# Energy and carbon audit of a rooftop wind turbine

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**Abstract:** Microgeneration is being promoted as a means of lowering carbon dioxide ($CO_2$) emissions by replacing electricity from the grid with production from small domestic generators. One concern over this drive is that the use of smaller plant could lead to the loss of economies of scale. Partly, this relates to cost but also in terms of energy consumed and $CO_2$ emitted over the life cycle of the microgenerator.

Here, an analysis is presented of a life-cycle audit of the energy use and $CO_2$ emissions for the 'SWIFT', a 1.5 kW rooftop-mounted, grid-connected wind turbine. The analysis shows that per kilowatt-hour of electricity generated by the turbine, the energy intensity and $CO_2$ emissions are comparable with larger wind turbines and significantly lower than fossil-fuelled generation. With energy and carbon intensities sensitive to assumed levels of production, assessments were carried out for an annual production range of 1000–4000 kWh, representing capacity factors of 8–31 per cent. For the manufacturer's estimated production of 2000 to 3000 kWh and, giving credit for component recycling, the energy payback period was found to be between 17 and 25 months, whereas the $CO_2$ payback was between 13 and 20 months. Across the full production range, the energy and carbon payback periods were 13–50 months and 10–39 months, respectively.

A key outcome of the study is to inform the manufacturer of the opportunities for improving the energy and carbon intensities of the turbine. A simple example is presented showing the impact of replacing one of the larger aluminium components with alternative materials.

**Keywords:** audit, carbon emissions, energy intensity, life-cycle analysis, microgeneration, wind turbines

## 1 INTRODUCTION

As part of the effort to reduce the carbon dioxide ($CO_2$) emissions resulting from power generation, many governments are promoting renewable generation. In the UK, the target is for 10 per cent of electricity to be from renewable sources by 2010 [**1**]. There is particular interest in promoting microgeneration for the domestic sector powered by photo-voltaic cells, microwind turbines, and domestic combined heat and power. One of the primary reasons for this is that by siting generation close to the electrical load, there is potential to significantly reduce energy losses in generation, transmission, and distribution. With most electricity generation produced in thermal power stations, typically two-thirds of the energy is wasted as heat to the environment. Further losses occur in the transmission system and particularly in the lower voltage distribution network: UK average transmission losses are ~1.5 per cent [**2**], whereas distribution network losses are on average 7 per cent with marginal losses as high as 30 per cent at the extreme edges of the grid [**3**].

The concept of microgeneration is quite different from the centralized generating paradigm developed in the twentieth century, which relied on a relatively small number of large power stations. Replacing large plant with smaller grid-connected ones offers benefits in terms of reduced losses as well as the harvesting of lower carbon renewable resources, but it also creates new problems, not least in terms of the ability of electrical networks to accept the

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power generated while maintaining system stability. A further issue relates to the loss of economies of scale with smaller plant. One aspect of this relates to the relative performance of smaller generators in terms of the amount of energy and $CO_2$ emissions associated with their manufacture, deployment, operation, and dismantling, compared with the energy they produce and the $CO_2$ avoided during their lifetimes. There is clearly a need to assess the new breed of small-scale generators in terms of their life-cycle energy and $CO_2$ performance.

This article sets out a life-cycle analysis of the 1.5 kW 'SWIFT' rooftop-mounted turbine, produced by Edinburgh-based Renewable Devices Ltd. It evaluates the energy and $CO_2$ emissions involved in each stage of its life cycle and these are compared with those from larger wind turbines and other generating sources. From these, the energy and $CO_2$ emission payback times are derived. Section 2 sets out the background of life-cycle analysis, whereas section 3 introduces the SWIFT turbine before exploring data collection and assumptions made for the analysis of the life cycle. Section 4 presents the results and section 5 sets them in context before section 6 draws conclusions.

## 2 LIFE-CYCLE ASSESSMENT OF WIND TURBINES

### 2.1 Overview

Originally developed for the assessment of both direct and embodied energy requirements for the provision of foods and services [**4**], energy and $CO_2$ life-cycle assessments (LCAs) are increasingly being used to analyse the methods for generating, transmitting, and consuming energy. In particular, they have been used to analyse a number of large wind turbines and, in some cases, entire wind farms [**5**–**7**]. LCA aims to be an objective process which when applied to a product or activity identifies the energy and materials used and wastes released to the environment as a means of evaluating and improving environmental impact [**8**].

Each stage of the product life cycle – from the 'cradle to the grave' – is evaluated in detail (Fig. 1). Data on the energy and emissions from each stage are then gathered and, where not available, justifiable assumptions made. This results in a comprehensive analysis of the turbine, highlighting the components, materials, or stages of its life cycle that have the largest environmental effects. This information can then be used to identify areas of possible product improvement in terms of energy consumption through material selection and its end-of-life scenario.

Although the LCA can be used to give a technical estimate of the energy and emissions of a product, it does not exclusively provide an assessment of a product's sustainability [**7**]. For this, financial and social factors including noise, impact on animal life, and land usage must also be assessed in conjunction with the LCA. The main limitation to life-cycle analysis is that assumptions regarding system boundaries and data sources must be made, which may introduce subjectivity [**9**]. More detailed information on LCA can be found in reference [**10**].

### 2.2 The SWIFT rooftop wind turbine

The device analysed here is the 1.5 kW SWIFT wind turbine produced by Renewable Devices Ltd in Edinburgh, UK. The manufacturer states that their five-bladed rooftop turbine (Fig. 2) is designed for virtually silent and maintenance-free operation [**11**]. It may be connected to an immersion heater, to batteries for off-grid operation or, as of interest here, to grid via a power-electronic inverter. Further technical specifications are given in Table 1.

