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Environmental impacts of micro-wind turbines and their potential to contribute to UK climate change targets☆

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A B S T R A C T

This paper evaluates the life cycle environmental sustainability of micro-wind turbines in the UK in comparison with grid electricity and solar PV (photovoltaics). The results suggests that per kWh electricity generated, the majority of environmental impacts from the wind turbines are lower than from grid electricity, ranging from 26% lower terrestrial toxicity to 92% lower global warming. However, depletion of abiotic elements, fresh-water and human toxicities are 82%, 74% and 53% higher than for grid electricity, respectively. The wind turbines are more environmentally sustainable than solar PV for seven out of 11 impacts, ranging from 7.5% lower eutrophication to 85% lower ozone layer depletion. However, depletion of fossil resources, fresh-water, human and terrestrial toxicities are higher for the wind turbine than for the PV, ranging from 5% for the former to 87% for the latter. UK-wide deployment of micro-wind turbines would save between 0.6 and 1% of GHG (greenhouse gas) emissions on 2009 levels. Therefore, the potential of micro-wind turbines to contribute towards UK's climate change targets is limited.

1. Introduction

Micro-generation is being promoted as one of the promising ways for reducing greenhouse gas (GHG) emissions. In the UK, the Government has introduced a range of incentives to encourage the uptake of micro-generation technologies, including Feed-in-Tariffs (FiT) [1], the Green Deal [2] and removal of the need for planning permissions [3].

Among other technologies, micro-wind turbines are expected to help reduce the GHG emissions from electricity use in the domestic sector [4,5] and to contribute towards UK's climate change targets (34% reduction of GHG emissions by 2020 and 80% by 2050 on 1990 levels) [6,7]. However, the uptake is still slow and by the end of 2010 there were around 21,000 micro-wind turbines in the UK of which over 90% are up to 10 kW [8] with the most common size being 6 kW [9]. The total installed capacity was 42.97 MW, generating 55.75 GWh of electricity per year [8]. By comparison, the total number of micro-wind installations in the US is 151,300 with a total capacity of 179 MW [10]. However, the UK is still the third largest market for micro-wind turbines and with the FiT payments of 25.3–36.2 p/kWh of electricity generated, it is expected to challenge both the US and China in the coming years [11]. The UK is already the leading country in terms of annual growth of installed capacity, with 153% increase in 2010 compared to a 26% reduction in the US [11]. According to some predictions, by 2020, between 455,000 and 600,000 micro-wind turbines could be installed in the UK [12,13]; more optimistic estimates put the number of installations at around 1.3 million [14].

However, field trials of micro-wind turbines in the UK suggest that many of the sites where the micro-wind turbines are installed – and likely in the UK as a whole – are generating less energy than predicted owing to insufficient wind resource [13]. This is despite the UK having the best wind resource in Europe [12]. For example, only a third of free-standing turbines had average annual wind speeds of 5 m/s or greater and those sited in built up areas did not perform well due to wind obstructions [13]. Furthermore, not one of the 38 roof-top wind turbines monitored produced more than 200 kWh per year [13].

Therefore, despite the claims that micro-wind turbines can save significant GHG emissions compared to grid electricity and other fossil-fuel options (e.g. [4,5,8,12,14]), the actual performance data through field trials cast some doubt over these claims. For this reason, this paper sets out to explore the environmental sustainability of micro-wind turbines and the potential role they could play in helping the UK meet the climate change targets. First, the life cycle environmental impacts of a micro-wind turbine are estimated per unit of electricity generated and compared to two other options: grid electricity as the current main source of electricity and

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solar photovoltaics (PV) as one of the fastest-growing micro-generation technologies in the UK [14].

This is followed by considering the projected UK-wide deployment of micro-wind turbines to estimate if and how much this could contribute to the reduction of national GHG emissions. Due to the ineffectiveness of roof-mounted turbines [13], only free-standing mast-mounted turbines are considered.

2. Methodology

The life cycle environmental sustainability of micro-wind turbines in comparison to grid electricity and solar PV has been evaluated using life cycle assessment (LCA). LCA has been chosen as a tool in this study rather than other related methodologies such as input–output or hybrid LCA as it enables more detailed, specific consideration of the unit processes and life cycle stages within the system, rather than aggregated, sector-level analysis used in the other two approaches. The LCA study has been carried out following the guidelines in the ISO 14040/44 standards [15,16]. LCA software GaBi v.4.4 [17] has been used to model the three electricity options considered. The LCA impacts have been calculated according to the CML 2 Baseline 2001 methodology [18]. The following sections detail the electricity systems, the assumptions and data used in the study.

2.1. Goal and scope definition

The following are the main goals of the LCA study:

i) to estimate the life cycle environmental impacts of micro-wind turbines for electricity provision in UK homes; and
ii) to compare the environmental impacts of micro-wind with two alternatives: grid electricity and solar PV.

The functional unit is defined as 'generation of 1 kWh of electricity'. The scope of the study for all three options considered is from 'cradle to grave' (see Figs. 1–3 and Table 1). A 6 kW turbine is considered as the most common size of micro-wind installations in the UK [9]. The operating life of the turbine is assumed at 20 years [19–21]; shorter and longer lifetimes are also considered as part of sensitivity analysis in Section 3.3.

2.2. System description, data and assumptions

2.2.1. Micro-wind turbine

Micro-wind turbines generate electricity by the rotation of turbine blades as wind passes over them [22]. The low-speed rotation of the input shaft connected to the rotor is converted to high-speed rotation by a gearbox. The high-speed shaft then drives the generator to produce electricity. A yaw system is used to orientate the turbine towards the blowing wind. An inverter is necessary to convert the DC electricity produced by the turbine to AC electricity suitable for use in dwellings.

In line with UK trends, the turbine is assumed to be free-standing, mast-mounted (85% of market share in 2010) with horizontal-axis design (98% of the market) [8]. It is assumed to be installed at a location with an annual average wind speed of 5 m/s with no nearby obstructions, as the minimum requirements for a suitable location [13,23]. The analysis is based on the 6 kW Proven 11 turbine, producing 7800 kWh per year [20]. The general specification of the turbine is given in Table 2

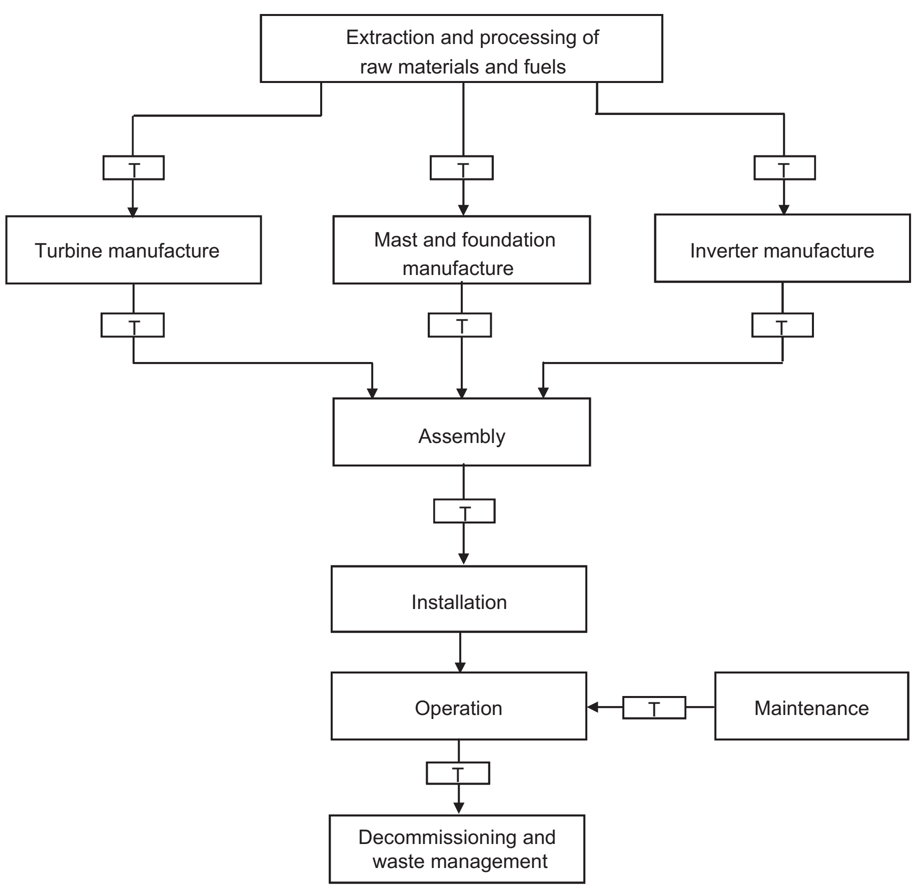

Fig. 1. The life cycle of micro-wind turbine. T – transport.

