INTEGRATED APPRAISAL OF MICRO-GENERATORS: METHODS AND APPLICATIONS

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ABSTRACT

A range, or ‘toolkit’, of integrated appraisal techniques have been utilised to study the performance of various domestic micro-generators. Energy, environmental impact and cost-benefit analysis methods, employed on a ‘whole systems’ or life-cycle basis, are described. The application of the appraisal techniques is illustrated via the evaluation of three micro-generators: a micro-wind turbine with 1.7m rotor diameter and power rating 600W at 12m/s; a generic 15m^2, 2.1kW$_p$, monocrystalline solar photovoltaic array; and a solar hot water system based upon a 2.8m^2 collector. They are estimated to typically provide 25–49% of the average UK household electricity or hot water demand, and have energy paybacks well within their estimated lifetimes. Significant life-cycle environmental impacts are associated with the use of aluminium to produce the solar hot water unit and micro-wind turbine. All three domestic micro-generators were found to be uncompetitive in the present UK liberalised market. Increased production volumes, and technical improvements in the next generation of devices, such as their manufacturing processes and operational efficiencies, are necessary in order to improve their economic performance.

INTRODUCTION

The UK domestic building sector, which contributes around 30% of final energy demand, and about 23% of greenhouse gas emissions, can play an important role in carbon dioxide (CO_2) abatement. An uptake of low or zero carbon (LZC) distributed energy resources (DERs), sometimes referred to as micro-generators, would help this sector to reduce fossil fuel energy use and CO_2 emissions. However, energy efficiency and demand reduction measures (Butcher *et al.*, 2006; Hammond and Stapleton, 2001) should be adopted before embarking upon the installation of such micro-generators. For example, householders could save energy by the adoption of higher levels of thermal insulation (including draft proofing, external cladding or double glazing), low-energy consumption patterns (energy efficient appliances, low energy light bulbs, and by turning electronics off and avoiding standby), and better control of central heating systems. Once implemented these low-energy load profiles should be used to determine the potential role that DERs can take.

‘Decentralised’, or ‘distributed’, energy supply refers to the generation of energy close to the point of use (Allen *et al.*, 2008a). It can denote a range of generator sizes; from community or district-level down to individual households. Domestic ‘micro-generation’ embraces a variety of technology options, including micro-wind turbines, solar PV arrays, SHW systems, micro-combined heat and power (CHP) units, and heat pumps. Some of these technologies are based on renewable resources (which are essentially ‘zero carbon’), while some increase the energy efficiency of fossil fuel use (and are consequently ‘low carbon’ options). For example, domestic-scale CHP (micro-CHP) plants capture some of the heat rejected during electricity generation and provide it for space and water heating. The Energy Saving Trust (EST) suggested that micro-generators could meet 30 – 40% of the UK’s electricity requirements by 2050 (EST *et al.*, 2005). Micro-generation provides householders with more independence and, if the system were so designed, it could satisfy space heating, hot water and electricity in the event of a central network power cut (Allen *et al.*, 2008a). They also have the potential to stimulate behavioural change in terms of energy awareness and efficiency improvements.

The notion of integrated appraisal and whole systems thinking is open to a variety of interpretations. Here it is viewed as a mechanism and toolbox for illustrating the interconnections within the energy system, and for identifying significant constraints associated with the adoption of particular technological innovations for the home and associated electricity system. They are viewed as being ‘integrated’ in the sense that they are applied concurrently to yield differing perspectives within a ‘sustainability framework’ (see Hammond and Winnett, 2006). It helps to provide a performance ‘snapshot’ in time, based on both quantitative and qualitative evaluations. The approach, employed on a life-cycle (‘full fuel cycle’) basis, is illustrated here by reference to a number of selected DERs in the UK context: a micro-wind turbine, a solar photovoltaic array, and a solar hot water system. Thermodynamic, environmental and cost-benefit evaluation techniques are described (after Hammond and Winnett, 2006), and then applied to the selected micro-generators.

METHODS

Energy Analysis

In order to determine the primary energy inputs needed to produce a given amount of product or service, it is necessary to trace the flow of energy through the relevant industrial system. This idea is based on the First Law of Thermodynamics, that is, the principle of conservation of energy, or the notion of an energy balance applied to the system (Hammond, 2004). It leads to the technique of First Law or 'energy' analysis, sometimes termed 'fossil fuel accounting', which was developed in the 1970s in the aftermath of the oil crisis [see, for example, Roberts (1978) or Slesser (1978)]. Analysis is performed over the entire life-cycle of the product or activity, ‘from cradle to grave'. It yields the whole-life or 'gross' energy requirement (GER) of the product or service.

