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A review of CO₂ emission reductions due to wind turbines using energy benchmarks: a focus on the Irish electrical energy market

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Abstract: The installed capacity of wind turbines in Ireland increased from a value of 2,250 MW in 2014 to 3,318 MW in 2017, a 43% increase in the four years, supported through climate mitigation policies. The main aim of this study is to determine if the increase in wind turbine installed capacity is impacting on efforts to reduce CO₂ emissions. The study utilises a review methodology. The findings show that the steady rise in wind turbine installed capacity year-on-year is not reflected in the Irish CO₂ g/kWh energy benchmark. The benchmark value was 457 g CO₂/kWh in 2014 and 437 g CO₂/kWh in 2017, an improvement of just 5%. There is no consistent correlation between the increase in wind turbine capacity and a reduction in CO₂ emissions. Future research into the quality of the wind turbine power output is recommended, in particular, the variability aspect in the power output signal.

Keywords: wind turbines; stakeholders; energy benchmarks; CO₂ emissions; review; Ireland.

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Biographical notes: Tony Kealy is a Lecturer in the School of Electrical and Electronic Engineering in TU Dublin, City Campus, Ireland. He holds a BEng in Electronic Engineering from Dublin City University and an MPhil from the Technological University Dublin. His research interests are in the area of sustainable development and he has developed a novel framework to robustly evaluate renewable energy projects as part of corporations' sustainable development efforts. The framework is developed as part of his PhD thesis.

1 Introduction

Energy systems in many countries around the world are moving toward decarbonised energy systems (Senatia and Bansal, 2018). The energy sector, which includes many sub-sectors such as power generation, industry, transport and HVAC, contribute over 60% of global green house gas (GHG) emissions (Sgobba and Mesckell, 2019). Wind

power is perceived to be a major player in meeting the energy demand sustainably (Wang et al., 2019; Arbabzadeh et al., 2015). This review study analyses the effectiveness of wind turbines, used as alternative (renewable) energy sources, to reduce harmful GHG (mainly CO₂) emissions associated with traditional fossil-fuel driven power generators. The subject being reviewed is CO₂ emissions. One of the reasons for the selection of the review methodology is that it is possible to access a large amount of relevant available data in a short space of time. There is many historical data available for public scrutiny that is linked to the area of CO₂ emissions. The data accessed for this current study is quantitative with two of the main variables being

- 1 the quantity of CO₂ emitted for every kWh produced
- 2 the total installed capacity of wind turbines connected to the Irish electricity system.

An advantage of using quantitative data is that it is objective and therefore adds rigour to the study. While methods to analyse qualitative data have improved mainly due to the development of qualitative data analysis software, there is still a risk of inconsistencies in the data analysis process due to the, still necessary, human input to the process (Bergin, 2011). Social science concerns are very suited to qualitative research methods, while the natural sciences are generally suited to quantitative research methods. Publications relating to practical results from experiments, case studies, and action research are reviewed in addition to publications proposing theoretical models utilised to evaluate renewable energy effectiveness. One of the disadvantages of the theoretical approach is that the models may not have the capability to consider all the impacts that variable renewable energy resources (such as wind and PV) bring to the electricity system (Senatia and Bansal, 2018). While the review research methodology does not produce any new data in a particular study, it allows for an assessment of a phenomenon with already available data and identifies areas in which further research would be beneficial (Chen et al., 2014). The case study and survey methodologies are not utilised in this current study because there are already available relevant data that is

- 1 accessible
- 2 up-to-date.

Section 1 outlines the background to businesses embracing a social responsibility to protect and respect the natural environment during its operations and activities. The deployment of wind turbines in this context can mitigate the harmful effects of burning traditional fossil-fuels in electrical generators. Electrical consumers are now becoming also producers at a local level; they produce distributed energy with decentralised systems located nearby, satisfying their own energy needs and any excess energy may be exported back to the national grid (Sgobba and Meskell, 2019). The focus is predominantly on the Irish CO₂ emission reduction benchmarks, but global emission results are also briefly discussed. The roles and influences of several stakeholders in the wind energy industry are also discussed in section 1. European Union (EU) climate mitigation policies on renewable energy and GHG emissions have influenced the electricity sector of the Member States such as Ireland, and these policies have driven the acceleration of wind farm deployment in Ireland, supported through market support mechanisms (Gaffney et al., 2017). While wind is the dominant renewable energy technology preference, other renewable energy options are discussed in Section 2. Section 3 collates the results of CO₂ emission reduction efforts from several government

publications and peer-reviewed publications. Both macro-level (national energy benchmarks in Table 5) and micro-level (10-kW and 300-kW embedded wind turbines) results are presented. The conclusions to the review are discussed in Section 4, which includes recommendations for future research. The objectives of the study are

- 1 to quantify the installed capacity from wind turbines in Ireland currently
- 2 to analyse Irish energy benchmarks to evaluate if the steady increase in wind turbine capacity is helping to reduce CO₂ emissions in a similarly steady manner.

This study uses empirical quantitative data in the CO₂ emission evaluation process in contrast to the projections and simulations used by Tian and De Wilde (2016) and also neural network modelling used by Woo and Cho (2018). Ma et al. (2019) forecast the CO₂ emissions in Shandong Province (China) from 2017 to 2030 using four different scenarios. In a similar vein, Ozer et al. (2017) use different scenarios to simulate CO₂ emission reduction of the electricity sector in Turkey. Ozer et al. (2017) utilise the long-range energy alternatives planning (LEAP) system model and calculates the CO₂ emission mitigation costs for each scenario.

