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The carbon payback of micro-generation: an integrated hybrid input-output approach

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Abstract: Feed-in tariffs (FiTs) in the UK have been introduced to stimulate growth in small-scale renewables such as photovoltaics and micro-wind. They form one of the UK's key policies to decarbonise electricity by 2030. However, the evidence used to inform the policy was predominantly related to costs, capacity and deployment; not contribution to meeting decarbonisation targets. This paper employs an integrated hybrid lifecycle assessment method, which overcomes boundary limitations of traditional process-based assessments, to measure the full lifecycle emissions of solar PV and micro-wind technologies eligible under FiTs. Environmental assessments of policies often don't take account of the lifecycle emissions of technologies, therefore underestimating their emissions contribution and overestimating the success of policies towards decarbonisation targets. Considering the full lifecycle emissions, the paper assesses the effectiveness of FiTs for driving the UK's low carbon transition. The results demonstrate that, while there is still significant variation and uncertainty with such estimates, even with the most conservative figures, both the technologies can offer substantial emission savings compared to fossil fuel alternatives when installed in suitable locations. However, the renewable resource of installation sites is critical to the carbon intensity that the technologies can offer. Under a poor renewable resource their impacts can be as high as fossil fuels alternatives. As FiTs makes no distinction between installation sites this should form part of the assessment of funding. Finally, despite their potential for carbon reduction, with the full lifecycle of the considered technologies taken into account, a target of 50 gCO_2e/kWh is not possible with the current technology generation efficiencies. The paper concludes that a complete re-assessment of the role of technologies in the decarbonisation of electricity is required to take into account the full lifecycle impacts to gain a more realistic picture of the mitigation potential.

Highlights

- We apply novel lifecycle analysis methodology to solar PV and micro-wind technologies
- We explore the implications of lifecycle emissions for meeting decarbonisation targets
- A 50 gCO_2e/kWh target cannot be achieved for the case studies considered
- Availability of renewable resource is critical to the carbon intensity of electricity generation

- The effectiveness of feed-in tariffs for driving decarbonisation in the UK is evaluated

Key words: Energy, Hybrid integrated input-output lifecycle analysis, Feed-in Tariffs, Microgeneration, Decarbonisation.

Nomenclature

CCS	-	Carbon capture and storage
CSP	-	Concentrated Solar Power
FiTs	-	Feed-in Tariffs
gCO_2e	-	Grams of carbon dioxide equivalent
IPCC	-	International Panel on Climate Change
kWh / MWh / TWh	-	Kilowatt hour / Megawatt hour / Terawatt hour
kWp	-	Kilowatt peak
LCA	-	Lifecycle analysis
m	-	metres
m/s	-	Metres per second
PV	-	Photovoltaic
UK	-	United Kingdom

1 Introduction

Carbon budgets have been devised to ensure the UK is on track to meet its legislative 80 % greenhouse gas emission reduction target by 2050 from 1990 levels [1]. Reasonable evidence exists that electricity generation will have to be at 50 gCO_2e/kWh for electricity by 2030 in order to meet these targets. The UK's electricity intensity in 2010 stood at 494 gCO_2e/kWh [2] and has climbed since then as the proportion of coal in electricity generation has increased. Of the 382 TWh of electricity generated in 2011, 7 % was from renewable sources (26 TWh) [3]. The Committee on Climate Change suggests that 30 – 40 GW of additional low carbon supply is needed to meet the decarbonisation target by 2030 [4].

Feed-in tariffs (FiTs) are one of a package of policies aiming to drive innovation in low carbon technologies and stimulate growth by providing price certainty in the market. Feed-in tariffs are available for a range of renewable electricity generating technologies up to a 5 MW rating and are the main incentive for the installation of micro-generation technologies. Since their introduction in April 2010 they have caused a revolution in uptake of solar photovoltaics (PV), resulting in significant growth in installations to the current installed capacity of over 1.5 GW by the end of May 2013 (rising from under 1 MW of capacity before its introduction) [5].

FiTs do not discriminate between different generation technologies, despite the fact that the lifecycle emissions in their production could vary significantly. For example, where technologies are deployed in locations with a poor renewable resource the carbon intensity per kilowatt hour generated increases due to the fact that their lifecycle emissions are fixed. The implications of this have not been considered in discussions related to the possibility of achieving an electricity emissions target of 50 gCO_2e/kWh. There is a major concern that past analyses of the lifecycle emissions of micro-generation technologies provide a significant underestimate of emissions. This paper addresses these issues by:

- Employing a novel Integrated Hybrid Lifecycle Analysis (LCA) to calculate the lifecycle emissions of PV and micro-wind case studies.
- Developing a number of scenarios that forecast the changing carbon intensity of PV and micro-wind supply chains up to 2030.
- Considering the extent that micro-generation technologies and supporting policy incentives contribute towards decarbonising the electricity sector in the UK.

1.1 Aims and objective

The objective of this paper is to determine the carbon payback of solar PV and small-scale wind technologies under different installation conditions. It then goes on to assess the extent to which the FiTs scheme encourages the maximisation of their decarbonisation potential. FiTs forms part of a policy framework to decarbonise the UK energy system, however, the evidence used to inform the policy was predominantly related to costs, capacity and deployment; not the contribution to meeting decarbonisation targets. When calculating the UK's electricity intensity it is important to recognise and monitor the embedded emissions of such technologies to ensure that their full impact is taken into account. The following aims are met:

- To conduct a detailed lifecycle assessment measuring greenhouse gas emissions of solar PV and micro-wind using integrated hybrid LCA;
- Considering the full lifecycle emissions, to determine whether or not decarbonisation policy includes an overly optimistic appraisal of the role of technology in emissions reduction now and in the future; and
- To assess the feasibility of FiTs contributing towards such a low emission target for electricity generation in the UK.

2 Materials and Methods

The following section outlines the methods used to conduct the analysis of micro-wind and solar PV generation technologies. A context for existing studies of such technologies is given and the need for use of the integrated hybrid LCA methodology is outlined. Finally, the case study data and assumptions about the technology life cycle are detailed.

