorough knowledge of economics would enable robust financial appraisal of investment decisions to be carried out. The easily-calculated simple payback period (PP) for the wind turbine investment is 7.34 years (Section 4.1), and for the hydro-electric investment, the simple PP is less than two years (Section 4.2). The calculation of the net present value (NPV), internal rate of return (IRR), and accounting rate of return (ARR) may provide the scope to lead to a more robust economic appraisal of investment decisions (Kealy, 2014). The large corporation that invested in the 850-kW wind turbine installation in the first case study can afford to employ people across a broad range of disciplines and are better suited than the SME (second case study) to carry out a robust evaluation with more specific appraisal methods. In terms of inhibitors, a lack of interdisciplinary knowledge limits the decision-makers' ability to assess the company's SD/CSR efforts robustly. In this current study, the SME owners have limited experience outside their speciality discipline and sought external assistance (from this researcher) to evaluate their decision to invest in the hydro-electric plant upgrade. The simple PP financial appraisal method was useful in this case, as all stakeholders easily understood it.

Secondly, in terms of enablers, the quality of the Fluke 1735 Power Logger enabled high-resolution (500 milli-second) objective data to be gathered and presented in this study (Figs. 2, 3 and 6). The Schneider ION™ meter is also high-quality and produces accurate 1-s data to generate the 15-min plot in Fig. 4. Chen et al. (2018) highlight the importance of the objectivity and reliability of the measured data used in the sustainability reporting process.

Table 6
Summary of sustainability/strategy integration issues.

Enablers	Inhibitors
Senior personnel buy-in to sustainability	A small company may not have resources
Education/Knowledge of sustainability	PQA does not measure power dispersion
Multidisciplinary sustainability education	Lack of comparative studies
Quality of measuring instruments	

The objectivity and reliability of the power output data obtained for this current study were augmented by the engagement of a data triangulation method. The triangulation method examined the quantity of kWh electrical units, the quality of the output power, and the energy benchmarks that add rigour to this study. In terms of inhibitors, the short-term variations of the renewable energy system's power output are seldom measured, thereby reducing management knowledge of this critical aspect of embracing alternative energy systems as alternatives to fossil-driven traditional generators. It was also challenging to design a three-phase Rotating-Disc-Meter (RDM) analogue-type to handle the different voltage and current levels generated by the 850-kW wind turbine. The measurement difficulties sometimes stated as a criticism of the TBL framework (Elkington, 1997), are also discussed in section 2 (See Table 6).

5. Discussion

A time-series analysis of the case study data uncovered some interesting results. In the renewable generator power quality analysis, the dispersion characteristic was identified as highly significant. The quality of electrical power from the 40-kW hydro-electric generator greatly exceeded the quality of the power from the 850-kW wind turbine generator, based on the standard deviation and coefficient of variation (CV) dispersion calculations. The CV computation ranged between 2.8% and 3.9% for hydro-electric, and between 128% and 939% for the wind turbine. The high CV values is an indication of poor power quality. Variations and dispersion in the power output from the wind turbine are eroding the potential CO_2 emission reductions due to the inability of back-up, unwieldy, fossil-fuel generators to respond in the milli-second timeframe required for effective power compensation (Kaffine et al., 2013). This finding concurs with the findings of Kealy (2017) and Kealy (2014), who investigated a 300-kW embedded wind turbine and a 10-kW wind turbine, respectively. The dispersion on the 300-kW on-site wind turbine output (CV values between 30% and 50% shown in Table A1) and the 10-kW on-site wind turbine (CV values between 45% and 77% demonstrated in Table A2) appears likely to work against the concept of cleaner production, in which the consensus is that renewable energy generators increase the efficiency of electrical energy. The power output from all the wind turbines discussed in this current study (850-kW DFIG turbine in Figs. 2, Fig. 3, Fig. 4; 300-kW DFIG turbine in Fig. A.1; and 10-kW synchronous turbine shown in Fig. A.2) appears to be fluctuating on a sub-second (milli-second) time basis and not just, as previously suggested by Rehman et al. (2015), on an hourly, daily, weekly, monthly, and annual time basis.