Table 1 shows the manufacturer's estimates of annual production to be between 2000 and 3000 kWh. To put these values in context, the average UK household consumption is ∼4450 kWh [**12**, **13**], which implies that in higher wind speed areas, the typical house could potentially generate between 45 and 67 per cent of its electricity from microwind. The issue of production estimates for microwind turbines is somewhat contentious, not least because the cubic power law makes estimates very sensitive to assumptions regarding wind speed. Estimating wind speeds in urban and suburban areas is particularly difficult because of complex wind flow patterns. The greater drag associated with buildings means that wind speeds tend to be lower and less predictable in urban areas [**13**]. The issue is also clouded by manufacturers claiming optimistic production figures, while some commentators suggest that device capacity factors may be as low as 10 per cent [**13**]. In contrast, there is evidence of a speed enhancement effect caused by the flow pattern over

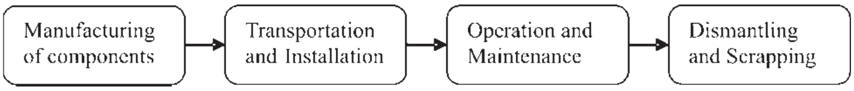

**Fig. 1** Life-cycle stages of a typical product

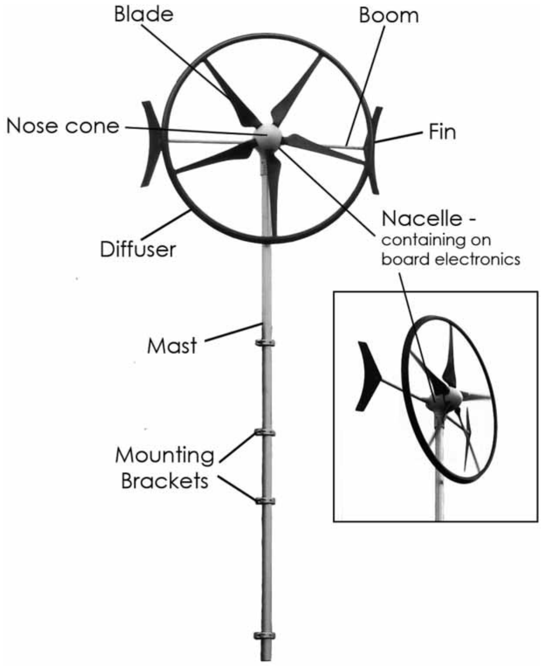

**Fig. 2** Key components of the SWIFT rooftop wind turbine [**11**]

buildings from which roof-mounted turbines can benefit from higher speeds. In specific cases, the effect appears to raise speeds by as much as 30 per cent, although this is very much dependent on the wind direction [**14**] and on the geometry of the building.

Although the manufacturer does not explicitly state the assumptions regarding wind speed and production, it is possible to use traditional wind analysis techniques to do this. Typically, production estimates will be based on site measurements or by the assumption of a Weibull distribution. However, the Rayleigh distribution, which is specified solely by mean wind speed [**15**], offers a convenient and simple approach. A tool developed for use in climate impact assessments [**16**] was used to estimate production using the Rayleigh distribution. Wind speed is modelled incrementally and the distribution defines the duration of time (in hours) for which each wind speed increment is experienced over a year. Combining this with the turbine power curve (Fig. 3, which details turbine output at given wind speeds) and summing across all increments provide an estimate of annual energy production.

Using this model, the manufacturer's estimated production is equivalent to sites having mean wind speeds of ~5.5–6.3 m/s. The European Wind Atlas suggests that most UK urban dwellings are in areas where 50 m height mean wind speeds are between 4.5 and 6 m/s [**13**]. Adjusting these to 10 m hub height reduces speeds by ~60 per cent to less than 4 m/s. These are below the manufacturer's estimate but for turbines sited in coastal or rural locations and for much of Scotland, the estimates are reasonable. Given the wide range of wind speeds likely to be encountered, the analysis will assume an annual production range of 1000–4000 kWh, encompassing the manufacturer's estimates. This corresponds to wind speeds of 4–7.2 m/s and implies turbine capacity factors of between 8 and 30 per cent.

The amount of $CO_2$ avoided by the production from the turbine is heavily dependent on the assumptions made regarding the carbon intensity of the grid electricity its output replaces. In some studies, it has been common practice to calculate $CO_2$ savings on the basis that coal-fired generation is being displaced, attracting carbon benefits of ~0.9 kg $CO_2$/kWh. Although this is an arguable point, it has become more standard to use the weighted average carbon intensity. In 2005, the UK generation mix [**17**] was shown in Table 2, with gross average emissions of 0.460 kg $CO_2$/kWh. It is necessary to adjust this figure to account for the fact that transmission and distribution losses are also avoided. Although losses will vary from site to

**Table 1** Key manufacturer's technical specifications for the SWIFT turbine [**11**]

| | |
|---|---|
| Rated power output | 1.5 kW |
| Claimed annual power generated | 2000–3000 kWh |
| Claimed annual $CO_2$ displacement | 1300 kg |
| Product life | 20 years |
| Cut-in speed | 2.3 m/s |
| Rated speed | 12 m/s |
| Cut-out speed | None (electronically braked) |
| Rotor | 2 m diameter moulded carbon fibre |
| Generator | Brushless permanent magnet (PMG) |

