Energy 109 (2016) 818–829

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

The cost of energy associated with micro wind generation: International case studies of rural and urban installations

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ARTICLE INFO

Article history:
Received 9 December 2014
Received in revised form
30 December 2015
Accepted 16 May 2016

Keywords:
Micro wind turbines
Wind energy
Micro-generation
Sensitivity analysis
Levelized cost of energy

ABSTRACT

National targets for increased renewable energy are common-place internationally and small/micro-generation may help achieve such goals. Energy yields from such technologies however, are very location and site specific. In rural environments, the average wind speed is relatively high and the homogeneous landscape promotes laminar air flow and stable (relatively) wind direction. In urban environments however, the wind resource has lower mean wind speeds and increased levels of atmospheric turbulence due to heterogeneous surface forms. This paper discusses the associated costs per unit of electricity generated by micro wind energy conversion systems from the perspective of both urban and rural locations, with three case studies that consider the potential and financial viability for such systems. The case studies ascertain the cost of energy associated with a standard HAWT (horizontal axis wind turbine), in terms of exemplar rural and urban locations. Sri Lanka, Ireland and the UK, are prioritised as countries that have progressive, conservative and ambitious goals respectively towards the integration of micro-generation. LCOE (Levelized cost of energy) analyses in this regard, offers a contextualised viability assessment that is applicable in decision making relating to economic incentive application or in the determination of suitable feed-in tariff rates.

1. Introduction

From a renewable energy perspective, significant momentum is actively being achieved in economic "greening" and in 2014 alone, there was a 17% increase in global investment in renewable energy (representing $270.2 billion) [1]. During the period 2000 to 2012, the increase for wind power globally was 266 GW whereas over the same period, the increase in nuclear power was only 9 GW [2]. The majority of this new renewable capacity comes from larger plant (such as wind farms), but the residential sector's influence should not be neglected. In 2011 the residential proportion of total electricity consumption accounted for 36.3% [3] and 30.9% [4] in the US and Euro zone respectively. Engagement by small and micro-generation at consumer level - or indeed in green community developments that encapsulate domestic consumption - could therefore contribute positively in this regard. Indeed, from an environmental perspective, Greening and Azapagic [5] in their evaluation of life cycle environmental sustainability of micro wind turbines in the UK, point out that the majority of environmental impacts from wind turbines are lower than from grid electricity. Furthermore, wind turbines are more environmentally sustainable than solar PV (Photovoltaic) for seven out of 11 impacts, ranging from 7.5% lower eutrophication to 85% lower ozone layer depletion.

Globally, the use of SWT (small wind turbines) is increasing; driven by the need for electricity in rural environments, higher energy costs and an increased emphasis on environmental concerns [6]. Micro or small wind was originally defined by its characteristics to produce small amounts of electricity for house appliances or to cover various household-based electricity demand. Depending on location however, domestic consumption could warrant a 10 kW turbine (USA) or a turbine with 1 kW capacity (China) [7]. The capacity of these technologies is currently defined

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http://dx.doi.org/10.1016/j.energy.2016.05.045
0360-5442/

by IEC (International Electrotechnical Commission) 61400-2 as having a rotor swept area of less than 200 m^2, equating to a rated power of up to 50 kW (approx.) [7], but there are different definitions used by different countries. The WWEA (*World Wind Energy Association*), in its 2014 Small Wind Report (which uses 100 kW as a temporary reference for the upper capacity level) states that at the end of 2012, a cumulative total of at least 806,000 small wind turbines were installed all over the world. This represents an increase of 10% compared with the previous year and an installed capacity of more than 678 MW, which itself is an increase of 18% over the capacity recorded in 2011 [7].

From a European perspective, micro-generation is currently defined through the EN (European Norm)50438 standard. In the UK, the G83 standard applies but both standards employ the same definitions for connection to the distribution network. In this regard, micro-generation capacity (output) may be 5.75 kW_e (25 A) at single phase or 11 kW_e (16 A) at three phase. The micro wind energy sector is still at an early stage of development, but there is evidence, particularly in the UK of a growing market for micro wind systems [8]. This growth is mainly in the rural environment where the average wind speed is relatively high and wind speed/direction is reasonably stable.

Wind energy is a major renewable energy resource, accounting for the largest share (32%) of new EU (European Union) power capacity in 2013 [9], but within urban environments, this renewable energy source has yet to be embraced in any meaningful way. There are still relatively few examples of these systems within urban settings where demand is greatest and where they could provide an alternative to centralised generation, which by virtue of fossil fuel reliance, is carbon emission intense [10].

In urban environments installation opportunities are highly influenced by landscape heterogeneity and surrounding building morphology. In this regard, ill-considered technology positioning greatly undermines the potential for energy realization. Therefore, location/position and the nature of the wind resource in urban environments need to be appreciated if there are to be viable opportunities for micro wind energy systems as cost effective power generation options [11]. Available test studies investigating the viability of micro wind generation vary from damning [12] to tentatively optimistic, i.e. the technology can work if installed correctly and in appropriate locations [13]. However, since the population centres are urban centres, implementation of all forms of micro-generation for urban dwellings is essential if renewable energy targets are to be achieved [10]. Indeed, as the global population becomes increasingly concentrated in urban areas [14], the potential for accessing the available wind resource could become a necessity. Cities are responsible for 71%–76% of CO_2 emissions from global final energy use [15], much of it is derived from fossil-fuel based electricity generation. The development of small and micro wind generation systems at consumer level could contribute positively towards national renewable energy targets.

From an economic viability perspective and not withstanding broader issues such as market structure and associated regulation, the most important parameters in evaluating the viability of micro wind turbine systems are the initial cost and the cost associated with generating the energy. These parameters depend on the average wind speed, turbine type, size, mechanical design and the ability to optimise the generation output. Cost remains the main challenge in the dissemination of small wind [7]. In the USA, the installed cost estimates of top ten small wind turbine models in 2011 ranged between \$2300/kW and \$10,000/kW (€2000–7000/kW). The Chinese small wind industry yielded, in comparison, a significantly lower average turnover of 12,000 Yuan/kW (€1700/kW).

This paper discusses various issues that influence the viability of micro wind systems. Three countries are considered as test cases with each country having varying degrees of renewable energy aspirations and/or micro wind embracement polices. The wind turbine utilised for each context is a *Skystream 3.7* (2.4 kW); a standard, commercially available HAWT (horizontal axis wind turbine). In the analyses presented here, the HOMER (*Hybrid Optimisation Model for Electric Renewables*™) optimisation software, as developed by the National Renewable Energy Laboratory, USA, is employed. *HOMER* is used to evaluate LCOE (levelized cost of energy) evaluations for rural and urban exemplar contexts for each of the three case studies. *HOMER* facilitates a simplified means to evaluate the LCOE based on the associated energy source data, system components and a given load demand [16]. It further facilitates a techno-economic analysis of a system in terms of system parameter sensitivity. In the context of this paper, the annual energy produced by the wind turbine and the cost of energy demand, are measured against the cost of energy production for each case study. The cost of energy production considers the initial cost and maintenance costs over the life time of the turbine and is calculated through a net present cost evaluation for generation of unit energy. In this regard, *HOMER* performs energy balance calculations (demand/generation) for the representative system configurations. Each case study is analysed on an hourly basis over the course of a year (8760 h) through a net metering evaluation. Accordingly, the viable initial cost per kW installation and cost of energy use of the micro wind turbine are determined for the three case study countries.

An LCOE analysis will provide an economic cost-competitiveness metric for each case study rural/urban wind energy system comparison. It will not in isolation however, quantify or qualify the intra-dependencies or system variable interactions in how it is derived. A DOE (Design of Experiments) analysis [17,18] will therefore be performed to acquire a context of how system parameters, such as primary energy (rural/urban wind resource), capital cost and loan/finance interest rate individually and collectively affect the understanding of a wind energy system LCOE.

