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Citation for published version:
Rankine, RK, Chick, J & Harrison, G 2006, 'Energy and carbon audit of a rooftop wind turbine', *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, vol. 220, pp. 643-654. https://doi.org/10.1243/09576509JPE306

Digital Object Identifier (DOI):
10.1243/09576509JPE306

Document Version:
Peer reviewed version

Published In:
Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy

Energy and Carbon Audit of a Rooftop Wind Turbine

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ABSTRACT

Micro-generation 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 lifecycle of the micro-generator.

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 kWh of electricity generated by the turbine the energy intensity and CO_2 emissions are comparable to larger wind turbines and significantly lower than fossil-fuelled generation. The energy payback period was found to be about 17 months, reducing to 12 months when credit for component recycling was included. CO_2 payback was about 14 months, with recycling credit reducing this to 9 months.

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

KEYWORDS

Audit, carbon emissions, energy intensity, life cycle analysis, micro-generation, 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% of electricity to be from renewable sources by 2010 [1]. There is particular interest in promoting micro-generation for the domestic sector powered by photo-voltaic cells, micro-wind 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 atmosphere. Further losses occur in the transmission system and particularly in the lower voltage distribution network: UK average transmission losses are around 1.5% [2] while distribution network losses are on average 7% with marginal losses as high as 30% at the extreme edges of the grid [3].

The concept of micro-generation is quite different from the centralised generating paradigm developed in the 20th Century which relied on a relatively small number of large power stations. Replacing large plant with smaller ones offers benefits in terms of 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 power generated whilst 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 paper sets out a life-cycle analysis of the 1.5 kW 'SWIFT' rooftop mounted turbine, produced by Edinburgh-based Renewable Devices Ltd [4]. 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 while section 3 introduces the SWIFT turbine before exploring the 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 requirement for the provision of foods and services [5], energy and CO_2 Life Cycle Assessments (LCA) are increasingly being used to analyse the methods for generating, transmitting and consuming energy. In particular, they have been used to analyse numerous large wind turbines and, in some cases, entire wind farms [6], [7], [8].

Life Cycle Assessment 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 [9].

Each stage of the product life cycle – from the ‘cradle to the grave’ – is evaluated in detail (Figure 1). Data on the energy and emissions from each stage is 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.

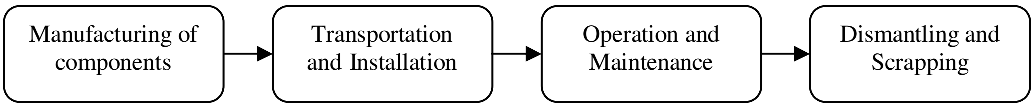

Figure 1: Life cycle stages of a typical product

An LCA can be used as a comparative analysis tool, a design improvement tool, and to aid in purchasing decisions [10]. The manufacturer could use the information 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 form the foundation to assess a product's sustainability [8]. 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 limitations to life-cycle analysis are that assumptions regarding system boundaries and data sources must be made (which may introduce subjectivity) [11].

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 (Figure 2) is designed for virtually silent and maintenance-free operation [4]. It may be connected to an immersion heater, to batteries for off-grid operation, or as of interest here, grid connected via a power-electronic inverter. Further technical specifications are given in Table 1.