The system boundary in energy analysis should strictly encompass the energy resource in the ground (e.g., oil in the well or coal at the mine), although this is often taken as the national boundary in practice. Thus, the sum of all the outputs from this system multiplied by their individual energy requirements must therefore be equal to the sum of inputs multiplied by their individual requirements. The process consequently implies the identification of feedback loops, such as the indirect, or 'embodied', energy requirements for materials and capital inputs. Different 'levels of regression' may be employed (Slesser, 1978), depending on the extent to which feedback loops are accounted for, or the degree of accuracy desired. The procedure leads to an estimate of the GER, sometimes loosely termed the primary ‘energy cost’. It can be used to determine the least energy-intensive industrial processes and materials from amongst a number of alternative options.

There are several different methods of energy analysis; the principal ones being statistical analysis, input-output table analysis and process analysis [see, for example, Roberts (1978) or Slesser (1978)]. The first method is limited by the available statistical data for the whole economy or a particular industry, as well as the level of its disaggregation. Statistical analysis often provides a reasonable estimate of the primary energy cost of products classified by industry. However, it cannot account for indirect energy requirements or distinguish between the different outputs from the same industry (Roberts, 1978). The technique of input-output table analysis, originally developed by economists, can also be utilised to determine indirect energy inputs and thereby to provide a much better estimate of the GER. This approach is constrained only by the level of disaggregation that is available in national input-output tables. Process energy analysis is the most detailed of the methods, and is usually applied to a particular process or industry. It requires process flow-charting using conventions originally adopted by the International Federation of Institutes of Advanced Studies in 1974-1975 (Roberts, 1978; Slesser, 1978). The application domains of these various methods overlap, and a combination of methods is often adopted.

Environmental Life-Cycle Assessment

It is now widely recognised that in order to evaluate the environmental consequences of a product or activity the impact resulting from each stage of its life cycle must be considered. This has led to the development of a range of analytical techniques that now come under the 'umbrella' of environmental life-cycle assessment (LCA). Along with other environmental management tools, LCA is becoming more widely adopted in the context of national and international environmental regulations, such as those associated with eco-labelling. In a full LCA study, the energy and materials used, and pollutants or wastes released into the environment as a consequence of a product or activity are quantified over the whole life-cycle; again ‘from cradle-to-grave’ (Heijungs *et al.*, 1992; Udo de Haes and Heijungs, 2007).

The methodology of LCA follows closely that developed for energy analysis (Udo de Haes and Heijungs, 2007); specifically that of process analysis. But it evaluates all the environmental burdens associated with a product or process over its whole life-cycle. This requires the determination of a balance or budget for the raw materials and pollutant emissions (outputs) emanating from the system. Energy is treated concurrently, thereby obviating the need for a separate inventory of embodied energy. LCA is a product or system-based form of environmental auditing which is often geographically diverse; that is, the material inputs to a product may be drawn from any continent or geo-political region of the world. Due to an early lack of consensus regarding methodology, LCA was codified under the auspices of the Society of Environmental Toxicology and Chemistry (SETAC) at a series of workshops in the early 1990s (Udo de Haes and Heijungs, 2007). These largely defined the standard framework for LCA, which subsequently formed the basis of the ISO 14040 series of LCA standards. These were modified, and reduced from four to two standards, in 2006 (ISO 2006a and 2006b).

The LCA software package *SimaPro* was used for the present study (following Allen *et al.*, 2008b). It is a commercial package developed from that originally reported by Heijungs *et al.* (1992) at the Institute of Environmental Sciences (CML), Leiden University, the Netherlands. This software enables the manipulation and examination of inventory data in accordance with the ISO LCA Standards.