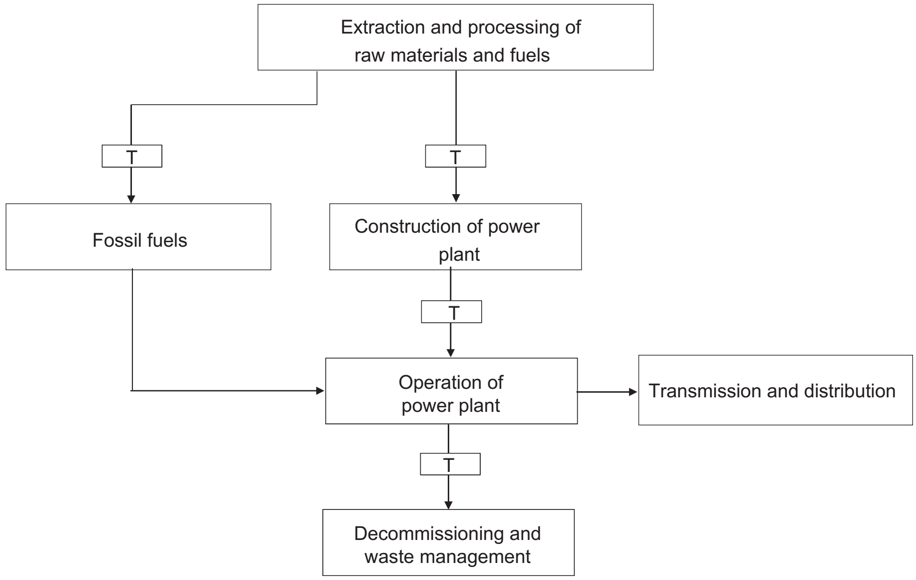

Fig. 2. The life cycle of grid electricity. T – transport.

and the materials and energy used in the life cycle of the turbine are given in Table 3.

Data for the operation of the turbine have been obtained from manufacturers and field trials [13,20,23]. The life cycle inventory data for turbine manufacture, installation and maintenance have been sourced from the Ecoinvent database [24]. As the Ecoinvent data are for a two-bladed turbine with the capacity of 30 kW, two adjustments have been made to correspond to the turbine considered here. First, the number of blades has been increased from two to three to correspond to typical designs of UK turbines [20]. Secondly, the size of the turbine has been scaled down from 30 kW to 6 kW to estimate the materials needed for a smaller

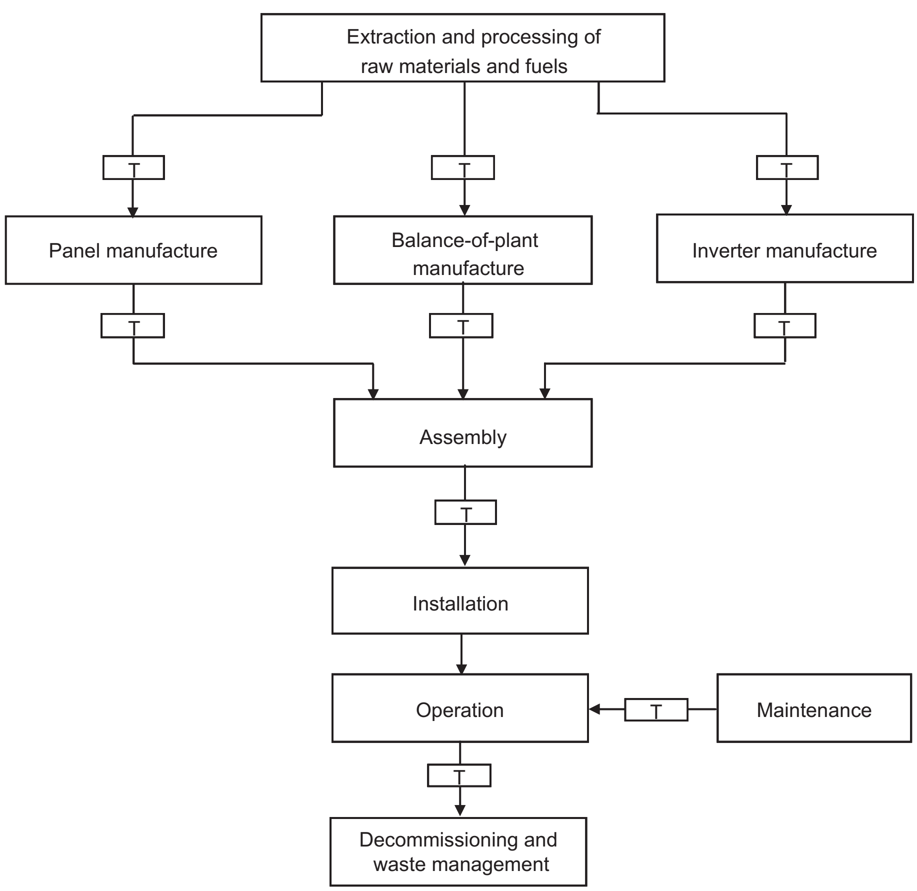

Fig. 3. The life cycle of solar PV. T – transport.

Table 1
System boundaries for micro-wind turbine, grid electricity and solar PV.

Micro-wind turbine	Grid electricity	Solar PV
• Extraction and processing of fuels and raw materials • System manufacture: rotor, nacelle, mast, foundation, inverter and assembly • Installation: use of explosives • Operation • Maintenance (replacement of lubricating oil) • Decommissioning: metal recycling, inert material landfill disposal • All transport	• Extraction and processing of fuels and raw materials • Construction of power plant, transmission and distribution network • Operation (including transmission and distribution) • Decommissioning: metal recycling, inert material landfill disposal • All transport	• Extraction and processing of fuels and raw materials • System manufacture: panel, balance of plant, inverter and assembly • Installation: energy, mounting frame, electrical wiring • Operation • Maintenance: inverter replacement • Decommissioning: metal recycling, inert material landfill disposal • All transport

turbine. Instead of the usual simplified linear approach normally used in LCA for scaling the size of infrastructure, a non-linear approach has been used here, based on the 'economies of scale' method typically used for scaling the capital costs of process plants of different sizes [25] as follows:

$$C_2 = C_1 \times \left(\frac{c_2}{c_1}\right)^{0.6} \tag{1}$$

where C_1 and C_2 are costs of the larger and smaller turbine, respectively, here representing the amounts of materials and energy used in the life cycle of the turbines; c_1 and c_2 are capacities of the larger and smaller turbine, respectively; 0.6 is the 'economy of scale' factor.

All data reflect UK conditions including UK energy mixes, transport distances and the current waste management practices for the different materials [26,27]. Further detail on the assumptions is provided below.

2.2.1.1. Micro-wind turbine. It is assumed that the turbine is manufactured in the UK [8,28]. The turbine consists of a rotor, nacelle, tower, foundation and electronics. The rotor consists of three fibreglass blades and a cast iron hub, which serves as a base for the blades connecting them to the nacelle. The rotor also consists of stainless steel extenders to secure the blades to the hub. The nacelle houses the mechanical components of the turbine and is made from a stainless steel frame and fibreglass panelling. The yaw-system is made from low-alloyed steel (bearing) and stainless steel (brakes and hydraulics).

As indicated in Table 3, cast iron, chromium steel and low-alloyed steel are the main materials used for the mechanical components (shafts, gear box and generator). Aluminium and copper are also required for the generator. Aluminium, lead, copper, tin, low-alloyed steel, high density polyethylene, polypropylene and polyvinylchloride are the main materials assumed to be used for the electronic components and mains connection. The mast is made from low-alloyed steel galvanised with zinc. The exterior of

Table 2
General specification of the micro-wind turbine [20].

Lifetime	20 years minimum
Maintenance frequency	Once per year
Rated power (1 min average at 11 m/s)	6 kW
Peak power (1 min average)	6 kW
Annual energy output (at 5 m/s)	7800 kWh
Cut-in wind speed	3.5 m/s
Mast height	9 m
Number of blades	3
Rotor diameter	5.5 m
Blades	Carbon-fibre reinforced epoxy
Tower	Tubular galvanised steel
Foundation	Concrete block with anchor
Corrosion protection	Galvanised steel and other non-corrosive materials

Table 3
Inventory data for the micro-wind turbine.