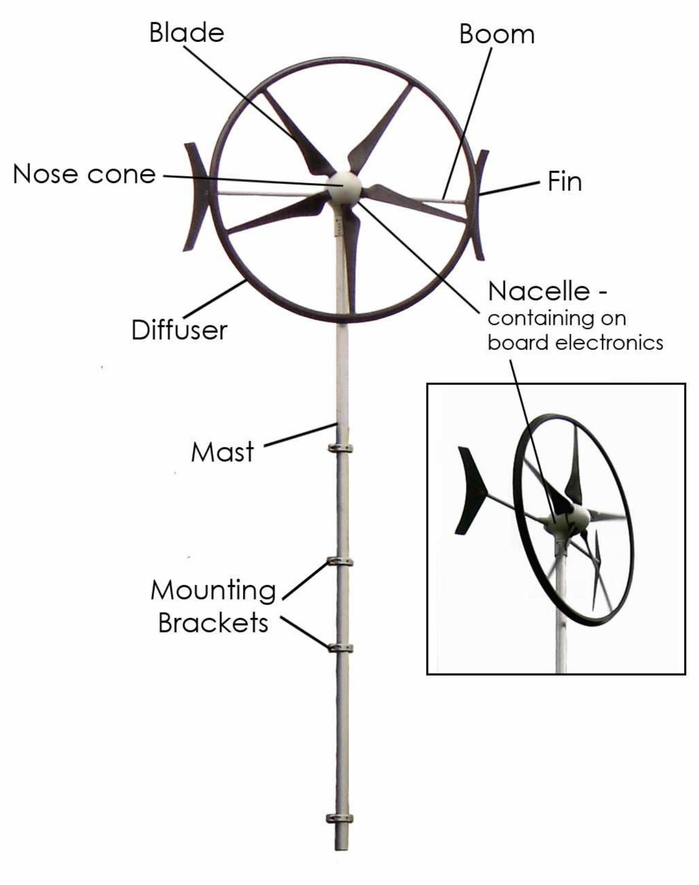

Figure 2: SWIFT turbine [4]

Rated power output	1.5 kW
Annual power generated	4,000 kWh
Annual CO_2 displacement	1,600 kg
Product life	20 years
Cut in speed	3.5 m/s
Rated speed	10.5 m/s
Cut out speed	None (electronically braked)
Rotor	2 m diameter moulded carbon fibre
Generator	Brushless Permanent Magnet

Table 1 SWIFT Technical Specification [4]

The manufacturer's values for annual production and CO_2 displacement (Table 1) were determined using the Retscreen International Wind Energy Model [12] which estimates wind production based on mean wind speed, the Rayleigh wind speed distribution and the turbine power curve (Figure 3). A similar tool developed for climate impact assessment [13] was used to confirm these: annual production was estimated to be 4051 kWh (for a mean wind speed of 7.25 m/s) while the annual amount of CO_2 avoided was found to be 2042 kg of CO_2. The difference in CO_2 avoided arises from the higher carbon intensity used which was the weighted average carbon intensity of the UK generating mix in 2005 [14] as adjusted by average transmission and distribution losses: 0.504 kg CO_2/kWh, which matches figures given elsewhere [15].

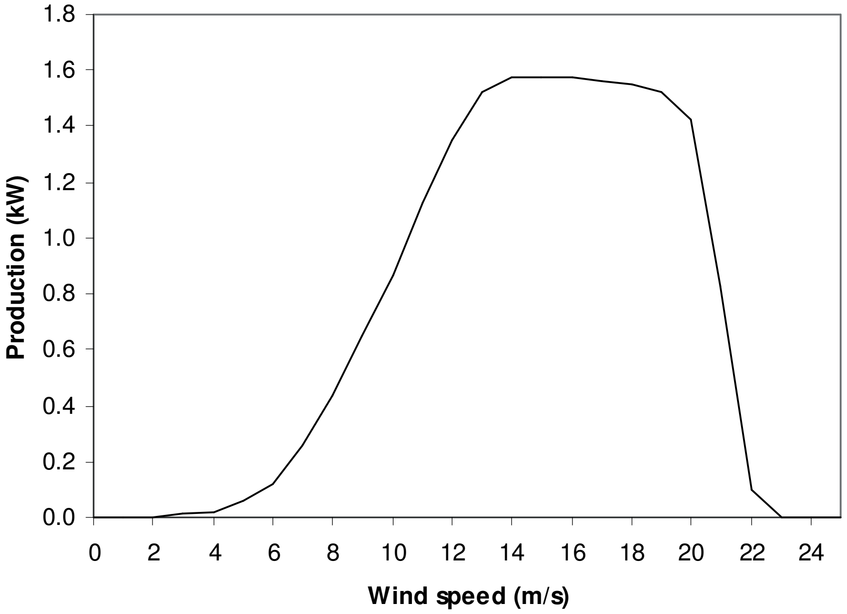

Figure 3: Power curve for SWIFT turbine [16]

2.3 System Boundary

In the life cycle, manufacturing involves the production from raw material to final assembly, while transport and installation includes the emissions from the transportation of individual components to the assembly location and also includes emissions when transporting the finished product for installation. Operation and maintenance includes 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 includes 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 (Figure 4) shows the various unit processes considered in the LCA. Processes in dashed boxes have not been 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.