2. Wind energy conversion

Wind turbines extract kinetic energy from moving air, converting it into mechanical energy via the turbine rotor and then into electrical energy through the generator. The two defining aspects of a wind turbines performance are the blade sweep area and the associated power curve for the turbine. The blade sweep area defines the amount of power that can be captured from the available wind whilst the power curve illustrates the turbines performance against varying wind speeds. The mechanical energy captured by the wind rotor is described by (1).

$$P_{Mech} = \frac{1}{2} \cdot c_p \cdot \rho_{air} \cdot A_{rotor} \cdot u^3 \tag{1}$$

where c_p is the power coefficient or the power extracted by the turbine relative to that available in the wind stream, ρ_{air} is the mass density of air A_{rotor} is the rotor area and u is the wind speed.

Clearly, the power generated is proportional to the cube of the wind speed, so that small variations in wind speed will have a significant impact on the wind turbines productivity. The aerodynamic conversion losses are significant for wind turbines and according to the Betz law, only 59.25% of the kinetic wind energy can theoretically be converted into mechanical power (P_{Mech}). The reality however, is that when blade roughness, hub loss, wake rotation and tip losses are considered, the limit can be as low as 36.2% for large scale wind turbine systems [19]. A power-coefficient/tip-speed-ratio ($C_p - \lambda$) relationship describes the power extraction capability for a turbine in terms of aerodynamic influences. For a typical wind turbine, Muljadi et al. suggest a $C_p - \lambda$ of around 42% [20]. When this is considered in conjunction with typical generator efficiencies of around 90% [21] and converter losses of 5% [22], wind turbines can have overall efficiencies in the order of 30% [23].

For small wind turbines, however, the power generated is ultimately reliant on the site specific prevailing wind characteristics, which are dependent on terrain conditions, obstacles, elevation and global wind potential. In this paper, exemplar wind characteristics prevalent at indicative rural and urban locations - for each case study - are employed using local data to compare the performance of a wind energy system at these locations. In this regard, the power generation, by a particular wind turbine (same power curve and control parameters), is prioritised so that to provide consistency across each comparison.

2.1. Wind energy in rural and urban locations & HOMER

Cities are aerodynamically (very) rough and morphologically heterogeneous with a highly localised and complex wind environment. Whereas opportunities for wind energy engagement within urban environments are limited or not clearly understood, there is significant research assessing the wind energy resource in non-urban or ‘rural’ locations [24,25]. In either environment however, air flow will interact with the underlying landscape to acquire its distinctive characteristics. In this regard for example, Allen et al. [26] considered wind turbine performance in respect of varying geographical locations (urban and rural) and varying mounting heights. They observed that the height positioning of the turbine, by virtue of the cubic relationship associated with wind speed, significantly affects the energy harnessing of such technologies. Furthermore, this cubic relationship, in terms of a fluctuating wind resource, makes for very challenging wind energy extraction opportunities within urban environments. In contrast, when one considers the generation profile associated with Solar PV, the peak in the associated primary energy (solar irradiance) always occurs around midday. From an economical consideration perspective, some literature has capitalized on this knowledge. In Ref. [27], Pillai et al., consider the dynamics of a domestic solar PV. They employed an evaluation methodology in which the consumption, exportation and importation of electricity were considered on the basis of generic load/insolation profiles. Such an approach is difficult (if not impossible) for wind energy application, as a *typical* wind resource is not possible to describe.

The wind resources employed for each case study were acquired through site specific observations and in the Sri-Lankan context, an estimation tool (*Wind Resource Assessment Model*) was employed. Furthermore and in consideration of the different anemometer heights at each case study location, *HOMER* facilitates *scaling* so that each case study is considered in terms of a consistent wind turbine hub height. This scaling, (2) is based on the ratio of the wind speed ($u_{(hub)}$) at hub height (z_{hub}) to the wind speed ($u_{(anem)}$) at anemometer height (z_{anem}) and is cognisant of the surface roughness length applicable to the urban location (z_0).

$$\frac{u_{hub}}{u_{anem}} = \frac{\ln\left(z_{hub}/z_0\right)}{\ln\left(z_{anem}/z_0\right)} \tag{2}$$

For this study, Table 1 details the respective case study anemometer heights at which wind speed observations are made for both the rural and urban considerations. As well as a generic surface roughness length (based on the *Davenport* scale [28]), which is indicative of the roughness prevalent at each location, Table 1 also indicates both the anemometer reference height and the turbine hub height for the sites being investigated.

For the work presented here, *HOMER* facilitates a net-metring evaluation on an hourly basis in terms of a manufacturer's power curve, exemplar load profiles and the wind resource prevalent at each case study location.

3. Case study rationale

Three countries, Sri Lanka, Ireland and the UK, with varying degrees of micro-generation ambitions, are considered. For each case study, exemplar rural and urban wind resource contexts are employed based on the wind resources prevalent at each location and through indicative surface roughness (z_0) classifications. From a wind climatology perspective, there will be some consistency in comparing the Irish and UK contexts, as the urban wind exemplars for each country are defined by the associated surface roughness transitions from rural to urban considerations. Sri Lanka on the other hand has a monsoon wind climate.

Domestic/residential electricity demand depends on a number of factors, such as the number of occupants, age, lifestyle habits and the quantity and nature of electrical devices. Pillai et al. in Ref. [27] suggest that to be representative of all type of residential houses, family sizes and occupancy patterns, seasonal ADMD (*after diversity maximum demand*) profiles are required. This approach is adopted for each of the three case studies considered.

The micro wind energy system considered for each context is the *Skystream 3.7* (2.4 kW) wind turbine (Fig. 1). By considering one turbine only for each case study, a basis for comparison is established.

Table 2 provides the financial context applicable for each case study and illustrates the input parameters utilised by *HOMER* in evaluating LCOE analyses for the Sky stream 3.7 micro wind energy system in terms of the rural/urban exemplar wind resources.

The real interest rate illustrated in Table 2 depends on the national policy for each case study. It reflects an attempt to identify the future value of investment as the associated cash flows devalue over time. The interest rate in this regard is employed as a discount factor. In other words, it facilitates a consideration of the economic, business and political/social stability and level of risk associated with each investment and how they contribute to the future value of the investment. Essentially, the value of discount reflects the cost of time, risk and expected inflation in the future. One way of considering the discount factor is in terms of the national (case study) cost of borrowing, i.e. the 10 year bond rates with some estimated risk factor included. In this regard, Ireland and the UK currently have low interest rate (0.05% and 0.5% respectively) and the interest rate for Sri Lanka currently stands at 6.0%. However, in Ireland, the Department of Public Expenditure and Reform suggests a test discount rate for economic evaluation and appraisal purposes of 5% and in the UK, the HM (Her Majesty) Treasury's The Green Book *(2003)*, suggests a discount rate of 3.5%.

This paper presents a rural/urban wind energy system techno-economic analysis based on the LCOE. However, this LCOE analysis is provided by considering the general national energy policies associated with each case study as this can also assist in informing policy/market development.

3.1. Levelized cost of energy

Cost of energy and initial cost of the system are the most important parameters in evaluating economic viability of small wind power systems. Levelized cost of energy (LCOE) can be thought of as the price at which energy must be sold to break even over the lifetime of the technology [29]. Alternatively, LCOE can be

Table 1
Case Study Turbine Height & surface roughness characteristics.