2.1 Context and Background - Lifecycle Impact of Energy Technologies

Lifecycle assessment (LCA) methods are intended to capture the resource inputs and environmental impacts at every stage in the lifecycle of a process or product, in this case electricity production from solar PV and micro-wind. It is a flawed assumption to presume that renewable energy technologies are zero carbon as they rely on existing fossil fuel infrastructure for material extraction, fabrication, assembly, delivery and so forth. Without conducting a lifecycle analysis of the full supply chain impacts of energy technologies, only the direct emissions from combustion will be captured, leading to an underestimate of their impact. Lifecycle assessment is the dominant method for quantifying the environmental impacts generated throughout a products lifecycle.

A review of lifecycle emissions of energy technologies by the International Panel on Climate Change (IPCC) [6] indicates the potential lifecycle emissions of renewable electricity generation technologies in comparison to conventional fossil fuels (Table 1). It should also be noted that, particularly for wind technologies, reviews show that power ratings tend to result in higher carbon intensity of electricity generation [7]. Whilst this perspective attaches emissions to renewable electricity technologies, they are still overwhelmingly more favourable than production from fossil fuels.

	Energy Source										
	Bio-power	Solar		Geothermal	Hydropower	Ocean	Wind	Nuclear	Natural gas	Oil	Coal
		PV	CSP								
Min.	-633	5	7	6	6	2	2	1	290	510	675
Max.	75	217	89	79	43	23	81	220	930	1170	1689
CCS min.	-1368								65		98
CCS max.	-594								245		396

Table 1: Aggregated LCA results (gCO2e/kWh) from electricity generation technologies [6]

It is difficult to compare the results of each technology due to methodological diversity, differing data sources and technological characteristics assumed across studies. For example, both process-based and economic input-output methods are used for life cycle analysis; when bottom-up product specific inventories are not available they are compiled from different life cycle databases; and processes deemed significant to be included in an inventory are subjective (compiler judgement). Some studies adopt a cradle-to-gate perspective where decommissioning activities are excluded; others include these but make different assumptions on recycling and disposal options. Published standards for LCA (ISO14040 and PAS 2050) provide guidelines, but no consistent method is defined. A methodology that reduces discrepancies between comparable studies is therefore desirable.

Hybrid LCA methods provide an opportunity to overcome elements of error inherent in traditional LCA methods. Supply chains associated with energy technologies are numerous and complex. Additionally, their global nature means pressures are dispersed, creating a large and distant web of suppliers and a near-infinite number of possible production layers. Conventional LCA methods have had to set a system boundary since it is near impossible to collect process-specific data for such a large number of possible supply chain paths. As a result, some upstream activities are excluded from the analysis leading to significant truncation errors. It has been estimated that up to 50 % of the impacts can be 'lost' [8, 9]. This underestimation is compensated for by using economy-wide data in the form of input-output analysis. However, whilst the input-output method characterises a complete 'boundary-less' system, it is constrained by aggregated sector representation. In the context of energy technologies, electricity is represented as one economic sector, not distinguishing between specific technologies.

Published in the late 1970s [10], but becoming more applied in the last decade, is the emergence of a new breed of hybrid methods to overcome the limitations of boundary truncation errors whilst maintaining product specificity. Conceptually hybrid methods combining process-analysis and input-output analysis have been relatively well documented [11-16]. These began as a 'tiered hybrid analysis' where additional upstream emissions were added using input-output analysis missed from process-based inventories. This later developed to a completely integrated hybrid LCA where a process database is embedded in an input-output table and all interactions between individual processes and economic sectors or industries are modelled in a consistent framework.

In theory, a fully integrated hybrid LCA is favoured, however due to computational complexity applications are sparse [11]. To our knowledge Wiedmann et al. [17] were the first to apply an integrated multi-regional hybrid LCA using the case study of supply chain emissions of wind power generation in the UK. Acquaye [18] applied the same model to an emissions assessment of biodiesel adding additional estimates for emissions originating from land use change. The same model is applied in this paper.

2.2 Integrated hybrid input-output method

The integrated-hybrid LCA model described in Wiedmann et al. [17] is applied to calculate the lifecycle emissions of case study solar PV and micro-wind generation technologies. This methodology allows a more comprehensive environmental evaluation of the use of micro-generation technologies and their corresponding policy incentives. A brief description of the method is given here and the reader is referred to Wiedmann et al. for a detailed technical description. The technical characteristics and data sources for this application are described in detail below. Figure 1 illustrates the methodological framework employed to conduct the LCA.

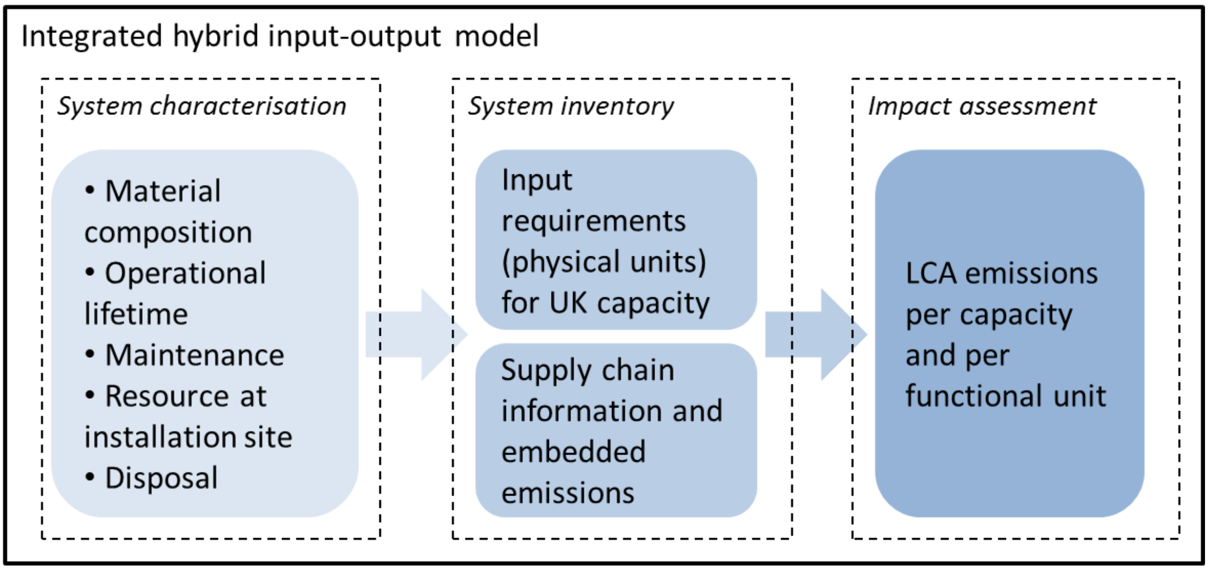

Figure 1: Methodological framework of lifecycle analysis.