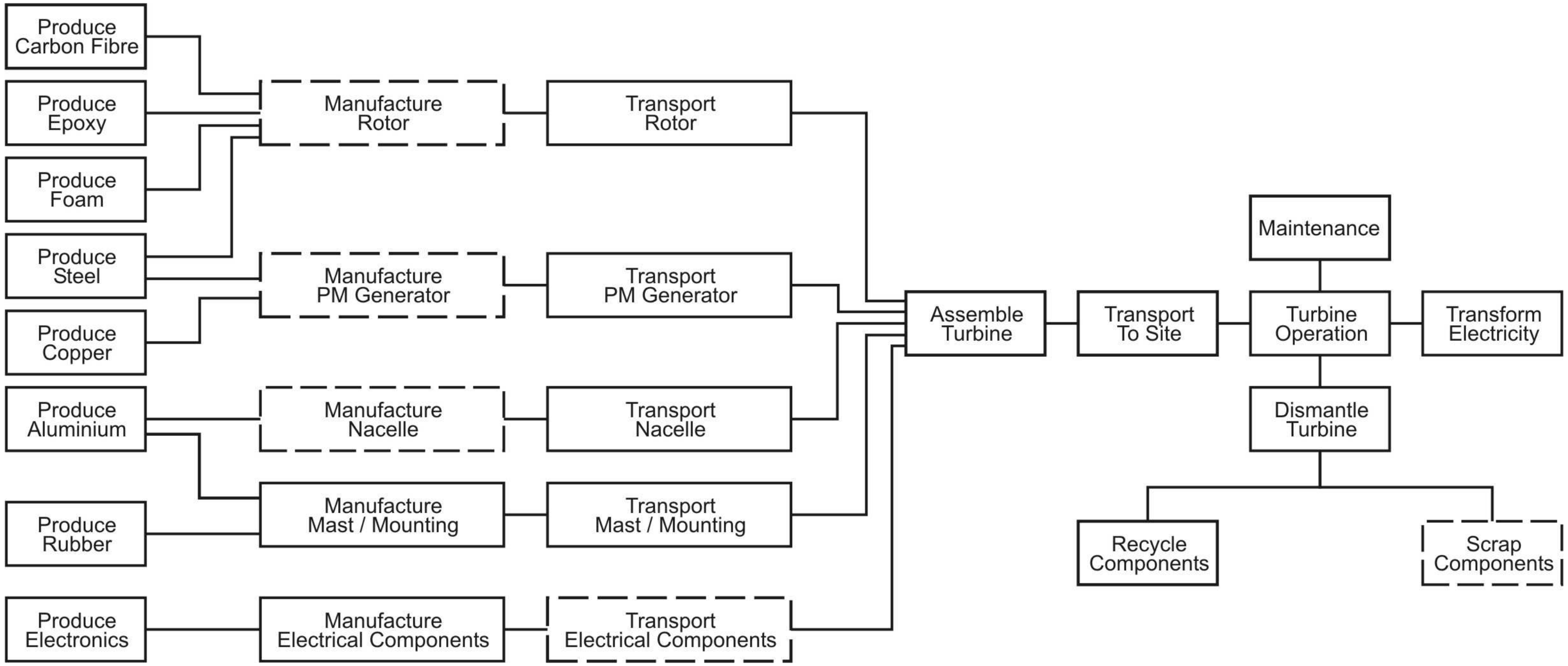

Figure 4: Process flow diagram

3 ENERGY AND CO_2 EMISSIONS 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 through operation and maintenance [8]. 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 a significant percentage of the turbine total mass then an assumption was made; where it was less than 1% of the mass, it was ignored on the basis that its non-inclusion would have little effect on the analysis.

Where possible, energy and emissions data is based on official sources adhering to ISO 14040 [17] which specifies the general framework, principles and requirements for conducting and reporting life cycle assessment studies.

3.2 Raw Materials

For raw materials, data (Table 2) has been obtained from lifecycle assessments performed by recognised 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 prioritising those which are considered of high energy content.