	Turbine hub height (z_{WT}) [m]	Anemometer height (z_{WT}) [m]	Surface roughness, (z_0) [m]	
Sri Lanka	20	50	0.25	*Hambantota* (Rural)
		50	1.5	*Colombo* (Urban)
Ireland	20	10	0.02	*Dublin* (Rural)
		26	1.1	*Dublin* (Urban)
UK	20	10	0.03	*London* (Rural)
		43	0.75	*London* (Urban)

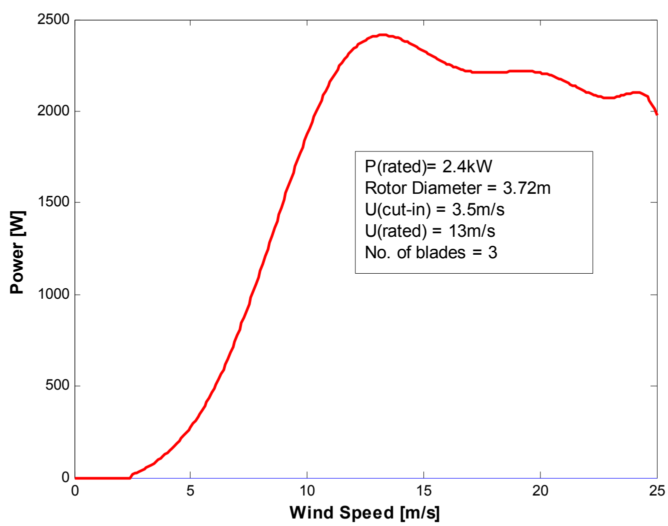

Fig. 1. *Skystream 3.7* (Manufacturer) Power Curve including turbine operating characteristics.

considered as the average cost per 1 kW h of useful electrical energy produced by the system, and may be defined by (3). The initial cost of small wind turbines depends on the size and type of the turbine. A 2.4 kW small grid connected wind turbine system (SW (Southwest Windpower)-Skysream3.7), is considered at each location, where there are different wind characteristics affecting the amount of wind energy generation. In accordance with manufacturer specifications, it is assumed that project life time and maintenance costs are equal in each installation. Furthermore, sensitivity analysis is carried out by considering cost parameters, performances and specifications of the specific small grid connected wind turbine system. Initial cost (including tax) is combined with annual maintenance requirements; such as oiling, regular safety inspections, checking of electrical connections, checking wind turbines for corrosion and the guy wires supporting the tower for proper tension, etc. The operation and maintenance cost (O&M) is estimated to be 1.5%–3% of the turbine cost but increases with time as the turbines get older [30] and for this analysis, 3% O&M was considered for each case study. The life time of the system for each case study is set at 20 years with replacement cost being considered as equal to initial cost of the system and salvage cost is neglected. AEP (Annual Energy Production) is computed based on the power curve provided by the manufacturer (Skystream 3.7). The levelized cost of energy (LCOE) in €/kWh may be represented as:

$$COE = \frac{C_{ann,tot}}{E_{prim} + E_{def} + E_{grid,sales}} \quad (3)$$

where $C_{ann,tot}$ is the total annualised cost of the system (€Year), E_{prim} is the primary load served (kWh/Year), E_{def} is the deferrable load served (kWh/Year) and $E_{grid,sales}$ is the total grid sales (kWh/Year). The total annualised cost of the system ($C_{ann,tot}$) is the sum of the annualised capital cost ($C_{ann,cap}$), annualised replacement cost and annual operation and maintenance cost. The annualised capital cost is:

$$C_{ann,cap} = C_{cap} \cdot CRF(i, R_{proj}) \quad (4)$$

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (5)$$

where C_{cap} is the initial capital cost in € (which includes the costs of the power converter and connection to the grid), *CRF(i, N)* is the capital recovery factor, *i is the a*nnual real interest rate, R_{proj} is the project lifetime and *N* is the number of years.

Power generation by the wind turbine is determined by considering the manufacturers power curve of the wind turbine and associated wind potential for each respective location. Grid sales and purchases are calculated by considering hourly based wind data, energy generation and demand data over the course of a year. The results illustrate the correlation between the initial cost of

Table 2
Case study financial context including turbine cost, maintenance cost and unit cost (consumption/export).

	Case Study Reference			
	Sri Lanka	*Ireland*	*UK*	
VAT	12%	23%	20%	
Currency	*$(US)*	*€*	*£(stlg.)*	
Real interest rate	6.0%	5.0%	3.5%	
Cost of Turbine (national currency)	$9,887	€14,520	£9,500	
Currency Exchange rate (? → €)	*0.817*	*1.000*	*1.271*	
Cost of Turbine (€)	€8,080	€14,520	€12,076	
Annual Maintenance Cost (€)	€242	€436	€362	
Annual Maintenance Cost (% Capital Cost)		*3%*		
Capacity of Turbine (kW)		**2.40**		
Cost/kW	**€3,367**	**€6,050**	**€5,032**	
Unit cost (purchase)	*$0.20*	*€0.18*	*£0.15*	*RATE Scheduling*
	€0.163	€0.180	€0.191	
Unit Cost (Sale)	*$0.20*	*€0.09*	*£0.21*	
	€0.163	€0.090	€0.267	

wind turbine, the annual mean wind speed and the associated cost per kWh generated. For the case studies being considered, an analysis of the cost effectiveness of a grid-connected wind turbine as a source of electricity within rural and urban contexts is presented.

3.2. Case study 1: Sri Lanka

Sri Lanka, from a perspective of a baseline position, represents a progressive ambition for renewable energy engagement. Demand for electricity in Sri Lanka is estimated to rise at an annual pace of 8–10% [31]. To tackle this demand, generation from renewable energy sources, including wind, are being encouraged. In this regard, the Sri Lankan attitude is progressive and potentially open to embracing small wind energy systems and indeed, has a target of 10% of electricity supply from renewable energy by 2015 [6].

In this study, the viability of a micro wind system was reviewed at two locations in Sri Lanka; representing both a rural (Hambantota) and urban (Colombo) perspective. The WRAM (*Wind Resource Assessment Model*) map was employed to estimate rural/urban wind speeds at an elevation of 50 m height [32]. The wind speeds at a 20 m elevation (hub height), are acquired through *HOMER* extrapolation (2), in terms of the indicative surface roughness parameters listed in Table 1. The monthly wind speed estimates at the wind turbine mounting height (20 m) for both the Colombo suburbs and the rural location Hambantota are illustrated in Table 3.

Typical seasonal (domestic) Sri Lankan electricity consumptions (1st day of January and the 1st day of July), are illustrated in Fig. 2 in context with the rural/urban wind resource over both exemplar days. Sri Lankan household electricity demand is approximately 1993 kW h/yr. The wind resource for each location in the Sri Lankan case study is such that the Skystream wind turbine can generate 1372 kW h/year in the Colombo (urban) suburbs and 5680 kW h/year near Hambantota (rural). A summary of annual grid sales/purchases at each location, as a percentage of annual consumer demand, is shown in Table 4.

Fig. 3 illustrates the monthly productivity of the wind turbine (gen O/P) for each location in context with local consumption and exportation of electricity (grid import and grid export, respectively). The import/export of the generated electricity is dictated by the domestic load profile (shown in Fig. 2). In the analysis presented for each case study, grid import and export is evaluated by *HOMER* by considering energy demand and generation on an hourly basis. In this regard, one year of wind and load data was included. The energy demand (for typical summer and winter days) is presented in Fig. 3 with generation calculated by using hourly base wind data and turbine power curve. Whereas, the variability of the wind speed and its intermittency will dictate generator output, this intermittency is further complicated by the load profile not coinciding with the generator productivity prevalent at both sites.

Table 3
Sri Lankan monthly average wind speeds for both the urban and rural locations in the context of the wind turbine hub height (z_{WT}).

Month	Hambantota (rural @20 m) [m/s]	Colombo (urban @20 m) [m/s]
Jan	6.8	3.0
Feb	5.9	2.0
Mar	5.1	2.5
Apr	3.8	2.8
May	7.2	4.9
Jun	7.4	5.3
Jul	7.7	5.0
Aug	8.3	5.3
Sep	5.7	4.7
Oct	6.4	3.8
Nov	2.9	2.8
Dec	3.5	3.0
Average	***5.9***	***3.8***

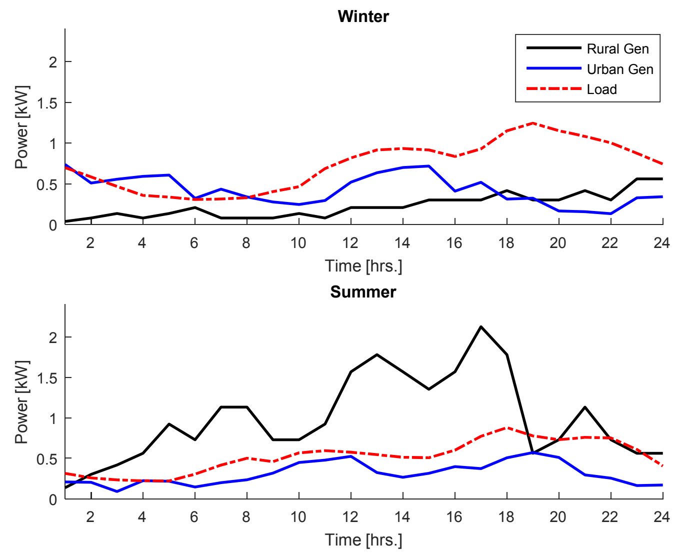

Fig. 2. Seasonal generation output profiles in context with (exemplar) domestic load/demand (Sri-Lanka, 2011).