A total requirements matrix links an m*m process matrix describing the inputs of goods to processes in physical units (A_{gp}) to an n*n input-output technology matrix derived from financial transactions between economic sectors ($I-A^{*}_{ss}$). This is done via an n*m upstream matrix (C_u) and an m*n downstream matrix (c_d). Commodity flows from the input-output sectors cut-off from the process inputs matrix complete the upstream component, and physical goods produced by specific processes used in the background economy (the input-output system) complete the downstream component. The trade interactions of all processes and products globally are integrated into a two-region UK-centric model. The total requirement matrix *H* can be written as equation (1):

$$H = \begin{bmatrix} -A_{gp} & -C_d \\ -C_u & I - A_{ss}^{*} \end{bmatrix} \qquad (1)$$

Negative numbers indicate inputs to processes and positive numbers indicate outputs of a process. The process matrix is populated by a 3931*3931 matrix from ecoinvent v.2.1 (2009)[1] data and a two region supply and use table representing 224 economic sectors[2]. Using a multi-region model extends the national boundary to account for international trade. Only sectors in the input-output table deemed to have been cut-off in the process matrix are retained upstream. It has been assumed that the electricity generated is used by the transmission sector.

Greenhouse gas emissions[3] are calculated by pre-multiplying *H* with direct emissions data and post-multiplying by demand for the good in question (electricity from micro-renewables), represented by equation (2):

$$q = [B\ B^{*}] \times H \times [y] \qquad (2)$$

B and B^* are vectors representing greenhouse gas emissions from each process and the emissions intensity of each economic sector respectively. For example, electricity generated by the micro-generation installation will have zero emissions (unlike combustion of fossil fuels) however emissions will be associated with resource inputs such as steel or silicon production. y is a vector specifying the level of demand for the process or sector of interest. Direct emissions are re-proportioned to the final good (micro-generation electricity) via the interactions represented in the integrated matrix. Results can be separated from the process and input-output model; therefore process only results can be compared to those employing the hybrid method. To enable comparison, emissions associated with 1 kWh of each energy technology are calculated (and not the total capacity of both).

Solar PV and micro-wind generation technologies eligible for FiTs and most representative of present and near-future UK use are selected and characterised according to the variables identified in Figure 1. A process-based system inventory of first order inputs for each technology is collated in physical units. Where first-hand data is available from a company this is applied and each input is allocated to the equivalent goods represented in ecoinvent to determine a unique production recipe; where data

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[1] Ecoinvent is a supplier of life cycle inventory data, http://www.ecoinvent.org/

[2] The dimensions of the two region supply and use input-output table are 224 * 4 = 896

[3] The greenhouse gases considered are those considered in the Kyoto Protocol, namely carbon dioxide, methane, nitrous oxide, Hydrofluorocarbon, perfluorocarbons and sulphur hexafluoride. These are reported in CO_2 equivalent quantities based upon their global warming potential.

is not available a relevant process from the ecoinvent database is selected[4]. The case studies used for solar and wind resource assessment are outlined below (sections 2.3 and 2.4).

2.2.1 Data sources

Data has been collected for the case study of solar PV and micro-wind systems for material composition, technology manufacture, transportation, energy consumption and waste generation within the manufacturing process from companies operating within the UK and Europe. Assumptions have also been made for the processes of materials extraction and production, as well as the installation based upon consensus within the literature and ecoinvent database. It is assumed that all components are produced from newly extracted materials and don't contain any recycled content. The impact of all materials and products used in the infrastructure has been included. We acknowledge that in reality, the technologies considered may contain some recycled content which would bring down the overall life cycle impact of the product however due to uncertainty in the proportions, a worst-case scenario of no recycled materials has been assumed. Where specific transportation distances were not available distances have been assumed for manufacture within Europe or the UK (as appropriate). An outline of the distances used within the study for solar PV and micro-wind systems are detailed in Table A.1 and Table A.2 in the appendix respectively. After connection to the grid, the transmission and distribution of the electricity have not been taken into account. This is usually not technology dependant and therefore not necessary for this study. Disposal of the technologies has not been considered in this study.

2.3 Case study: solar PV

Single crystalline cells are considered most representative of the type of panels which will be predominantly used in the UK in the coming years [19] and since solar PV installations have little variation between designs [20], a typical monocrystalline silicon installation is therefore considered as the case study. Data was taken directly from the ecoinvent database v.2.1 (2009). The case study installation consists of 22.1 m^2 of laminated panels sized 125 cm^2 which are each made up of 72 single crystalline silicon solar cells and has a total capacity of 3 kWp.

2.3.1 Material Composition

Figure 2 shows the composition of materials used in a single solar PV crystalline panel. A detailed lifecycle inventory for the panel is detailed in Table A.5 of Appendix D. Solar glass makes up the majority of the material within the panel, with aluminium and steel contributing 25% of the remaining materials. Electronics and silicone make up only 1% each.

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[4] Represents a range of European processes