Material	Energy Consumption (MJ/kg)	CO_2 Emissions (kg CO_2/kg)
Aluminium alloy [18]	193.7 – 238.9	10.47 – 13.08
Mild steel [19]	15.9	1.1
Stainless steel [20]	54.0	6.1
Copper [21]	49.2	3.35
Epoxy resin [22]	137.1	5.7
Carbon fibre [23]	7.56	Not available

Table 2: Energy consumption and CO_2 emissions for several raw materials

3.3 Component Manufacture

The main turbine components are shown in Figure 2 and consist of the extruded aluminium mast, cast aluminium nacelle and on board electronics, carbon fibre reinforced epoxy rotor blades/diffuser, 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 electrical control system) of the turbine is shown in Figure 5.

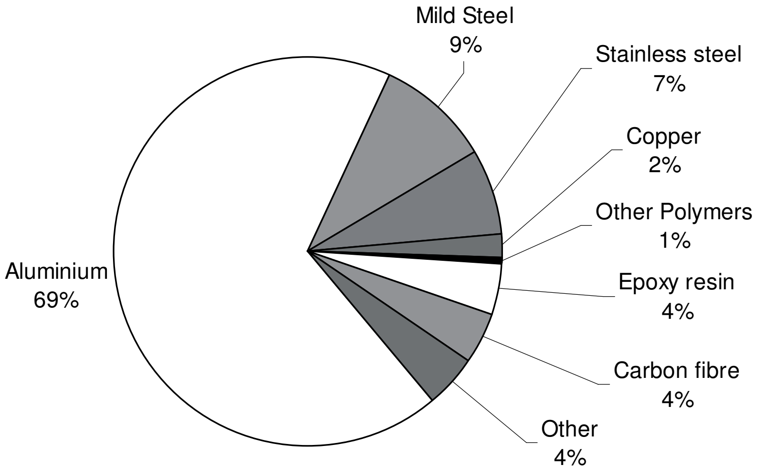

Figure 5: Material use in turbine as a percentage of the total mass

3.3.1 Metal components

Aluminium is the main contributor to the turbine's weight, responsible for almost 70%, almost half of which is contained within the extruded aluminium mast. Life cycle data on primary aluminium production and processing (casting, extrusion etc.) was sourced [18], [24]. The range of energy consumption and CO_2 emissions is given in Table 2. Detailed data on energy and emissions for machining processes was not available, machined components are assumed to be equivalent to primary aluminium ingot (energy consumption for milling is only 2.3 kJ per cm^3 of aluminium removed [25] and hence any errors are expected to be minor).

Steel accounts for approximately 16% of the total weight (7% stainless and 9% 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% 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 [21].

3.3.2 Rotor components

The 2 metre diameter rotor comprises five blades and diffuser ring both of which are made of low-density foam encased by a carbon fibre-reinforced epoxy resin skin. Energy and CO_2 emissions data was readily available for epoxy resins [22]. Data for carbon fibre was not readily available: [23] gave values for energy consumption but not for CO_2 emissions. Given the relatively low mass of the carbon fibre content the emissions were not included. The foam filler is a specialist compound and no literature was available. However, for the purpose of this study it has been assumed to have energy and CO_2 values equivalent to that 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.* [26] 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 production and component manufacturing stages but does not account for transportation of the final product. Takayoshi segregates components into several categories and gives conversion factors for the energy (MJ) and CO_2 emissions (kg CO_2) per Japanese Yen (¥). Using the exchange rate in 1998 (£ 1 = ¥ 224 [27]), gave the values shown in Table 3. After allowing for inflation over the intervening period, the energy and emissions for each group of components was calculated.

A similar analysis was not possible for the inverter as a bill of components was not available. However, a LCA carried out by the inverter manufacturer found that the energy involved in its production was 1550 MJ [28]. CO_2 emissions were not provided, and these have been neglected.

Component Group	Energy (MJ/£)	CO_2 (kg/£)
Semiconductor	4.68	22.62
Liquid Crystal Display Devices	4.21	19.64
CRT's	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

Table 3: LCI Data for each electronic component group, after Takayoshi [26]

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 was 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 (3,200 kg [29]) curtain-sided truck was used. This defined its contribution which was multiplied by the emissions based on the journey from the respective supplier based on the data shown in Table 4.