Environmental Cost-Benefit Analysis

The idea that prices reflect economic value led to the development of the techniques of cost-benefit analysis (CBA) for the assessment of public works projects (Dorfman and Dorfman, 1993). They now provide an important input into the evaluation of many projects that have significant impacts on the environment. In such cases it is necessary to internalise some of the costs and benefits that might otherwise be viewed as being external to the market. This valuation process is uncertain and potentially controversial, often relying on the determination of shadow prices. In mainstream environmental economics, time is routinely dealt with by discounting. The costs and benefits in monetary terms are progressively discounted for future years in order to allow for the 'time value of money'. This is a source of much criticism from environmentalists, for practical and ethical reasons (see, for example, Broome, 1992). Ultimately, the application of CBA results in the determination of a single decision criterion; typically the net present value (NPV) over the project life, the corresponding discounted cost-benefit ratio, or some related parameter. In dealing with risk, standard environmental economics generally assumes a world of calculable probabilities. Thus, a probability distribution for the decision criterion, such as the discounted cost-benefit ratio, is obtained if uncertainty is explicitly taken into account (Hammond and Winnett, 2006).

Discounted CBA techniques do not adequately reflect the resource depletion problem, at least as long as resource prices reflect mainly short-term trends (Hammond and Winnett, 2006). Nonetheless, the evaluation of social and environmental costs is obviously useful in identifying where the market has failed to internalise them. This provides governments with an indication of those areas in which action needs to be taken by way of the introduction of economic instruments (such as 'green' taxes and emissions permits) that can offset market deficiencies.

Other Approaches

Energy analysis as described above takes no account of the ‘quality’ of the energy source in a thermodynamic sense. Electricity, for example, may be regarded as an energy carrier having a high quality, or exergy, because it is readily converted into work. In contrast, low-temperature hot water, although also an energy carrier, can only be used for heating purposes. 'Exergy' is a property that stems from both the First and Second Laws of Thermodynamics (see, for example, Hammond, 2004). The distinction between energy and exergy is very important when considering the adoption of different types of electricity generation stations, including CHP plant. Thus, Hammond (2004) has argued that it is preferable to employ ‘exergy’ analysis, alongside a traditional First Law energy analysis in order to illuminate these issues. This was, however, beyond the scope of the present study.

Some of the more ardent advocates of CBA techniques for evaluating new projects with significant environmental impacts imply that they can be used as the sole method of assessment (see the discussion in Hammond and Winnett, 2006). There are a number of reasons for discouraging such an approach. Firstly, the various methods for valuing external costs and benefits are all open to criticism (Stirling, 1997 and 1998). The second, and arguably more important, reason for discouraging the sole use of CBA techniques is that they obscure rather than highlight the range of impacts that may emanate from a given project. Decision-makers are typically presented with a single, aggregate decision criterion (such as the discounted cost-benefit ratio), which actually hides many disparate environmental impacts. It is vitally important that the implications of these impacts are faced, particularly by politicians, rather than obscured by the methodology [see Hammond and Winnett (2006) and Stirling (1997 and 1998)]. Similar remarks apply to other techniques, including ‘multi-criteria decision analysis’ (MCDA), that also aggregate various distinct impacts of the technological options.

There are a number of other factors, beyond those discussed here, that should also be considered when assessing energy systems. These include electricity network design and operation issues, geographical suitability, planning permission requirements and so on. The integrated appraisal methodology utilised here should therefore be seen as part of a wider inter-disciplinary assessment process, or toolkit.

APPLICATIONS: COMPARATIVE MICRO-GENERATOR ASSESSMENTS

The Selected Micro-generators

The integrated appraisal methods described above were applied to three micro-generator technologies, all commercially available in the UK: a micro-wind turbine, a solar photovoltaic array, and a solar hot water system. The grid-tied micro-wind turbine was a horizontal-axis design with a rotor diameter of 1.7m and a power rating of 600W at 12m/s (Allen *et al.*, 2008b). The assumed lifetime was 15 years. The turbine has a range of installation options, including free-standing mast or building-mounted. The grid-tied solar PV array was a generic 15m^2, 2.1kW$_p$, monocrystalline system. The SHW system considered comprised a 2.8m^2 freeze-tolerant flat plate collector that connects directly to a domestic hot water storage cylinder. Water is circulated by a small pump that is powered by a PV module. The assumed lifetime for both solar systems was 25 years.

Energy Analysis

The micro-generators considered here provide energy carried via electricity or hot water. The differences in thermodynamic quality between electricity and hot water, as discussed above, should ideally be considered alongside the energy (output) quantities presented below. The output estimates are energy supplied *to the point of use*. This is the plug socket and the taps, for electricity and hot water respectively. For comparative purposes, a representative UK home is assumed to utilise gas-fired central heating (based upon Shorrock and Utley, 2003). Annual hot water demand is assumed to be 2900 kWh (DTI 2001). Furthermore, assuming electrical cooking, the average UK household uses approx. 3500 kWh of electricity (Allen *et al.* 2008a).