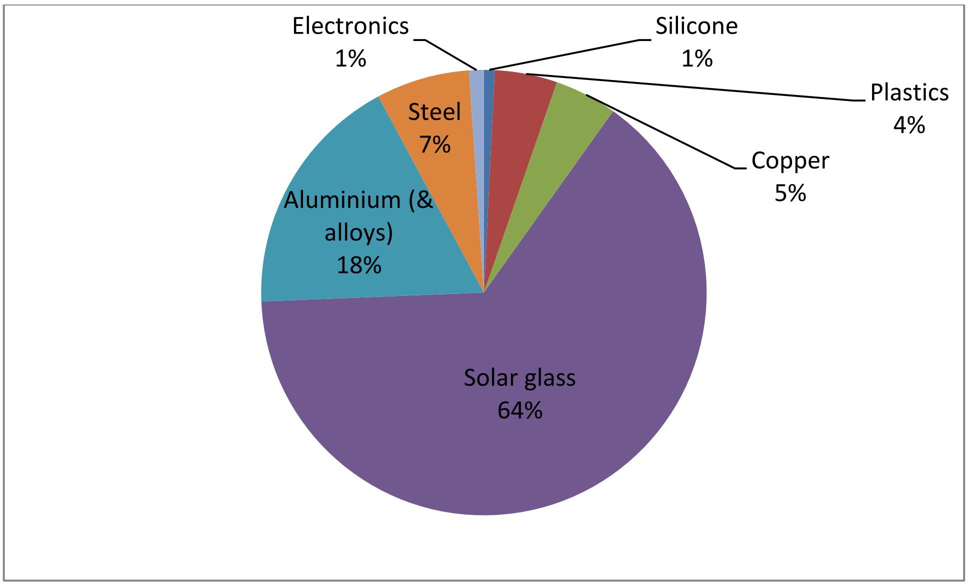

Figure 2: Material Composition of the considered solar PV single crystalline panel

2.3.2 Operational lifetime

Manufacturers offer a warranty for a system for 25 years. However, the International Energy Agency solar PV LCA guidelines (2009) and published academic literature [21] suggest that the modules are more likely to degrade in efficiency as opposed to meeting a “fixed catastrophic failure point” and will therefore operate for longer than 25 years. A 30 years lifetime with an age related level of efficiency degradation has therefore been assumed for this paper (see section 2.3.3).

The main maintenance necessity for solar PV installations is the replacement of inverters which convert the DC current generated by the panels into grid compatible AC current. The ecoinvent database states that the average lifespan of an inverter is 12.5 years but there is variation due to factors such as differences in durability [22]. To account for inverter lifespan variation, an average use of 2.4 inverters is assumed over an installation’s lifetime. Aside from occasional cleaning of the modules (which has negligible impact) it is assumed that no other maintenance is required since solar PV panels have no moving parts.

2.3.3 Solar resource at installation site

Levels of horizontal irradiation[5] in the UK range from 750 kWh/m^2/year in northern Scotland to 1100 kWh/m^2/year in southern England. Different levels have been considered over this range to reflect the variation in UK conditions. As well as the level of irradiation, the output is also dependent on the panel area, performance ability and durability of the panels. For this study, panel size is 125 cm^2 and

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[5] Solar radiation received on a given surface area over a given time period

the installation was assumed to have a lifetime of 30 years, an efficiency of 14.4 % and a performance ratio of 0.75.

Degradation due to aging of the system was also considered [20, 23]. Degradation of the panel results in a linear reduction in performance over its useful lifetime. Despite system degradation being identified as an important area of assessment for photovoltaic electricity LCA, it is often neglected in studies. The degradation factor[6] effectively reduces the average performance over the system lifetime of 30 years by 20 %.

The total electricity output over the 30 years is given by equation (3):

$$K = A \, . \, \eta \, . \, R_p \, . \, L \, . \, d \, . \, I_j \qquad (3)$$

Where K = total electricity output over the panel's lifetime (kWh); A = area of the panel (m^2); η = panel efficiency (%); R_p = performance ratio; L = panel lifetime (30 years); d = average degradation factor; I_j = annual irradiance at installation site (kWh/m^2).

Table 2 details the calculated system generation (kWh).

Annual irradiance, I_j (kWh/m^2)	Initial Annual Output (kWh)
700	1,557
800	1,780
900	2,002
1000	2224
1100	2447

Table 2: Expected electricity generation (kWh) for different annual irradiance values (kWh/m^2)

2.4 Case studies: micro-wind

There are wide variations in micro-wind turbine designs and their material compositions, resulting in varying lifecycle analysis results. Three case study micro-wind turbines have been considered within this study, all of which are suitable for connection to the grid (see Table 3). This does not take account of the numerous turbine designs that are eligible for FiTs but is intended to give an initial indication of the carbon intensity of electricity from micro-wind technologies.

Turbine	Characteristics	Description
A	Swift 1.5 kW horizontal axis turbine by the	Turbine A was originally considered in a study by Rankine et al. [24] at the University of Edinburgh. It has five blades and a

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[6] The degradation factor is given as $D(t) = 1 - 0.00667(t - 1)$, where t is the life of the panel in years

	Edinburgh-based manufacturers Renewable Devices	diffuser ring which reduces the noise created by the turbine as it turns. The material composition considered is for a standard wall-mounted turbine with a 5 m aluminium mast. The original study obtained detailed inventory information from the turbine manufacturers, enabling a high level of accuracy within the data.
B	2 kW vertical axis turbine from a French manufacturer[7]	Data was sourced through personal communication with the manufacturer as well as from publically available technical specifications. Where specific data was not available approximations have been used by scaling data from the inventory of turbine A based upon weight (see Table A.3 in the appendix). The final data used within the analysis was checked and approved by the manufacturers as a realistic approximation.
C	6 kW vertical axis turbine from a French manufacturer[7]	See turbine B (Table A.4 in the appendix).

Table 3: Micro-wind turbine descriptions

2.4.1 Material composition

Figure 3 and Figure 4 show the proportions of materials used in both turbine models. The masts of the turbines account for the most significant proportion of the turbines' materials. Turbine A has an aluminium mast whereas Turbines B and C have galvanised steel masts. The turbine blades are composed of carbon fibre reinforced epoxy resin and this makes up the next biggest contribution to the turbine materials.