With these turbines being installed throughout the UK, a representative round-trip delivery distance of 533 km was calculated based on the average distance between Edinburgh and all major cities [30]. The use of a light commercial vehicle (e.g., Transit van) was assumed (energy and carbon values in Table 4). Transportation relating to operations and maintenance was evaluated based on fuel consumption and emissions for a company car travelling the average installation distance (Table 4).

Vehicle	Fuel consumption (litre/km)	CO_2 Emissions (kg CO_2/km)
Curtain-sided truck	0.34	0.894
Light commercial vehicle	0.08	0.212
Medium-sized car	0.0672	0.155

Table 4: Fuel consumption and CO_2 emissions for vehicles in use [31], [32]

3.6 Installation and Maintenance

Data relating to installation procedures was provided by the manufacturer which specified typical activities and timings. With many of these activities, e.g. use of ‘cherry-picker’, etc. not specified explicitly in available emissions data, the energy and emissions from these activities were taken to be equivalent to those of a light commercial vehicle operating for 40 minutes (Table 4). Since 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 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% through saving primary energy and mineral resources required [33]. A method consistent with ISO 14040 to quantify the environmental profile of stainless steel was developed in [34]. It indicates that if a significant level of recycling is employed, energy consumption and CO_2 emissions can be reduced by 30%. 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 recycle energy or carbon credit.

Lenzen and Munksgaard [35] reviewed the effect of recycling on energy usage for several different wind turbines with power ratings from 0.3kW to 600kW and showed that the proportion of energy recovered through recycling was in the range of 12.5% to 31.9 %. A recycling credit of 31.9%, based on the 75% 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. 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% [20]. The impact of recycling is significant and our 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 selected life cycle stages. The results show that component manufacture accounts for the majority of energy consumption, while 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 21,558 MJ.

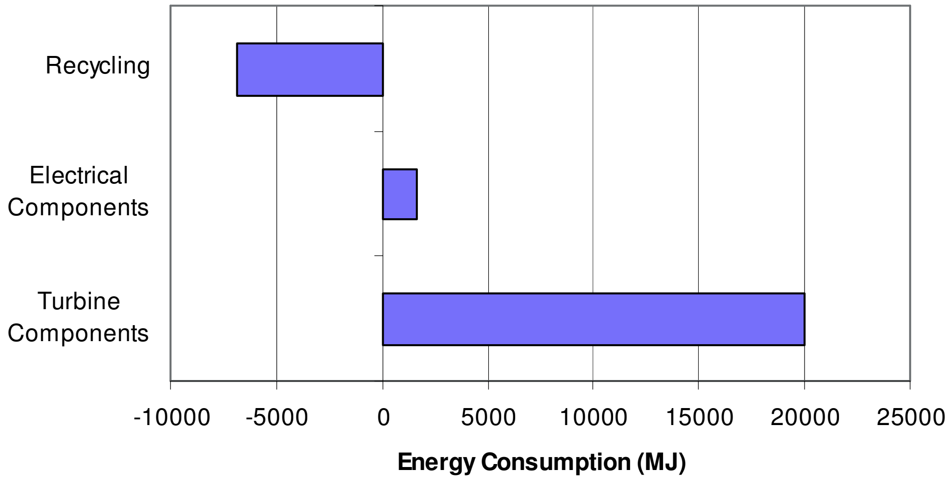

Figure 6: Graph of energy consumption per life cycle stage

Examination of the SWIFT's component production shows that most of the energy consumed is due to the presence of so much aluminium in the turbine design. Indeed, due to the inherent energy intensity of aluminium, it represents a disproportionate share (Figure 7).