The electricity output of the micro-wind turbine was estimated through combination of the turbine's published power curve, grid-tie inverter characteristics, and a dataset of measured hourly-average wind speeds from across the UK (totalling 2.3 million hours between 1990 and 2006). For 18 'open' sites (i.e., well exposed, most rural terrain), the analysed installation was mast-mounted, away from the household. In the case of 8 'urban' sites the represented installation was building-mounted. The estimated annual electricity outputs had a mean value of 870 kWh (range: 280–1500 kWh) for the 'open' environments and 160 kWh for the 'urban' environments (range: 60–310 kWh); see Allen *et al.* (2008b) for further details. The estimated 'urban' outputs are low compared to the average use above, and consequently, only 'open' wind turbines were considered for the remainder of this study. The annual electricity output of the solar PV array was estimated as 1300–2000 kWh, with a UK-mean of 1720 kWh. These values are based upon Suri *et al.* (2007) and DTI (2006). The energy supplied by the SHW system was estimated for a range of UK sites, via a combination of measured performance data (DTI, 2001) and characteristic monthly solar irradiation quantities (Suri *et al.*, 2007). It was assumed that the installation was unshaded and SE–SW facing, with a pitch angle of 15–50°. Distribution losses (between the hot water tank and the taps) are assumed to be 15% of the energy leaving the tank, in accordance with the estimates made by BRE (2002). The annual hot water output of the system is estimated as 650–980 kWh. In such a case, top-up heating is required year-round to satisfy total monthly demand.

A summary of the energy output estimates is given in Table 1. The selected values are used in the economic analysis, and to produce the avoided impacts due to operation in the LCA, below. All DERs considered here have variable outputs in the time-domain, as they are dependent on the solar and wind resources available in the UK. The annual output of the two solar technologies is relatively predictable, given a suitable installation as described above. Micro-wind turbines for household application are a relatively young technology at present. Local terrain and mounting height, amongst other factors, have a significant effect on wind energy potential, and as yet there is little empirical evidence to validate the grid-tied estimates. The estimated range of energy outputs for micro-wind should therefore be viewed as tentative. The results of ongoing UK micro-wind turbine field trials, due to report in 2008, will aid validation of the output estimates presented here (Allen *et al.*, 2008b).

Table 1: Energy supplied by micro-generators to the point of use (estimated)

	Energy supplied (kWh)		
	Min	Selected	Max
'Open' micro-wind	280	870	1500
Solar PV	1300	1720	2000
SHW system	650	815	980

The energy supplied by the micro-generators will displace energy that would otherwise have been provided by conventional means. In the case of electricity, this is a centralised network in the UK that is dependent primarily upon large-scale fossil- or nuclear-fuelled power stations. In practice, micro-wind and solar PV will displace the most responsive centralised generators, such as gas turbines. Domestic space- and water-heating, in contrast, are typically provided together by one on-site central heating system powered by a gas-boiler (Shorrock and Utley, 2003). The use of a micro-generator avoids much of the environmental impact of conventional energy supply. It is by considering these wider energy systems that micro-generators are perceived to ‘save’ energy or CO_2 emissions (along with avoiding other environmental impacts). Savings will vary as the conventional supply systems change (this is likely to occur, significantly, over decades). The whole life-cycle environmental impacts of the micro-generators may therefore be determined by comparing savings (‘avoided impacts’) with the impacts of their production, use and disposal. This will be discussed further in the LCA section below.

The energy payback period (EPP) is one useful metric that can be derived from energy analysis, and is analogous to a financial payback period (often termed the ‘break-even point’). Figure 1 shows the variation of the EPP of each micro-generator with annual energy supplied to the point of use. The EPP represents the number of years that a system must operate until its cumulative energy output equals the whole life or primary energy input, the latter being calculated via the LCA software. When the cumulative energy output is accounted in terms of the absolute quantity of electricity or hot water supplied, the ‘conventional’ energy payback period is produced. For example, the primary energy requirement of the micro-wind turbine is approximately 1370 kWh (4930 MJ_{NCV} – Table 2). If the annual electricity supply is 870 kWh (the chosen value for this study) the turbine will break-even in terms of the energy ‘investment’ within 1.6 years (Figure 1). However, this turbine output will displace electricity from the UK’s existing supply system. This system requires approximately 3.1 units of primary energy to supply 1 unit of electricity to the end user (Allen *et al.* 2008). Each unit of electricity generated by the micro-wind turbine will therefore displace 3.1 units of primary energy. When the cumulative energy output of the turbine is accounted for in these terms, the ‘displaced’ energy payback period is produced (0.5 years in this case). This concept has previously been described as the ‘opportunity cost convention’, from its precursor in the economic literature [Allen *et al.*, (2008); Roberts (1978); Slesser (1978)].

