Onsite Energy Yield and Demand in the Urban Built Form:
Balancing yield and demand to achieve zero carbon communities

IAN HAMILTON[1], MICHAEL DAVIES[1], PHILIP STEADMAN[1]

[1]University College London, London, United Kingdom

ABSTRACT: This paper considers the implications of increasing urban density and the ability to meet the UK Government's zero carbon homes and building targets through onsite low and zero carbon (LZC) energy technologies. A definition of what sources of energy should be considered as 'onsite incident resources' is offered. Then, the available onsite incident energy yield is assessed and compared against the annual energy demand for a range of urban densities. A mixed-use development site, typical of the Southeast UK is used to assess the availability of onsite incident energy against which the urban densities energy demands are compared. This illustrates the likely carrying capacity of the site. The outcome of the study indicates that, given the projected energy demand, meeting onsite annual energy requirements sustainably is achievable even at high urban densities (e.g. 120dph); however, the demand may be greater than the yield in a given month, and less likely at an hourly or instantaneous scale. In addition, the work indicates that sharing infrastructure allows for energy to be better balanced to serve the urban form, particularly in heating systems. The paper also considers the impact that designing urban environments for optimal onsite energy yield may have on urban design.
Keywords: zero carbon, domestic energy use, onsite incident energy resources, renewables

INTRODUCTION

The current initiative in the UK is to re-establish, re-invest and seek growth in town and city centres, and to establish higher housing densities for new developments [1, 2]. Current government policy is to supply approximately 250,000 dwellings per year, for a total of 3 million new homes by 2020 [3]. As more dwellings are added to the landscape there is an increase in the required energy and resources used to supply these built environments.

The UK Government's Climate Change Act [4] indicates that along with this growth, a reduction of CO_2 emissions by 80% of 1990 levels should be met by 2050. Buildings account for approximately 50% of total UK energy use and CO_2 emissions [5], against which the Act's CO_2 reductions must take place. Part of the expected reductions in buildings will come from energy efficiency, and the rest will come from low and zero carbon energy generation. Under current Government proposals, dwellings are meant to achieve zero carbon emissions by 2016 [6]. Net zero, as is currently defined, states that <u>all</u> a dwelling's energy use must be found via zero carbon onsite or near-site sources [7]. This definition has been subject to controversy, both in terms of the associated costs, technical feasibility, and method of implementation [8, 9, 10]. The Government is consulting on a new definition that looks at how 'zero carbon' should be defined and met, and in particular examining the definitions of 'onsite' and 'offsite'.

The ability to meet this energy demand sustainably via onsite or near-site low and zero carbon energy technologies is directly related to the available 'onsite incident energy resources' and their yield to meet demand. This paper considers the feasibility of meeting the energy demand of urban buildings and the ability to meet zero carbon via onsite sources and the physical and technical limitations associated with this.

METHODOLOGY

In this assessment, only those sources of energy that are onsite are considered. In order to establish to what extent these onsite energy sources can supply energy to an urban site, not just reduce CO_2 emission, they must be meaningfully quantified and qualified. Technical engineering solutions are distilled during a process of high-level assessment down to detailed design, therefore the first step in attaining true zero carbon development is a first-principles assessment of both the yield and demand. The application of these energy systems must not be a 'token' carbon reduction tool, but should seek to help reduce the energy demand from large and inefficient power plants and insecure fuel sources whose supply and price are volatile and which have a heavy impact on the local and global environment.

This study considers how (1) the onsite incident energy resources for a site can be defined. It then (2) describes an example 1ha site in Southeast England by its physical features and bio-climatic characteristics. Then,

(3) several urban development densities are outlined along with their likely energy demand in 2016. (4) A methodology for qualifying and quantifying the availability of the onsite incident energy resources, in terms of the likely delivered energy, is applied to the varying densities of the 1ha site. Following this, (5) the different densities and their energy demand are compared against the related onsite energy yield. (6) The results are discussed and final conclusions on the appropriate scales of development are reached.

This study is informed by energy demand models and solar radiation estimates for urban areas as developed by the EPSRC funded LUCID project (The Development of a Local Urban Climate Model and its Application to the Intelligent Design of Cities).