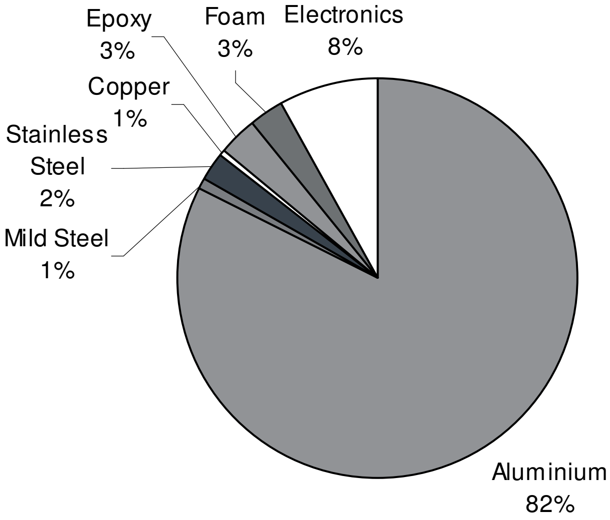

Figure 7: Share of energy consumption from primary turbine materials

4.2 CO_2 Emissions

The CO_2 emissions for the complete life cycle of the turbine, excluding recycling, amounts to 2,345 kg. As illustrated in Figure 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.

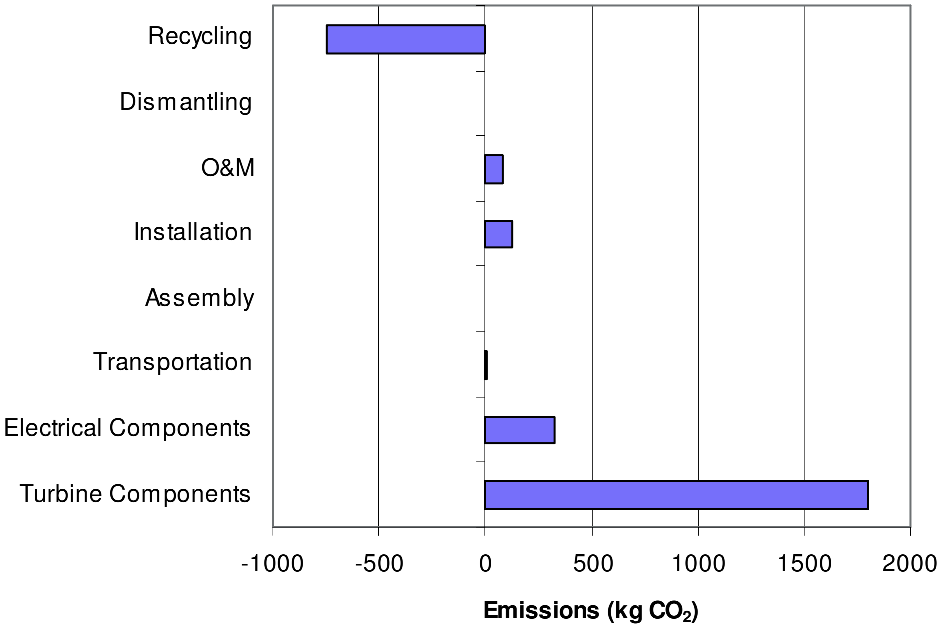

Figure 8: Graph of emissions from life cycle stages

4.3 Energy and Emissions per kWh

To allow comparisons to be made between generating electricity using the turbine and using other technologies, the energy and CO_2 emissions per kWh were calculated. This was done by dividing the overall energy and emissions by the total kWh produced by the turbine over the period of its lifetime. The results, with and without recycling credit, are shown in Table 5.

	Energy Intensity (kJ/kWh)	CO_2 Emissions (g CO_2/kWh)
Without Recycling Credit	266.1	28.9
With Recycling Credit	181.2	19.7

Table 5: Energy and emissions per kWh

4.4 Payback time

The payback periods for both energy and CO_2 are given in Table 6. The primary energy used in the lifetime of the SWIFT turbine, excluding recycling, is 21,558 MJ. With recycling credit, this is reduced to 14,681 MJ. The energy payback was calculated by dividing this amount by the annual production of the turbine (4051 kWh):

$$\text{Energy Payback} = \frac{\text{Total lifecycle energy consumption}}{\text{Lifetime energy production}}$$

The lifetime CO_2 emissions of 2,345 kg CO_2 decreases to 1,597 kg when recycling is included. The carbon payback time was calculated by dividing the amount by the carbon avoided by not taking grid electricity based on its CO_2 content of 0.504 kg CO_2/kWh:

$$CO_2 \text{ Payback} = \frac{\text{Total lifecycle } CO_2 \text{ production}}{\text{Total } CO_2 \text{ avoided by renewable generation}}$$

	Energy Payback (months)	Carbon Payback (months)
Without Recycling Credit	17.24	13.78
With Recycling Credit	11.74	9.39

Table 6: Energy and emissions payback time

The sensitivity of this analysis to variation in the annual power production from the turbine is shown in Figure 9.