The actual cost for the *Skystream* system in the Sri Lankan context is considered to be €8080.25 (*€7214.51 + 12% (VAT)*). The annual energy produced by the wind turbine in terms of an electricity unit purchase and sale cost of €0.163/kWh is considered in Table 5. This table illustrates the cost per unit (kWh) generated by the generation system at both sites, expressed in terms of a mean wind speed, an interest rate of 6% and an initial cost per kW. The LCOE in terms of the assumed capital cost per kW and the associated site specific mean wind speed over the year is highlighted (in red). The significance of the (green) shading for this table (and the subsequent analyses in the other case studies) is to indicate at what wind speed, with respect to initial cost per kW, that a grid-connected wind turbine can provide a cost effective source of electricity, i.e. in the context of Sri Lanka, this implies less than €0.163/kWh. The calculations underpinning Table 5 are based on a particular tower height, as indicated in Table 1. It is a practical height for small scale generation. If the turbine height is increased, power generation may also increase but capital cost will increase at a much higher rate.

3.3. Case study 2: Ireland

Irish commitment to a renewable share of gross electricity consumption is 40% by 2020 [33]. While this renewable energy engagement appears ambitious, the reality from a small/micro-generation perspective is quite different. Micro wind generation capacity represents more than 75% of installed micro-generation capacity in Ireland. However, with a total metered micro-generation capacity of 2.9 MW by the end of 2011 [34], the uptake of micro wind generation opportunities remains low. Compounded with the cessation of any Governmental incentive schemes (since April 2012), Irish policy in respect of small/micro wind generation systems in general, can be considered conservative.

For Ireland, two sites were selected as being representative of a rural and urban location. The first, Dublin Airport, is indicative of a rural site. The Airport wind speed observations were through a synoptic weather station at an observation height of 10 m. The urban wind speed reference was acquired from a meteorological

Table 4
Annual Grid Sales and Purchases in Sri-Lankan locations as percentages of annual load consumption of 1993 kW h

	Hambantota (rural)		Colombo (urban)	
Grid sales	4250 kW h/yr	213%	613 kW h/yr	31%
Net (€) purchases/sales	3677 kW h/yr	185% (Sales)	619 kW h/yr	31% (Purchases)

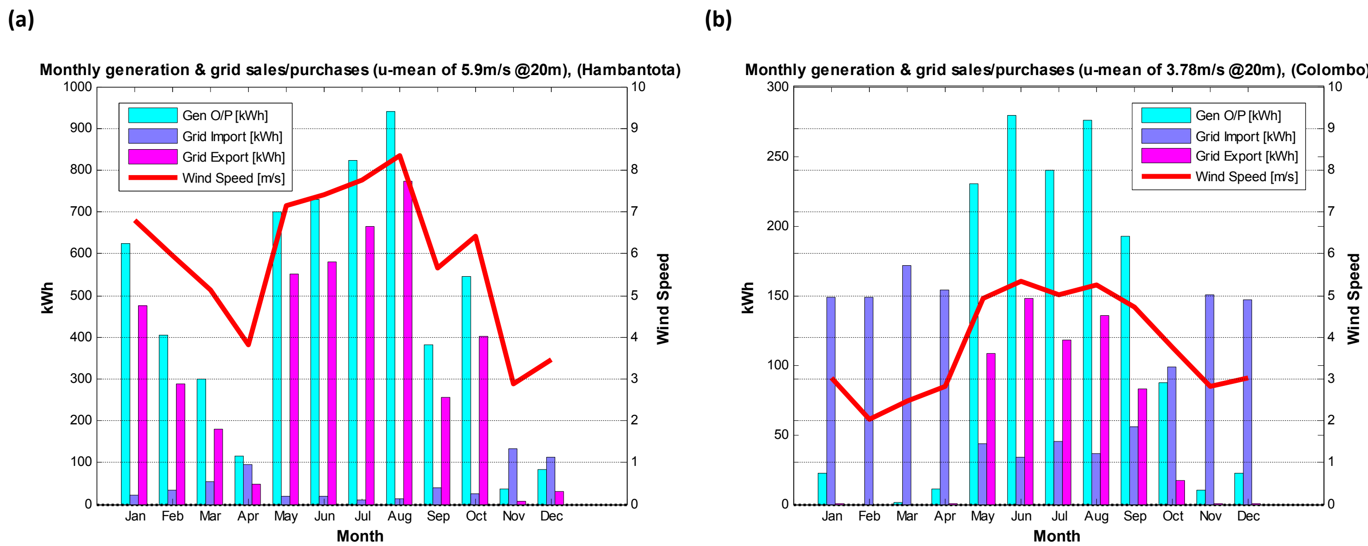

Fig. 3. Monthly mean wind, energy production and grid purchases for the rural (a) and urban (b) Sri-Lankan case study.

Table 5
Annual Energy Production (Sri Lanka) and cost of energy production by the wind turbine (kWh).

HAMBONTOTA AIRPORT (Rural)

Initial Cost per 1kW installation	Annual Mean Wind Speed: 3m/s	4m/s	5m/s	5.91m/s	6m/s	7m/s	8m/s	9m/s
€ 5,050	€1.87	€0.71	€0.38	€ 0.25	€0.24	€0.18	€0.14	€0.12
€ 4,208	€1.56	€0.59	€0.31	€ 0.21	€0.20	€0.15	€0.12	€0.10
€ 3,367	€1.25	€0.47	€0.25	**€ 0.17**	€0.16	€0.12	€0.10	€0.08
€ 2,525	€0.94	€0.35	€0.19	€ 0.13	€0.12	€0.09	€0.07	€0.06
€ 1,683	€0.62	€0.24	€0.13	€ 0.08	€0.08	€0.06	€0.05	€0.04
€ 842	€0.31	€0.12	€0.06	€ 0.04	€0.04	€0.03	€0.02	€0.02
AEP (kWh/$u_{Mean(annual)}$)	759	2003	3775	5680	5874	7982	9873	11460

Unit cost €/kWh

COLOMBO SUBURB (Urban)

Initial Cost per 1kW installation	Annual Mean Wind Speed: 3m/s	3.78m/s	4m/s	5m/s	6m/s	7m/s	8m/s	9m/s
€ 5,050	€2.43	€1.03	€0.86	€ 0.43	€0.26	€0.18	€0.14	€0.12
€ 4,208	€2.03	€0.86	€0.71	€ 0.36	€0.22	€0.15	€0.12	€0.10
€ 3,367	€1.62	**€ 0.69**	€0.57	€0.29	€0.17	€0.12	€0.09	€0.08
€ 2,525	€1.22	€0.52	€0.43	€ 0.21	€0.13	€0.09	€0.07	€0.06
€ 1,683	€0.81	€0.34	€0.29	€ 0.14	€0.09	€0.06	€0.05	€0.04
€ 842	€0.41	€0.17	€0.14	€ 0.07	€0.04	€0.03	€0.02	€0.02
AEP (kWh/$u_{Mean(annual)}$)	584	1372	1657	3308	5490	7946	10133	11903

Unit cost €/kWh

weather station located on the outskirts of the city centre. The weather station in this regard is placed at the top of a 10 m tower, which itself is fixed on the roof of a 16 m building. Table 6 illustrates the (*HOMER*) scaled monthly wind speeds for the respective locations, in terms of the surface roughness description, to the turbine hub height (20 m) as illustrated in Table 1.