ONSITE INCIDENT ENERGY RESOURCES

In order to establish the available onsite incident energy resources available to a site, a definition is offered that attempts to frame this issue. This definition can be applied to any site to describe the surrounding energy resource conditions available to the development. A definition of the available onsite incident resources, as it applies to onsite energy yield, is offered as:

> *"The available energy (primary or delivered) captured via useful energy converting/ generating systems that are directly on or within the site curtilage or boundary – the site boundary is considered as the spatially limiting constraints (physical or political) surrounding the site."*

To be considered as 'onsite' a fuel cannot be imported from outside the site boundary. The ability for a site to produce its own energy would therefore favour those resources that are renewable and can be harvested or yielded within its boundary at a rate that is sustainable for use over the period of demand.

Figure 1 illustrates an example of a single dwelling's site boundary from within which the energy resources would be assessed.

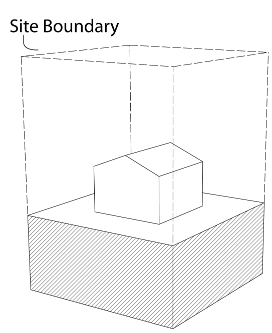

Figure 1 - Site Boundary of an example dwelling

Quantifying the Available Onsite Energy The method used to assess the availability of onsite energy resources is to first quantify the primary energy characteristics and bioclimatic conditions of the site through estimating their incidence, and then their capture or conversion to a useful energy source. The primary energy characteristic can be assessed for a seasonal period to show availability for the site using measured meteorological and geological data. This primary energy is then converted into an energy supply for use (i.e. thermal or electrical). As more specific detail is applied, the more exact the assessment becomes. Table 1 provides a list of those resources that can provide both primary and delivered energy to a site:

Table 1 - Primary & Delivered Energy Sources

Primary	Delivery Systems/ Techniques	Units
Earth:	GSHP, ATES, BTES, Geo-thermal	°C W/m^{2}K, l/s
Wind:	Wind turbines, air source heat pump	m/s
Water:	Hydro-mechanic/electric	l/s, m
Solar:	Photovoltaic, solar thermal panel	W/m^2
Biomass:	Any biomass product converted for heat or power.	kj/kg

The above energy resources shown in ***Table 1*** will contribute a varying amount of delivered energy to a site as defined by the physical and political limiting factors (e.g. site aspect, cultivation area, or legislative restrictions). The conversion of the available resources into useful energy for a development is the product of the technologies employed to convert and distribute the energy.

In this paper the assessment makes use of desk-based data sources, such as local climate data, and standardised industry benchmark and data on technology efficiency. However, as an energy strategy is further developed more rigorous testing would be required (e.g. onsite anemometer or boreholes). The delivered energy can then be described as annual or daily available incident onsite energy for a site (e.g. kWh), and compared against the likely energy demand for the selected built environments.

SITE DESCRIPTION

The location chosen to demonstrate the process of estimating the available onsite incident energy and comparing it against the energy demands of several built environment densities is located in the Southeast of England, approximately 150km from London, in the District of Horsham. It is an arable greenfield, south sloped with a small semi-dry creek. The earth is Weald Clay formation. A 1ha sample of the site is used to illustrate the comparison, as this is approximately the size of a typical development block, both in terms of urban regeneration and new development, and is therefore subject to similar spatial planning issues.

Notional Development On the chosen site, a notional mixed-use development, at varying urban densities, is used to describe the energy demand, which is based on notional figures for dwelling and non-domestic area. The notional dwelling in this study is a 3-bedroom, 5-person semi-detached dwelling. It is arranged as a 2-storey unit, with a footprint of $50m^2$, the roofs of the dwelling are also $50m^2$ and flat. In the higher density examples the dwelling becomes a terrace, for which a different heat loss parameter and resulting heat energy demand is applied.

The related non-domestic area is a collection of non-domestic building types, including: retail, office, GP, community centre, a primary school and library. The proportion of each is 19, 52, 6, 6, 2 and 15 percent respectively; these are applied pro rata as $8m^2$ of commercial space per domestic unit. In addition to the dwellings and non-domestic floorspace, approximately 35% of the 1ha is attributed to road area. All other development area is considered as open or arable land.

Development Densities In order to appreciate the magnitude of available onsite energy yield as compared to the likely energy demand, several urban densities are presented and compared. These illustrate how yield, demand, and physical constraints impact on the ability to balance supply and demand, thus suggesting a carrying capacity for a development site based on these limiting factors.