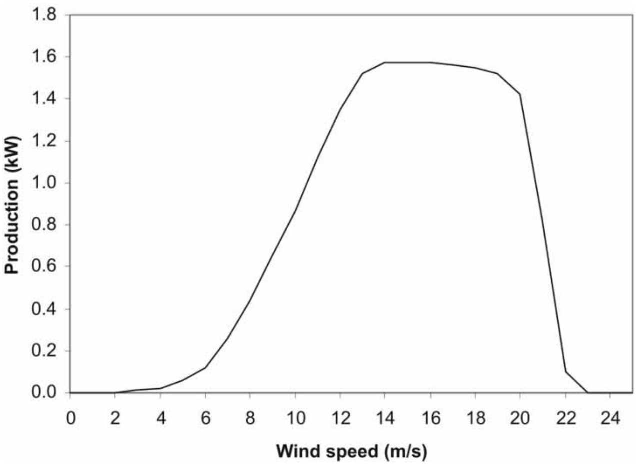

**Fig. 3** Power curve for SWIFT turbine showing output as a function of wind speed (D. Anderson, 2006, Personal Communication)

**Table 2** UK electricity generation mix in 2005 [**17**]

| Source | Proportion of mix (%) | $CO_2$ emissions (kg/kWh) |
|---|---|---|
| Coal | 33.4 | 0.910 |
| Natural gas | 39.3 | 0.360 |
| Nuclear | 20.6 | 0.0 |
| Renewables | 3.8 | 0.0 |
| Other | 2.9 | 0.500 |
| Gross weighted average | | 0.460 |

site and also by time of day, it is again standard practice to use average losses for the UK as a whole (8.5 per cent). After loss adjustments, the net carbon intensity of UK electricity is found to be 0.504 kg $CO_2$/kWh. Using this figure, the wider production range suggests an annual offset of between 504 and 2016 kg of $CO_2$, whereas the manufacturer's estimates imply between 1008 and 1512 kg, which agrees broadly with their own 1300 kg estimate (Table 1).

### 2.3 System boundary

In the life cycle, manufacturing involves the production from raw material to final assembly. Transport and installation include the emissions from the transportation of individual components to the assembly location and also when transporting the finished product for installation. Operation and maintenance include any emissions or energy related to the operation and maintenance of the turbine throughout its lifetime, including site visits and replacement parts estimated to be required throughout its 20 year lifetime. Dismantling and scrapping include emissions from cranes and other vehicles required for decommissioning and transportation of the turbine at the end of its life. Recycling or disposal of materials is also included.

The process-flow diagram below (Fig. 4) shows the various unit processes considered in the LCA. Processes in dashed boxes have not been fully accounted for in this study. With the exception of paint, all material production has been evaluated. Emissions and energy resulting from processes upstream of these, for example, the manufacture of machinery required to process the raw materials, have not been considered as it is deemed negligible in the overall analysis. In terms of the processing of the material into specific components, quantifying the environmental effects has been more difficult. Excluding electronics, transportation of every component within the UK has been evaluated. All aspects of assembly, operation, and maintenance have been considered. In terms of the end-of-life scenario, the system has been evaluated with and without recycling credit. Information on the energy and emissions resulting from scrapping the turbine was not available and is, therefore, not accounted for in this study.

## 3 ENERGY AND $CO_2$ EMISSION ANALYSIS

### 3.1 Procedure

Previous studies have shown that for wind turbines, the most significant environmental impact arises during the manufacture of the turbine rather than

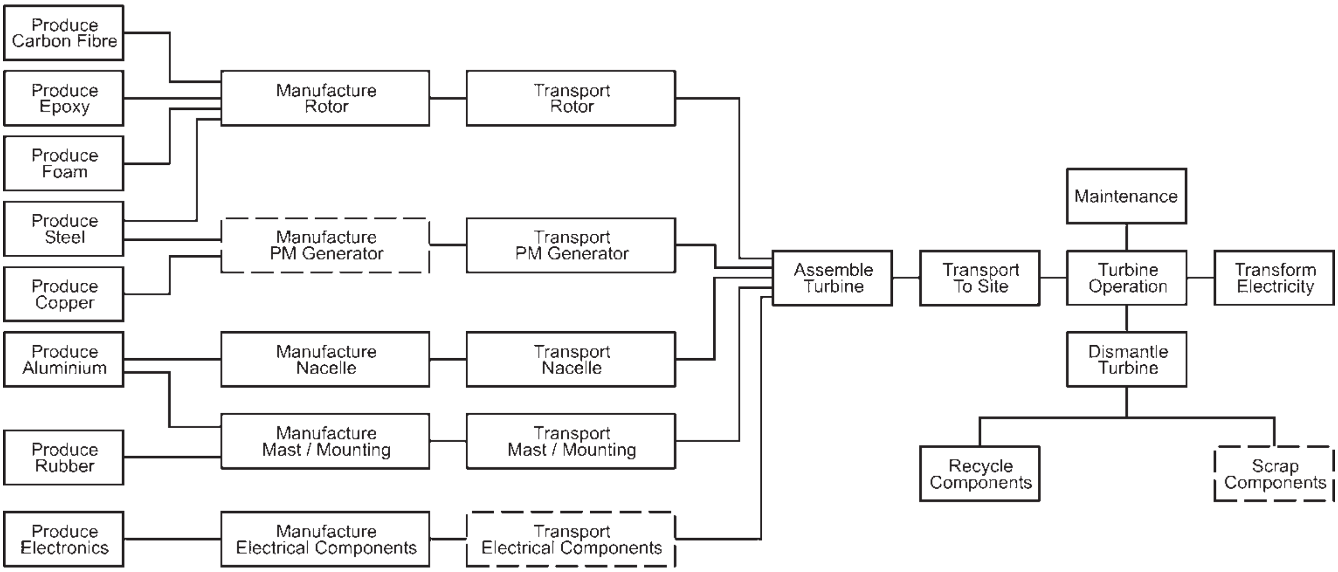

**Fig. 4** SWIFT life-cycle analysis showing activities considered in the product life cycle (dashed boxes indicate aspects that have not been fully accounted for)

through operation and maintenance [**7**]. The primary focus has, therefore, been on collecting the most accurate data available for the manufacturing stage of the life cycle.