Typical (seasonal) Irish load data (again over the 1st day in January and the 1st day in July) is illustrated in context with the rural/urban wind resource for both days, is illustrated in Fig. 4.

For the Irish case study, the wind turbine can generate 4477 kW h/year in rural Dublin and 1339 kW h/year in urban Dublin. Typical annual household electricity demand in Ireland is 5074 kW h/yr. As for the Sri-Lankan case study (Table 4), Table 7 illustrates the overall balance of grid sales/purchases for the Irish rural and urban locations in respect of the turbine performance and the hourly consumer demand at each location. Fig. 5 provides a monthly summary of the wind turbine output in terms of net grid purchases (grid import) and grid sales (grid export) for each location.

The annual energy produced by the wind turbine for both Irish (rural/urban) locations, cognisant of an electrical energy (unit) purchase cost of €0.18/kWh and sale price of €0.09, is considered in Table 8. The table illustrates, the cost per unit (kWh) generated by the wind turbine system, expressed in terms of a mean wind speed, an interest rate of 5% and an initial cost per kW. The cost of the wind generation system was considered to be €14,521 (*€12,000 + 12% (VAT)*). The specific LCOE, in terms of the assumed capital cost per kW and the associated site specific mean wind speed over the year, is highlighted in red.

3.4. Case study 3: UK

The UK has a strong commitment to the embracement of power generation from micro wind energy systems with 160.96 MWe installed capacity across the (small/micro-generation) sector [8]. This commitment is considered to represent an ambitious attitude to the sector. Whilst micro wind power currently represents only 0.35% of total wind capacity [6], with potential for micro-generation as high as 30–40% of the UK's electricity needs [35], micro wind generation capacity is expected to increase significantly.

The UK case study was considered in terms of Heathrow Airport and a suburb within the greater London area as locations representative of a rural and urban landscape, respectively. Hourly wind speed records for both locations were acquired through the BADC (*British Atmospheric Data Centre*) and the MIDAS (*Met Office Integrated Data Archive System*). As the anemometry position heights at both locations were 10 m (rural) and 43 m (urban) respectively, *HOMER* extrapolated both wind speed data sets to the wind turbine hub height of 20 m; consistent with both previous case studies. Table 9 illustrates the monthly wind speed at turbine hub height in terms of the respective site surface roughness lengths provided in Table 1.

Consistent with the Sri-Lankan and Irish considerations, Fig. 6 illustrates a typical UK (seasonal) domestic electrical energy demand (again, the 1st days in January and July respectively) in context with the urban/rural wind resource over both days.

The calculated annual grid sales and purchases at each location for the UK case study, based on a generation of 3544 kW h and 1243 kW h for the rural and urban locations respectively, are shown in Table 10. These generator outputs are in context with an annual

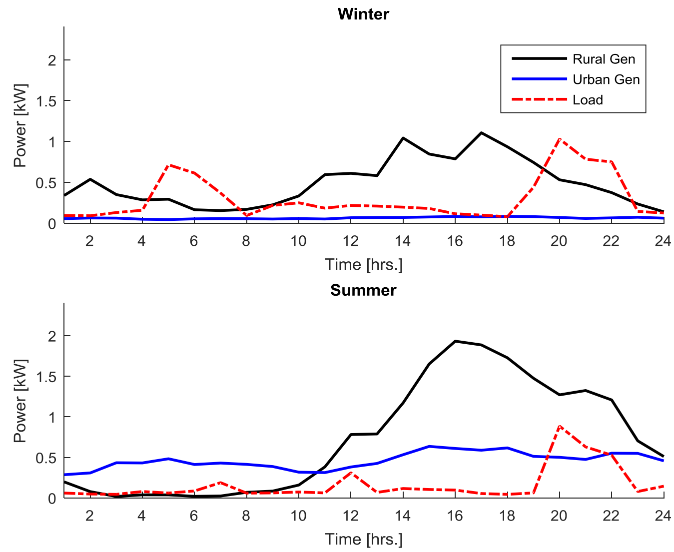

Fig. 4. Seasonal generation output profiles in context with (exemplar) domestic load/demand (Ireland, 2011).

consumer demand of 4417 kW h/yr.

Based on the consumer demand specified and the generator productivity for both locations, Fig. 7 provides a monthly summary of the wind turbine output in terms of net grid purchases (grid import) and grid sales (grid export) for each location.

The capital cost for the *Skystream 3.7* system was considered as €12,076 (10,063 excl. 20% VAT). The annual energy produced by the wind turbine in respect of electricity unit consumption and sales costs of €0.191/kWh and €0.267 respectively, is considered in Table 8. The table illustrates, the cost per unit (kWh) generated by the wind turbine system, expressed in terms of a mean wind speed, an interest rate of 3.5% and an initial cost per kW. As with the previous case studies, the specific LCOE, in terms of the assumed capital cost per kW and the associated site specific mean wind speed over the year, is highlighted in red.

3.5. Case study comparison and analysis

The analysis presented in the preceding section highlights the complexities associated with matching consumer load to generator productivity at both rural/urban locations. Furthermore, the depleted wind resource available in sub/urban locations makes for a difficult economic argument for urban system deployment. Indeed, in the context of urban locations, the results indicate that

Table 6
Irish rural monthly average wind speeds in context with monthly average wind speeds for both the urban location and turbine mounting height contexts.

Month	Dublin Airport (rural @20 m) [m/s]	Dublin suburb (urban @20 m) [m/s]
Jan	6.3	4.7
Feb	4.8	3.5
Mar	5.3	3.0
Apr	4.8	3.3
May	4.7	3.0
Jun	4.5	2.9
Jul	6.0	3.0
Aug	5.2	2.9
Sep	5.5	3.6
Oct	5.8	3.0
Nov	6.5	3.7
Dec	4.8	3.8
Average	***5.4***	***3.4***

Table 7
Annual Grid Sales and Purchases in Irish locations as percentages of annual load consumption of 5074 kW h

	Dublin Airport (rural)		Dublin suburb	
Grid sales	1817 kW h/yr	36%	215 kW h/yr	4%
Net (€) purchases/sales	601 kW h/yr	112% (Purchases)	3735 kW h/yr	74% (Purchases)

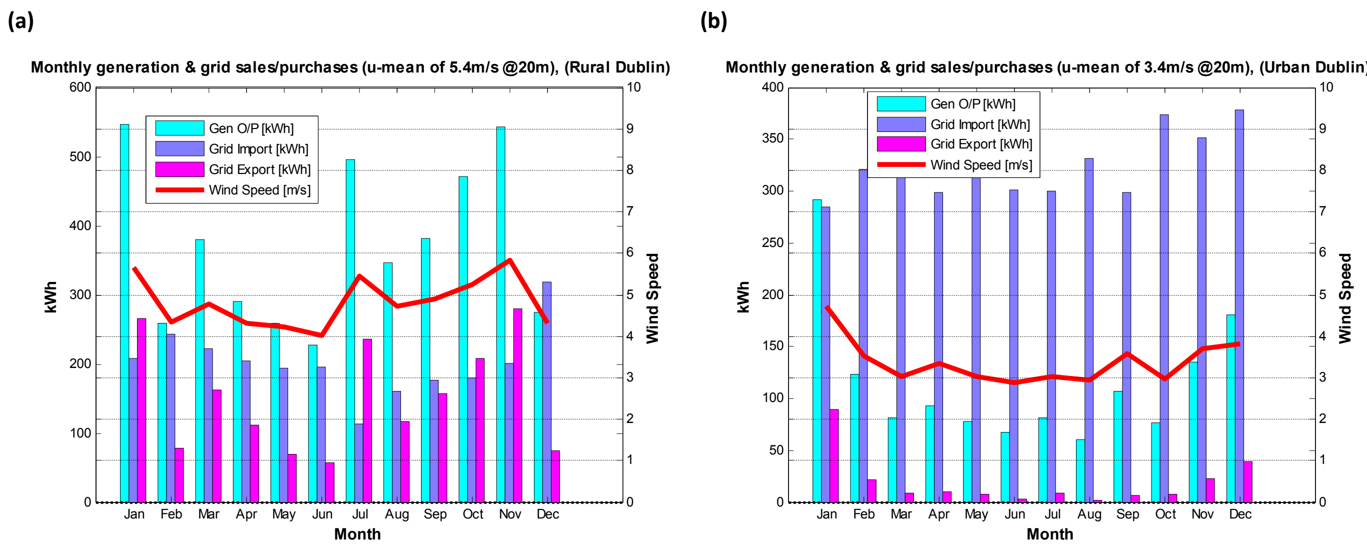

Fig. 5. Monthly mean wind, energy production and grid purchases for the rural (a) and urban (b) Irish case study.