Current UK Government policy is to provide a minimum density of 30 dwellings per hectare (dph) for urban developments [6]. Often, greater densities are sought by Local Authorities and developers for commercial and social reasons (e.g. minimum density for a primary school) [11]. This increase in density will in turn have implications on the energy demand and thus the carrying capacity of the site. In this paper, four density types are considered. They are:

- 15dph (rural type density)
- 30dph (minimum density – PPS3)
- 60dph (typical urban density)
- 120dph (very-high density urban form)

Table 2 outlines the land use associated with the above densities.

Table 2 - Land use of varying urban densities

Area Calculations for Varying Urban Densities							
Urban Development Density	Dwelling Footprint Area = 50m2	Non Domestic Area	Built Area	Road Area (35%)	Open/ Arable Area	Built + Open	Site
15dph (rural)	750	75	825	3,500	5,675	6,425	10,000
30dph (suburban)	1,500	150	1,650	3,500	4,850	6,350	10,000
60dph (urban)	3,000	300	3,300	3,500	3,200	6,200	10,000

Urban environments at this range of densities are capable of meeting the needs of the residents whilst providing a suitable amount of private and communal space and the critical mass to which energy infrastructure can be applied. ***Figure 2*** illustrates an example of the urban environment densities described in this study. At higher densities (i.e. 90pdh and above) the available land that is open or arable is limited.

Figure 2 - Mixed-use urban density of 120dph

ENERGY DEMAND

The current definition states that in order to be zero carbon compliant the dwellings must have a heat loss parameter of $0.8W/m^2K$ [7]. The effect of a more efficient building fabric and ventilation system is to decrease the overall space heating demand; this will in turn increase the proportion of electricity within the total demand. This places a greater emphasis on those onsite technologies that are capable of providing sustainable electricity. The non-domestic floorspace annual and daily energy demand make use of best practice UK benchmarks [12, 1], against which an assumed efficiency increase of 20% is applied.

The energy demands associated with the four densities are quantified using the above notional dwelling and non-domestic floorspace and are applied to the 1ha site, from which a total annual and daily demand is estimated. ***Figure 3*** illustrates the annual energy demand for the urban environments, categorised in domestic and non-domestic. This figure illustrates the relationship between increased densities and increased energy demands.

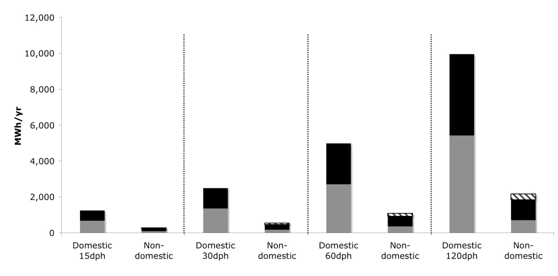

Figure 3 - Annual energy demand for selected mixed-use urban environments

In order to optimise the distribution of the captured and converted energy, and meet the zero carbon target efficiently a balancing of demand and yield is necessary. This balance will come from considering where, when and how much heat and electricity are needed through a period via a shared energy infrastructure. Shared infrastructure would mean linking all the buildings to a centralised heat and coolth network in order to store and distribute energy (e.g. heat/coolth and power batteries, cables, and pipes). This will also increase the diversity of demand and allow for a more constant operating baseload. Such a strategy has been considered the most appropriate method of attaining zero carbon developments [8] This infrastructure, along with the capture and conversion of the onsite incident energy will lead to the creation of more sustainable communities that are capable of operating both within the confines of their environment, meeting their energy demands, and reducing overall carbon emissions.

AVAILABLE ONSITE INCIDENT ENERGY

The available onsite incident energy yield is estimated for each density in order to compare the yield to the likely demand and assess the carrying capacity.

The primary energy sources data is collected and plotted as annual average and daily values. The values, in this study, are derived from Meteonorm®, which provides local climate data, and a British Geological Survey, which gives details on aquifer and borehole water yield and ground conductivity. The average annual conditions are:

- Wind 4.9m/s, 5.7m/s, 6.2m/s at 10m, 25m 45m
- Solar Radiation – 2.67kWh/m^2/day
- Ground Temperature 15°C
- Air Temperature – 11°C
- Ground Diffusivity – 0.05m^2/day

Figure 4 shows the seasonal trends of these bioclimatic conditions for the selected site.