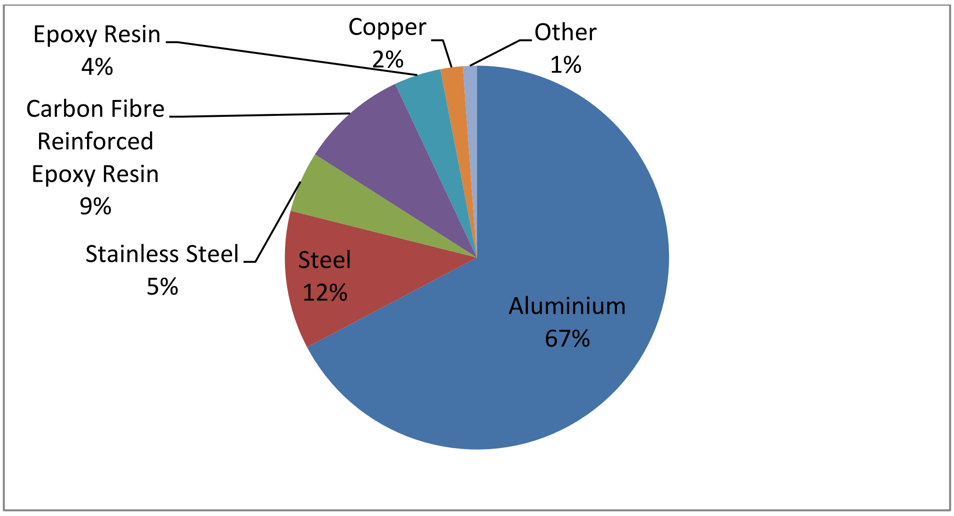

Figure 3: Material Composition of Turbine A (1.5kW)

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[7] The name of the manufacturer has been kept anonymous within this paper at their request

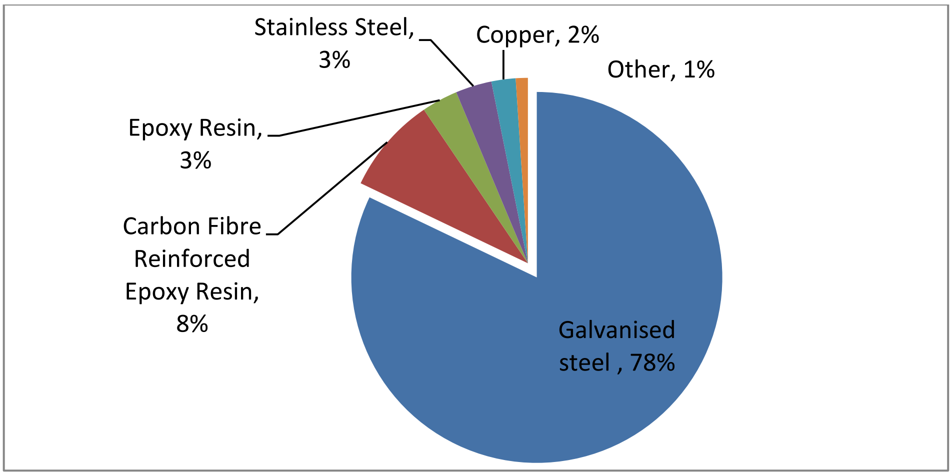

Figure 4: Material Composition of Turbines B and C. Both models have been assumed to have the same proportions.

2.4.2 Performance

The manufacturers of each turbine publish the expected power output that would be achieved at a given wind velocity. Figure 5 displays the power curves for turbines A, B and C. All three turbines begin to generate electricity with a wind speed of 3 m/s. The cut-out wind speed of turbines B and C is 20 m/s whereas turbine A does not cut out until a wind speed of 21 m/s.

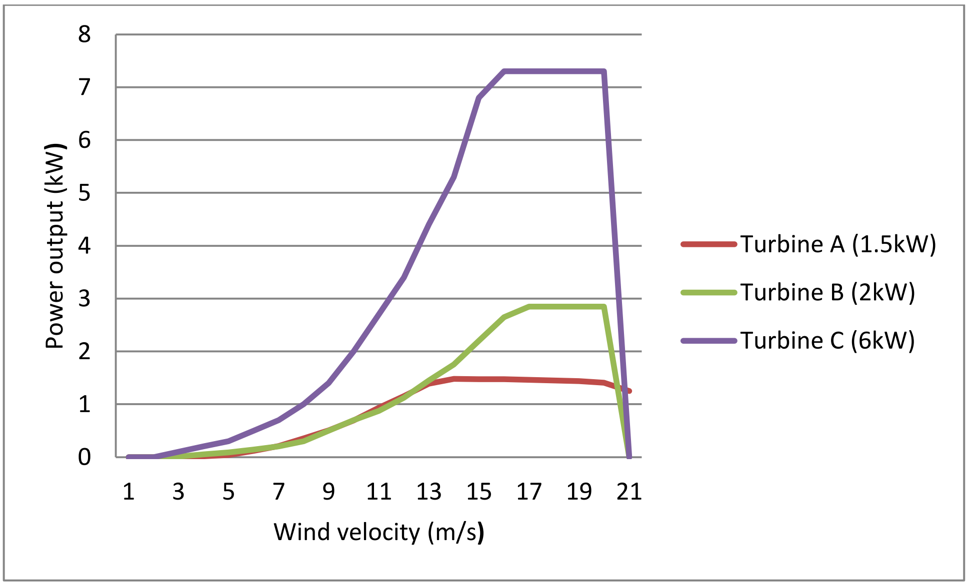

Figure 5: Expected power output of each turbine (kWh) for a given wind velocity

2.4.3 Operational lifetime

At present there is insufficient data to make accurate estimations of wind turbine lifetimes since there are very few turbines that have reached the end of their working life [25]. Manufacturers estimate lifetimes that range from 10-30 years [26, 27] and this could vary with differing maintenance regimes and installation sites. There could also be variation in the lifetime of parts within each turbine. This study assumes turbine lifetimes as specified by the manufacturers. Turbine A is estimated to last 20 years and Turbines B and C are estimated to last 30 years.

Regular maintenance of turbines is thought to prolong their useful life and maintain their efficiency. Unfortunately, there is little information regarding maintenance requirements provided by manufacturers and there is a similar lack of field studies to provide real life data [24-26]. In accordance with most studies to date, maintenance has been omitted from the study.

2.4.4 Resource at installation site

The electricity generated by a wind turbine is determined by the power in the wind. The wind's power is proportional to the wind speed cubed and therefore understanding the wind speed at an installation site is critical to calculating the likely generation of a wind turbine. Estimating wind speed is complex due to the temporal variability of wind speeds over seasons and years, as well as the spatial variability of wind speeds due to the impact of features such as buildings or terrain changes.

Typically, power generation from wind turbines is calculated based upon approximations for the mean annual wind speed and the distribution of wind speeds over the course of a year. This study has used a Weibull distribution to approximate the annual wind speed distribution since it is representative of a large number of wind regimes [28].