Component, system or life cycle stage	Micro-wind turbine
Rotor	• Fibreglass reinforced plastic: 106 kg • Cast iron: 30 kg • Stainless steel: 52.54 kg
Nacelle	• Stainless steel: 91.38 kg • Fibreglass reinforced plastic: 22.84 kg
Mechanical components	• Stainless steel: 112.49 kg • Synthetic rubber: 1.20 kg • Cast iron: 71.96 kg • Aluminium: 2.72 kg • Copper: 6.47 kg • Copper wiring: 6.47 kg
Metalworking (rotor, nacelle and mechanical components)	• Aluminium sheet: 2.72 kg • Stainless steel sheet: 401.1 kg
Mast	• Epoxy resin: 14 kg • Welding: 32 m • Low-alloyed steel: 2017.49 kg • Zinc piecework: 591.66 m^2
Yaw system	• Low-alloyed steel: 18.66 kg • Lubricating oil: 3.8 kg • Stainless steel: 23.88 kg
Foundation	• Concrete: 9 m^3 • Low-alloyed steel: 901.19 kg
Electronic components	• Copper: 1.14 kg • High density polyethylene: 10.23 kg • Polyvinylchloride: 2.28 kg • Tin: 0.19 kg • Lead: 0.19 kg • Low-alloyed steel: 23.98 kg • Aluminium: 0.015 kg • Copper wiring: 1.14 kg • Low-alloyed steel sheet: 23.98 kg • Aluminium sheet: 0.015 kg
Mains connection	• Polypropylene: 7.61 kg • Copper: 83.76 kg • High density polyethylene: 83.38 kg • Polyvinylchloride: 60.16 kg • Copper wiring: 83.76 kg
Manufacturing	• Electricity (medium voltage): 790.85 MJ
Installation	• Explosive: 3.8 kg • Diesel: 19.30 MJ
Maintenance	• Lubricating oil: 31.98 kg
Decommissioning	• Steel: 61.7% recycled; 38.3% landfilled Aluminium: 90% recycled; 10% landfilled • Copper: 41% recycled; 59% landfilled • Glass–fibre reinforced plastic: 65% incinerated with energy recovery; 35% landfilled • Lubricating oil: 100% to hazardous waste incineration • Plastics: 100% landfilled

the tower is coated with paint. Steel-reinforced concrete is used for the foundation, which has a volume of 9 m^3.

2.2.1.2. Inverter. A 6000 W inverter is assumed to be integrated with the turbine. The inverter is made predominantly from steel, copper and aluminium. Other materials include plastics such as polyethylene, polyvinylchloride and polystyrene. Components include capacitors, transistors, resistors, inductors and diodes.

2.2.1.3. Installation. The installation of the turbine includes the excavation of an area for the foundation using explosives and machinery (e.g. concrete mixers, cranes, etc.) fuelled by diesel to produce the foundation and position the turbine.

2.2.1.4. Maintenance. The turbine is considered to be low-maintenance with one annual servicing by an engineer and the replacement of the gear box oil every four years. In addition, the inverter is replaced after 10 years.

2.2.1.5. Decommissioning. At the end of its service life the turbine is dismantled and metal components are recycled assuming the current UK recycling rates (see Table 3). All plastic materials are assumed to be landfilled, except for the fibreglass plastic 65% of which is incinerated and the rest landfilled. The system has been credited for the recycled materials and electricity recovery from incineration, with the latter assuming the displacement of the grid electricity.

2.2.1.6. Transport. Raw materials are assumed to be transported 100 km by lorry and 200 km by rail (see Table 4). The turbine is transported at a distance of 200 km by van to the installation location. The life cycle inventory data for transport have been sourced from Ecoinvent [24,29].

2.2.2. Grid electricity and solar PV

The UK electricity mix considered in this work is given in Fig. 4. Transmission and distribution losses of 13% are assumed [30]. For solar PV, the average size of UK installation of 3 kWp is considered [9], assuming an average global mix of PV technologies and an electrical efficiency of 8.6%, adapted for the UK insolation levels [31]. As mentioned previously, the system boundary for both grid electricity and solar PV is from cradle to grave, encompassing all activities from raw material extraction to final disposal (see Figs. 2 and 3). The lifetime of PV is assumed at 35 years during which the inverter is replaced once. The LCA data for grid electricity are from Ecoinvent [24] and for the PV from Stamford and Azapagic [31].

3. Results and discussion

3.1. Environmental impacts

The life cycle environmental impacts of the micro-wind turbine per kWh electricity are given in Fig. 5, in comparison with electricity from the grid and solar PV. As shown, the majority of impacts from grid electricity are higher than for the wind turbine, ranging from 26% higher terrestrial toxicity to 92% higher global warming.

Table 4
Summary of transport modes and distances for the micro-wind turbine.

Transport stage	Transport mode	Distance (km)
Raw materials for the turbine	Freight train	200
	Lorry > 16 tonne	100
Turbine installation	Lorry > 16 tonne	200
Maintenance	Van < 3.5 tonne (equipment to site)	200
	Van < 3.5 tonne (equipment to site)	200

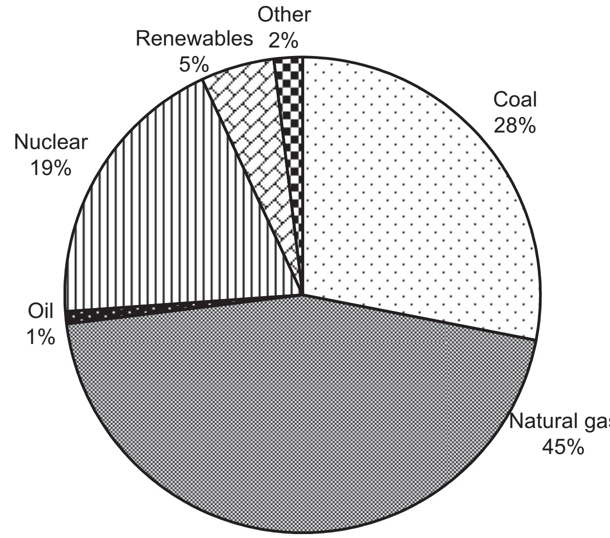

Fig. 4. The UK electricity generation mix in 2009 [32].

This is largely due to the emissions from combustion of fossil fuels used to generate electricity. The exception to this are depletion of elements, fresh-water and human toxicities which are 82%, 74% and 53% lower for grid electricity, respectively. The reason for this is the use of steel in wind turbines which leads to depletion of non-renewable resources (molybdenum) and emissions of heavy metals (chromium).

The results also suggest that the wind turbine is more environmentally sustainable than solar PV for seven out of 11 environmental categories, ranging from 7.5% lower eutrophication to 85% lower ozone layer depletion. However, depletion of fossil resources, fresh-water, human and terrestrial toxicities are higher for the wind turbine than for the PV, ranging from 5% for the former to 87% for the latter. This is again due to the use of steel as well as copper and the related impacts in their respective life cycles.

Fig. 6 indicates the contribution of different life cycle stages to the impacts. The major contributor is the manufacturing process, contributing on average 83.5% to the total, ranging from 35% for ozone depletion to 99.5% for terrestrial toxicity. As indicated earlier, this is mainly due to the high steel content of the turbine and the life cycle impacts associated with steel manufacture. Transport contributes on average around 13%, with the highest contribution of 53.5% to ozone depletion due to the emissions of halon 1311. Installation, maintenance and disposal contribute little to the environmental impacts, accounting for an average of 2%, 1% and 0.5%, respectively. No impacts are generated during the operation of the turbine. The following gives an overview of the main contributors to each environmental impact.

3.1.1. Abiotic depletion potential (ADP elements and fossil)

The wind turbine depletes 5.39 mg Sb eq./kWh of abiotic elements (Fig. 5). As shown in Fig. 6, 99% of this is incurred in the manufacturing stage due to the depletion of molybdenum used for steel production. The depletion of fossil fuels is estimated at 1.15 MJ/kWh. This is again in the manufacturing stage which contributes 85.5% to the total consumption of fossil fuels due to energy used for steel production.

3.1.2. Acidification potential (AP)

This impact is estimated at 0.31 g SO_2 eq./kWh. The major contributor are SO_2 emissions from the generation of energy used for copper and steel production.