Where complete data for a component has been difficult to obtain, alternative sources have been used including previous LCA studies. Where insufficient data existed for a particular component, a materiality test was applied: where the mass of an individual component contributed $>1$ per cent of the total turbine mass, then an assumption was made; where it was less, it was ignored on the basis that its non-inclusion would have little effect on the analysis.

Where possible, data on energy and emissions are based on official sources adhering to ISO 14040 [**18**], which specifies the general framework, principles, and requirements for conducting and reporting LCA studies.

## 3.2 Raw materials

For raw materials, data (Table 3) have been obtained from LCAs performed by recognized bodies such as the International Primary Aluminium Institute. However, in terms of material, energy, and $CO_2$ emissions resulting from raw material processing and producing the final component, it has been a case of prioritizing those which are considered of high energy content.

## 3.3 Component manufacture

The main turbine components are shown in Fig. 2 and consist of the extruded aluminium mast, cast aluminium nacelle and on-board electronics, and carbon fibre-reinforced epoxy rotor blades and diffuser as well as aluminium fins. An inverter is required to grid-connect the turbine. A bill of materials was supplied by the manufacturer listing each component. Each component was examined and their materials and masses noted. A breakdown of the material consumption (excluding the on-board electronics and the electrical control system) of the turbine is shown in Fig. 5.

**Table 3** Energy consumption and $CO_2$ emissions for key materials used in the manufacture of the SWIFT turbine

| Material | Energy consumption (MJ/kg) | $CO_2$ emissions (kg $CO_2$/kg) |
|---|---|---|
| Aluminium alloy [**19**] | 93.7–238.9 | 10.47–13.08 |
| Mild steel [**20**] | 15.9 | 1.1 |
| Stainless steel [**21**] | 54.0 | 6.1 |
| Copper [**22**] | 49.2 | 3.35 |
| Epoxy resin [**23**] | 137.1 | 5.7 |
| Carbon fibre-reinforced epoxy [**24**] | 200 | 11.2 |

### 3.3.1 *Metal components*

Aluminium is the main contributor to the turbine's weight, almost 70 per cent, about half of which is contained within the extruded aluminium mast. Life-cycle data on primary aluminium production and processing (casting, extrusion, and so on) were sourced [**19, 25**], allowing the more significant components such as the mast and nacelle to be accounted for directly. The range of energy consumption and $CO_2$ emissions is given in Table 3. As detailed data on energy and emissions for machining processes were not available, machined components are assumed to be equivalent to primary aluminium ingot. As the energy consumption for milling is only 2.3 kJ/cm$^3$ of aluminium removed [**26**], any errors are expected to be minor.

Steel accounts for $\sim$16 per cent of the total weight (7 per cent stainless steel and 9 per cent mild steel). A large proportion of this is contained in the permanent magnet generator (PMG), with the remainder from small fixings such as nuts, bolts, and washers. Copper accounts for 2 per cent of the overall mass of the turbine and is used almost exclusively in the PMG: values have been based on life-cycle data for copper wire [**22**]. The assembly of the PMG is understood not to contribute significantly to its embedded energy and carbon.

### 3.3.2 *Rotor components*

The 2 m diameter rotor comprises five blades and a diffuser ring, both of which are made of low-density foam encased by a carbon fibre-reinforced epoxy resin skin. Estimates of energy consumption for carbon fibre-reinforced polymers (CFRPs) vary

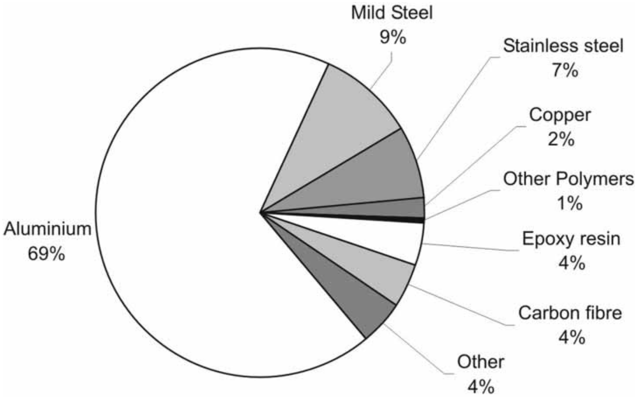

**Fig. 5** Breakdown of material usage in the turbine as a percentage of the total mass

widely. Ashby suggests between 130 and 300 MJ/kg for the energy content of a CFRP moulding [**27**], a figure which is in agreement with values of 286 MJ/kg given by Suzuki and Takahashi [**28**] for 2004 production techniques and 200 MJ/kg from Rydh and Sun [**24**]. The value used in this study is 200 MJ/kg. Data for $CO_2$ emissions from CFRP manufacture and processing are not readily available; however, they have been estimated using the convenient correlation between primary energy use and $CO_2$ emissions provided by Rydh and Sun [**24**]

$$\mathrm{CO_2\ emissions}\left(\frac{\mathrm{kg}}{\mathrm{kg}}\right) = 0.058 \times \mathrm{Energy\ input}\left(\frac{\mathrm{MJ}}{\mathrm{kg}}\right) - 0.391 \qquad (1)$$

The foam filler is a proprietary compound with no readily available data. However, for the purpose of this study, it has been assumed to have energy and $CO_2$ values equivalent to those of epoxy resin.

