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

Keith M. Sunderland [a, *], Mahinsasa Narayana [b], Ghanim Putrus [c], Michael F. Conlon [a], Steve McDonald [d]

[a] Dublin Institute of Technology, Ireland
[b] University of Moratuwa, Sri Lanka
[c] Northumbria University, UK
[d] Newcastle University, UK

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

* Corresponding author.
E-mail addresses: keith.sunderland@dit.ie (K.M. Sunderland), mahinsasa@uom.lk (M. Narayana), ghanim.putrus@northumbria.ac.uk (G. Putrus), michael.conlon@dit.ie (M.F. Conlon), steve.mcdonald@newcastle.ac.uk (S. McDonald).

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