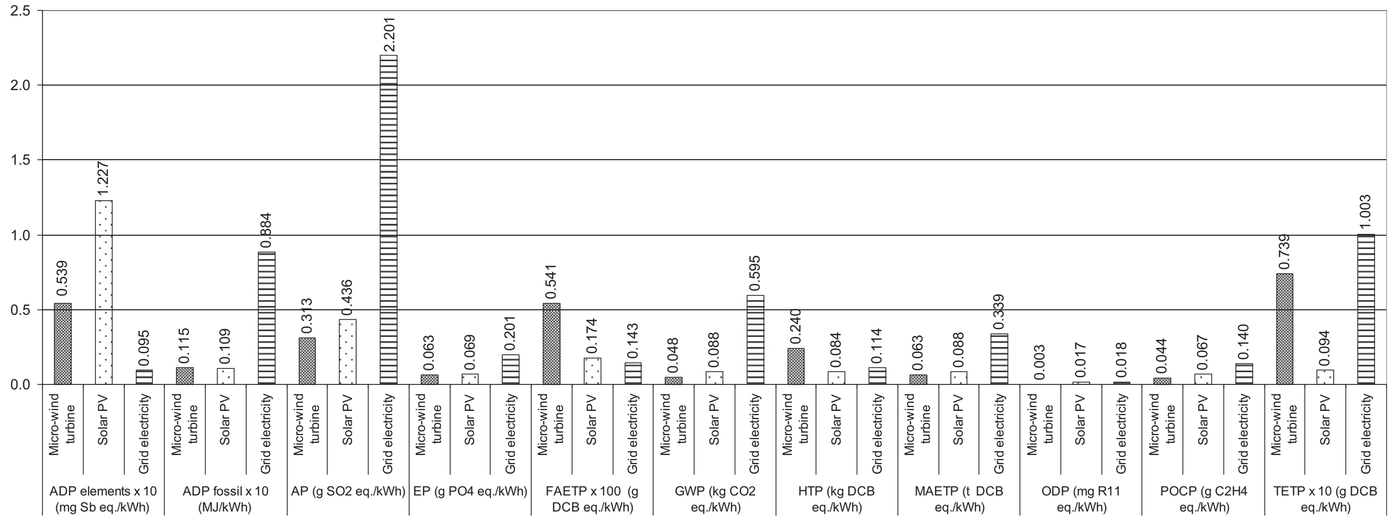

Fig. 5. Life cycle environmental impacts of the micro-wind turbine compared to grid electricity and solar PV. ADP elements: abiotic resource depletion of elements; ADP fossil: abiotic resource depletion of fossil fuels; AP: acidification potential; EP: eutrophication potential; FAETP: fresh-water aquatic ecotoxicity potential; GWP: global warming potential; HTP: human toxicity potential; MAETP: marine aquatic ecotoxicity potential; ODP: ozone layer depletion potential, POCP: photochemical oxidant creation potential; TETP: terrestrial ecotoxicity potential. DCB: dichlorobenzene.

3.1.3. Eutrophication potential (EP)

The EP for the wind turbine is equal to 0.06 g PO_4 eq./kWh, with 73% arising from steel manufacturing and particularly the emissions of NO_x related to the energy used for steel production.

3.1.4. Fresh-water aquatic eco-toxicity potential (FAETP)

The FAETP is estimated at 54.13 g DCB eq./kWh. Emissions of cobalt, nickel and vanadium to fresh water, predominantly during steel manufacture, are the main contributors (99%) to this impact.

3.1.5. Global warming potential (GWP)

Estimated at 48.2 g CO_2 eq./kWh, this impact is mainly due to CO_2 emissions from the energy used to manufacture the turbine components (in particular steel) and for the assembly of the turbine.

3.1.6. Human toxicity potential (HTP)

The emissions of chromium to air during turbine manufacture are the main contributor (99.5%) to this impact, estimated at 0.24 kg DCB eq./kWh.

3.1.7. Marine aquatic eco-toxicity potential (MAETP)

Wind turbines emit 0.06 t DCB eq./kWh, 97.5% of which is from hydrogen fluoride emissions to air and heavy metal (Ni and Co) emissions to fresh water during steel manufacture.

3.1.8. Ozone depletion potential (ODP)

The estimated value for ODP is 0.003 mg R11 eq./kWh. Emissions of halons (1211 and 1311) during the transport of the fixed parts (53.5%) and the production of the concrete, fibreglass and steel (35%) are the major contributors to this impact.

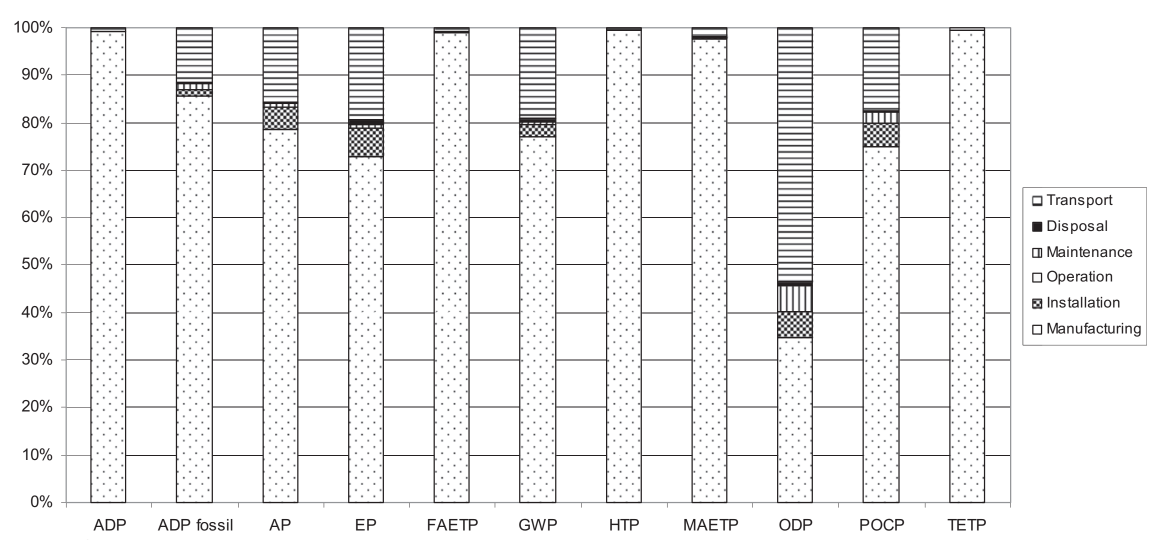

Fig. 6. Contribution of different life cycle stages to the life cycle impacts of the micro-wind turbine. For impacts nomenclature, see Fig. 5.

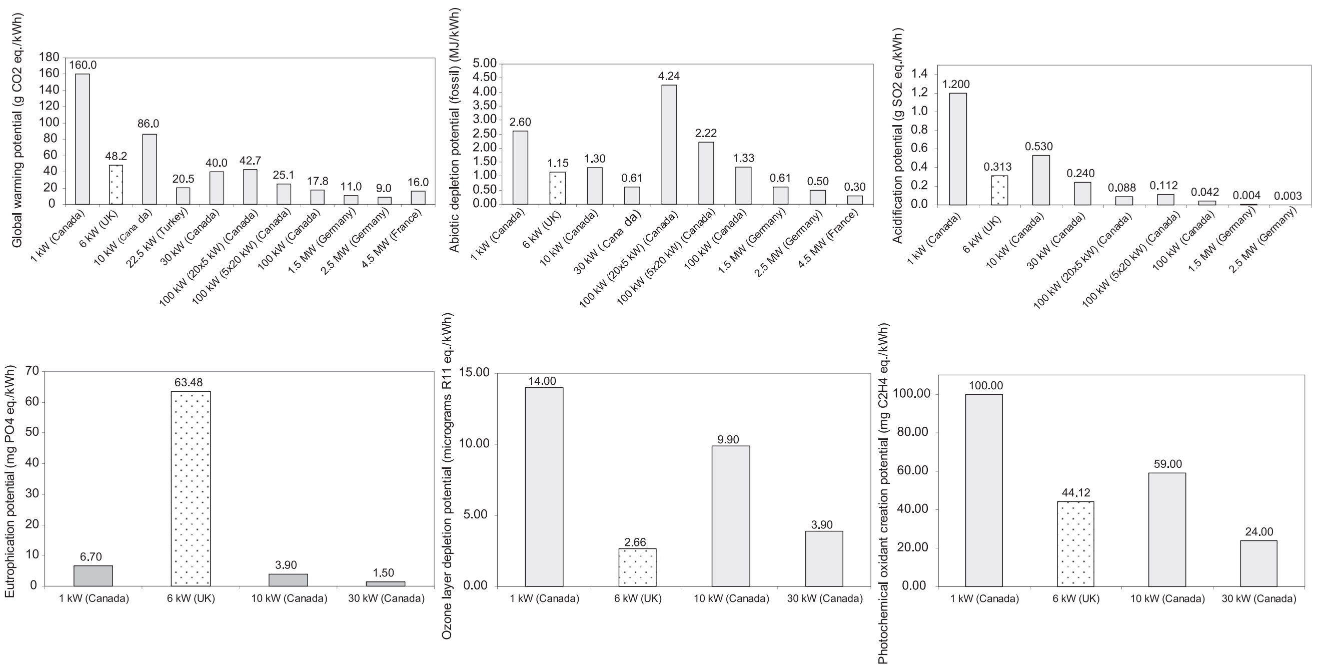

Fig. 7. Comparison of environmental impacts of wind turbines reported in different studies. Sources: 1 kW (Canada): [34]; 6 kW (UK): This study; 10 kW (Canada): [34]; 22.5 kW (Turkey): [43]; 30 kW (Canada): [34]; 100 kW (20 × 5 kW) (Canada), 100 kW (5 × 20 kW) (Canada), 100 kW (Canada): [42]; 1.5 MW (Germany), 2.5 MW (Germany): [44]; 4.5 MW (France): [40]. The study by Kabir et al. [42] considered different configurations of wind farms: 5 turbines of 20 kW and 20 turbines of 5 kW capacity. Most studies considered only GWP, ADP fossil and AP, except for Amor et al. [34] which also considered EP, ODP and POCP.