The distribution of wind velocities at a site over the period of a year can be represented using the family of Weibull probability distributions [29]. The distribution is given by equation (4):

$$Probability\ of\ wind\ velocity\ (V)\ at\ a\ point\ in\ time\ f(V) = \frac{k}{c}\left(\frac{V}{c}\right)^{k-1} e^{-\left(\frac{V}{c}\right)^{k}} \qquad (4)$$

Where V = the wind velocity (m/s); $k = Weibull\ shape\ factor$; $c = scale\ factor$ [29]. The shape factor and scale factor are used to tailor the Weibull distribution for a particular installation site.

In order to examine the impact of differing wind resources at installation sites a number of average annual wind speeds have been considered. For simplicity of analysis, a general shape factor representative of potential UK installation sites was determined as *k=1.89* and scale factor or *c = 1.124*, based upon a study of a number of UK sites in rural, coastal, suburban and urban settings [28]. The expected annual generation for a variety of average annual wind speeds has been calculated using the power curves published by the manufacturers (Table 4). The annual generation of each turbine (K) for an average annual wind speed ($\overline{V}$) is calculated using equation (5):

$$K(\overline{V}) = \sum_{i=1}^{10} f(V_i)\ .P(V_i)\ .60\ seconds\ .60\ minutes \qquad (5)$$

Where $K(\overline{V})$ = annual generation (kWh) for a site with average annual wind velocity of $\overline{V}$ (m/s); $f(V_i) =$ Weibull probability distribution of wind velocity V_i given $\overline{V}$; $P(V_i)$ = power output from the turbine at wind velocity (kW) according to the manufacturers' published power curves (Figure 5).

Average wind speeds below 3 m/s are not considered since the cut-in speed of turbines A, B and C for beginning to generate electricity are between 3 m/s – 4 m/s.

	Annual generation (kWh)		
Average annual wind speed (m/s)	Turbine A	Turbine B	Turbine C
3	73	122	485
4	245	296	1035
5	535	584	1897
6	913	998	3109
7	1324	1510	4572
8	1715	2049	6082
9	2045	2544	7437
10	2296	2947	8514

Table 4: Estimated average annual generation (kWh) for varying average annual wind speeds in the UK

2.5 Methodology for Scenarios

The carbon intensity of the technologies will change over time with the introduction of renewable technologies in the electricity sector combined with improvements in carbon intensity across other sectors. To give a more useful interpretation of the emission payback time on micro-renewables, a number of scenarios have been constructed with varying levels of decarbonisation in the electricity and other sectors. The aim of this analysis is to recognise that the lifecycle emissions of micro-generation technologies are likely to reduce over time.

The scenario methodology employed is consistent with the approach described in Barrett and Scott [30]. In summary, the methodology considers the changing carbon intensity of the UK and trading partners taking into account historical changes over the past 20 years, future potential opportunities for improvements in individual sectors and government policies specifically related to the decarbonisation of the electricity sector.

The scenarios are not an attempt to forecast the future, but recognise a range of possible outcomes of an uncertain future. With this in mind, the scenarios show the highest and lowest possible carbon intensity of both micro-wind and PV based on the outcomes of a number of uncertain variables, these being the rate of decarbonisation of the electricity sector in the UK and abroad, carbon intensity of production by sectors in the UK and abroad and the location of production.

3 Results and analysis

The following section presents the results of the integrated hybrid LCAs for the case study technologies. The implications of these results are then considered for various natural resource scenarios in the UK to gain an understanding of where the technologies offer a carbon emissions reduction. Finally, scenarios for future emissions and their implications for the LCA results are considered.

3.1 Solar PV - lifecycle emissions

Lifecycle results for solar PV are presented in Figure 6. In this instance, for the sake of comparison of the two methods, both the process and integrated hybrid method results are shown. It can be seen that adoption of the integrated hybrid method, to overcome truncation error, results in an emission increase of 20 % of the process method results. Wafer construction contributes 50 % of emissions using the process analysis, and its share reduces slightly to 47 % when using the hybrid method. Installation is the second highest contributor at 15 % and 17 % respectively. An improvement in efficiency in these two areas is therefore most likely to make a significant reduction in the embodied emissions associated with solar PV installations.

The remainder of the results will utilise the integrated hybrid method. Using an integrated approach over a pure process or input-output approach has shown to yield truer results in terms of the detail of physical flows combined with system completeness. However, this does not escape uncertainties associated with data sources and model assumptions. Wiedmann et al. (2011) specifically discuss uncertainty relating to the models used in this paper. Examples of uncertainty in the hybrid model relate to the process inventory, the manipulation of input-output tables and the conversion between monetary and physical data when integrating the two datasets. Exclusive to this study error will also arise from assumptions about the grid intensity, which is assumed to remain constant throughout the lifetime of the micro-generation technologies. When comparing with other studies Wiedmann et al. (2011) showed that the capacity in terms of power output, disposal and recycling assumptions, and the location of production and operation of generation technologies will lead to the most significant differences in results.