1.1 CSR – environment – electrical power generation link

Holme and Watts (2000) declare that ‘corporate social responsibility (CSR) is the continuing commitment by businesses to behave ethically and contribute to economic development while improving the quality of life of the workforce and their families as well as of the local community and society at large’. CSR and its related term sustainable development (SD) (Weber et al., 2014) can be considered to be a decision-making platform that reflects a firm’s financial, human, and environmental impacts (Maniora, 2018) illustrated in Figure 1. The three dimensions of the decision-making process have been considered by Elkington (1997), who devised a framework entitled the triple-bottom-line (TBL). The TBL accounting concept shifts the focus from a business being assessed on its financial bottom line alone to one that also considers its social and environmental bottom lines (Anvari and Turkay, 2017). One of the appropriate business decisions to be made, in the context of the environmental bottom line, is the decision to obtain a source of electrical power that is crucial to business operations. Traditional sources of electrically generated power were focused mainly on the process of combustion of fossil fuels such as coal, gas, and oil. Much research claims that in the combustion process, harmful GHG emissions take place. One of the methods used to reduce such environmentally-damaging GHG emissions, including CO₂ emissions, is to reduce our dependence on fossil fuels by examining alternative sources of electrical power (Pusat and Akkoyunlu, 2018). This current review focuses on one specific aspect of CSR/SD, namely the environment, and more concisely one aspect of the environment, namely climate change and how alternative energy systems can help to mitigate climate change by reducing harmful GHG emissions. This study reviewed publications such as EU Directives, Irish government papers, reports on company websites, and peer-reviewed journal articles. Energy benchmarks are utilised to evaluate public and private efforts to reduce CO₂ emissions. Benchmarking is a systematic process of comparing performances of similar organisations or processes in order to learn from the best performers and thereby improve one’s performance (Petrovic et al., 2018). Benchmarking in this study compares energy benchmarks systematically year-on-year to identify best performing

years and discuss factors that are expected to influence such benchmark values. Finding the best performers will assist in the energy policy decision-making process. CSR/SD is a decision-making platform that encompasses environmental, social, and economic components (Figure 1). Alternative energy systems are part of the environmental component and include solar photovoltaic (PV) panels, hydro-electric, biomass, and wind turbines (Table 2). Publications in the environmental dimension of CSR/SD have dealt with issues such as water security (Whaley and Weatherhead, 2016), pollution (Galupa et al., 2014), deforestation (Tsurumi and Managi, 2014), waste disposal (Ghoseiri and Lessan, 2014), loss of biodiversity (Santos et al., 2015) and specifically in this review the phenomenon of climate change and global warming (Anderson et al., 2016; Pusat and Akkoyunlu, 2018). This issue of climate change currently exercises the most discourse and debate in current times (Carrington, 2016). The decision to implement wind power projects to mitigate climate change and global warming and safeguard scarce resources is considered to be part of the environmental component (Figure 1) of CSR/SD (Wolsink and Breukers, 2010).

Figure 1 Triple-bottom-line (see online version for colours)

Source: Elkington (1997)

1.2 Ireland's energy-related CO₂ emission reduction targets

As a member state of the EU Ireland is committed to reducing environmentally-damaging CO₂ emissions by complying with EU directives. One such directive is the EU Directive 2009/28/EC, which mandates the levels of renewable energy use within each member state. The Directive sets a target for Ireland of 16% share of energy from renewable sources in the gross final consumption of energy in 2020. Failure to reach this binding EU target will result in substantial fines being imposed on the Irish government. A breakdown of this EU overall target of 16% shows that 40% of electricity generation is due to come from renewable sources, and this currently stands at 30.1% [SEAI, (2018),

p.23]. Irish government energy policy has prompted recent intense activity in wind turbine proposals and installations in the expectation that wind will be a significant contributing factor in reaching that 40% target, making Ireland one of the highest penetrations of variable wind power in the world (Gaffney et al., 2017). It is expected that every unit of energy generated by carbon-neutral wind turbines 'offsets' pollution that would have been emitted by the burning of fossil fuels in a conventional generator (Cullen, 2013). The burning of fossil fuels in traditional electricity power generation plants produces pollutants such as carbon dioxide (CO₂), nitrogen oxides (NO_x), and sulphur dioxide (SO₂) and is thought to be contributing to the well documented undesirable increase in global temperatures. As a result of these pollutant emissions, there is a generally accepted need for businesses to either reduce the number of kWh energy units they use (demand-side-management) as suggested by Cai et al. (2018) and/or purchase electricity from renewable energy sources [supply-side-management (SSM)] in order to help address this threat of global warming. Wind turbines are perceived to play an essential role as carbon-neutral renewable energy sources of electricity (Table 2). However, despite the renewed interest in wind turbine projects, there appears to be a dearth of empirical research conducted into the measured outcome evaluation of the expected benefits to the environment by deploying wind turbines. Some authors (Karassin and Bar-Haim, 2016) suggest that one of the reasons for this may be that there is no single standard measurement system that accurately represents and allows comparison of environmental performance across different industries. Their study (Karassin and Bar-Haim, 2016) involving regression analysis was conducted in 2013–2014 and involved 11 medium and large Israeli industrial facilities. Fifty-four top managers were interviewed, and 412 workers responded to a questionnaire as part of the data collection process. They claimed that the filling out of the sustainability reports which is carried out on a self-reporting basis has the potential to impose a limitation on data availability (that which is measured), transparency (that which is released or reported), and quality (accuracy and truthfulness of the data reported). Karassin and Bar-Haim (2016) claim that these limitations are most evident in countries where compliance databases are sparse. The development of a standard measurement system may require *collaborative* research involving engineers, managers, and economists.

1.3 Power performance of wind energy systems

Wind-generated power is considered one of the most promising options in the global efforts to reduce CO₂ emissions (Huenteler et al., 2018). However, one of the problems associated with wind-generated power is the random nature of the power output due to the randomness of the source wind (Sgobba and Meskell, 2019). The output power variations are a function of short-term wind speed variations (Wan, 2004). Long duration wind variations cause problems, e.g., congestion and reliability of the system, for the network operators who can put in place established strategies like generation forecasters, dispatch and contingency analysis, and real-time control (Senatia and Bansal, 2018). Long duration wind variations are generally in the hour or half-hour time frames. By contrast, turbulence and gusts are examples of short-duration wind variations, variations in the wind velocity from 10-minute averages, the effects of which are more challenging to observe. Research by Roy (2013) sought to estimate the standard deviation (SD) of

power output by a wind turbine generator in the presence of short duration wind variations. The author uses the two-parameter Weibull statistics as a description of wind variations around stable mean values. The Weibull probability distribution function uses the quadratic relationship between wind power and wind speed. The short duration output power and the output power variability are estimated using the generally available turbulence intensity measure. Turbulence intensity is the ratio of the wind speed SD to the mean wind speed, determined from the same set of measured data samples and taken over a specified period (I.S. EN 61400-1: 2005). Research by Lin et al. (2012) sought to quantify the variations in wind turbine power output using field-measured wind power output data, the data being obtained using 1-minute average data. Four different types of wind farms were analysed in the research by Lin et al. (2012):

Type 1 Induction generator with fixed rotor resistance, fixed speed.