3.1.9. Photochemical oxidant creation potential (POCP)

Emissions of CO and SO_2 during the production of steel contribute 75% to this impact, estimated at 0.04 g C_2H_4 eq./kWh. The next largest contributor (17.5%) are non-methane volatile organic compounds from transport.

3.1.10. Terrestrial eco-toxicity potential (TETP)

The TETP is estimated at 7.39 g DCB eq./kWh. This is almost exclusively (99.5%) due to the emissions of heavy metals to air, predominantly chromium from steel production.

3.2. Comparison of results with literature

A number of LCA studies of wind turbines have been carried out [33–45] but direct comparison of the results among them is difficult due to different assumptions, including turbine capacities, energy outputs, load factors,[1] lifetimes and geographical regions where the turbines are installed. Different background data, such as national energy mixes assumed for the manufacture of turbines, also lead to different results. For these reasons, as illustrated in Fig. 7, the environmental impacts of wind turbines reported in different studies vary greatly. For example, the GWP ranges from 9 to 160 g CO_2 eq./kWh for the capacities ranging from 1 kW to 4.5 MW. At 48 g CO_2 eq./kWh, the GWP estimated in this study for the 6 kW turbine falls within this range. As there are no other studies for this capacity, the nearest turbine size available in literature is 10 kW for which the GWP is estimated at 86 g CO_2 eq./kWh [34]. Apart from different countries in which these turbines are assumed to be installed (UK and Canada), the reasons for the difference in the results include the fact that recycling is not considered for the 10 kW turbine and transportation distances from supplier to installation are much larger (1500 km compared to 200 km for the 6 kW turbine). Similar differences are observed for the other environmental impacts, except for eutrophication, for which the 6 kW turbine considered here has a much higher impact than the 10 kW installation in Amor et al. [34]: 63.48 vs 3.9 mg PO_4 eq./kWh. This is due to different methodologies used to estimate the EP in the two studies, with the current study considering both nitrogen and phosphorous emissions to the aquatic and terrestrial ecosystems (as in the CML 2001 methodology) while the study by Amor et al. considered only phosphorous emissions to water, using the Impact 2002+ methodology [46]. As NOx emissions from the steel life cycle contribute to the EP significantly (see the above summary for the EP), this means that this impact is underestimated in the Amor et al. study.

The results also suggest that there is no apparent relationship between the environmental impacts and the size of the turbine, although on average, micro-turbines (up to 100 kW) have higher GWP, ADP fossil and AP than the larger turbines (>1.5 MW); see Fig. 7. This is due to a much lower amount of electricity generated over the lifetimes of the micro-turbines compared to the larger scale installations. For example, the 4.5 MW turbine produces 1.7 GWh of electricity per year and has a GWP of 9 g CO_2 eq./kWh [40]. In contrast, the 1 kW turbine generates only 2314 kWh/year and its GWP is 160 g CO_2 eq./kWh [34]. Therefore, the findings from these studies would suggest that larger-scale turbines are environmentally more sustainable than micro-installations.

3.3. Sensitivity analysis

The amount of energy generated by a wind turbine is one of the key factors that determines its environmental impacts. The energy output is in turn determined by the load factor and the lifetime of the turbine. Therefore, the next sections explore the influence of these two parameters on the environmental sustainability of the 6 kW turbine.

[1] Load factor is a percentage of the actual energy output of a turbine compared to its rated capacity.

Table 5
Range of annual load factors and corresponding energy outputs considered in the sensitivity analysis.

Load factor (%)	Annual energy output (kWh/yr)
14.8	7800
18.3	9600
19.0[a]	10,000
21.7	11,400
24.0	12,600
27.4	14,400
30.8	16,200
34.2	18,000

[a] Average annual load factor for free-standing micro-turbines in the UK [13].

3.3.1. Load factor

A field trial of micro-wind turbines in the UK found that the average load factor for free-standing installations was 19%, with a maximum of over 30% at best (rural) sites [13]. Therefore, a range of annual load factors and the corresponding energy outputs are considered (see Table 5) in line with these findings to find out the effect on the life cycle environmental impacts from the wind turbine. These results are compared to the base-case load factor assumed in this study of 14.8%, based on manufacturer's specification [20].

The results in Fig. 8 indicate that the environmental sustainability of the micro-wind turbine improves with load factors as the energy output of the turbine is increased. For example, for the UK average annual load factor of 19%, the environmental impacts are reduced by around 21% compared to the load factor of 14.8% assumed in this study. For instance, the GWP reduces from 48 to 38 g CO_2 eq./kWh. For the annual load factor of 34.2%, the environmental impacts are 57% lower than for the base load factor of 14.8%, with the GWP estimated at 21 g CO_2 eq./kWh. The same trend is observed for all other environmental impacts. This is summarised in Table 6, which shows the relationships between load factors and different environmental impacts obtained as part of this work. These can be used to estimate the impacts for load factors at specific sites.

Although the installation of a turbine in locations where higher annual load factors can be achieved improves its environmental sustainability, even for the highest load factors, some impacts are still higher for the wind turbine than for grid electricity, notably depletion of elements and fresh-water toxicity (see Fig. 9). However, the turbine with the highest load factor of 34.2% would have 35% lower ozone layer depletion and 9% lower human toxicity than grid electricity, in contrast to the lower load factors for which these impacts from the wind turbine are higher than from grid electricity. It should be noted that if in future carbon capture and storage (CCS) technologies become available, the GWP of the grid electricity would be somewhat reduced but would still be higher than for the wind turbines. For example, Odeh and Cockerill [47] suggest that for a 90% capture efficiency, the GHG emissions from coal power plants with CCS could reduce by 75–84%, from around 1 to approximately 0.2 kg CO_2 eq./kWh, depending on the technology used. This would mean that for the current contribution of coal to the grid electricity of 28%, the GWP of the grid would go down from 0.595 kg CO_2 eq./kWh to around 0.36 kg CO_2 eq./kWh. However, at the same time, the increase in other air pollutants such as NO_x and NH_3 would lead to higher eutrophication and acidification potentials [47].

Comparison of the impacts with solar PV reveals that for the highest load factor the fresh-water, human and terrestrial toxicities remain higher for the wind turbine than for the PV, the same trend

Table 6
Equations for estimating the environmental impacts of micro-wind turbines for different load factors (LF).

Environmental impact[a]	Equation[b]
ADP elements (mg Sb eq./kWh)	ADP el. $= 92 \times LF^{-1.043}$
ADP fossil (MJ/kWh)	ADP f. $= 19.607 \times LF^{-1.043}$
AP (g SO_2 eq./kWh)	AP $= 5.3398 \times LF^{-1.043}$
EP (g PO_4 eq./kWh)	EP $= 1.083 \times LF^{-1.043}$
FAETP (g DCB eq./kWh)	FAETP $= 923.55 \times LF^{-1.043}$
GWP (kg CO_2 eq./kWh)	GWP $= 0.8224 \times LF^{-1.043}$
HTP (kg DCB[c] eq./kWh)	HTP $= 4.096 \times LF^{-1.043}$
MAETP (t DCB eq./kWh)	MAETP $= 1.0814 \times LF^{-1.043}$
ODP (mg R11 eq./kWh)	ODP $= 4.54 \times LF^{-1.043}$
POCP (g C_2H_4 eq./kWh)	POCP $= 0.7527 \times LF^{-1.043}$
TETP (g DCB eq./kWh)	TETP $= 126.17 \times LF^{-1.043}$

[a] For impacts nomenclature, see Fig. 5.
[b] Regression coefficient for all equations: $r^2 = 0.9921$.
[c] DCB: dichlorobenzene.