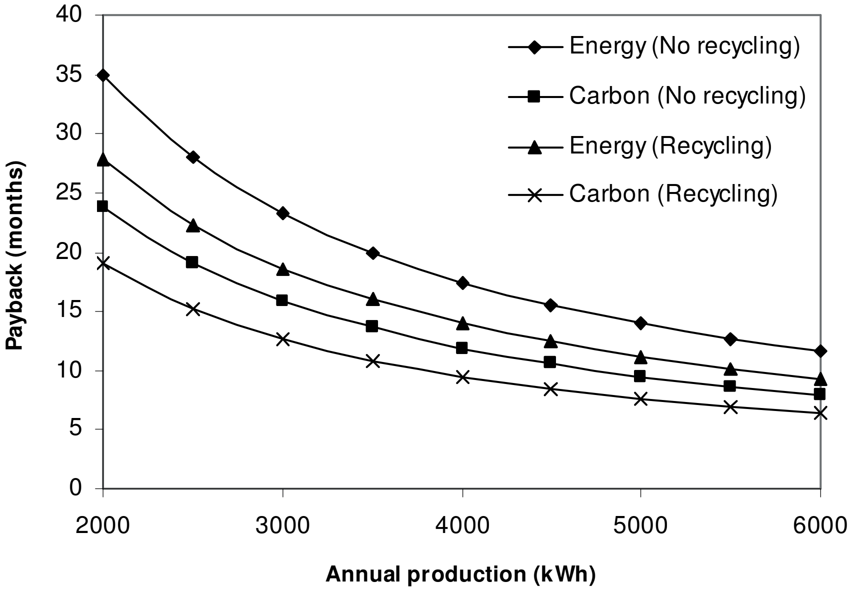

Figure 9: Graph of annual production against payback time.

5 DISCUSSION

5.1 Comparison with other sources of electricity

While the results for the SWIFT turbine are, in themselves interesting, the real interest is in its performance relative to other wind turbines and generation technologies. A range of technologies are given in Table 7 for both energy consumption and carbon emissions.

Generating Technology	Energy Intensity (kJ/kWh)	CO_2 Intensity (g CO_2/kWh)
Coal [36]	884	910
Oil [35]	Not Available	755.7
Gas CCGT [36]	334	360
Hydro [35]	Not Available	17.1
Nuclear [37]-[38]	40	3-5
Wind turbines at coast [37]	120	9
SWIFT rooftop wind turbine	181	20
Wind turbines inland [37]	350	25
Photovoltaic [35]	30,000	130

Table 7: Energy and CO_2 intensities of electricity production methods

Lenzen [35] lists the CO_2 emissions per kWh of electricity generated from a variety of wind turbines and indicates emission intensities ranging from 8.1 to 123.7 g CO_2/kWh. Given that these results span a wide range of power, size, wind speed and recycling scenarios, it is difficult to make an accurate comparison between the data and that for the SWIFT. However, it would appear that the SWIFT lies towards the lower end of this range, indicating relatively low emissions per unit of electricity. Furthermore, the SWIFT lies between larger wind turbines sited at the coast with high wind speed conditions and inland sites with lower speeds. Overall there appears to be limited evidence of increased energy and carbon intensity as a result of loss of scale.

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 which 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 (approximately 200 MJ/kg [18]).

Two recommendations which could potentially reduce the emissions and CO_2 over the turbine lifetime are:

- Replacing primary with recycled aluminium
- Replacing major aluminium parts with steel

Aluminium is considered to be a fully recyclable material and recycling can save 95% of the energy and emissions connected with primary aluminium ingot production [24]. For example, extruded recycled aluminium requires 31.7 MJ/kg of energy compared to 213.5 MJ/kg for primary material while CO_2 emissions fall from 11 to 2 kg CO_2/kg [18]. 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 8 assuming that all aluminium components are either recycled or primary. Residual emissions from recycled and primary aluminium production results in a more modest reduction of CO_2 payback time. It is clear that the procurement of recycled aluminium would result in significant energy and carbon savings.