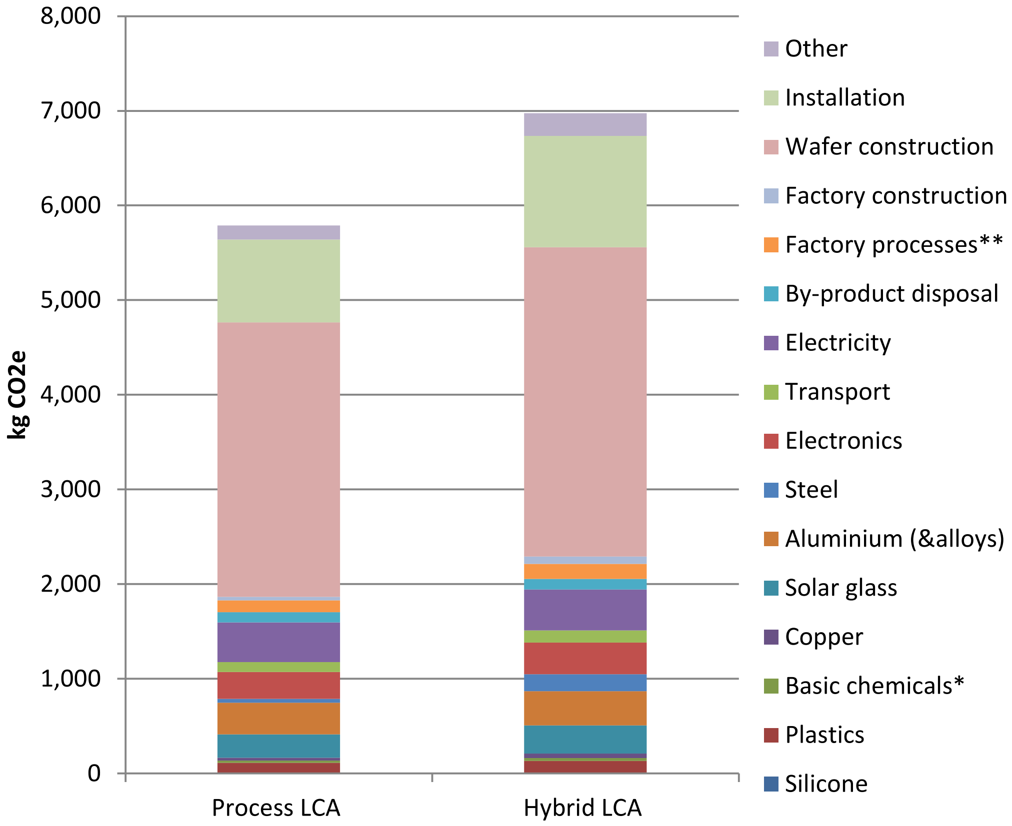

Figure 6: Emission results from single silicon solar PV installation (3kWp) comparing process-based and hybrid-based results.

3.1.1 Current carbon intensity of solar PV

The energy output of solar PV depends on the irradiation received. The carbon intensity at different rates of irradiation is given in Figure 7 and is compared with the intensity of electricity from micro-wind in the policy analysis section (3.3). As is expected, the higher the irradiance received, the lower the carbon intensity. The value of the carbon intensity decreases from over 160 gCO_2/kWh in areas with the worst irradiance in the UK to around two thirds of that value in areas with the best irradiance in the UK.

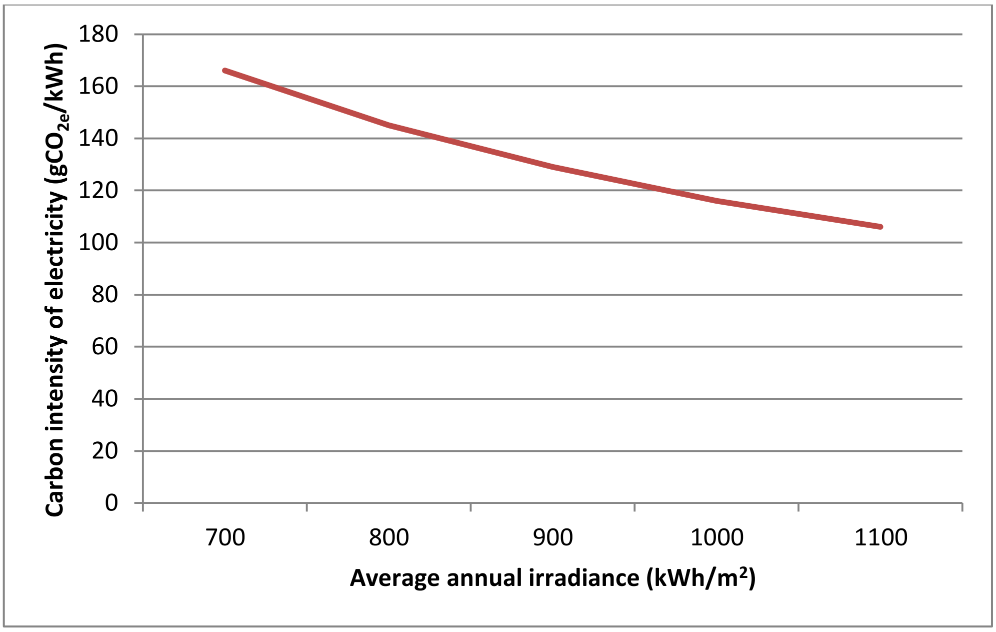

Figure 7: Carbon intensity of solar PV for different levels of average annual irradiance

3.2 Micro-wind – life cycle emissions

Lifecycle results for micro-wind are presented in Figure 8. The larger the turbine, the higher the resource input and the higher the embodied emissions. The mast material of each turbine makes up the largest proportion of the embedded emissions. In turbine A, the mast is composed of aluminium, in comparison to turbines B and C which are composed of mainly steel. The second notable difference between turbine A and turbines B and C is the emissions embodied in transport, where turbine A is manufactured in the UK and therefore has to be transported a shorter distance to installation site (Appendix B).