### *3.3.3 Electrical components*

The electrical components include the on-board electronics, control system, and an inverter. Collating detailed information for each individual component is difficult. However, Takayoshi *et al.* [**29**] developed a means of relating the energy and emissions from the production of various grades of components to their retail price. This provides a convenient method of estimating energy and emissions during the production and component manufacturing stages, but does not account for at during the transportation of the final product. Takayoshi *et al.* segregate components into several categories and give conversion factors for the energy (MJ) and $CO_2$ emissions (kg $CO_2$) per Japanese Yen (¥). Using the exchange rate in 1998 (£1 = ¥224 [**30**]) gave the values shown in Table 4. After allowing for inflation over the intervening period, the energy and emissions for each group of components were calculated.

A similar analysis was not possible for the inverter as a bill of components was not available. However, an LCA carried out by the inverter manufacturer found that the energy involved in its production was 1550 MJ (SMA Technologie AG, 2005, Personal Communication). $CO_2$ emissions were not provided and these have been neglected.

**Table 4** LCI data for each electronic component group, after Takayoshi *et al.* [**29**]

| Component group | Energy (MJ/£) | $CO_2$ (kg/£) |
|---|---|---|
| Semiconductor | 4.68 | 22.62 |
| Liquid crystal display devices | 4.21 | 19.64 |
| CRTs | 7.03 | 46.59 |
| Passive components | 8.78 | 42.34 |
| Connecting components | 2.35 | 10.26 |
| Transducers | 4.44 | 20.32 |
| Printed circuit boards | 11.38 | 47.94 |

## 3.4 Assembly

Assembling the turbine requires the use of a range of electrically powered tools. The energy consumption and $CO_2$ emissions resulting from the electricity required for these tools were quantified. The carbon content of grid electricity was taken as 0.504 kg $CO_2$/kWh, as defined earlier.

## 3.5 Transportation

Three stages of transportation were identified and evaluated relating to transportation of components, installation, and operations and maintenance. To evaluate the emissions from the transportation of each component, a number of factors had to be considered. For components transported from various locations within the UK (often in bulk), the percentage contribution of each component to the payload of a fully laden (3200 kg) curtain-sided truck was used. Its contribution was multiplied by the emissions on the basis of the journey from the respective supplier using the data shown in Table 5.

With these turbines being installed throughout the UK, a representative round-trip delivery distance of 533 km was calculated on the basis of the average distance between Edinburgh and all major cities [**31**]. The use of a light commercial vehicle (e.g. Transit van) was assumed with the energy and carbon values given in Table 5. Transportation relating to operations and maintenance was evaluated on the basis of fuel consumption and emissions for a company car travelling the average installation distance (Table 5).

## 3.6 Installation and maintenance

Data relating to installation procedures were provided by the manufacturer, which specified typical

**Table 5** Fuel consumption and $CO_2$ emissions for vehicles in use [**32**, **33**]

| Vehicle | Fuel consumption (l/km) | $CO_2$ emissions (kg $CO_2$/km) |
|---|---|---|
| Curtain-sided truck | 0.340 | 0.894 |
| Light commercial vehicle | 0.080 | 0.212 |
| Medium-sized car | 0.067 | 0.155 |

activities and timings. With many of these activities, e.g. use of ‘cherry-picker’, not specified explicitly in available emission data, the energy and emissions from these activities were taken to be equivalent to those of a light commercial vehicle operating for 40 min (Table 5). As the turbine is explicitly designed for maintenance-free operation, no emissions have been calculated for maintenance or replacement parts.

### 3.7 Scrapping and recycling

With none of the turbines having reached the end of the life cycle, activities for dismantling have been estimated and are broadly the same as for installation.

All major metal components and potentially some others can be recycled and this can significantly reduce the energy consumption and emissions during the product life cycle. Aluminium is fully recyclable and can reduce the energy and emissions connected with primary aluminium ingot production by 95 per cent through saving primary energy and mineral resources required [**34**]. A method consistent with ISO 14040 to quantify the environmental profile of stainless steel was developed in reference [**35**]. It indicates that if a significant level of recycling is employed, energy consumption and $CO_2$ emissions can be reduced by 30 per cent. The current technology for recycling carbon fibre components is still limited to shredding and usage as a filling material in plastic or concrete manufacture or high-temperature incineration. Neither process yields a significant energy or carbon credit.

Lenzen and Munksgaard [**36**] reviewed the effect of recycling on energy usage for several different wind turbines with power ratings from 0.3 to 600 kW and showed that the proportion of energy recovered through recycling was in the range of 12.5–31.9 per cent. A recycling credit of 31.9 per cent, based on the 75 per cent recycling of a 0.3 kW turbine, was deemed as the closest approximation to the 1.5 kW SWIFT turbine and has been used throughout the analysis as the recycling scenario. This appears to be a reasonable value as it is similar to the 30 per cent recycling credit assumed in reference [**7**]. With no equivalent analysis for carbon emissions, it has been assumed that the percentage reduction in $CO_2$ emissions would be equal to that of the energy. This assumption is consistent with stainless steel recycling, which reduces both the energy and $CO_2$ by 30 per cent [**21**]. The impact of recycling is significant and the analysis, therefore, presents scenarios both with and without recycling credit. Further analysis of the sensitivity of the results to recycling is discussed in section 5.

## 4 RESULTS

### 4.1 Energy consumption

Figure 6 shows the energy consumption for the most significant life-cycle stages with others omitted as they are negligible by comparison. The results show that component manufacture accounts for the majority of energy consumption, whereas assembly, installation, and operations and maintenance are less significant. The energy consumption for the complete life cycle of the turbine, excluding recycling, is calculated to be 22 829 MJ.