		Payback (months)	
		Energy	CO_2
Primary Al	No recycling credit	17.24	13.78
	Recycling credit	11.77	8.39
Recycled Al	No recycling credit	5.69	9.22
	Recycling credit	3.87	6.27

Table 8: Payback times with recycled aluminium

In comparison with aluminium alloys, steel requires far less energy in its production: 15MJ/kg and 54MJ/kg for unprocessed mild and stainless steel respectively. Processing of the steel does not significantly contribute to the overall energy and CO_2 balance [8]. 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 the original aluminium one 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 etc. The higher levels of strength and stiffness of steel provides further potential for energy and carbon reductions through redesign of the mast. While 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%. This reduction in mass would make installation more manageable and also reduce the overall turbine energy content by 30.2% for mild steel and 19.4% for stainless. CO_2 emissions fall by 14.7% and 1.7% for mild and stainless steels 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 above 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. Without considering recycling, these payback times are increased by 5 and 4 months respectively. Since 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%, and seen as representative of the turbine under investigation, has been used. The literature suggests recycling energy credits of 95% for aluminium and 30% for steel, respectively. To investigate the effect of the recycling assumptions on the overall energy usage, three scenarios are compared:

- No recycling: which corresponds to the higher values presented throughout the analysis,
- The current situation with a recycling credit of 31.9%,
- Energy credits of 95% and 30% 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% recycling credit, the zero-credit scenario sees energy consumption rise by 47% while the maximum recycling of aluminium and steel reduces energy by almost 63%.

This emphasises 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 etc) and of the electronic components has not been accounted for in this study due to 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 make unjustified assumptions on these parameters it was decided not to include them. In utilising the results from this study it should be noted that the energy and emissions for the transportation of components is likely to be an underestimate.

5.3.3 Data for the production of carbon fibre

Accurate data for the production of carbon fibre was not available but it is estimated that the production of carbon fibre is relatively energy intensive and may generate emissions that could have a measurable effect on the overall results. However, since carbon fibre constitutes only 4% of total material usage in the current design the effect of errors in this analysis are anticipated to be slight.

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 lifecycle analysis might benefit from further investigation into the following areas: transportation of electrical components, energy content and emissions arising from the production of carbon fibre and end-of-life recycling scenarios.

6 CONCLUSIONS

The increasing penetration of micro-generation 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 related to costs but also in terms of energy consumed and CO_2 emitted over the lifecycle of the micro-generator.

Here, an analysis is presented of a lifecycle 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 kWh of electricity generated by the turbine the energy intensity and CO_2 emissions are comparable to larger wind turbines and significantly lower than fossil fuelled generation. The energy payback period was found to be just over 17 months reducing to almost 12 months when credit for component recycling was included. The CO_2 payback was almost 14 months decreasing to 9 months when recycling credit was given.

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 with an aluminium component replaced with recycled aluminium or steel.

7 ACKNOWLEDGEMENTS

The authors wish to thank staff at Renewable Devices Ltd, Edinburgh for their prompt and efficient response to queries. Additionally, the authors are grateful for the advice and assistance of Jessica Lovell and colleagues at the Edinburgh Centre for Carbon Management.

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9 TABLE CAPTIONS

Table 1 SWIFT Technical Specification [4]

Table 2: Energy consumption and CO_2 emissions for several raw materials

Table 3: LCI Data for each electronic component group, after Takayoshi [26]

Table 4: Fuel consumption and CO_2 emissions for vehicles in use [31], [32]

Table 5: Energy and emissions per kWh

Table 6: Energy and emissions payback time

Table 7: Energy and CO_2 intensities of electricity production methods

Table 8: Payback times with recycled aluminium

10 FIGURE CAPTIONS

Figure 1: Life cycle stages of a typical product

Figure 2: SWIFT turbine [4]

Figure 3: Power curve for SWIFT turbine [16]

Figure 4: Process flow diagram

Figure 5: Material use in turbine as a percentage of the total mass

Figure 6: Graph of energy consumption per life cycle stage

Figure 7: Share of energy consumption from primary turbine materials

Figure 8: Graph of emissions from life cycle stages

Figure 9: Graph of annual production against payback time.