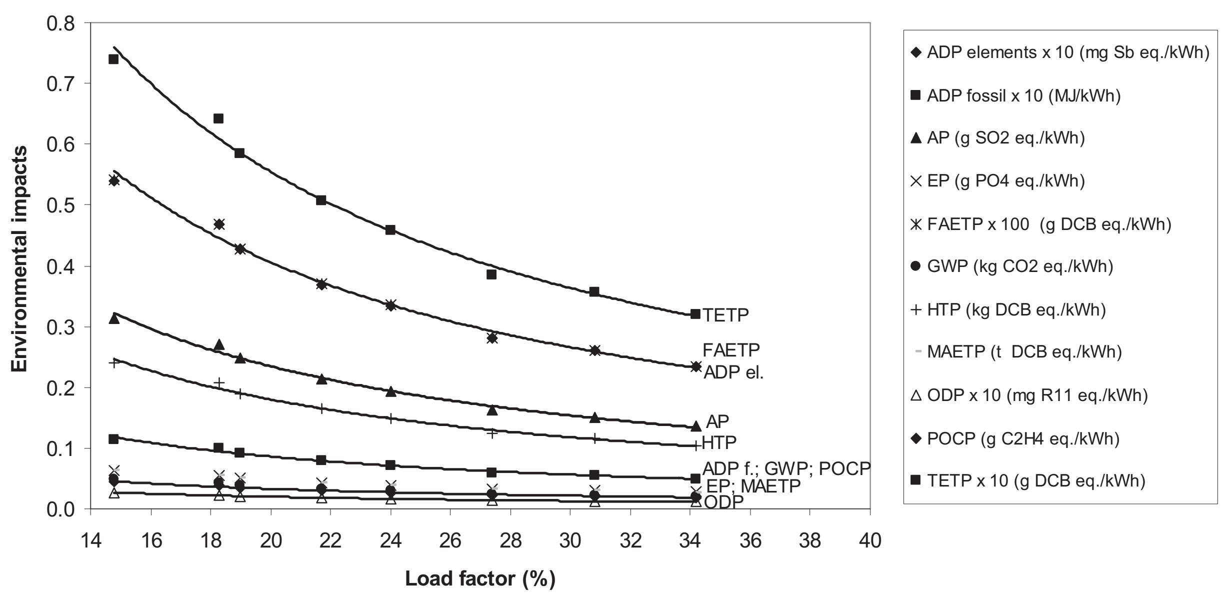

Fig. 8. The influence of the load factor on the environmental impacts of the micro-wind turbine. For impacts nomenclature, see Fig. 5.

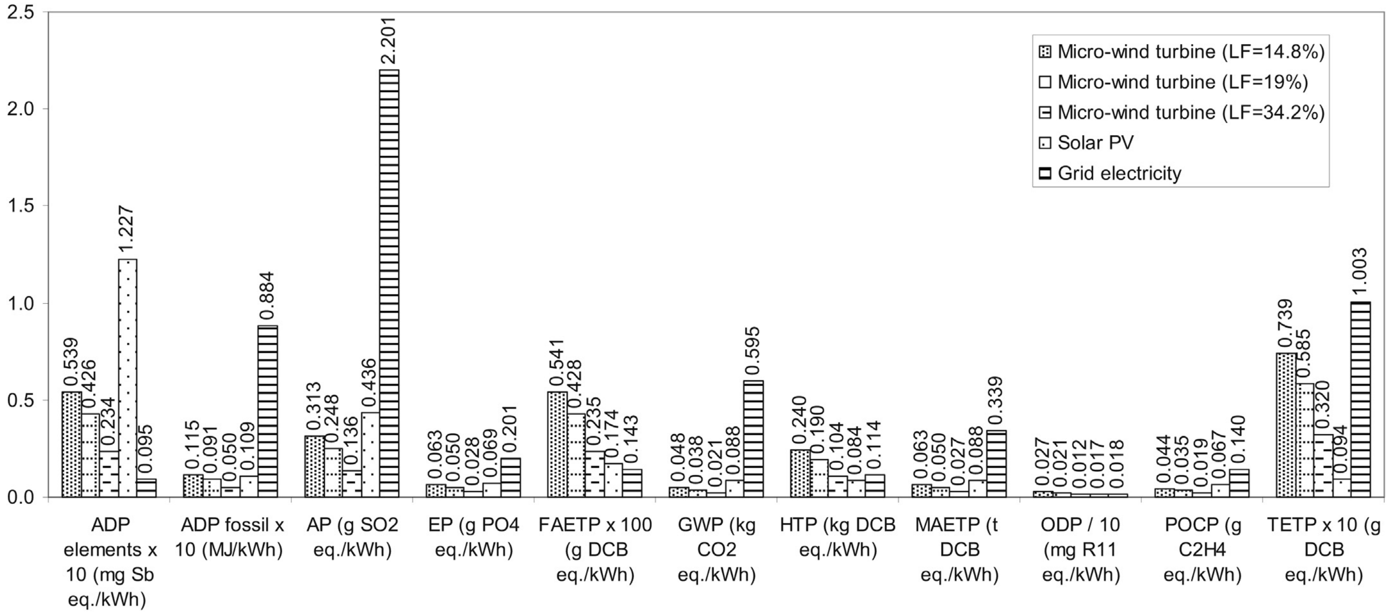

Fig. 9. Environmental impacts of micro-wind turbine compared to grid electricity and solar PV for the average and highest load factors recorded for free-standing micro-wind turbines in the UK. LF = 14.8%: load factor assumed in this study. LF = 19% and LF = 34.2%: average and highest load factors, respectively, recorded in the UK [13]. For the impacts, nomenclature, see Fig. 5.

found for the base load factor assumed (14.8%). However, depletion of fossil resources is now 54% lower than for the PV.

3.3.2. *Lifetime*

The lifetime of a turbine depends on many factors, including the quality of the turbine and the local climatic conditions. Most manufacturers assume the lifetime of 20 years although the lifetime of between 15 and 30 years has also been claimed [48]. Since micro-wind turbines are still a new technology, it is not clear yet how long they can actually last. We therefore consider the influence of different lifetimes on the environmental impacts of turbines, ranging from 15 to 30 years.

As can be observed in Fig. 10, the impacts decrease with longer lifetimes owing to the higher energy outputs. For example, for a lifetime of 30 years, the impacts are reduced on average by 30% compared to the 20 years originally assumed. This is despite the fact that the inverter would need replacing 2 or 3 times over the time. By contrast, the lifetime of 15 years would increase the environmental impacts on average by 23% compared to 20 years.

However, even if operating for 30 years, depletion of elements, fresh-water and human toxicities remain higher than for grid electricity (see Fig. 11) as was the case for the 20 years. Similar is true for the impacts relative to solar PV: fresh-water, human and terrestrial toxicities remain higher for the wind turbine than for the PV even at 30 years, although depletion of fossil resources is in that case 28% lower than for the solar option.

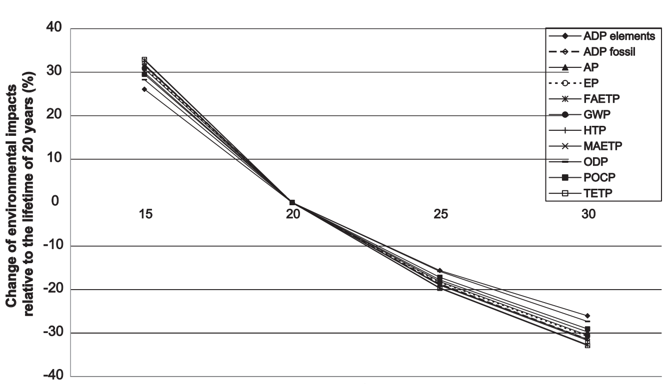

Fig. 10. The influence of lifetime on the environmental impacts of the micro-wind turbine. For impacts nomenclature, see Fig. 5.

4. Environmental implications of UK-wide deployment of micro-wind turbines

The results discussed in the previous section suggest that micro-wind turbines have potential to reduce some environmental impacts and worsen others compared to grid electricity. It is, therefore, important that the implications of a projected future UK-wide deployment of micro-wind turbines are explored to inform future policy decision making. We first examine the life cycle environmental implications of displacing grid electricity by an equivalent amount of energy generated by micro-wind turbines. This is followed by an analysis of direct[2] GHG emissions to find out what potential role micro-wind turbines could play in helping the UK achieve its climate change targets.[3] Prior to that, the assumptions used for these estimates are outlined below.

4.1. *Assumptions*

The estimates of the potential for micro-wind installations in the UK range widely. The field trials by EST [13] taking into account the minimum required wind speed of 5 m/s suggest that the maximum potential for domestic micro-turbines is around 456,000 installations. A market review by the renewable energy trade association BWEA [12] suggests that this potential is around 600,000 installations. More optimistic estimates put this figure at 1.3 million

[2] Direct emissions are emitted during generation of electricity, as opposed to indirect emissions which are emitted in the rest of the life cycle. For grid electricity, direct emissions are those from combustion of fossil fuels. In the case of wind turbine, there are no direct emissions from generation of electricity so that all the emissions are generated in the rest of the life cycle.

[3] Climate change targets are for direct GHG emissions.