Examination of the SWIFT’s component production shows that most of the energy consumed is owing to the presence of so much aluminium in the turbine design. Indeed, owing to the inherent energy intensity of aluminium, it represents a disproportionate share (Fig. 7). The carbon fibre-reinforced blades and diffuser represent the next most significant energy contributer.

### 4.2 $CO_2$ emissions

The $CO_2$ emissions for the complete life cycle of the turbine, excluding recycling, amount to 2428 kg. As illustrated in Fig. 8, component production contributes significantly more to the emissions resulting from the lifetime of the turbine than any other stage. Note that recycling is displayed as having ‘negative’ emissions, as it is seen as credit to the overall system.

### 4.3 Energy and emissions per kilowatt-hour

To allow comparisons to be made between generating electricity using the turbine and using other technologies, the energy and $CO_2$ emissions per kilowatt-hour were calculated. This was done by dividing the overall energy and emissions by the total kilowatt-hour produced by the turbine over the period of its lifetime. The results, with and

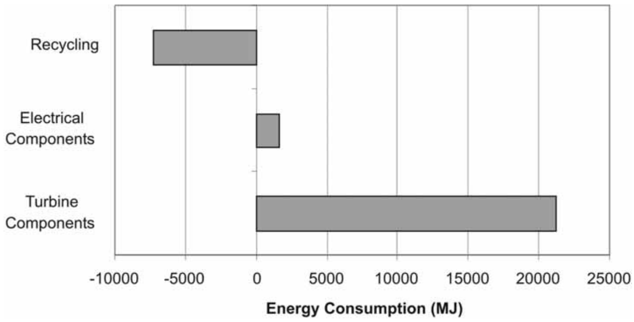

**Fig. 6** Graph of energy consumption per life-cycle stage

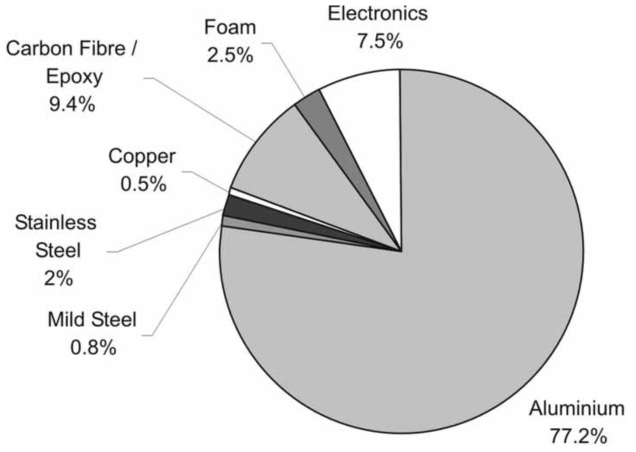

**Fig. 7** Percentage share of energy consumption of primary turbine materials based on the mass of turbine components

without recycling credit, are shown in Table 6. As mentioned earlier, a range of production estimates are used to capture the range of wind conditions that the turbine may experience. It is clear that both the energy and the carbon intensities are very sensitive to the level of production.

### 4.4 Payback time

The payback periods for both energy and $CO_2$ are given in Table 7. The primary energy used in the lifetime of the SWIFT turbine, excluding recycling, is 22 829 MJ. With recycling credit, this is reduced to 15 546 MJ. The energy payback was calculated by dividing this amount by the annual production of the turbine (1000–4000 kWh)

$$\text{Energy payback} = \frac{\text{Total life-cycle energy consumption}}{\text{Lifetime energy production}} \tag{2}$$

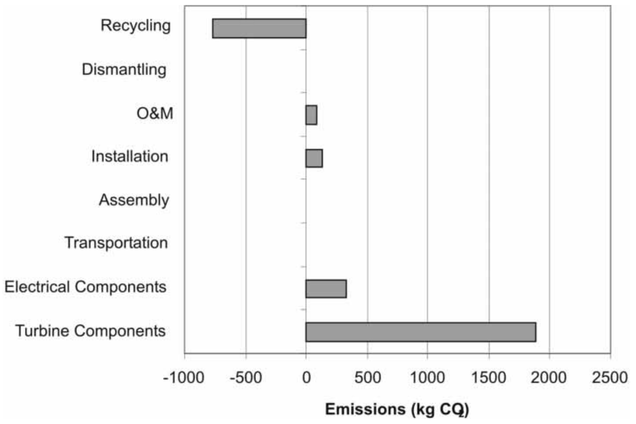

**Fig. 8** $CO_2$ emissions from different stages in the life cycle of the SWIFT

**Table 6** SWIFT turbine energy and emissions per kilowatt-hour of electrical output

| | Energy intensity (kJ/kWh) | | Carbon intensity (g $CO_2$/kWh) | |
|---|---|---|---|---|
| Production (kWh/year) | Without recycling | With recycling | Without recycling | With recycling |
| 1000 | 1141.4 | 777.3 | 121.4 | 82.7 |
| 2000 | 570.7 | 388.7 | 60.7 | 41.3 |
| 3000 | 380.5 | 259.1 | 40.5 | 27.6 |
| 4000 | 285.4 | 194.3 | 30.4 | 20.7 |

The carbon payback time was calculated by dividing the net lifetime $CO_2$ emissions by the carbon avoided by not importing grid electricity with a $CO_2$ content of 0.504 kg $CO_2$/kWh

$$CO_2\ \text{payback} = \frac{\text{Total life-cycle } CO_2 \text{ production}}{\text{Total } CO_2 \text{ avoided by renewable generation}} \tag{3}$$

The sensitivity of this analysis to assumed annual production from the turbine is shown graphically in Fig. 9, which shows the energy and carbon payback periods as a function of annual production. It is clear that the recycling credit has a major impact on the payback period.