Type 2 Induction Generators with variable rotor resistance, variable speed.

Type 3 Double-fed-induction-generators (DFIG).

Type 4 Generators with full-power converters.

Research by Boutsika and Santoso (2013) concludes by stating that the DGIG type of wind turbine (Type 3) has room for improvement when assessing wind power variability, and a full power converter (Type 4) may be a more practical option.

Kose et al. (2014) *predicted* a simple payback period of 6.44 years on a 6-MW wind farm in Turkey. The predicted value was based on statistical analysis on wind data accessed over one year. An empirical study by Kealy (2014) on a three phase 10-kW synchronous generator with full power converters calculated an *actual* simple payback period of twenty-three years. Part of the disappointing findings from the study by Kealy (2014) was the *actual* capacity factor of 8.3%. Henaghan (2013) analysed capacity factor data from 77 wind farms in Ireland for over five years. The range was between 38.48%, to 19.36% with an average value of 27.9%. An empirical study by Kealy (2017) found that the installation of a 300-kW embedded DFIG wind turbine (Type 3) failed to reduce the amount of CO₂ emissions associated with a Small-Medium-Enterprise (SME) and the project was not financially viable. The International Standard IEC 61400-12-1 (*Wind Turbines – Part 12-1: Power performance measurements of electricity producing wind turbines*) is a methodology used to measure and analyse turbine power performance. While it is a welcome development that such evaluations are standardised, the IEC 61400-12-1 method uses an *estimated* annual energy production value in its performance appraisal. The *estimated* and *actual* energy production values may vary significantly, as found by Kealy (2017). A study by Huenteler et al. (2018) compares the *potential* to the *actual* performance of (Chinese) wind farms performance with disappointing results. The significant issues identified as inhibitors to better wind turbine performance were

- 1 delays in grid connection
- 2 constraints in grid management.

Actual verified data was also utilised in the study by Hayashi et al. (2018), who examined the enablers in improvements in wind turbine generation performance. The study by Hayashi et al. (2018) was also based in the rapidly expanding Chinese wind power industry, and a learning curve analysis was undertaken based on a dataset of 312 Chinese wind farms.

1.4 Stakeholders in the wind energy industry

1.4.1 Independent Irish wind energy operators

Three of the leading independent developers and operators of wind energy projects in Ireland are Gaelectric, Mainstream Renewable Power and Element Power. These companies also operate in the global renewable energy market. Gaelectric was founded in 2004 and in September 2016 had 174-MW of wind generation connected to the grid. They developed energy storage projects in Northern Ireland, the UK, and the European mainland (Gaelectric, 2016). However, Gaelectric experienced trading difficulties due to the constant financing strains created by the development of stage wind farms, and when a Chinese state-backed fund pulled out of a merger deal, the company became insolvent. The level of Irish government support for the renewable energy sector allegedly disenchanted the Beijing-based company (Friemann, 2018). Mainstream renewable power was founded in 2008 by Eddie O'Connor who sold his previous company Airtricity to SSE and E.ON for €1.8 billion. Mainstream has offices in eight countries, across five continents and currently, employs 140 staff (Mainstream Renewable Power, 2016). Element Power was established in 2008 and has operations in eight countries. They develop, acquire, build, own, and operate a portfolio of onshore wind and solar power generation facilities worldwide (Element Power, 2016).

1.4.2 Global growth and promotion of wind turbine developments

While Blyth built the first wind turbine for electricity production in Glasgow in 1887 (Jones and Bouamane, 2011), it is only in recent decades that a sizeable number of articles concerning wind turbines began to be frequently published. Although they were not the first country to use wind power to generate electricity, it was in Denmark that the wind industry began to develop as a business venture wholly. In 1959 a Gedster wind turbine designed by a Dutch engineer named Johannes Juul began operating. The 200 kW turbine ran for ten years as the largest turbine in the world until it was shut down in 1967 (Jones and Bouamane, 2011). The Danish wind energy industry was further intensified when agricultural equipment manufacturers such as Vestas and Nordtank diversified into wind turbine manufacturing in the 1970s and 1980s. These companies knew how to build heavy machinery for a rural market and used these competencies to good effect in the design, manufacture, construction, and maintenance of heavy industrial wind turbines (Jones and Bouamane, 2011). While the global wind industry is smaller than the global conventional power generation technologies, it has received significant interest in the past couple of decades (Xu et al., 2016). The global wind power industry had record-breaking years in 2014 and 2015 with a 22% annual growth rate in 2015 while the country with the most power installed during the year was China with 30.8 GW of new installations (Global Wind Energy Council, 2016). China now has 77 GW of PV installed capacity as of 2016 (Senatia and Bansal, 2018). Other countries to have a steady wind growth rate in 2015 were Canada, Brazil, and Mexico. As of the end of 2016, the worldwide total installed electricity generation capacity from wind power amounted to 486.79 GW which is an increase of 12.5% on the 2015 value (Mauricio et al., 2018).

In a significant research piece from a European perspective, Gonzalez and Lacal-Arantegui (2016) present an overview of the regulatory framework for wind energy in the EU member states. Firstly the 2016 review paper presents the main aspects of each EU member states' National Renewable Energy Action Plans (NREAP), while secondly

concluding with an analysis of actual developments of wind energy activity in each member state. One of the main aspects discussed in this piece was the support schemes for wind energy promotion and growth. The support schemes discussed included

- 1 feed-in-tariffs
- 2 feed-in-premiums
- 3 tenders
- 4 quota obligations
- 5 tax incentives or exemptions
- 6 investment grants
- 8 financing incentives.

Commenting on grid connection, Gonzalez and Lacal-Arantegui (2016) highlight other issues such as cost allocation, priority use of the grid, and potential barriers for wind energy deployment. They concluded that there is a strong link between a favourable regulatory framework and actual deployment of wind energy. Some EU member states have a strong commitment to supporting wind energy while other member states have not provided enough support to stimulate the desired level of investment.