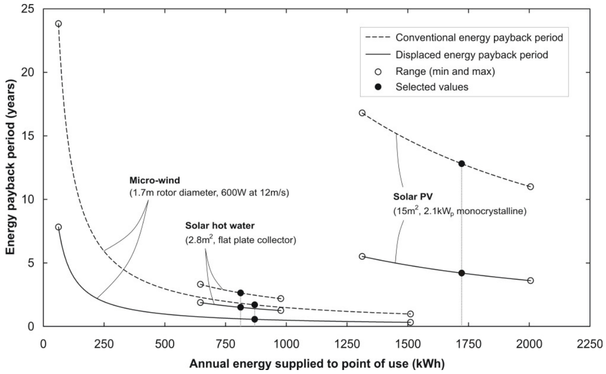

Figure 1: Energy payback periods of micro-generators

Figure 1 indicates that the micro-wind turbine and SHW system payback their whole life, primary requirements faster than the solar PV array, despite lower estimated annual energy supply. This is as a result of their lower primary energy requirements. All three LZC technologies payback their primary energy investment well within their estimated lifetimes for the annual outputs selected in the present study.

Environmental Life-Cycle Assessment

The micro-generators were examined in order to determine their life-cycle impacts. The micro-wind and solar thermal assessments were based on data gathered directly from the manufacturer. In contrast, the solar PV assessment was based upon the results of Wild-Scholten and Alsema (2005). The assessment of all of the systems has focused primarily on the production stage, as there has been little data available for maintenance and disposal of the DERs, due to the relative immaturity of these technologies. For this reason, the data produced is not strictly that of a life-cycle assessment as the boundaries have been drawn around the device production and its energy output. Disposal, maintenance and distribution have been excluded from this particular study. However, these have been examined in more detail for the micro-wind case study, and were shown to have little effect on the overall results [see Allen *et al.* (2008b) for further details on micro-wind LCA]. It is probable that the same is true for the solar PV and SHW as the maintenance and distribution networks will be similar. Little information is known about disposal stage, as few of these systems have yet reached their end-of-life.

Table 2 shows the comparison of the environmental impacts associated with the production of all three of the DERs together with the avoided impacts associated with the energy produced. For both the micro-wind turbine and the SHW system, the predominant impact associated with the production phase is the use of aluminium. For the SHW system this is attributable to the metal casing. This provides the system with its rigidity and strength, whilst maintaining a weight low enough to ensure that extra roof strengthening is not necessary. The casing gives rise to impacts in terms of carcinogens, heavy metals, greenhouse gases and

Table 2: Comparative environmental impacts of the production and operation of the systems

Impact category	**Unit**	**Solar Hot Water**		**PV**		**‘Open’ micro-wind**	
		Production	Operation	Production	Operation	Production	Operation
Greenhouse	kg CO_{2e}	337	-7060	3756	-24794	280	-7520
Acidification	kg SO_2	1.91	-7.36	15.61	-95.04	1.9	-28
Eutrophication	kg PO_4	0.18	-0.62	1.26	-5.96	0.14	-1.81
Heavy metals	kg Pb	0.01	-0.01	0.04	-0.22	0.02	-0.07
Winter smog	kg SPM	1.57	-4.65	11.34	-71.29	1.79	-21.6
Summer smog	kg C_2H_4	0.09	-1.54	1.72	-1.67	0.05	-0.51
Energy resources	MJ_{LHV}	7700	-128200	79417	-472713	4930	-143000
Solid waste	kg	0.79	0	229.18	0	221	0

energy resources. Other smaller impacts are associated with the silicon tubing and thermal insulation. Again, the predominant impacts concern heavy metals, carcinogens, energy resources and greenhouse gases.