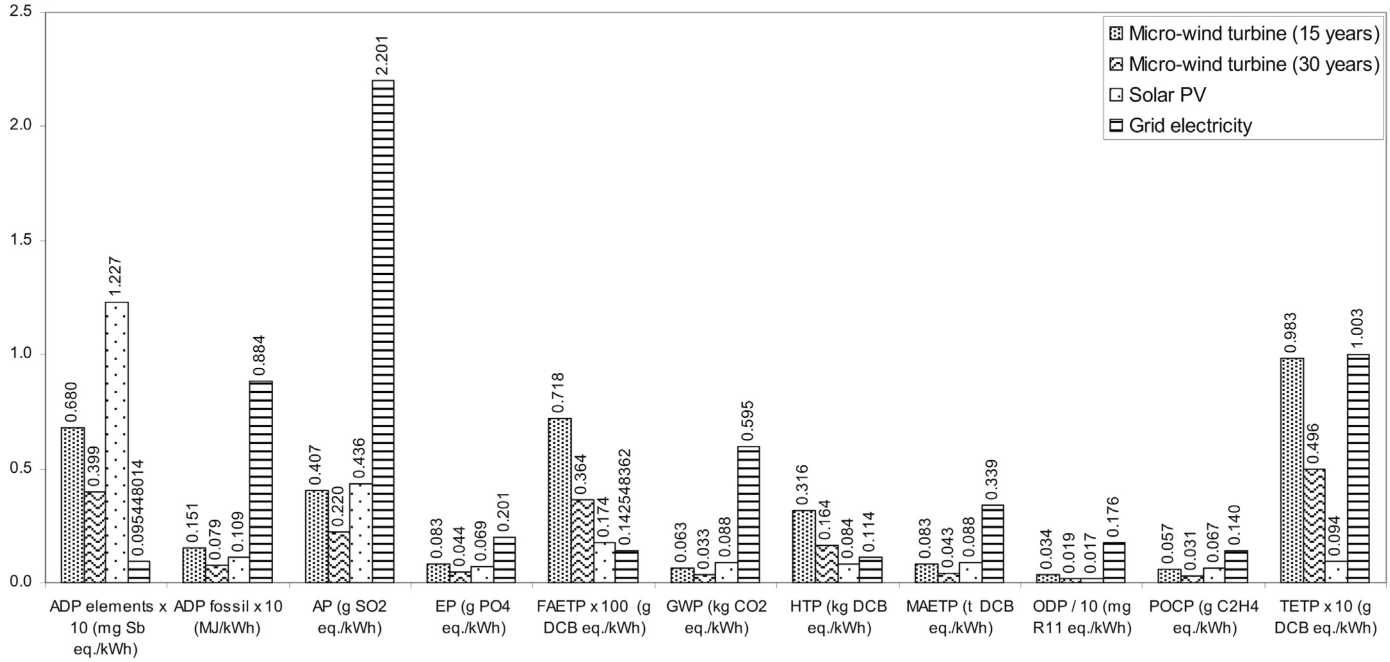

Fig. 11. Environmental impacts of the micro-wind turbine compared to grid electricity and solar PV for different lifetimes of the turbine. For impacts nomenclature, see Fig. 5.

by 2020 at the current level of FiT payments of around 30 p/kWh [39]; however, this projection does not take into account the suitability of the sites with respect to the wind speed. Nevertheless, in these calculations, we take the optimistic approach and assume 1.3 million installations, of which around half (676,000) are assumed to be free-standing turbines such as the one considered in this work. This number of free-standing installations is based on the EST's field trials [13] which suggest a roughly equal split between the potential for the free-standing and building-mounted turbines, taking into account the minimum requirement for the wind speed of 5 m/s.

In 2009 there were 27.108 million dwellings in the UK [40] each consuming on average 3281 kWh of electricity per year [49]. This equates to an overall domestic electricity consumption of 88.94 TWh per year. Assuming the 6 kW turbine generating 7800 kWh per year as considered in this study means that 676,000 micro-wind turbines would generate 5.27 TWh of grid electricity per year, displacing the need to generate the equivalent amount of grid electricity. To estimate the implications for the life cycle environmental impacts due to this, the life cycle impacts of the 6 kW turbine estimated in this study have been scaled up for 676,000 turbines. The methodology used for these estimates is outlined in the Appendix and the results are discussed below.

4.2. Life cycle impacts

The life cycle impacts of grid electricity with and without the micro-wind turbines are compared in Fig. 12. As indicated, eight out of 11 environmental impacts would be reduced if the micro-wind turbines were installed. However, in most cases the savings are relatively small. For example, the current GWP from domestic electricity provision without the micro-wind is estimated at 52.95 Mt CO_2 eq./yr

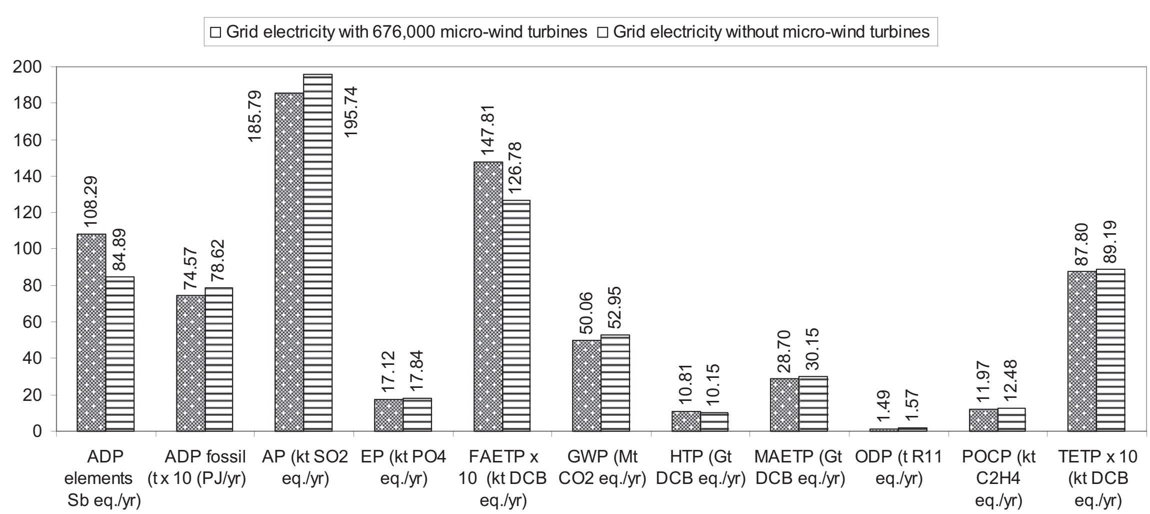

Fig. 12. Comparison of life cycle environmental impacts from electricity with and without micro-wind turbines. For estimates, see the Appendix. UK electricity mix in 2009 assumed [32]. For impacts nomenclature, see Fig. 5.

Table 7
Direct GHG emissions from grid electricity with and without micro-wind turbines [for estimates in this table, see the Appendix].

Power mix	Emissions per kWh (kg CO_2 eq./kWh)	Annual UK emissions from electricity (Mt CO_2 eq./yr)	Annual UK emissions from the domestic sector other than electricity (Mt CO_2 eq./yr)	Total annual UK emissions (Mt CO_2 eq./yr)
Grid electricity without micro-wind turbines	0.595	52.92	147.20[b]	566.30[b]
Grid electricity with 676,000 micro-wind installations	0.595[a]	49.78	144.06	563.16[c]

[a] There are no direct emissions from wind turbines.
[b] Reference year: 2009. Source: [30].
[c] Assuming the electricity mix in 2009 [30].

while that with 676,000 turbines is equal to 50.06 Mt CO_2 eq./yr, a saving of only 5.5%. A slightly smaller (4%) savings are observed for the other seven impacts. These relatively small reductions are a consequence of the limited number of sites suitable for domestic micro-wind, which means that over 26.4 million dwellings would still rely solely on grid electricity. Note that these estimates assume an optimistically high number of micro-wind installations. If the lower estimate of 237,000 installations was considered instead, based on the EST's estimates for the potential for the free-standing turbines [13], these savings would be much smaller, ranging from 0.5% for terrestrial toxicity to 2% for GWP.

On the other hand, the increase in some of the impacts would be much higher. For example, the depletion of abiotic elements would go up by 22%; fresh-water toxicity would be higher by 14%; and human toxicity would increase by 6%. As discussed earlier, this is due to the higher steel content of the turbine per unit of electricity generated in comparison to grid electricity.

Thus, some environmental trade offs will be needed if micro-wind turbines are to play a role in supplying future domestic electricity. Arguably, the main driver for micro-wind turbines is that they save GHG emissions compared to grid electricity. However, the question is whether these savings are significant enough to help the UK meet its climate change targets. The next section explores this issue; for estimates see the Appendix.