1.4.3 Wind turbine manufacturers

There has been a rapid accumulation of experience and knowledge by wind turbine manufacturers over the recent past number of years. There has been a significant capital investment in global wind turbine installations, with a particular emphasis in the larger wind turbine sizes which, some authors claim, appear to outperform the smaller wind turbine sizes (Daisuke et al., 2018). The information for the top global wind turbine manufacturers is taken from what is claimed to be the leading independent news magazine reporting solely on wind energy matters entitled *Wind Power Monthly* (2016). The magazine has been reporting non-stop since 1985. The top ten wind turbine manufacturers account for almost 270 GW of global installed capacity and much of the recent technological progress (*Wind Power Monthly*, 2016). The major global wind turbine manufacturers are listed in Table 1.

Table 1 Major global wind turbine manufacturers

Siemens	Market leader in offshore wind turbines. Siemens turbines have been running for more than 20 years at Vindeby, Denmark, the world's first offshore wind farm. Siemens has approximately 348,000 employees in over 200 countries (Siemens, 2016).
GE	US manufacturer. GE Energy's 1.5-MW series is the most widely-deployed wind turbine, with more than 16,000 installed across the globe (GE Renewable Energy, 2016).
Vestas	Focused completely on the wind industry, based in Denmark. They have been in the wind industry since the 1970s, and there are now more than 43,000 Vestas turbines installed in 66 countries. Vestas has offices in 24 countries (Vestas, 2016).

Table 1 Major global wind turbine manufacturers (continued)

Goldwind	Recently emerged as China's leading turbine manufacturer. Goldwind claims to be the worlds' leading manufacturer of permanent magnet direct-drive turbines. They produce 1.5-MW and 2.5-MW wind turbine models (Goldwind, 2016).
Enercon	The company was founded in 1984 as a dedicated wind turbine manufacturer. Enercon now has more than 20,000 turbine installations around the world. The German company depends heavily on the German market (Enercon, 2016).
Gamesa	Spanish manufacturer with a strong presence in India and Latin America. They put a significant focus on the servicing industry. They now have manufacturing plants in the USA, Brazil, China, and India (Gamesa, 2016).
United Power	This company is part of one of China's most prominent power producers, China Guodian (United Power, 2016).
Ming Yang	This company is based in China, but unlike the other Chinese wind turbine manufacturers does not benefit from being state-owned. The company was established in 2007. The company is heavily dependent on European technology and expertise (Yang, 2016).
Senvion	German turbine manufacturer formerly called Repower. They employ approximately 3,500 people in 14 countries (Senvion, 2016).
Nordex	Based in Germany, Nordex is one of the pioneers in wind turbine technology. It produced the first megawatt-size turbine in 1995 with the N54-1MW model (Nordex, 2016).

1.4.4 Wind turbine installers

There is minimal research published about wind turbine installers. Local electrical contractors may complete the installation work under the strict guidelines of the project manager. The Irish Wind Energy Association (IWEA) (2016) provides several services on their website among which is a directory of wind turbine installers. The contact details are listed for each of these installers. The IWEA is a non-governmental-organisation (NGO) who claims to be committed to the promotion and education of wind energy issues. They are also a lobbying group who work to influence government policy on renewable energy. The equivalent association in the UK is the British Wind Energy Association (2016).

1.4.5 Local communities

In a study by Firestone et al. (2018), some barriers were identified that affect wind turbine developments in the USA. A positive attitude by communities residing in proximity to wind turbine developments was identified as an essential facet for the success of the projects. Such a positive attitude was helped by a developer who was open and transparent to all aspects of the wind turbine project, including the aesthetics, landscape, and wind turbine noise issues. In a similar vein, the acceptance by local communities of wind energy technologies was deemed to be crucial to the success of such projects (Langer et al., 2016). In a qualitative study, using the interview research methodology conducted with a range of stakeholders in the German region of Bavaria, Langer et al. (2016) identified the factors that influenced the acceptance of wind energy in that region. Factors that emerged from this study included

- 1 the distance of wind turbines to the place of residence
- 2 the visual appearance of wind turbines
- 3 involvement of citizens and societal actors in the project mainly in the participation of profit or rental income
- 4 the perception that the political process towards sustainable energy development is shaped by trust, transparency, and the perceived fairness of the development process.

Langer et al. (2016) found that some of the local community not directly involved in the wind energy project can feel envious if they suspect that the wind turbine owners are getting a good profit on the investment while they are left out. Supporting these findings and within an Irish and Scottish context, Warren et al. (2005) carried out two case studies using face-to-face questionnaire surveys conducted at residents' homes which explored the public perceptions of onshore wind farms in those areas. A vast majority of the negative responses within the study's results were attributed to the wind turbine being unattractive, the aesthetic nature of the turbines being the most important single influence in public attitudes (Warren et al., 2005). There were some positive responses to the acceptance of the turbines, particularly in Ireland, with the not-in-my-back-yard (NIMBY) effect diminished over time. The worry by residents that noise pollution could be a factor was not a finding in the study by Warren et al. (2005). It is claimed that some wind turbine developers and local communities use their political power by lobbying government personnel to guide activity in the alternative energy area (Lock and Seele, 2016). Research by Wolsink and Breukers (2010) found that a more collaborative perspective on decision-making about wind power increased the chance of successful outcomes in the venture. Host communities have certain expectations regarding involvement in, and revenues from, wind farm installations.

2 Other renewable energy source options

While wind projects made the most substantial renewable energy contribution in Ireland in 2017, Table 2, there are other renewable energy sources available for consideration and these include bioenergy, solar PV, hydro, and ocean energy sources. Table 2 displays the sources of renewable electricity by technology and their installed capacity and contribution to gross electricity consumption in Ireland in 2017 (SEAI, 2018). Poor decision-making manifests itself in the lack of exploring suitable alternatives (Snell, 2010) so perhaps solar PV and hydro renewable energy sources could be considered in more detail as potential alternatives to wind in SSM strategies. While solar PV is a relatively new addition to Ireland's energy mix, hydro-electric has a long and established history dating back to the foundation of the Irish state (Gaffney et al., 2017). During the infancy of the development of Ireland's electricity sector in 1929, the Ardnacrusha hydro-electric plant on the river Shannon was adequately sized to meet the entire national electricity demand thereby making Ireland's electricity 100% renewable. The Shannon hydro-electric scheme utilised a 30-metre head height on the river to deliver an electrical output of 85 MW (Gaffney et al., 2017). The only other substantial hydro-electric plant

commissioned in Ireland since the Ardnacrusha plant is the pumped hydro energy storage plant at Turlough Hill, with an installed capacity of 292 MW (4×73 MW). One of the issues that must be considered when planning a hydro-electric plant is the welfare of the fish stock that passes through the waters on which the plant is constructed (McCarthy et al., 2008).