It appears that the solar PV unit requires significantly more energy (and produces more greenhouse gases) in its production phase than either of the other two systems. It also has significantly higher impacts in terms of the other environmental categories considered. However, the PV system has a larger rated capacity of 2.1kW$_p$, compared with the 0.6kW micro-wind turbine. Whilst over its entire lifetime this reduces the impact per unit energy generated, the PV unit generally has higher production impacts than does the micro-wind turbine. The production process of high-grade silicon, as used in PV cell manufacture, requires the consumption of a large amount of energy, and this gives rise to these relatively high production impacts.

Environmental Cost-Benefit Analysis

The total costs of the 3 micro-generators have been compared to their benefits (displaced energy and reduced environmental externalities) over their lifetimes using a discount rate of 3.5%. The latter is the current Test Discount Rate (TDR) employed by the British Government for investment appraisal purposes. The total cost of installing the micro-wind turbine was £4,628. The PV system was estimated to cost £10,992and the SHW system £3,523. The maintenance costs for the PV and SHW units were assumed to be near zero, as indicated by the manufacturers. In contrast, the manufacturer of the micro-wind turbine estimated maintenance costs of approximately £40 per year.

The quantification of environmental externalities was achieved using values extracted from the ExternE study (Dones *et al.*, 2005) inflated to present values. These damage factors refer to the most important airborne pollutants, and represent an average location of the emission sources notionally within the EU15 (Dones *et al.*, 2005). However, for carbon emissions a higher range of values were adopted as appropriate in the UK context. These were taken from the equity-weighted values employed by Clarkson and Deyes (2002); approximately £77/tC in 2007 (2000 prices), raised by £1/tC each subsequent year. Table 3 indicates the average estimated annual benefits (£/yr) from the reduction of environmental pollutants, as a result of reduced energy (electricity or gas) consumption from installing the DERs. These benefits should be taken as an indicative, or only representative values. The environmental externality benefits have been combined with that for displaced energy (electricity 12p/kWh, gas 3.5 p/kWh) to estimate the total benefits.

Table 3: Environmental externality benefits from installing micro-generators

Impact category	**Damage factors** (£$_{2007}$/kg)	**Micro-wind** £ (mean benefit/yr)	**PV** £ (mean benefit/yr)	**SHW** £ (mean benefit/yr)
Greenhouse (kg CO_{2e})	0.02	10.1	40.0	9.4
Acidification (kg SO_2)	2.0	3.5	14.9	0.7
Heavy metals (kg Pb)	1098	3.7	18.8	0.4
Winter smog (kg SPM)	13.4	17.7	73.8	2.8
	TOTAL	**34.9**	**147.4**	**13.3**

Table 4 shows the results of this cost-benefit analysis. Strictly financial investment appraisal of these micro-generators indicates that they are all presently uncompetitive under the current UK liberalised market conditions. The costs significantly outweigh the benefits, even when avoided environmental externalities are included. The scenarios indicate that the mean cost-benefit ratio for micro-wind is approximately 1:0.34, while that of the PV array is 1:0.65 and the SHW is 1:0.30. Therefore, for every £1 invested in micro-wind, it will currently yield only 34p in benefits (65p for PV and 30p for SHW). The levelised costs of micro-wind, PV and SHW were even less attractive. They were estimated to be approximately 50p/kWh, 39p/kWh and 26p/kWh respectively. The payback period of micro-wind was estimated to be 26-136 years (mean of 44 years), for the PV array 45-70 years (mean of 53 years), and for the SHW unit between 75-113 years (mean of 90 years). It should be noted however that not all of the benefits could be properly quantified, due to a lack of information (e.g., concerning the impacts of eutrophication and summer smog). Further cost factors, such as system balancing, security of supply, efficiency changes, and other system requirements for the uptake of DERs, are dependent upon penetration levels and therefore could not be included here.