Table 8
Annual Energy Production (Ireland) and cost of energy production by the wind turbine (kWh).

DUBLIN AIRPORT (Rural)

Initial Cost per 1kW installation	Annual Mean Wind Speed: 3m/s	4m/s	5m/s	**5.36m/s**	6m/s	7m/s	8m/s	9m/s
€9,076	€2.95	€1.16	€0.63	€ 0.54	€0.42	€0.31	€0.25	€0.21
€7,563	€2.46	€0.97	€0.53	€ 0.45	€0.35	€0.26	€0.21	€0.18
€6,050	€1.96	€0.77	€0.42	***€ 0.36***	€0.28	€0.21	€0.17	€0.14
€4,538	€1.47	€0.58	€0.32	€ 0.27	€0.21	€0.15	€0.12	€0.11
€3,025	€0.98	€0.39	€0.21	€ 0.18	€0.14	€0.10	€0.08	€0.07
€1,513	€0.49	€0.19	€0.11	€ 0.09	€0.07	€0.05	€0.04	€0.04
AEP (kWh/$u_{Mean(annual)}$)	*815*	*2073*	*3790*	*4447*	*5753*	*7751*	*9619*	*11203*

Unit cost €/kWh

DUBLIN (Urban)

Initial Cost per 1kW installation	Annual Mean Wind Speed: 3	**3.38m/s**	4m/s	5m/s	6m/s	7m/s	8m/s	9m/s
€9,076	€2.69	€ 1.79	€1.08	€0.60	€0.40	€0.30	€0.25	€0.22
€7,563	€2.24	€ 1.50	€0.90	€0.50	€0.33	€0.25	€0.21	€0.18
€6,050	€1.79	***€ 1.20***	€0.72	€0.40	€0.27	€0.20	€0.16	€0.14
€4,538	€1.34	€ 0.90	€0.54	€0.30	€0.20	€0.15	€0.12	€0.11
€3,025	€0.90	€ 0.60	€0.36	€0.20	€0.13	€0.10	€0.08	€0.07
€1,513	€0.45	€ 0.30	€0.18	€0.10	€0.07	€0.05	€0.04	€0.04
AEP (kWh/$u_{Mean(annual)}$)	*894*	***1339***	*2227*	*4014*	*6040*	*8000*	*9719*	*11141*

Unit cost €/kWh

the net grid sales are zero for each case study and grid purchases range from 31% (Sri Lanka) to 72% (UK). However, this does imply that 69% and 28% of consumer demand for the respective case studies is provided for by the local generation.

As a further means to compare the individual case study results, a generic LCOE evaluation is considered where no VAT is applied and the interest rate is fixed for each case study. This generic levelized cost of energy evaluation ($LCOE_{gen}$) therefore considers the respective mean wind speed (u_{Mean}) at each location, a fixed interest rate of 4.8% and VAT is excluded from the capital cost of each case study wind turbine system. The 4.8% interest rate is the average of the individual case study interest rates. Such an approach facilitates a comparison that focuses primarily on the effect of the wind resource at each rural/urban location and the associated wind turbine system capital cost. In this regard, Table 12 summarises a comparison of the LCOE for each case study based on the parameters highlighted in Table 2 against this generic LCOE ($LCOE_{gen}$).

Table 9
UK rural monthly average wind speeds in context with monthly average wind speeds for both the urban location and turbine mounting height contexts.

Month	London Airport (rural @20 m) [m/s]	London (urban @20 m) [m/s]
Jan	4.5	3.2
Feb	5.3	3.6
Mar	3.9	2.8
Apr	4.1	3.0
May	5.7	3.9
Jun	4.9	3.3
Jul	4.1	2.9
Aug	4.3	2.8
Sep	5.3	3.3
Oct	5.3	3.4
Nov	4.2	2.9
Dec	6.2	4.0
Average	***4.8***	***3.3***

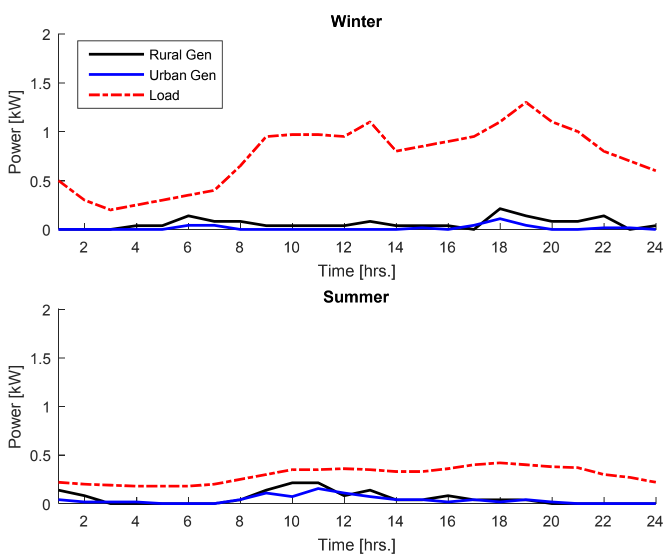

Fig. 6. Seasonal generation output profiles in context with (exemplar) domestic load/demand (UK, 2011).

constituent parameters that define LCOE contribute and/or interact in its evaluation. In other words, the LCOE for the wind energy generated at the respective sites provides for an economic appreciation of generator performance but it doesn't facilitate an understanding of how it can be optimised. A DOE (*Design of Experiments*) analysis [17,18] or a '*designed experiment*', can offer this context of how the case study parameters, as defined in Table 2, contribute individually - and collectively – to the LCOE calculated. These parameters are otherwise referred to as *factors*. A designed experiment is a series of tests, in which the input variables are varied purposefully to establish their effects. The approach facilitates identification of the key factor for the LCOE, but it also contextualises the effect of interactions between factors as well. For the case studies here, the factors were varied ± 5% of their respective nominal values for each case study. A Pareto chart, shown in Fig. 8, is used to display the importance of a factor and the interactions between factors.

Fig. 8 clearly identifies that the main contributing factor to the LOCE is the local wind speed, with the capital cost playing a secondary role in its determination. Furthermore and consistent with observations from Table 12, it is apparent that the interest rate is not significant in its contribution to LCOE.

4. Discussion

The viable initial costs per kW installation of small wind turbines were determined based on the results illustrated in Figs. 3,5 and 7 and tabulated in Table 5, Tables 8 and 11. A summary of the results in terms of the viable initial cost per 1 kW generation capacity, based on a mean wind speed, are presented in Table 13 for each location in each case study.

In Table 13, the annual wind speed column represents a reference to which the wind speeds at the different locations are scaled. The point here is that irrespective of the *scale*, the mean wind speeds retain the statistical characteristics and shape of the baseline site specific data but the wind speed magnitudes will vary depending on the factor required to achieve this scale reference. In other words, the table provides a means to consider the viable maximum cost per 1 kW capacity in terms of a variation to the

Table 10
Annual Grid Sales and Purchases in the UK locations (% of annual load consumption of 4417 kW h).