The 850-kW wind turbine output energy was exported directly to the national electricity grid, in parallel with hundreds of other generators; therefore, it is difficult to access specific energy benchmarks on this single unit. However, the g CO_2/kWh national carbon intensity of electricity energy benchmark values shown in Fig. 5 are utilised in this study to indicate the effectiveness of wind turbines. The results (Fig. 5) do not point to any significant improvement, which is to be expected as the number of wind turbine installations continues to increase at a consistently high rate year-on-year. Indeed, a five-fold increase in the connected capacity of carbon-neutral wind energy between 2005 and 2017 is not reflected in the values in Fig. 5.

The number of kWh units produced by the 850-kW wind turbine, measured by both analogue and digital-type instruments, was found to be similar over 14 days. It appears that the 850-kW turbine is indeed producing the quantity of electrical energy units that it claims to be producing, but the problem seems to be that the reduced power quality is eroding the expected benefits of such an investment.

The quality of the power output from the 40-kW hydro-electric generator is of a high standard based on the CV value used as a gauge of its quality. The CV values for the hydro-electric plant in Fig. 6 range from 2.8% to 3.9%. The steady-state hydro-electric power output is replicated in Fig. A.3, wherein the CV is 3% (a test carried out on a different day, as statistical results showed in Table A.3). For the energy benchmarks calculation, the hydro-electric generator not only supplied 100% of the number of kWh electrical energy units required by the SME between 5th September 2017 and 15th September 2017 but also produced 4590 kWh units over and above the SME load requirements. Therefore, the SME was in a position to export the excess kWh units to the national grid via the local distribution transformer (Table 5) during the same ten-day period. The third component of the triangulated data measurement stage, i.e., the analogue and digital quantity of energy produced, showed no difference (error) in their respective values. This positive case study result is a justification for the use of hydro-electric technology as an alternative electrical energy generating system. Hydro-electric is already well established in mature economies such as Iceland (which gets 100% of its electricity from either geothermal or hydro-electric sources) and Norway (which gets 97% of its electricity generation from hydro-electric sources). From this study, it appears that the stability of the hydro-electric generator power output is a major contributing factor to the successful operation of hydro-electric schemes.

The education, competencies, and knowledge of the researcher critically enabled the successful development of the novel closed-loop renewable energy evaluation framework: this required multidisciplinary engineering, business management, and economic inputs in the development and validation stages. These competencies allowed for an electrically safe action research/case study to proceed, where some methods of data collection were carried out on low-voltage electrical equipment. While academic institutions are not the sole places of learning, they surely are in an ideal position to educate future SD/CSR professionals in sustainability education and to include a multidisciplinary dimension.

6. Conclusions

The novel closed-loop framework (Fig. 1) presents a methodology for assessing the TBL value of a renewable energy project. The framework was developed using real-world contextual data from two case studies, embracing the action research methodology. There are limited contextual data in academic literature in this area. The wind turbine project was found to have unclear environmental, economic, and social value. Part of the reason for the disappointing results is due to the reduced power quality associated with wind turbine electrical generators. In particular, the short-term ramping effect on the output, measured in the form of the coefficient of variation, was a significant cause of concern. High CV values indicate poor quality power. The disappointing results could lead to ineffective corporate efforts in cleaner production and sustainability. In contrast to the wind energy project, the hydro-electric generator assessment (with very low coefficient of variation metrics representing good quality power) found that positive values could be attributed to each of the TBL dimensions of the project. The direct correlation between low power quality of the wind system and lower CO_2 emissions reduction is due to the inability of the heavy, cumbersome traditional generators to adjust its output in the millisecond time frame required for adequate power compensation. Continuous ramping is occurring in the wind turbine outputs.

The researcher recommends that routine measuring of the ramping/short-term variations from renewable energy generators must be included as part of the overall power quality analysers' (PQA) suite of measurements associated with such power signals. Future research into the best method to quantify the variations is recommended, possibly including an algorithm in proprietary power quality analysers software.