4.3. Direct GHG emissions

As indicated in Table 7, direct GHG emissions from the domestic electricity provision in 2009 are estimated at 52.92 Mt CO_2 eq./yr. With the assumed 676,000 installations of micro-wind turbines, these emissions decrease to 49.78 Mt CO_2 eq./yr, saving annually 3.14 Mt CO_2 eq. For the whole domestic sector, this equates to a saving of 2% (down from 147.2 to 144.06 Mt CO_2 eq./year; see Table 7). At the national level, this represents an additional saving of only 0.6% on the actual GHG emission reductions achieved in 2009 (from 566.3 to 563.16 Mt CO_2 eq./year; Table 7). Even if the number of the micro-wind turbines is doubled to 1.3 m installations [14], assuming that all the installations are free-standing, the saving would still be only around 1%. If a less optimistic assumption is made than in the estimates used here, assuming 237,000 installations [13], only 0.75% of the GHG emissions would be saved in the domestic sector and 0.2% at the national level. This therefore demonstrates the very limited potential of micro-wind turbines to contribute towards the UK climate change targets, particularly given that the field trials found that only a third of free-standing turbines had average annual wind speeds of 5 m/s or greater [13].

5. Conclusions

The results from this study suggest that per kWh of electricity generated, the majority of environmental impacts from the wind turbine are lower than from grid electricity, ranging from 26% lower terrestrial toxicity to 92% lower global warming. The exceptions to this are depletion of abiotic elements, fresh-water and human toxicities which are 82%, 74% and 53% lower for grid electricity, respectively. This is largely due to the steel content in the turbine which contributes on average 83.5% to its impacts.

The results also suggest that the wind turbine is more environmentally sustainable than solar PV for seven out of 11 environmental categories, ranging from 7.5% lower eutrophication to 85% lower ozone layer depletion. However, depletion of fossil resources, fresh-water, human and terrestrial toxicities are higher for the wind turbine than for the PV, ranging from 5% for the former to 87% for the latter. This is again due to the use of steel as well as copper and the related impacts in their life cycles.

Situating the turbine in a location where high annual load factors are achievable can reduce its environmental impacts substantially. For example, for the UK average annual load factor of 19%, the environmental impacts are reduced by around 32% compared to the base load factor of 14.8%. For the annual load factor of 34.2%, the environmental impacts are 57% lower than for the base load factor. Longer lifetimes can also reduce the environmental impacts of the turbine. For instance, increasing the lifetime from 20 to 30 years, reduces the impacts by up to 30%.

UK-wide deployment of micro-wind turbines would reduce the life cycle environmental impacts compared to grid electricity. For example, with 676,000 installations, the global warming potential of electricity provision in the domestic sector would go down by 5.5% relative to the current situation. The majority of other life cycle impacts would be reduced on average by 4%. However, the depletion of abiotic elements would go up by 22%, fresh-water toxicity would be higher by 14% and human toxicity would increase by 6%. For a smaller number of installations, the environmental savings would be much smaller. Assuming 237,000 turbines, the reductions in impacts would range from 0.5% for terrestrial toxicity to 2% for GWP.

With 676,000 of micro-wind installations, 3.14 Mt CO_2 eq. of direct GHG emissions would be saved annually. This is due to the avoidance of the emissions from combustion of fossil fuels for generation of grid electricity. For the whole domestic sector, this equates to a saving of 2%. At the national level, this represents a saving of only 0.6% on the actual GHG emission reductions achieved in 2009. Even if the already optimistic assumption of 676,000 installations is doubled to 1.3 m, the GHG savings would still be only around 1%. For a more realistic assumption of 237,000 micro-turbines, only 0.75% of the GHG emissions would be saved in the domestic sector and 0.2% at the national level. Therefore, these results suggest that micro-wind turbines have little potential to contribute towards the UK's climate change targets, even for the most optimistic assumptions in terms of their market penetration.

Acknowledgements

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Appendix

A1. Estimation of life cycle impacts

The annual life cycle impacts of domestic electricity provision with and without the micro-wind turbines have been calculated as follows (note that the figures shown below have been rounded off):

i) With micro-wind turbines

- Annual life cycle impacts of 676,000 micro-wind turbines producing 5.27 TWh/yr (676,000 × 7800 kWh/yr):
  (1) Annual life cycle impact of micro-wind turbines (t eq./yr) = total electricity supplied by turbines (5.27 TWh/yr) × life cycle impact of turbine per kWh (t eq./kWh)
- Remaining domestic electricity supply met by grid electricity:
  (2) Remaining domestic electricity supply = total domestic electricity supply (88.94 TWh/yr) − domestic electricity supply by turbines (5.27 TWh/yr) = 83.67 TWh/yr
- Annual life cycle impacts of grid electricity supplying 83.67 TWh/yr of domestic electricity:
  (3) Annual life cycle impact of grid electricity (t eq./yr) = electricity demand supplied by grid electricity (83.67 TWh/yr) × life cycle impact of grid electricity per kWh (t eq./kWh)
- Total life cycle impacts of micro-wind turbines and grid electricity:
  (4) Total life cycle impacts (turbine + grid electricity) = (1) + (3).

ii) Without micro-wind turbines

- Annual life cycle impacts of grid electricity for the domestic demand met by the grid (88.94 TWh/yr):
  (5) Annual life cycle impacts of grid electricity (t eq./yr) = electricity demand supplied by grid electricity (88.94 TWh/yr) × life cycle impact of grid electricity per kWh (t eq./kWh)

The results of (4) and (5) are then compared to estimate the difference in life cycle environmental impacts with and without micro-wind turbines.

A2. Estimation of direct GHG emissions

For estimations detailed below, see also data in Table 7.

i) Without micro-wind turbines

- Direct emissions from domestic electricity demand met using grid electricity:
  (1) Annual direct emissions from grid electricity (Mt CO_2 eq./yr) = electricity demand supplied by grid electricity (88.94 TWh/yr) × CO_2 emissions from grid electricity per kWh (0.595 kg CO_2 eq./kWh) × 10^{-6} (Mt) = 52.92 Mt CO_2 eq./yr
- Direct emissions from the domestic sector other than electricity provision:
  (2) Direct emissions from the domestic sector other than electricity (Mt CO_2 eq./yr) = Total emissions from the domestic sector (147.2 Mt CO_2 eq./yr) − Annual direct emissions from grid electricity (52.92 Mt CO_2 eq./yr) = 94.28 Mt CO_2 eq./yr
- Direct emissions from sectors other than domestic:
  (3) Direct emissions from other sectors (Mt CO_2 eq./yr) = Total UK annual emissions (566.3 Mt CO_2 eq./yr) − Annual direct emissions from the domestic sector (147.2 Mt CO_2 eq./yr) = 419.1 Mt CO_2 eq./yr

ii) With micro-wind turbines

- Annual direct emissions from 676,000 of turbines supplying 5.27 TWh/yr of electricity:
  (4) Annual direct emissions from turbines (Mt CO_2 eq./yr) = total electricity supplied by turbines (5.27 TWh/yr) × emissions from turbines per kWh (0 kg CO_2 eq./kWh) × 10^{-6} (Mt) = 0 Mt CO_2 eq./yr
- Remaining domestic electricity supply met by grid electricity:
  (5) Remaining domestic electricity supply = total domestic electricity supply (88.94 TWh/yr) − domestic electricity supply by turbines (5.27 TWh/yr) = 83.67 TWh/yr
- Annual direct emissions from grid electricity supplying the remaining 83.67 TWh/yr of domestic electricity demand:
  (6) Annual direct GHG emissions from grid electricity (Mt CO_2 eq./yr) = electricity demand supplied by grid electricity (83.67 TWh/yr) × direct emissions from grid electricity per kWh (0.595 kg CO_2 eq./kWh) × 10^{-6} (Mt) = 49.78 Mt CO_2 eq./yr
- Total direct emissions grid electricity with micro-wind:
  (7) Total direct GHG emissions grid electricity with the wind turbines (Mt CO_2 eq./yr) = (4) + (6) = 0 Mt CO_2 eq./yr + 49.78 Mt CO_2 eq./yr = 49.78 Mt CO_2 eq./yr
- Total direct domestic emissions other than from electricity when micro-wind is considered as part of the electricity mix:
  (8) Total domestic emissions with micro-wind turbines (Mt CO_2 eq./yr) = (2) + (7) = 94.28 Mt CO_2 eq./yr + 49.78 Mt CO_2 eq./yr = 144.06 Mt CO_2 eq./yr
- Total UK direct emissions for all sectors when micro-wind is considered as part of the electricity mix:
  (9) Direct emissions from other sectors with micro-wind included in the electricity mix (Mt CO_2 eq./yr) = (3) + (8) = 419.1 Mt CO_2 eq./yr + 144.06 Mt CO_2 eq./yr = 563.16 Mt CO_2 eq./yr.

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