	London Airport (rural)		London (urban)	
Grid sales	1384 kW h/yr	31%	172 kW h/yr	4%
Net (€) purchases/sales	873 kW h/yr	20% (Purchases)	3174 kW h/yr	72% (Purchases)

As evident from Table 12, both VAT and the interest rate are influential on the LCOE. Based on the results acquired for Ireland and Sri Lanka, one could argue that the capital cost is less influential as a factor in the evaluation of LCOE. The capital cost/kW of the wind turbine system for the Irish context is 28% more than the Sri Lankan case study, but the associated LCOE/$LCOE_{gen}$ comparison shows an affect that differs by only 3% (for broadly similar mean wind speeds). However, the lower interest rate applied to the generic Sri Lankan consideration is also influential, representing a 20% reduction to the rate specified in Table 2 (6%), as opposed to a 4% reduction for the Irish case study (5%). The influence of the interest rate is further apparent in the relatively diminished effect derived for the UK LCOE/$LCOE_{gen}$ comparison. For the UK generic consideration, the fixed (4.8%) interest rate represents an increase of 27% compared to the UK rate specified in Table 2 (3.5%).

Table 12 also demonstrates the difficulty in ascertaining how the associated mean wind speeds across each case study location. Fig. 9 illustrates a frequency distribution comparison of the wind resource for the Irish rural and urban locations, illustrating the different statistical characteristics for the wind resource at both locations.

Fig. 9 further emphasises that wind potential for power generation by a wind turbine is not dependent solely on mean wind speed. Wind speed variation is also a considerable factor. So for variable mean wind speed references (as illustrated in column one of Table 13), the mean wind speeds observed/calculated at each of the case study rural/urban locations were *scaled* (to a greater or lesser degree) to be representative of the reference mean wind speeds. In this regard therefore, the baseline statistics representative of each location will also be considered, as a wind turbine positioned at any location could have different productivity for the same mean wind speed reference. In this way, Table 13 presents a

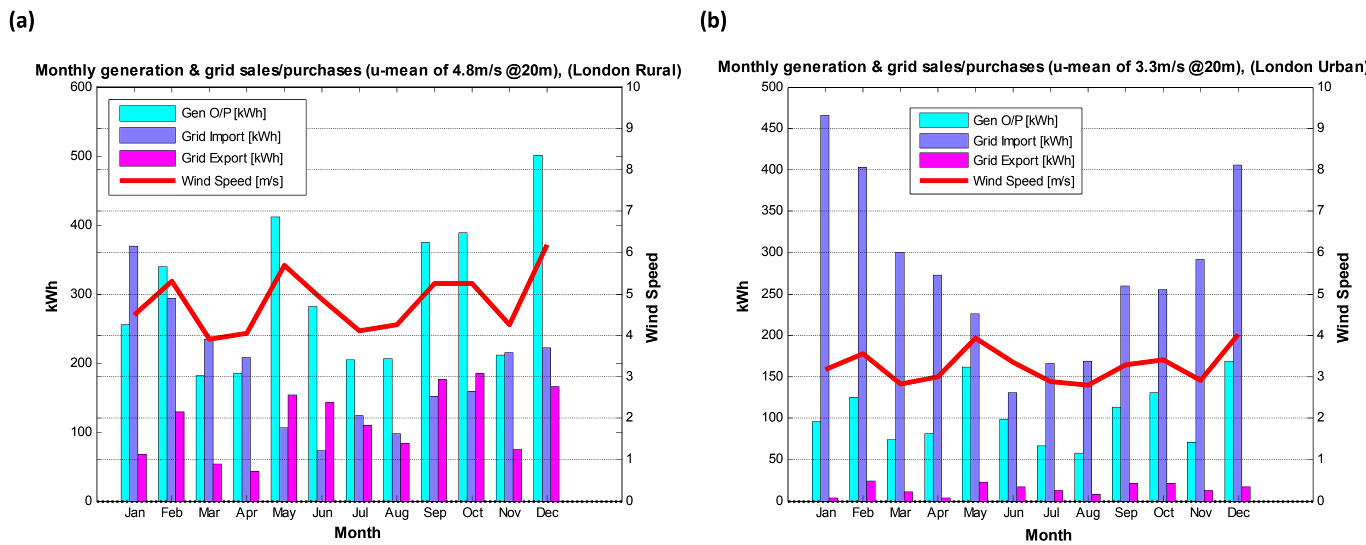

Fig. 7. Monthly mean wind, energy production and grid purchases for the rural (a) and urban (b) UK case study.

Table 11
Annual Energy Production (UK) and cost of energy production by the wind turbine (kWh).

LONDON AIRPORT (Rural)

Initial Cost per 1kW installation	Annual Mean Wind Speed: *3m/s*	*4m/s*	***4.8m/s***	*5m/s*	*6m/s*	*7m/s*	*8m/s*	*9m/s*	
€7,548	€2.15	€0.84	€0.51	€ 0.47	€0.31	€0.23	€0.19	€0.16	Unit cost €/kWh
€6,290	€1.79	€0.70	€0.43	€ 0.39	€0.26	€0.19	€0.16	€0.14	
€5,032	€1.43	€0.56	***€ 0.34***	€0.31	€0.21	€0.15	€0.13	€0.11	
€3,774	€1.07	€0.42	€0.26	€ 0.23	€0.15	€0.12	€0.09	€0.08	
€2,516	€0.72	€0.28	€0.17	€ 0.16	€0.10	€0.08	€0.06	€0.05	
€1,258	€0.36	€0.14	€0.09	€ 0.08	€0.05	€0.04	€0.03	€0.03	
AEP (kWh/$u_{Mean(annual)}$)	*846*	*2162*	***3544***	*3909*	*5884*	*7826*	*9571*	*11111*	

LONDON CITY (Urban)

Initial Cost per 1kW installation	Annual Mean Wind Speed: 3m/s	***3.26m/s***	4m/s	5m/s	6m/s	7m/s	8m/s	9m/s	
€7,548	€1.94	€1.46	€0.78	€ 0.44	€0.29	€0.22	€0.18	€0.16	Unit cost €/kWh
€6,290	€1.62	€1.22	€0.65	€ 0.36	€0.24	€0.19	€0.15	€0.14	
€5,032	€1.29	***€ 0.98***	€0.52	€0.29	€0.20	€0.15	€0.12	€0.11	
€3,774	€0.97	€0.73	€0.39	€ 0.22	€0.15	€0.11	€0.09	€0.08	
€2,516	€0.65	€0.49	€0.26	€ 0.15	€0.10	€0.07	€0.06	€0.05	
€1,258	€0.32	€0.24	€0.13	€ 0.07	€0.05	€0.04	€0.03	€0.03	
AEP (kWh/$u_{Mean(annual)}$)	938	***1243***	2327	4162	6191	8143	9833	11191	

Table 12
Generic LCOE consideration in terms of the specific case study LCOE.

	Initial Capital Cost/kW (excl. VAT)	Interrest Rate (*i*)	u_{Mean} (m/s)	$AEP_{Generator}$ (kWh)	$LCOE_{generic}$ (€)	$LCOE_{case}$ (€)	***Affect***	
Sri Lanka	€ 3,006.05	4.8%	5.9	5680	0.14	*0.17*	***-17.0%***	*Rural*
			3.8	1372	0.57	*0.69*	***-17.0%***	*Urban*
Ireland	€ 4,919.04		5.4	4447	0.29	*0.36*	***-19.7%***	*Rural*
			3.4	1339	0.96	*1.20*	***-19.7%***	*Urban*
UK	€ 4,193.06		4.8	3544	0.31	*0.34*	***-9.6%***	*Rural*
			3.3	1243	0.88	*0.98*	***-9.6%***	*Urban*

comparison of wind turbine productivity at exemplar rural and urban sites for respective countries in terms of a single mean wind speed value.