The hypothesis, stated in the Literature Background, that wind turbine electrical generators demonstrate significantly different characteristics under ideal test laboratory conditions than those in real-world holds. Future research is recommended for measuring real-world power quality, particularly active power variations from wind turbines in the 3-MW range and variations associated with photovoltaic (PV) systems, using the framework developed in this study.

Author contribution section

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.

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Appendix A

The Rotating-Disc-Meter (RDM) used for the 850-kW Wind Turbine tests has a voltage ratio of 3.2 (meter voltage coil is 125 V, phase-neutral measuring a Three-phase, 4-Wire, 400 V Phase to Neutral and 690 V Phase to Phase from wind generator) and a current ratio of 200 (1000/5).

The weather conditions on 14th May 2018 were calm (Fig. 3). Between 11:04 a.m. and 11:23 a.m. the wind speed was averaging 5 m/s, but then dropped to an average value of less than 2.5 m/s. For values below this wind speed, the turbine stopped generating electricity.

ION is a power monitoring device by Schneider Electric.

For comparison purposes, a 300-kW DFIG three-phase wind turbine generator and a 10-kW synchronous three-phase wind turbine outputs are measured using the Fluke 1735 Power Logger. The results are demonstrated graphically in Fig. A.1 and Fig. A.2 respectively.

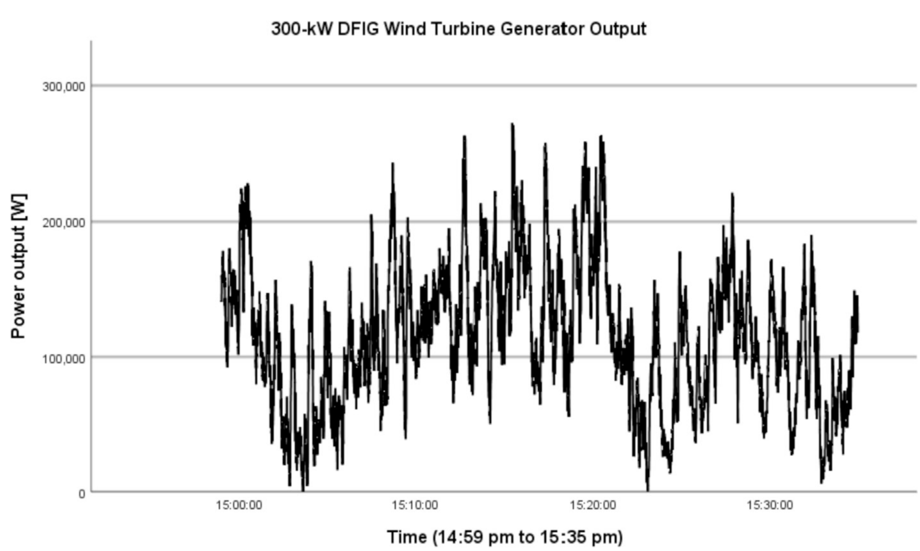

Fig. A.1. Power Output from 300-kW Wind Turbine on 10th November 2015, 500-ms interval data (Kealy, 2017)

The annual imported energy units, expected to reduce significantly after the installation and commissioning of the 300-kW wind turbine, are as follows:

[2011–723,160], [2012–921,578], [2013–1,226,945], [2014–1,377,185], [2015–1,500,588], [2016–1,644,252], [2017–1,545,600], [2018–1,679,208] (Kealy, 2017).