Table 2 Renewable energy contribution to gross electricity consumption, res-e normalised

<i>Renewable technology</i>	<i>% of gross electricity (normalised)</i>
Hydro	2.4
Wind	25.2
Biomass	1.8
Landfill Gas	0.5
Biogas	0.1
Solar PV	0.04
Total	30.1

Source: SEAI (2018, p.34)

The biomass contribution of 1.8% includes a small contribution of solid biomass CHP (combined-heat-power). The overall share of electricity from renewable energy increased significantly between 1990 and 2017 with a value of 5.3% in 1990 and 30.1% (normalised) in 2017. Biogas consists of landfill gas, sewage sludge gas, and other biogas produced by anaerobic digestion. The landfill gas contribution is reported separately, as shown in Table 2. SEAI warns that the value of the biogas contribution (waste-water Treatment plants and other Biogas installations in industry) to the Irish national energy balance shown in Table 2 is mostly an estimated figure. The estimated figure is due to the poor response rates to the SEAI annual surveys. The SEAI state that there are currently few grid-connected PV installations in Ireland although interest in the technology is growing. They also state that solar technology is one of the technologies being considered in the context of the new support scheme for renewable electricity generation. In Australia, solar PV accounts for approximately 3.2% of total energy supply. Solar PV installed costs are changing rapidly; future prices are expected to be lower, though how much lower is uncertain (Perkins, 2018). Solar PV is considered to be a varying power source, and this introduces power quality and voltage stability issues. An electrical system with high percentages of PV will have to procure inertia resource at an additional cost (Senatia and Bansal, 2018).

In comparison to wind-generated energy, solar energy presents a more predictable daily and seasonal trend (Sgobba and Mesckell, 2019). Sgobba and Mesckell (2019) modelled the potential for solar PV (and wind) to produce on-site electricity for self-consumption in a manufacturing facility in Ireland. They concluded by claiming that a substantial subsidy (e.g., carbon tax) is necessary to make such an investment viable. The growth of intermittent electricity generation from solar PV (and wind) is leading to a greater need for energy storage at the grid level (Perkins, 2018). Ocean energy (Tidal and wave) is in the research and development (R&D) stage and is expected to make some contribution in the future.

3 Results/discussion

3.1 Global energy-related GHG (CO₂) emission values

Despite the growing institutional, human, financial, and scientific resources made available nationally and globally in the fight against climate change GHG emissions, including CO₂, continues to rise at an unacceptable rate (IPCC, 2013). Global energy-related carbon dioxide emissions increased by 1.4% in 2017 to 32.5bn tonnes (International Energy Agency, 2018) and a record of 37.1bn tonnes in 2018 (Rustin, 2019). Andrade et al. (2015) suggest several factors that may explain the failure in the global efforts of reducing emissions, one of which is the lack of implementation and effectiveness of the global climate and energy governance regimes. Governance of the climate change initiatives is generally of a non-regulatory manner, and it is left up to each corporation (and each nation) to report voluntarily stating their non-financial aspects of its operations. Prado-Lorenzo and Garcia-Sanchez (2010) suggest that as the TBL reporting framework whereby companies show accountability for three aspects of their activities (people, profit, and planet) has a voluntary nature, it could be targeted at other business objectives. The authors claim that, as the production of these TBL reports creates high costs, it may be logical to expect the companies to search for positive effects, other than just concealing their less appropriate practices in the field of sustainability.

3.2 Energy management strategy options

3.2.1 Demand-side-management versus SSM

CSR (and its related concept sustainable business development) would appear to incorporate all three elements of corporate responsibility, namely people, profit and planet (Figure 1). Elkington (1997) proposed a model encompassing all three elements, namely the TBL framework. The planet (environmental) dimension of the TBL components includes methods by which businesses can reduce their carbon footprint due to their business operations. The carbon footprint can be reduced by utilising the electrical energy, vital for the business operations, more effectively and efficiently. There are two energy management strategies by which this can be implemented; *demand-side management* (DSM), which engages electrical consumers to alter their consumption patterns or directly control their loads by offering price incentives (Amarasekara et al., 2018), and/or *supply-side management* (SSM), which seeks to implement alternative natural energy sources. Irish public policy indicates that both strategies are employed, but a significant focus has been in the SSM-oriented wind energy industry (Figure 3). However, there may be issues and concerns for local communities who live in the vicinity of wind farms (Warren et al., 2005). Also, the effectiveness and efficiencies of such a wind energy focus are not definitive (Kealy, 2017). The Sustainable Energy Authority of Ireland (SEAI, 2012), stated that because of the increased penetration of renewable energy sources embedded in the electricity system:

- there is additional cycling associated with fossil-fuel generation plants
- the reduction in the output from fossil-fuel generators causes a reduction in the capacity factor of fossil-fuel generators

- the efficiency of fossil fuel generators drops when renewable energy sources are employed in the system.

While the output of fossil fuel driven electrical generators is reasonably predictable, the same cannot be said about the output from wind-driven electrical generators. Wind-driven electrical generator outputs are prone to ramping and uncertainty. This ramping phenomenon poses an extra challenge for the electricity system operator. Management of the unpredictability of the instantaneous wind speed is usually provided for by the intervention of *spinning reserve* of fossil fuel driven generators. A drop in wind speed signals the back-up fossil fuel generators to take up the load under short notice. While this is an effective method for managing the multiple sources of generators feeding the national electricity grid (fossil fuel and renewable) it has the effect of limiting the efficiencies of fossil fuel generators (SEAI, 2012).