The system cost of energy generation for each case study in terms of varying initial investment costs are illustrated in Fig. 10. Table 14 offers further context by illustrating the LCOE for each

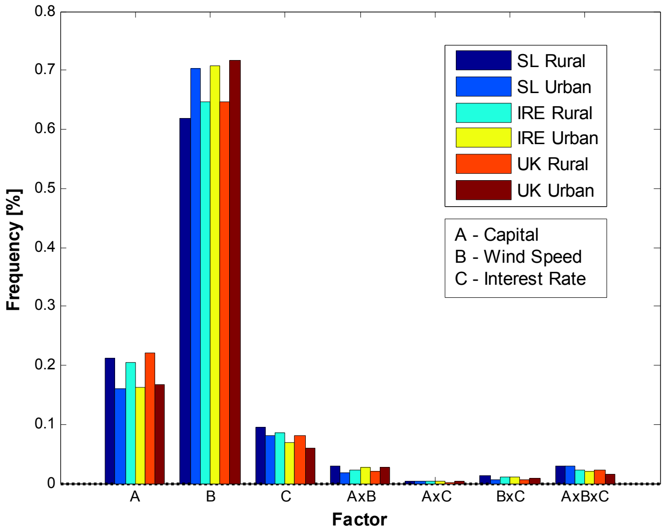

Fig. 8. Experimental Design in determining the significance of mean wind speed, capital cost and real interest rate.

Table 13
Viable initial cost per 1 kW generator capacity in terms of annual mean wind speed.

Annual mean wind speed	Viable maximum initial cost per 1 kW capacity installed (€/kW)					
	Sri Lanka		Ireland		UK	
	Rural	Urban	Rural	Urban	Rural	Urban
3 m/s	*NV*[a]	*NV*	*NV*	*NV*	*NV*	*NV*
4 m/s	€1263	€1044	*NV*	*NV*	*NV*	€1912
5 m/s	€2188	€1852	€2632	€2602	€2516	€3371
6 m/s	€3367	€3114	€2768	€2783	€4025	€5283
7 m/s	€4545	€4545	€4538	€4387	€5560	€7548
8 m/s	€5639	€5892	€5052	€4992	€7095	€9309
9 m/s	€6565	€6734	€5445	€5445	€8453	€10,063

[a] Not Viable.

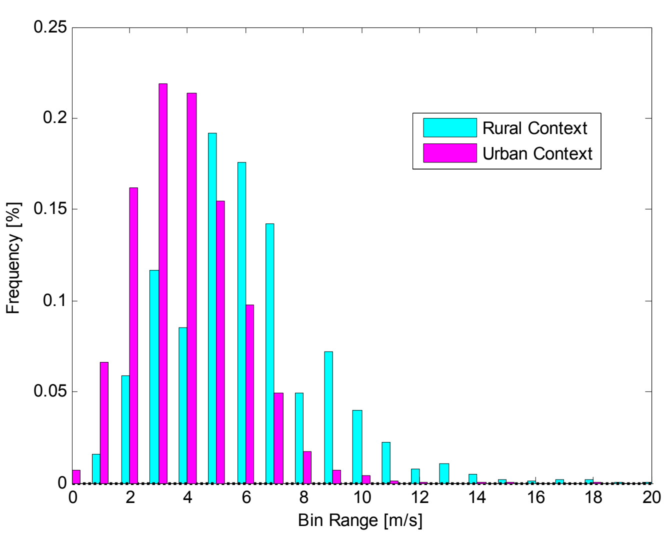

Fig. 9. Frequency Distribution comparison of the rural/urban wind resource (Ireland).

country in terms of their associated rural and urban installations at their specified costs per kW of the micro wind system.

The results suggest that the LCOE associated with micro wind systems installed in urban locations is preclusive from an optimisation perspective. For micro wind turbines to be viable in the urban environment, enhanced wind energy extraction optimisation is required. Improvements in the wind turbine aerodynamics and energy capture at low wind speed are essential in conjunction with reduced power losses in the generator and power electronic conversion modules. Contextualising the results with the broad national engagement commitments, as outlined in section3, does suggest that within current market forces micro/small wind energy systems are worth exploring in Sri Lankan rural locations. Looking at the UK situation, even with ambitious micro-generation integration goals, support or some form of subsidy will be required if an urban market is to be realised. From an Irish perspective however, the LCOE could provide a tipping point at which conservative engagement becomes non engagement.

5. Conclusions

If small wind generation systems are to effectively contribute in a future energy mix, there is a need to understand the influence of physical and financial considerations as they apply to optimal system performance. Physical considerations include the installation environment and available wind resource. The financial considerations should be cognisant of system costs, which can be fixed (e.g. capital and O&M costs) and variable in nature. The variable costs depend on the consumer demand and turbine output, but also relevant is the real interest rate over the life time of the system. Ultimately, turbine productivity and its effective system

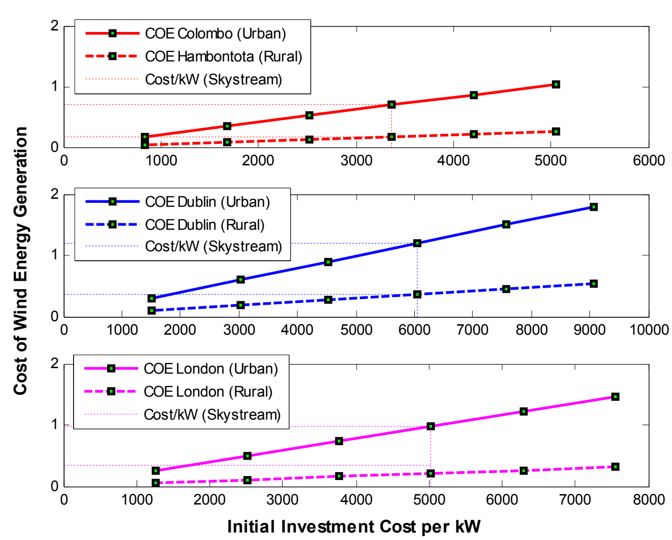

Fig. 10. Cost of wind energy generation vs. Initial investment.

Table 14
LCOE associated with the wind generator in respect of the annual mean wind speed and capital cost of generation system.

Cost of skystream 3.7 wind energy generation (€)	Rural context	Urban context
Sri Lanka	€0.17	€0.69
Ireland	€0.36	€1.20
UK	€0.34	€0.98

deployment are dependent on a good wind resource. The research presented in this paper primarily focuses on the system financial concerns. However, in evaluating the levelized cost of energy associated with a *Skystream 3.7* (2.4 kW) for three case studies, the effect of installation location choice, through rural and urban comparisons, was also considered.

Sri Lanka, Ireland and the UK, were prioritised as countries that have progressive, conservative and ambitious goals respectively towards the integration of micro-generation and offer an international context for assessing the potential for small wind energy systems. The results presented allow a range of conclusions to be drawn.

For an *LCOE* analysis, the results show that for urban wind harvesting opportunities, the cost in developing wind energy at micro level is currently preclusive. Moreover, in countries such as Sri Lanka where micro wind could support the developing rural distribution networks, the price awarded for energy export is insufficient to enhance viability in urban environments. Furthermore, while the UK Government is committed to the integration of micro-generation in general, for micro wind integration opportunities, both rural and urban, will require enhanced energy payment opportunities. Finally, for the Irish consideration, neither the rural or urban sites considered are cost viable in the context of current market prices.

The LCOE results were complemented with a *Design of Experiment* analysis, which facilitated an understanding of how the individual system components contribute to the LCOE calculated for each case study. In this regard, the DOE identified the wind resource as the biggest contributor to the LCOE for each case study. However, notwithstanding low mean wind speeds and the (logistic) challenges presented for small wind generation systems, with increasingly centralised global populations within cities, efforts to establish minimum requirements to make such installations commercially viable need to be explored. This means improved wind turbine aerodynamics and energy capture at low wind speed, through advanced dynamic control techniques (e.g. wind speed forecasting, predictive control, active yaw control, etc.) are required. It must be acknowledged however, system improvements will cause system capital costs to increase, which is why if national policies are to embrace this form of renewable energy, symbiotic market and Governmental encouragement will be required to make the technology accessible for market participants.

Acknowledgements

The authors would like to thank the Dublin Institute of Technology, Ireland, Northumbria University, Newcastle upon Tyne, UK, and the National Renewable Energy Centre, Blyth, UK for their support in this research. The authors would also like to thank both Dr. Dan Drew for his assistance in acquiring wind data for the UK case study and the National Engineering Research and Development Centre of Sri Lanka for providing wind data for the Sri Lankan case study.

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