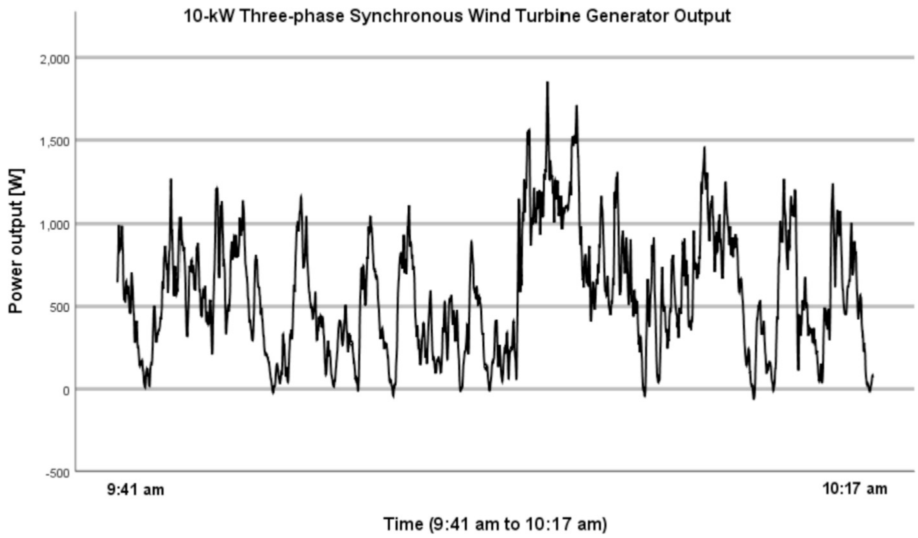

Fig. A.2. Power Output from 10-kW Synchronous Wind Turbine on 14th April 2016, 500-ms interval data

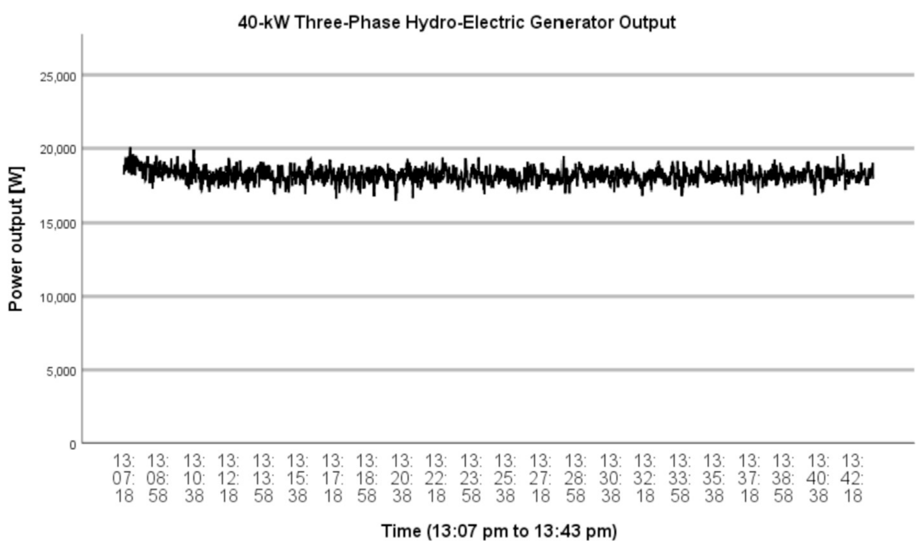

Fig. A.3. Hydro-Electric Generator Output on 12th October 2017, 500-ms interval data

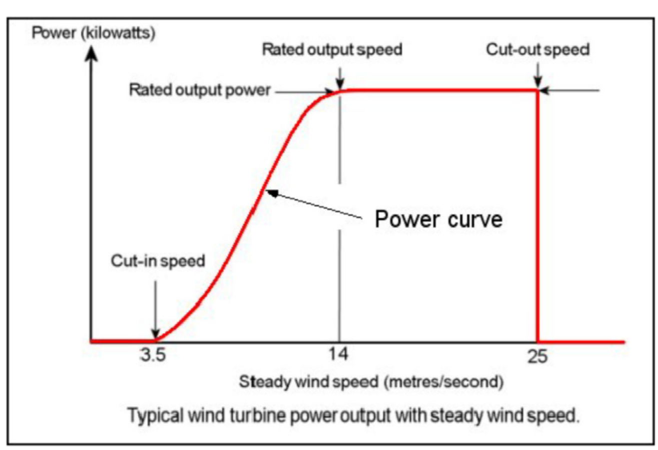

Fig. A.4. Typical Wind Turbine Power Curve (EE Power School, https://www.eepowerschool.com/)

Table A.1
Descriptive Statistics for 300-kW Wind Turbine Power Output on 10th Nov 2015 (data are shown graphically in Fig. A.1)