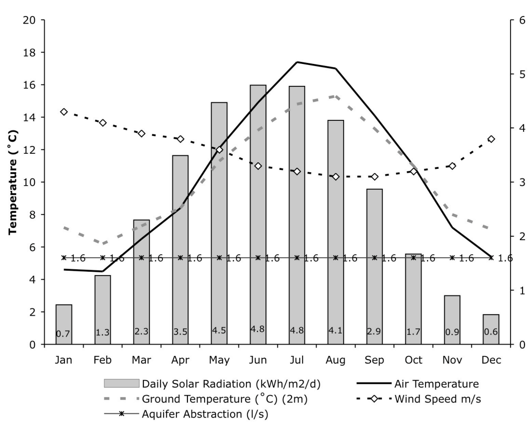

Figure 4 - Bioclimatic Site Characteristics

Annual Delivered Energy The availability of the primary energy is used to quantify the likely delivered energy, which can be compared to the demand associated with the varying urban densities. The incident resources are converted into useable energy sources (i.e. thermal or electric) via conversion systems. The systems proposed for use on the selected site are described in ***Table 3*** along with their associated efficiency and operation parameters; the system characteristics are defined from standard UK operating conditions and studies [13, 14]. In addition, any significant parasitic energy used for this process is identified (e.g. heat pump use of electricity) and shown as a negative value.

Table 3 - - Energy technology assumptions

Available Onsite Energy Resources for 1ha site with no contraints				
Primary	**Delivery Systems/ Techniques**	**Energy (kWh/yr)**	**Energy Type**	**Assumptions**
Earth	Ground Water Heat Pump	701,000 -176,000	thermal electric	4 boreholes at 1.6l/s abstraction 50m apart COP 4 + 5% distribution losses
	Ground Coupled Heat Pump - Vertical Electricity Use:	2,859,000 -1,057,000	thermal electric	Heat COP 3.2; standard borehole layout (34,352m) + 5% distribution losses
	Ground Coupled Heat Pump - Horizontal Electricity Use:	547,000 -214,000	thermal electric	Heat COP 3.2; standard loop layout (loop - 8,155m & trench 4,078m)
	Aquifer Thermal Energy Storage Cool Electricity Use: Heat Electricity Use:	1,790,000 -100,000 -448,000	coolth electric electric	4 boreholes at 1.6l/s abstraction, Heat COP 4; Cool COP 14 - Radiant system
	Geo-thermal	-	thermal	N/A
	Biomass	59,000	thermal	Oven dry willow - CV of 19.8GJ/tonne burned in a 95% efficient boiler + 5% distribution losses
Wind	Wind Turbine	1,747,000	electric	1no. 1MW Turbine
Water	Hydro	-	electric	N/A
Solar	Photovoltaic	1,230,000	electric	Mono-crystaline 15% efficiency; 15% system losses
	Solar Thermal	3,790,000	thermal	Glazed flat panel - Horizontal

Using the above assumptions, the following seasonal energy yield can be quantified according to the site conditions.

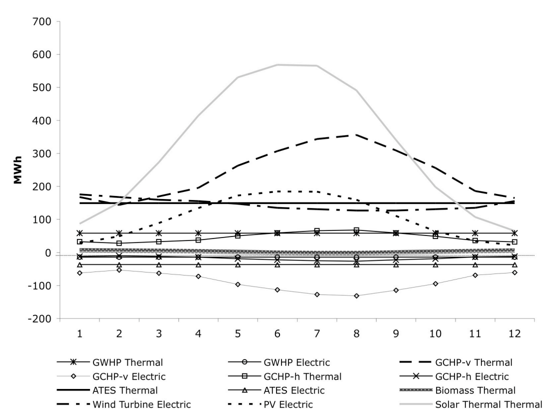

Figure 5 - Seasonal energy profile for 1ha site of typical energy technologies

The most prevalent energy source is unsurprisingly solar energy, and the most efficient use of this energy is for hot water purposes via solar thermal panels, as the heat capacity of water is higher. PVs are an alternative conversion system for solar energy, but the efficiency of these systems is still low over their operating life (between 10-15%), and is subject to further reductions due to the seasonal variation in high latitude countries such as the UK. Indeed, the ability to capture this source of energy is dependent on roof area, time of day, external temperature, and cloud conditions.