3.2.2 Wind energy as alternative energy systems

The dominant neoclassical business growth model has put pressure on our vast, but finite, natural resources (Catalin and Nicoleta, 2011). Traditionally, most of the electrical energy purchased by businesses was generated using fossil-fuel (oil, coal, or gas) driven generators but it is now widely accepted that the GHG emissions (such as CO₂), due to the burning of fossil fuels, contribute to the phenomenon of global warming (Senatia and Bansal, 2018). The increase in the average temperature of the Earth's climate system is termed global warming. It is therefore incumbent on business, from a corporate citizenship point-of-view and a public relations (PR) point-of-view that corporations endeavour to be responsible global citizens by embracing technologies that will reduce their dependence on fossil-fuel technology (Pinkse and Kolk, 2010). Empirical evidence of businesses embracing wind turbine technology is published in journal articles by Kealy (2017, 2014) on a 300-kW DFIG turbine and a 10-kW permanent-magnet synchronous wind turbine respectively. The area of GHG emissions is a major political issue gaining attention on a global platform (Cozier, 2019). Boiral et al. (2012) claim that social pressure to reduce GHG emissions is one of the main determinants or businesses commitment to climate change. Faced with increasing pressure from stakeholders, companies feel the need to disclose information on climate performance and GHG emissions in order to legitimise their industrial activities (Hrasky, 2012). A standard method of disclosing information on climate change is through sustainability reporting (Perego and Kolk, 2012). Sustainability reporting provides information on the non-financial aspects of the business operations, including the effect that their operations are having on the natural environment. By seeking alternative, renewable, energy sources to generate electrical power required in the business and therefore offsetting the amount of fossil-fuel driven CO₂ emissions, it is anticipated that the effect will be to slow down the phenomenon of global warming. It is in the context of a business's CSR to do what they can to mitigate climate change and global warming that many businesses have installed on-site embedded/autoproducing wind turbines. Some government energy policies are designed to encourage businesses to supply some, or all, of their electrical energy requirements, with an expectation of reducing business production and operation costs (Kealy, 2017). Renewable energy initiatives appear to be environmentally-friendly alternatives to fossil-fuel burning electrical power generators. However, there is minimal published empirical evidence to suggest that wind turbines are having the desired effect

on reducing GHG emissions. Indeed, Huenteler et al. (2018) claim that wind farms in China have produced lower environmental, economic, and health benefits than anticipated. This poor result is despite China having the world's most extensive installed base of wind power capacity and most of the Chinese wind farms cited in the wind-rich northern and western provinces. Wind energy turbines do not generally operate as stand-alone sources of electrical energy because of the variability and intermittency of the power source (wind); they require back-up generation such as gas generators to allow for the uncertainty and variability (Puga, 2010). The power output of a wind turbine depends upon the air density and wind speed at hub height (Diaz et al., 2018). The stochastic nature of wind is exacerbated by the fact that wind power generation is proportional to the *cube* of wind speed (Kaffine et al., 2012). Therefore if the wind speed halves, there is an eight-fold decrease in power output generation. The wind turbine power output varies rapidly, even when several sites are connected together (Katzenstein and Apt, 2009). The back-up (embedded) generators operate more efficiently when operating *steadily* near maximum capacity; operating at partial capacity may increase emission rates. Emissions rates can also change during ramping (Cullen, 2013). Periods, when a generator is ramping up, will have higher than average emission rates, and a lower emission rate when the generator is ramping down, although the effect is not necessarily symmetric. Much of the literature utilises modelled wind turbine data to predict and estimate the CO₂ emission savings as a result of embracing wind turbine technology (Katzenstein and Apt, 2009; Kose et al., 2014; Kaffine et al., 2012). There is a dearth of published literature demonstrating the actual *measured* benefits of embracing wind turbines as alternative energy systems. There is also a lack of peer-reviewed published literature indicating the quality of the power output from wind turbines. Such literature would indicate the degree to which the power output is varying.

3.2.3 Ireland's import energy dependency

A second significant anticipated advantage of Ireland embracing indigenous renewable energy sources (SSM) is to contribute to a reduction in the country's dependence on imported fossil fuel (Gaffney et al., 2017). A November 2015 report 'Energy in Ireland 1990 – 2014' commissioned by the Sustainable Energy Authority of Ireland (SEAI) claims that while there was a modest reduction in overall energy use by 0.5% in 2014, Ireland still had an import dependency of 85% in 2014, costing €5.7 billion. According to Eurostat, the EU's official statistics body, only Malta, Luxembourg, and Cyprus fared worse in terms of imported energy dependency in 2014. The UK had an imported energy dependency of 45.5%, below the European average of 53.4%. A step change was observed in Ireland's energy import dependency from 88% in 2015 to 66% in 2017 as a result of the Corrib gas field starting production. The final consumption of electricity in 2014 was almost static in the previous year at 24.14 TWh's with a 0.7% reduction in the fuel inputs. The final electricity consumption figures were sourced from data provided by the Commission for Energy Regulation (CER). As part of its role, the CER jointly regulates the all-Ireland wholesale Single Electricity Market (SEM) with the utility regulator in Belfast. The data is collected from the retail market reports published by the seven current active suppliers in the electricity retail business and domestic markets. A nine-year summary of final electricity consumption was:

- 26 TWh (2017)
- 26 TWh (2016)
- 25.49 TWh (2015)
- 24.14 TWh (2014)
- 24.2 TWh (2013)
- 24.2 TWh (2012)
- 24.9 TWh (2011)
- 25.4 TWh (2010)
- 25.3 TWh (2009).