## 5 DISCUSSION

### 5.1 Comparison with other sources of electricity

Although the results for the SWIFT turbine are, in themselves, important, the real interest is in its performance relative to other wind turbines and generation technologies. A range of technologies are given in Table 8 for both energy consumption and carbon emissions. The values for the SWIFT assume the recycling credit and are shown for the middle production range of 2000–3000 kWh.

What is immediately clear from Table 8 is that the carbon intensity of the turbine is far better than

**Table 7** SWIFT energy and carbon emission payback times for production estimate range

| | Energy payback (months) | | Carbon payback (months) | |
|---|---|---|---|---|
| Production (kWh/year) | Without recycling | With recycling | Without recycling | With recycling |
| 1000 | 74.0 | 50.4 | 57.8 | 39.4 |
| 2000 | 37.0 | 25.2 | 28.9 | 19.7 |
| 3000 | 24.7 | 16.8 | 19.3 | 13.1 |
| 4000 | 18.5 | 12.6 | 14. 5 | 9.8 |

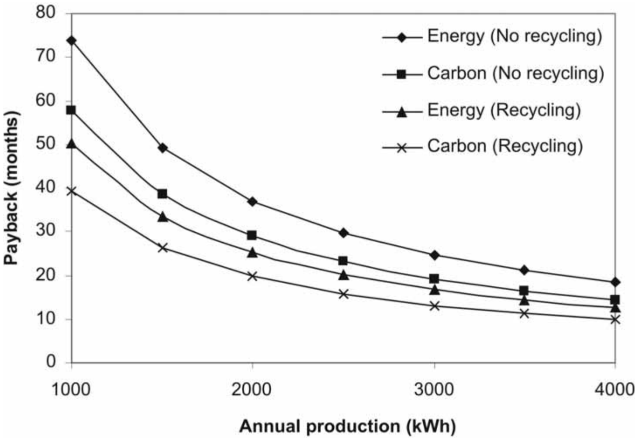

**Fig. 9** Graph of annual production against payback time

fossil-fuelled plant. Relative to larger wind turbines, the SWIFT appears to offer intensities closer to that for lower wind speed inland schemes rather than those sited at high wind speed coastal locations. Lenzen and Munksgaard [**36**] provide an extensive review of the energy intensity and $CO_2$ of electricity generated from a variety of wind turbines. It indicates that energy intensities range from 50 to 3650 kJ/kWh (with a mean value of 223 kJ/kWh), whereas $CO_2$ emissions are between 8 and 124 g $CO_2$/kWh. Although it is difficult to directly compare their results with this study, given the wide span of capacities, wind speeds, and recycling scenarios, it is clear that for both energy and carbon intensities, the SWIFT lies towards the lower end of this range, indicating relatively low emissions per unit of electricity even with unfavourable production conditions (1000 kWh/year). It is more difficult to compare the energy with carbon payback periods as relatively few studies publish these. However, a study [**7**] of the Vestas 2 MW V80-2.0 turbine showed that for a high wind speed coastal site, the energy intensity was 116 kJ/kWh and the energy payback period was 7.7 months. Overall, there appears to be some evidence of increased energy and carbon intensities as a result of loss of scale. In saying that, it should be remembered that commercial large wind turbines have been in development for over 20 years and there are significant improvements that could be made to the SWIFT turbine to reduce its energy and carbon intensities.

### 5.2 Potential improvements

It is clear from section 4 that aluminium is the main source of energy consumption and $CO_2$ emissions. This is due to the high proportion used in the design, together with its high level of embodied energy. Aluminium has a number of material properties that make it attractive for use in the design of the SWIFT: durability, corrosion resistance, and formability. Aluminium is also a relatively lightweight material making handling of the turbine in production, installation, and dismantling more manageable. However, compensating for these properties is the high level of embodied energy resulting from intensive processing required to produce ingot (~200 MJ/kg [**19**]). Two recommendations that could potentially reduce the energy and $CO_2$ emissions over the turbine lifetime are:

(a) replacing primary with recycled aluminium;
(b) replacing major aluminium parts with steel.

Aluminium is considered to be a fully recyclable material and recycling can save 95 per cent of the energy and emissions connected with primary aluminium ingot production [**25**]. For example, extruded recycled aluminium requires 31.7 MJ/kg of energy when compared with 213.5 MJ/kg for primary material, whereas $CO_2$ emissions fall from 11 to 2 kg $CO_2$/kg [**19**]. This substitution would considerably alter the payback time of the turbine. A comparison between the energy and $CO_2$ payback for both sources of aluminium is shown in Table 9, assuming that all aluminium components are

**Table 8** Comparison of energy and $CO_2$ intensities for different electricity production methods

| Generating technology | Energy intensity (kJ/kWh) | $CO_2$ intensity (g $CO_2$/kWh) |
|---|---|---|
| SWIFT rooftop wind turbine[a] | 259–389 | 27–41 |
| Wind turbines at coast [**37**] | 120 | 9 |
| Wind turbines inland [**37**] | 350 | 25 |
| Coal [**38**, **39**] | 334 | 916 |
| Oil [**39**] | Not available | 756 |
| Natural gas [**38**, **39**] | 884 | 360 |
| Hydro [**39**] | Not available | 17 |
| Nuclear [**37**, **40**] | 40 | 3–5 |
| Photovoltaic [**37**] | 1500–3000 | 60–130 |

[a] SWIFT annual production of 2000–3000 kWh.