The ground water systems (i.e. ATES and GSHPs) are also able to provide a significant amount of consistent heat, as the ground temperatures are relatively stable over the year; however, they in turn need electricity to operate the heat pumps that extract the heat energy from the ground, thus also relying on an onsite electricity generating system. Also, water quality and abstraction and injection rates must be carefully monitored in order to avoid over-cooling or heating the ground. Electricity via wind turbines also provide a reasonable amount of energy; however, they are constrained by the available area for their use and the surrounding environment – such as local turbulence (applied as a roughness factor to the daily and annual wind estimates) and irregular wind patterns found in urban environments [15].

COMPARISON OF SUPPLY AND DEMAND

The energy estimates of the notional urban developments, at the varying urban densities are compared against the onsite energy yield.

Onsite Incident Energy Strategy Of the above energy generating systems, only those that provide the most energy whilst using the least amount of resources are considered to be appropriate for an energy strategy and thus used in the comparison. Also, it should be noted that throughout this assessment, cost has not been considered as a constraint (e.g. capital or operational), but would be a significant factor in any decision on implementation. Therefore, those generating systems that are used for the site are:

- Aquifer Thermal Energy Systems (ATES)
- Wind turbines (area dependent)
- Photovoltaic panels
- Biomass (area dependent)

Figure 6 provides a comparison of the available annual onsite energy yield and the energy demand for the selected urban densities over a year.

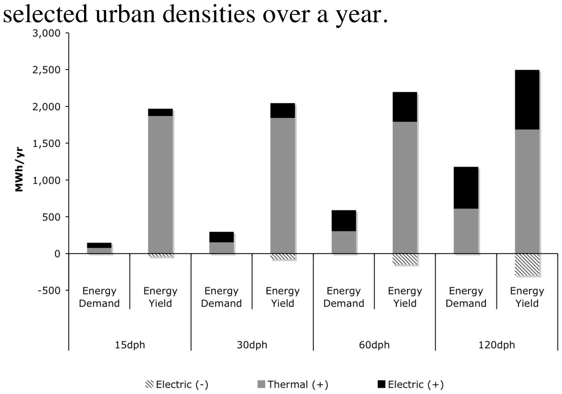

Figure 6 - Comparison of energy yield and demand for selected urban densities

The comparison shows that it is possible to meet all of the annual energy demand for the urban densities via onsite energy resources.

In comparison, however, the seasonal energy yield may not always meet the monthly or daily demand, as seen in Figure 7. This ability for more energy to be harvested, over an annual period, but limited in a monthly or daily period, is a significant point in considering to what extent zero carbon should be met through onsite energy generating technologies. A full energy strategy investigation would involve the simulation of hourly supply and demand over the course of a year.

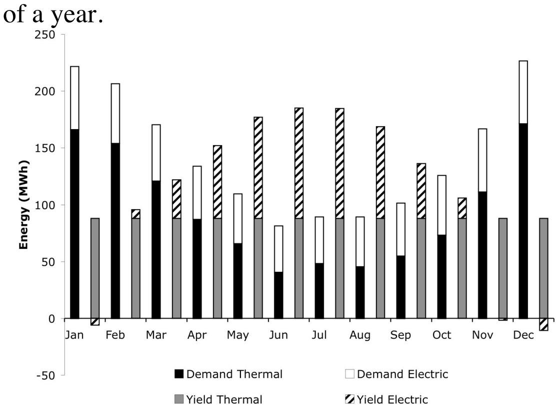

Figure 7 - Comparison of seasonal energy demand and yield for 120dph

DISCUSSION

This paper shows that it is possible to supply all the necessary annual energy required for a range urban densities using technologies that make use of onsite energy yield; however, the annual assessment is misleading as it does not indicate the ability to meet the heat and power demands. A monthly assessment provides a greater understanding of the likely variability and ability to meet demand, particularly at higher densities; however, further dynamic modelling at an hourly and instantaneous period is required to make a final selection on a strategy that meets the demand.

Several key points should be addressed regarding the yield of onsite energy. First, ground source systems (particularly those that use water) are able to provide a significant amount of thermal energy. The advantage that water systems have is the added specific heat capacity of water and thus the ability to capture and hold a greater amount of thermal energy, which can be used over a longer period. However, any heat pump system is also reliant on electricity, and thus is limited to the yield of onsite-generated electricity.

Also, the ability for solar thermal and PV systems to provide energy is related to the available roof space.

This study considered all dwellings as semi-detached or terrace, however, with higher urban densities (i.e. >60dph) incorporating blocks of flats with lower roof:floorspace ratios, there would be less roofspace for panels. On the other hand there could be more open space for wind turbines and biomass growth.