3.2.4 Irish energy benchmarks

Progress towards Ireland becoming a leader in sustainability and a better society with particular emphasis on all aspects of energy is overseen by the Sustainable Energy Authority Ireland (SEAI) with assistance from its specialist statistics team the Energy Policy Statistical Support Unit (EPSSU). Each year the SEAI produce a report on all aspects of energy in Ireland and the report is used in meeting its international reporting obligations, as well as advising policymakers and informing investment decisions (SEAI, 2016, 2017, 2018). The SEAI 'Energy in Ireland' report states, among other things Ireland's benchmarks for energy import dependency. Some historical energy import dependency benchmark values are 85% for 2012, 90% for 2013, 85% for 2014, 88% for 2015, 69% for 2016 and 66% for 2017. The much-improved energy import dependency benchmark in 2016/2017 was as a result of the Corrib gas field coming on stream. If upstream electricity-related emissions are omitted, then there was a 2.6% increase in CO₂ emissions from combustible fuels used on-site in industry in 2017 [SEAI, (2018), p.52]. The increase in emissions is a cause for concern as Ireland struggles to achieve its decarbonisation goals. The SEAI (2018, p.18) report states that 33% of primary energy use in 2017 was energy used for electricity generation (the remainder being 32.4% for Heat and 34.6% for Transport). The 2017 value for gross generation of electricity increased by 1.1% to 26 TWh with a 1.1% reduction in the fuels used in electricity generation. The primary energy input was 4,753 ktoe [SEAI, (2018), p.22] of which wind contributed 640 ktoe and natural gas contributed 2,423 ktoe. One of the striking values in the SEAI (2018, p.22) report is that 50% of the 4,753 ktoe energy inputs are lost in both 'own use/transmission loss' (254 ktoe) and 'electricity transformation loss' (2,132 ktoe), also noticeable in SEAI (2017, p.20). It was anticipated that the increasing use of high-efficiency combined-cycle-gas-turbine (CCGT) plants such as Tynagh (384 MW) in 2006 and Huntstown 2 in 2007 (401 MW) would have significantly helped to improve the electricity supply efficiency. Also, two new CCGT plants became operational in 2010 namely Whitegate and Aghada, and in 2015 a new 460 MW CCGT went into commercial operation in Great Island [SEAI, (2018), p.23]. However, the Year/Percentage Loss energy benchmarks, as shown in the first and last columns in Table 4 do not validate this

positive expectation and surely warrant more intense scrutiny. The efficiency is defined as the final consumption of electricity divided by the fuel inputs required to generate this electricity and expressed as a percentage. As more renewable energy sources, particularly wind, are added to the national electricity grid, the efficiency of the system should increase. Wind is termed a direct electricity input and does not have the transformation losses associated with fossil fuels and combustible renewables [SEAI, (2018), p.23]. By the end of 2017, the installed capacity of wind generation reached 3,318 MW [SEAI, (2018), p.35]. There are 1,458 MW of additional wind generation planned for connection in 2018 [SEAI, (2017), p.34]. These values suggest that wind is a significant contributor to the electricity generation mix. As an example of the overall instantaneous magnitude of the electricity system demand in Ireland, the actual system demand for 5 February 2019 is demonstrated in Figure 2. The peak demand of 6,122 MW (approximately 6.1 GW) occurred at 18:00 hours. In comparison, Denmark has a peak demand of 6 GW and Germany has a peak demand of 80 GW (Senatia and Bansal, 2018).

Figure 2 Daily load curve for 5 February 2019

Source: Eirgrid (2019)

In addition to the positives associated with high-efficiency CCGT generators and the increase in installed wind capacity, a third factor was expected to contribute to much improved energy benchmarks namely the amount of capital (€5.695 billion) invested by ESB Networks in the upgrading of its electricity infrastructure between the years 2006–2016 (ESB Networks, 2017) as shown in Table 3.

Table 3 ESB networks spend on infrastructure

<i>Year</i>	<i>Capital expenditure</i>
2006	€620,000,000
2007	€600,000,000
2008	€630,000,000
2009	€600,000,000
2010	€604,000,000
2011	€510,000,000
2012	€395,000,000
2013	€421,000,000
2014	€448,000,000
2015	€494,000,000
2016	€373,000,000
Total	€5,695,000,000

Table 4 Year/percentage loss energy benchmarks for electricity generation

<i>Year</i>	<i>Primary energy input (ktoe)</i>	<i>Own use/transmission loss (ktoe)</i>	<i>Electricity transformation loss (ktoe)</i>	<i>Percentage loss</i>
2017	4,753	254	2,132	50%
2016	4,812	254	2,242	52%
2015	4,499	245	2,046	51%
2014	4,365	262	1,960	51%
2013	4,382	262	2,004	52%
2012	4,622	270	2,244	54%
2011	4,506	272	2,097	53%
2010	4,925	282	2,445	55%
2009	4,840	281	2,402	55%
2008	5,102	303	2,518	55%
2007	5,043	229	2,550	55%
2006	5,116	303	2,690	59%
2005	5,100	280	2,726	59%

The annual carbon intensity of electricity benchmark is shown in Table 5. To calculate the figures shown in Table 5, SEAI firstly surveys all the electricity generators for their fuel usages and electricity produced figures, which they check against emissions trading figures to verify. SEAI then take those fuel quantities and use emission factors which they get directly from the Environmental Protection Agency (EPA) to calculate the amount of CO₂ produced, and then divide that by the amount of electricity produced to get carbon intensity. Information on CO₂ emission factors and net calorific values (NCV) are available for liquid, solid, and gaseous fossil fuels in the EPA's publication 'Ireland's National Inventory Report 2018 – Greenhouse Gas Emissions 1990–2016' (Table 4C of Annex 4, p.563). The calorific value of a substance is the amount of energy that is

released when burning a given amount of the substance. As wind turbines produce carbon-neutral electrical energy that ‘offsets’ fossil-fuel generated energy, the quantity of fossil fuel required to supply the national electrical load should decrease, and this is expected to be reflected in the carbon intensity of electricity benchmark.

Table 5 Carbon intensity of electricity benchmarks

<i>Year</i>	<i>CO₂ g/kWh</i>
2017	437
2016	483
2015	468
2014	457
2013	466
2012	529
2011	489
2010	530
2009	522
2008	547
2007	560
2006	596

Source: SEAI (2018)

3.2.5 *Installed capacity of wind generators in Ireland*

The share of electricity generated by wind in 2017 was reported to be 24.8% (25.2% normalised, [SEAI, (2018), p.23]. The value is calculated according to EU Directive 2009/28/EC and includes normalisation rules for wind. The EU Directive states that electricity from wind (and hydro) needs to be normalised to smooth out the effects of annual variations. Normalised generation is calculated using the weighted average load factor over the last five years for wind. In 2014 wind generation accounted for just 18.2% of electricity generated despite the increase in the number of wind turbine installations. Based on data published on Eirgrid’s and ESB Network’s websites, the installed capacity of wind generation in Ireland reached 3,318 MW by the end of 2017, and also there are 1,458 MW of additional wind generation planned for connection in 2018 (total capacity 4,776 MW) [SEAI, (2017), p.34]. The overall share of fossil-fuels used in electricity generation was 80.8% in 2014, down modestly from 82.6% in 2013. The total installed capacity of fossil-fuel driven generators is approximately 6,230 MW of electrical power indicated by the *red* horizontal line in Figure 3 (Eirgrid, 2015). A five-year summary showing the significant increases in installed wind capacity connected to the national grid between 2014 and 2018 is shown in Figure 3 (*green* vertical lines).