Table 4: Cost-benefit analysis results

Mid Case (min to max)	**NPV Benefits** (£)	**NPV Costs** (£)	**NPV** (£)	**Cost-Benefit Ratio**
Micro-wind (∅1.7 m)	1734 (518 to 3033)	5088	-3354 (-4570 to-2055)	1 : 0.34 (0.1 to 0.6)
PV (2.1 kW$_p$)	7112 (5154 to 8197)	10992	-3880 (-5838 to-2795)	1 : 0.65 (0.47 to 0.75)
SHW (2.8 m^2)	993 (761 to 1200)	3523	-2530 (-2762 to-2323)	1 : 0.3 (0.2 to 0.35)

The economics of micro-generators are not presently encouraging. However, cost reductions tend to occur as production volumes increase; a phenomenon reflected in so-called ‘experience’ or ‘learning’ curves (Allen *et al.*, 2008a). A (global) doubling of production volume leads to a reduction in cost to the indicated ‘progress ratios’ (PR) percentage value. For the solar PV and SHW technologies, progress ratios are indicated to be 85% (Enviros, 2005) and 92% (Hinnells, 2005) respectively, whilst micro-wind has a PR of 72%

(EST *et al.*, 2005). By comparison, established conventional energy technologies have progress ratios of above 95% (Allen *et al.*, 2008a). Micro-wind and solar PV, in particular, have favourable progress ratios indicating significant cost reduction potential. The EST et *al*. (2005) project annual growth rates (%) in double digits for most DERs over the next few decades, which would be likely to result in significant cost reductions. However, in the near-term, these decentralised energy sources are likely to remain uncompetitive in a liberalised market place that is dominated by conventional power. There remain, at present, substantial barriers to significant production increases and associated cost reductions (see Allen *et al.*, 2008a).

CONCLUDING REMARKS

A range of integrated appraisal techniques have been employed to study the performance of three micro-generators in a UK context: a micro-wind turbine with 1.7m rotor diameter and power rating 600W at 12m/s; a $15m^2$, $2.1kW_p$ monocrystalline solar photovoltaic (PV) array; and a solar hot water (SHW) system based upon a $2.8m^2$ collector. Energy, environmental impact and cost-benefit analysis methods, employed on a life-cycle ('full fuel cycle') basis, have been described. They can be viewed as being 'integrated' in the sense that they are applied concurrently to yield differing implications for the take-up of the micro-generators in terms of a 'sustainability framework' (see Hammond and Winnett, 2006). Such methods help to provide a performance 'snapshot' in time, based on both quantitative and qualitative evaluations. The approach encapsulates the 'whole systems' implications of the selected DERs, although there are other considerations appropriate to providing a complete appraisal.

On an annual basis, it has been estimated that the micro-wind turbine (installed in an 'open' environment) and solar PV array will provide 870 and 1720 kWh of electricity, respectively. These values represent 25 and 49% of the average UK household demand considered here, which comprises electrical cooking, lights and appliances. Similarly, it has been estimated that the solar hot water system will provide 815 kWh/yr of hot water in an average installation, which is 28% of the assumed annual demand. There is a good deal of scope to reduce demand from the average values considered here, through energy-efficiency and demand reduction measures. Such measures should be adopted prior to installation of a micro-generator, whose relative contribution will then accordingly increase. All micro-generators considered payback their energy investments well within their lifetimes. Considering the fossil-fuel energy savings that they offer, the 'displaced' energy payback periods are 0.5, 1.5 and 4.2 years for the micro-wind turbine, solar hot water system and solar PV array, respectively.

In terms of the environmental life-cycle assessment, both the production of the solar thermal and micro-wind turbine give environmental impacts associated with their use of aluminium. This material is often chosen due to its high strength to weight ratio, but it also gives rise to heavy metals, carcinogens and contributes to some types of smog, as well as using significant energy resources. These environmental impacts found via the LCA could easily be reduced by the greater use of recycled aluminium. The solar PV array has rather higher impacts emanating from its production, but this is offset by the larger energy generation during operation.

Cost-benefit analysis has been utilised to communicate more clearly the overall trade-offs involved in installing the three micro-generators. The most obvious rationale for installing these systems is related to the abatement of GHGs and other pollutants. The quantification and internalisation of the costs for these 'externalities', with all their uncertainties and limitations, presents a more complete picture of the DERs. This environmental CBA indicates a cost-to-benefit ratio of 1:0.34 for micro-wind, 1:0.65 for PV and 1:0.30 for SHW. The results suggest that the three micro-generators are all uncompetitive under the current UK liberalised market conditions, even allowing for environmental externalities. Increased production volumes, and technical improvements in the next generation of devices, such as their manufacturing processes and operational efficiencies, are necessary in order to improve their economic performance. Government initiated support may be required to encourage sufficient uptake for this to occur; especially in the short term. Only then will they be economic in comparison with separate supply via the electricity or natural gas networks, enabling them to fully deliver their undoubted environmental benefits (see Butcher *et al.*, 2006).

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