Further, it is shown that most of the predicted energy demand can be met via onsite incident energy resources, but that any further electricity demands from an increasing number of appliances cannot. This is largely due to the difficulty of converting electricity from inconsistent energy sources.

Despite this relatively positive comparison, the real issue with using onsite incident resources is the ability to meet both a base-load and spikes in real-time demand. The technologies selected in the comparison (i.e. ground linked systems) are capable of providing a relatively consistent thermal base-load, but they in turn require electricity, which would likely be unable to rely solely on the variable nature of onsite wind or solar-derived electricity. Relying on local resources alone to supply all the required heat and power (i.e. immediate demand) would likely be impractical and very costly, relying on very large thermal and electrical battery banks.

Influences on Urban Built Form Although this study has shown that it is possible to meet the annual energy demand, although not always the seasonal demand. The annual assessment can be misleading and a full investigation involving hourly and instantaneous demand is needed to assess whether the zero carbon target is actually met. Also, there must be further consideration for how the energy infrastructure and technologies are integrated into the urban design.

The comparisons have considered mixed-use developments in a limited capacity, where an increase in commercial space similar to that of a 'high-street' or town centre would vastly increase the energy demand – mostly in the form of electricity, which is limited in high density sites. Mixed-use developments are an important element in achieving more sustainable urban centres, as they reduce the need for travel and provide a local economy. The need to place constraints on the upper limit of development is key to balancing the available incident energy provision and the energy demands of the built form.

CONCLUSIONS

The goal of providing all of the annual energy demand via onsite energy technologies at varying densities is shown to be broadly achievable at an annual scale; however, the application of an energy strategy to meet zero carbon must consider the finer temporal scale (i.e. hourly).

The assessment has shown that caution regarding the ability to rely solely on onsite energy yield should be applied to the new definition of zero carbon. Requiring a development to meet its total demand through onsite resources is likely not practical or reasonable, thus there is still a need for a 'grid', albeit low carbon. However, this caution is not to say that onsite could not play a significant role in meeting zero carbon. Importing fuels, particularly biomass, from outside the site in order to meet zero carbon must be avoided as this only places the burden of supply somewhere else.

In order to achieve zero carbon communities in a reasonable and practical manner energy demand reduction must be applied as the first step. Communities, new ones in particular, should play a more important role in reduce CO_2 emissions and supplying energy at a more local scale should be utilised where practical.

ACKNOWLEDGEMENTS. Gratefully acknowledge funding from the EPSRC LUCID Project and data from Fulcrum Consulting.

REFERENCES

1. Department of Communities and Local Government (DCLG), (2006) Planning Policy Statement 3 (PPS3): Housing, The Stationary Office (TSO), London, November.
2. DCLG, (2007) Planning Policy Statement 1 (PPS1): Delivering Sustainable Development, TSO, London, January.
3. DCLG, (2007) Homes for the Future: more affordable, more sustainable, TSO, London, July.
4. Her Majesty's Government (HMG), (2008) UK Climate Change Act, London, December.
5. Defra, (2007) Local and Regional Estimates Summary 2005 – Main Report Spreadsheet, London.
6. DCLG, (2007) Building a Greener Future: policy statement, TSO, London, July.
7. HMG, (2007) Statutory Instrument 2007 no. 3437, The stamp duty land tax (zero-carbon homes relief) regulations 2007, TSO, London, December.
8. DCLG, (2008) Cost Analysis of the Code for Sustainable Homes – Final Report, TSO, London, July.
9. Renewable Advisory Board, (2007) The Role of Onsite Energy Generation in Delivering Zero Carbon Homes, Full Report, London, November.
10. UKGBC, (2008) The Definition of Zero Carbon, UK Green Building Council Zero Carbon Task Group Report, London, May.
11. MJP, (2007) Sustainable Suburbia – work in progress report, London.
12. Chartered Institute of Building Service Engineers (CIBSE), (2006) Environmental Design CIBSE Guide A, CIBSE Publications, Page Bros., Norwich, January.
13. BRECSU, (2003) Energy Consumption Guide 19 – Energy use in offices, TSO, London, April.
14. BSRIA, (2008) Illustrated Guide to Renewables, Berkshire, November.
15. CIBSE, (2007) Renewable Energy Sources for Buildings, CIBSE Publications, Page Bros. Norwich.
16. Carbon Trust, (2008) Small scale wind energy technical report, The Carbon Trust, London.