Figure 3 Comparison of installed wind capacities in MW (green) and fossil-fuel generation capacity in MW (red) (see online version for colours)

Analysing the numbers in Figure 3, it would appear that it is reasonable to expect more substantial savings and benefits considering the increase in installed wind capacity currently being experienced in Ireland. A lack of empirical data on the ramping effect of short-duration wind variation may contribute to the conflict between the *estimated* benefits of wind turbine generated power and *actual* benefits. Kose et al. (2014) *predicted* a payback period (PP) of 6.44 years for a 6 MW wind farm in Turkey. Kealy (2014) used actual data on a 10-kW three-phase synchronous wind turbine found a PP of 23 years. This *actual* measured data calculation is in contrast to many *predicted* calculations, so caution needs to be applied when businesses are embracing wind turbines for CSR/SD purposes. The owner/investor of the 10-kW wind turbine did not see any significant reduction in the number of imported energy units, kWh's after the turbine was installed. An empirical study by Kealy (2017) also found no savings in CO₂ emissions despite a €280,000 investment in an on-site embedded wind turbine project. Another empirical piece of research by Kealy et al. (2015) investigated the output of a 3.5 MW wind farm in Ireland and found satisfactory outcomes in terms of the capacity factor and the number of kWh units produced annually. However, the annual kWh energy output from the wind farm, 9,808,318 kWh's, were metered digitally and fed directly into the national grid (38 kV sub-station) and there was no further independent research to find out if this amount displaced the number of kWh units from traditional fossil-fuel sources.

Figure 4 CO₂ energy benchmarks and wind-generator capacity (see online version for colours)

Note: % difference on the previous year.

There is no direct correlation between an increase in wind-generator capacity connected to the Irish national grid and a reduction in the quantity of CO₂ emitted into the atmosphere as a result of generating one kWh unit of electrical energy based on the data presented in Figure 4. It is a hypothesis of this study that a substantial reduction in the CO₂ value would be the case. In 2015 and 2016 there was a significant increase in wind-generator capacity, but the energy benchmarks values increased, i.e., +2.4% and +3.2% respectively? In 2017 there was another increase in wind-generated power, and while the energy benchmark did improve, i.e., decrease, there is insufficient evidence to suggest a correlation exists between the two variables.

The lack of empirical research into the measurement of wind turbine effectiveness is worrying and may be stifling intellectual debate on the issue. In the national, Irish, narrative, Waters (2015) claims that there appears to be a *lack of intellectualism* and a *group-think* approach to many aspects of Irish society perhaps the wind energy debate being one such aspect. The groupthink claim is also one of the issues discussed in an Irish-based (and Denmark) study by Heaslip et al. (2016) who determine the enablers and barriers to implementing productive, sustainable energy communities. While influential organisations promote debate, plainly more detailed, independent, research needs to be carried instead of calls for ‘consensus-seeking’ conversations and listing corporations who have spent millions of Euro investing in wind turbine projects (Melia, 2015) without an independent appraisal of these projects. Independent research is needed to make claims about turbine installations, and this current research is contributing to that debate. A wind turbine embedded electrical generator is expected to reduce GHG emissions by offsetting electrical energy units usually supplied by fossil-fuel burning generators. However, it must be remembered that wind power output is variable, and when business owners/investors are making decisions of the appropriate wind turbine size and technology, it is useful to have metrics regarding wind turbine variability (Boutsika and Santoso, 2013). This current critique of wind turbine effectiveness will inform interested stakeholders in this regard.

4 Conclusions

The increase in wind-generator capacity year-on-year is an indication of the public and private confidence in the role of wind turbines to contribute to ‘decarbonise’ the generation of electrical energy in Ireland currently. This study aims to review and evaluate the effectiveness of wind turbine installations in efforts to reduce the amount of energy-related CO₂ emissions in Ireland. The study hypothesises that a significant increase in installed capacity of carbon-neutral wind turbines would significantly reduce the national carbon intensity of electricity benchmark values. This hypothesis does not hold for this current study. Publicly available energy benchmark data are utilised in the evaluation process. A limitation of the benchmarking process utilised in this research is that, because it has several variables involved in the process, benchmarking is not an exact science; it is merely an indicator by which further investigations may need to be directed. As the predominant renewable electricity energy source, wind is expected to play a significant role in Ireland’s efforts to reach EU binding renewable energy targets. Based on the findings of this study, there is minimal evidence to suggest that wind turbines are contributing significantly to a reduction in CO₂ emissions. The findings can be summarised as follows:

- there was a 43% increase in installed wind capacity connected to the Irish electricity grid between 2014 and 2017
- between 2014 and 2017 there was a small reduction in the carbon intensity of electricity benchmark of just 5%
- the ‘percentage loss’ benchmark for electricity generation has not seen any significant improvements despite the significant resources assigned to the electricity system.

The findings of this current Irish-based review study concur with the research findings of Huenteler et al. (2018) who concluded that despite the significant investment in wind turbine installations in China, the expected environmental, economic, and health benefits did not materialise. However, Li and Yu (2018) argue that wind energy will continue to be one of the most important renewable energy resources worldwide. In their study on the potential energy output from three sites in the Lake Erie area of the USA, Li and Yu (2018) use a simulation method to forecast the energy produced by the wind.

A core idea with a review methodology is to identify areas in which further research could be beneficial, and in this context, further investigations are recommended into the empirical measurement of the quality of power generated by wind turbines, instead of a simulated/modelled approach. If it is the case that the wind-generated power quality is poor, is this a contributory factor in the disappointing energy benchmark values? Do power quality analysers’ measure the variations in wind turbine power output as this variability aspect has been identified in the published literature as affecting carbon emission rates (Cullen, 2013)? These questions provide future research directions and opportunities in the struggles to mitigate climate change and global warming.

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