**Table 9** Comparison of payback times for SWIFT turbine for primary and recycled aluminium with annual production of 3000 kWh

| | Payback (months) | |
|---|---|---|
| | Energy | $CO_2$ |
| Primary Al | | |
| No recycling credit | 24.7 | 19.3 |
| Recycling credit | 16.8 | 13.1 |
| Recycled Al | | |
| No recycling credit | 8.1 | 12.9 |
| Recycling credit | 5.5 | 9.8 |

either recycled or primary and that annual production is 3000 kWh. Energy payback falls by almost two-thirds, whereas the residual emission associated with aluminium production means that $CO_2$ payback time falls more modestly by a third. It is clear that the procurement of recycled aluminium would result in significant energy and carbon savings and significantly improve its relative environmental position with larger wind turbines and fossil-fuelled generation.

In comparison with aluminium alloys, steel requires far less energy in its production: 15 and 54 MJ/kg for unprocessed mild and stainless steel, respectively. Processing of the steel does not significantly contribute to the overall energy and $CO_2$ balance [**7**]. It may not be practical to replace every aluminium component with steel. However, the effect of changing the material of one major component, the mast, is considered here.

A steel mast of the same cross-section as that of the original aluminium mast would weigh nearly three times as much, which, potentially, would create difficulties for installation. However, the mast is chosen to meet a range of engineering considerations: bending moments, fatigue, vibration, and so on. The higher levels of strength and stiffness of steel provide further potential for energy and carbon reductions through redesign of the mast. Although detailed analyses would need to be carried out by the manufacturer, the potential can be illustrated quite easily: for example, assuming the aim is to maintain the flexural rigidity of the mast (i.e. $EI$), the larger Young's modulus ($E$) for steel would allow the wall thickness of the mast cross-section to be reduced by at least 60 per cent. This reduction in mass would make installation more manageable and also reduce the overall turbine energy content by 30.2 per cent for mild steel and 19.4 per cent for stainless steel. $CO_2$ emissions fall by 14.7 per cent and 1.7 per cent for mild steel and stainless steel, respectively; the payback values fall at the same rate.

These and other potential energy and carbon intensity improvement measures have been communicated privately to the manufacturer for further investigation.

### 5.3 Sensitivity to assumptions

There are several possible sources of error in this study: e.g. not including energy and $CO_2$ associated with certain materials or processes, or unavoidable assumptions that had to be made, both due to data not being available. These exclusions or assumptions have been justified earlier and are expected to have little impact on the overall results of the LCA. The effects of the primary sources of error on the overall results are investigated further in this section.

#### *5.3.1 Recycling*

Recycling turbine components plays an important role in reducing the energy and $CO_2$ payback times of the turbine. Across the full production range considered, these reductions are 6–24 months for energy and 5–18 months for $CO_2$. As the turbine under investigation has not yet reached its end of life, it is difficult to predict the exact method and proportion of the turbine that will be recycled. As described earlier, a recycling credit drawn from the literature of 31.9 per cent, and seen as representative of the turbine under investigation, has been used. The literature suggests recycling energy credits of 95 per cent for aluminium and 30 per cent for steel, respectively. To investigate the effect of the recycling assumptions on the overall energy usage, three scenarios are compared:

(a) no recycling, which corresponds to the higher values presented throughout the analysis;
(b) the current situation with a recycling credit of 31.9 per cent;
(c) energy credits of 95 per cent and 30 per cent for the recycling of aluminium and steel, respectively.

The turbine's embodied energy shows major sensitivity to the recycling assumption. Relative to the current 31.9 per cent recycling credit, the zero-credit scenario sees energy consumption rise of 47 per cent, whereas the maximum recycling of aluminium and steel reduces energy by almost 63 per cent. This emphasizes the importance of the end-of-life procedure for the turbine. For a more complete LCA of the turbine, further investigation into the end-of-life scenario is needed.

#### *5.3.2 Transportation of raw material and electronics*

Transportation of the raw materials (aluminium, steel, epoxy, and so on) and of the electronic components has not been accounted for in this study because of the lack of reliable information. If raw materials originated overseas, transportation costs would be significant and may have an effect on the overall results. Rather than making unjustified assumptions on these parameters, it was decided not to include them. In utilizing the results from this study, it should be noted that the energy and emissions for the transportation of components are likely to be an underestimate, albeit a relatively small one.

### 5.4 Further work

This study represents a first approximation to the lifetime energy consumption and $CO_2$ emissions associated with the SWIFT rooftop turbine. The life-cycle analysis would benefit from further investigation of the transportation of electrical components, as well as the end-of-life recycling scenarios.

## 6 CONCLUSIONS

Microgeneration is being promoted as a means of lowering $CO_2$ emissions by replacing electricity from the grid with that produced by small generators in the home. One concern is that the use of smaller plant leads to the loss of economies of scale. Partly, this relates to costs but also in terms of energy consumed and $CO_2$ emitted over the life-cycle of the microgenerator.

Here, an analysis is presented of a life-cycle audit of the energy use and $CO_2$ emissions for the SWIFT, a 1.5 kW rooftop-mounted wind turbine designed to be interfaced to the electricity network. It shows that per kilowatt-hour of electricity generated by the turbine, the energy intensity and $CO_2$ emissions are comparable with larger wind turbines and significantly lower than fossil-fuelled generation. With energy and carbon intensities sensitive to assumed levels of production, assessments were carried out for an annual production range of 1000–4000 kWh. For the manufacturer's estimated production of 2000–3000 kWh and when credit for component recycling was included, the energy payback period was found to be between 17 and 25 months, whereas the $CO_2$ payback was period between 13 and 20 months. Across the full production range, the energy and carbon paybacks were 13–50 months and 10–39 months, respectively.

One of the key uses of the study will be to inform the manufacturer of the opportunities to improve the turbines energy and carbon performance. A simple example illustrates the potential where an aluminium component is replaced with recycled aluminium or steel.

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