Data Points (split into six time zones)	Mean Power Output [W]	Standard Deviation [W]	Coefficient of Variation (%)
1–1200 (0–10 Minutes)	101,937	51,325	50
600–1800 (5–15 Minutes)	117,875	45,437	39
1200–2400 (10–20 Minutes)	141,576	42,091	30
1800–3000 (15–25 Minutes)	134,715	57,052	42
2400–3600 (20–30 Minutes)	115,576	56,677	49
3000–4200 (25–35 Minutes)	97,059	45,078	46

Table A.2
Descriptive Statistics for 10-kW Synchronous Wind Turbine Power Output on 14th April 2016 (data are shown graphically in Fig. A.2)

Data Points (split into six time zones)	Mean Power Output [W]	Standard Deviation [W]	Coefficient of Variation (%)
1–1200 (0–10 Minutes)	541	302	56
600–1800 (5–15 Minutes)	464	304	66
1200–2400 (10–20 Minutes)	431	332	77
1800–3000 (15–25 Minutes)	675	434	64
2400–3600 (20–30 Minutes)	798	361	45
3000–4200 (25–35 Minutes)	595	351	59

The 10-kW synchronous wind turbine investment decision by the agricultural owners proved to have disappointing outcomes as found by Kealy (2014). The number of imported annual energy units, expected to reduce significantly after the turbine is operational, are as follows:

- 77,312 kWhs in 2009 (turbine not yet installed)
- 77,064 kWhs in 2010 (turbine installed in early 2010)
- 68,519 kWhs in 2011 (turbine fully operational)
- 76,338 kWhs in 2012 (turbine fully operational) (Kealy, 2014)

Table A.3
Descriptive Statistics for 40-kW Hydro-Electric Power Output on 12th Oct 2017 (data are shown graphically in Fig. A.3)

Data Points (split into six time zones)	Mean Power Output [W]	Standard Deviation [W]	Coefficient of Variation (%)
1–1200 (0–10 Minutes)	18,293	622	3
600–1800 (5–15 Minutes)	18,137	570	3
1200–2400 (10–20 Minutes)	18,101	565	3
1800–3000 (15–25 Minutes)	18,102	555	3
2400–3600 (20–30 Minutes)	18,109	538	3
3000–4200 (25–35 Minutes)	18,128	530	3

Capacity factor for 40-kW hydro-electric generator based on figures in Table 5 (Section 4.2):
Capacity Factor = (4590 + 552) ÷ (10-Days × 24-Hour × 40-kW) = 54%.
In addition to the 308, 850-kW wind turbines operational in the Republic of Ireland, there are eight similar turbines operational in Northern Ireland.

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Glossary

ARR: Accounting Rate of Return
CO_2: Carbon Dioxide
CSR: Corporate Social Responsibility
CV: Coefficient of Variation
DFIG: Double Fed Induction Generator
EGIP: Embedded Generator Interface Protection
EU: European Union
g CO_2/kWh: Grammes of CO_2 emitted for every kWh energy generated (benchmark)
GHG: Green House Gas
GRI: Global Reporting Initiative
GWh: Giga Watt/hour (1,000,000 kWh units of electrical energy)
IBM: International Business Machines
IRR: Internal Rate of Return
ktoe: (Thousand) tonne of oil equivalent energy metric
kW: Electrical Power Output (of electrical generators)
kWh: Unit of Electrical Energy
LOM: Loss-Of-Mains
MW: Million Watts Power Output (1000 kW)
NO_X: Nitrogen Oxides
NPV: Net Present Value
PP: Payback Period
PQA: Power Quality Analyser
PV: Photo Voltaic
RDM: Rotating Disc Meter (Analogue-type)
SCADA: Supervisory Control And Data Acquisition
SD: Sustainable Development
SDG: Sustainable Development Goals
SEAI: Sustainable Energy Authority of Ireland
SME: Small to Medium Enterprise
SO_2: Sulphur Dioxide
SPSS: Statistical Package for Social Science
TBL: Triple Bottom Line
UN: United Nations