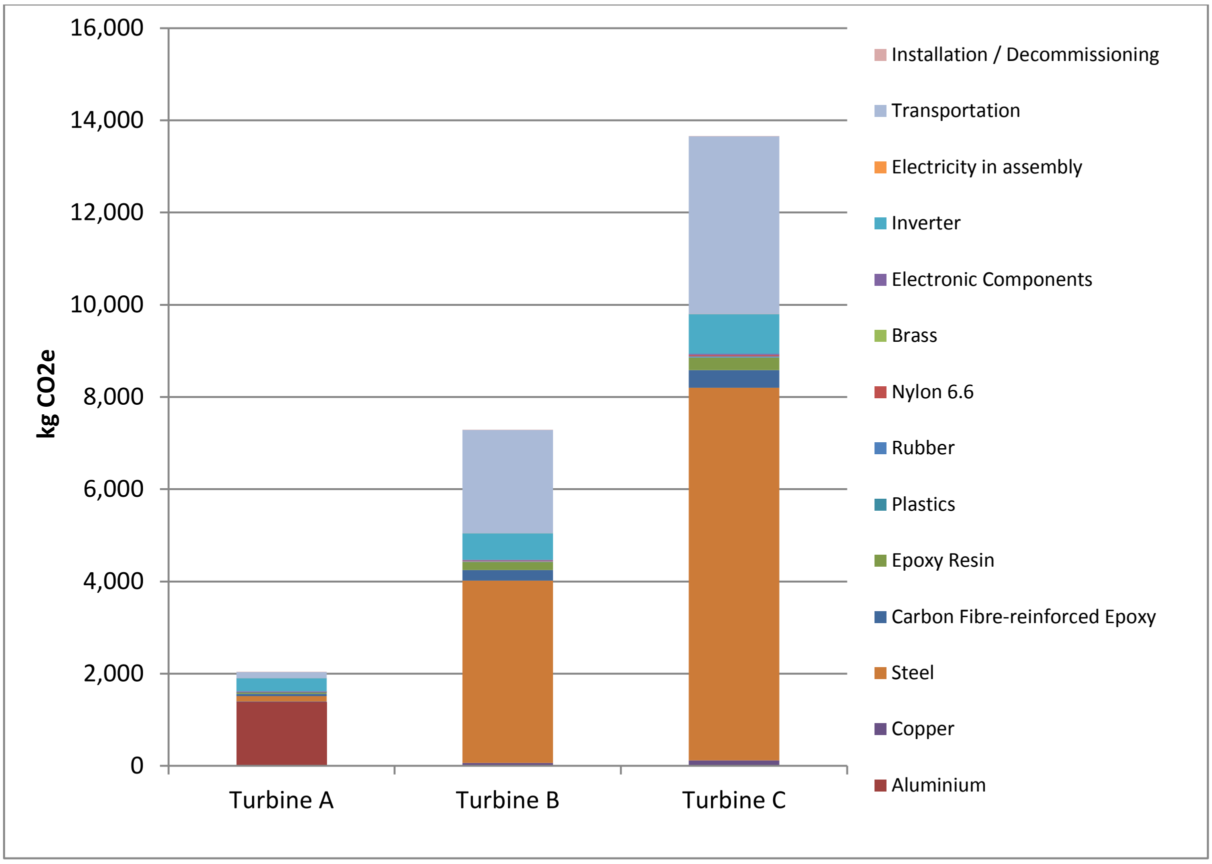

Figure 8: Emissions results from micro-wind comparing through the integrated hybrid-based method.

3.2.1 Current carbon intensity of micro-wind turbines

The carbon intensity of generation from the three micro-turbines has been calculated based upon expected generation at a site with a given average annual wind speed. Figure 9 details the resulting carbon intensities. At low annual average wind speeds of 3 m/s the carbon intensity of the turbines are nearly 1000 gCO_2/kWh in the case of turbines A and C, and reach as high as 2000 gCO_2/kWh in the case of turbine B. This is significantly higher than the existing electricity from the grid which stood at 494 gCO_2/kWh in 2010 [2]. However, from average annual wind speeds of 4 m/s or higher turbines A and C match or reduce the carbon intensity of their generated electricity compared to the grid. Turbine B achieves this from average wind speeds of 5 m/s. Unlike solar PV, the reduction in intensity is more exaggerated at lower wind speeds due to the cubic relationship between power and wind speed. Despite the similarities between the design of turbines B and C, the lower rated 2 kW turbine B generates more carbon intensive electricity since its material composition is not reduced relative to its reduction in generation capacity. Maximising the power output of the turbine (i.e. locating them in higher average annual wind speeds) minimises the carbon intensity.

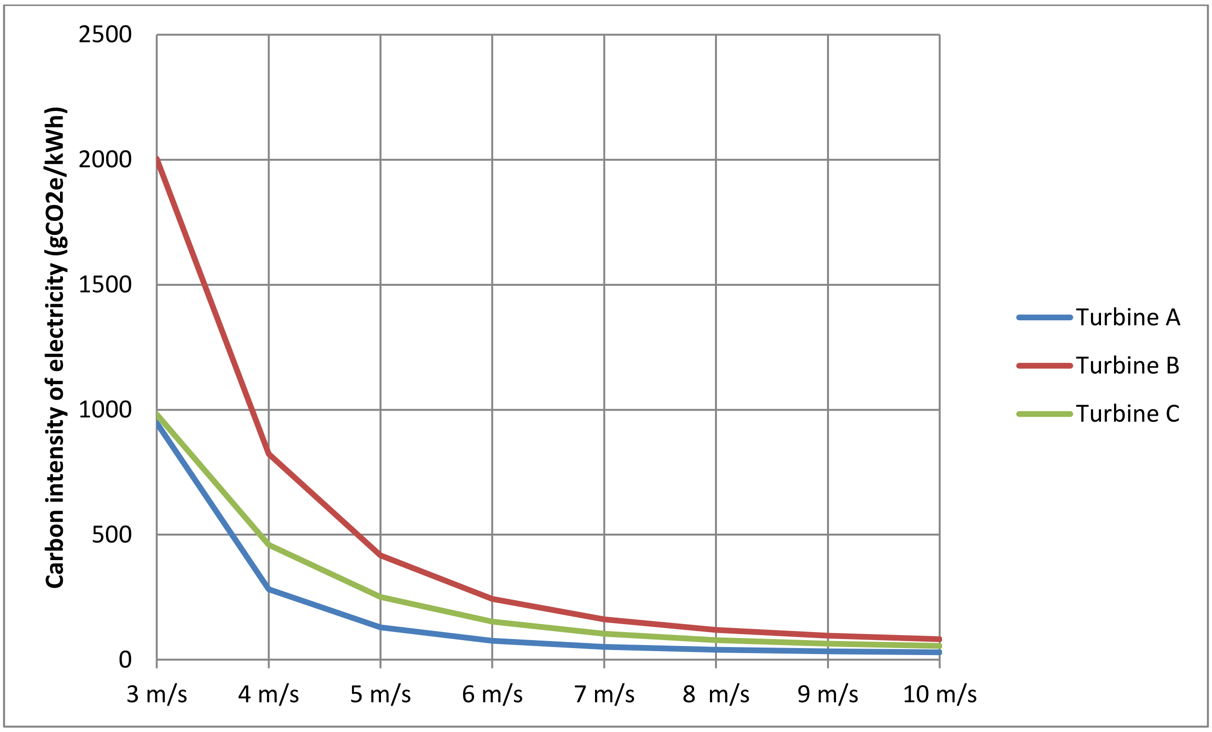

Figure 9: Carbon intensity of the three case study turbines for a range of annual average wind velocities (m/s)

It should also be noted that empirical studies from across the UK have shown that average annual wind speeds are unlikely to reach the higher end of this range apart from in the most ideal locations at over 10 m above canopy height [28, 31]. Therefore, most installation sites would have average wind speeds of 6 m/s or less.

3.3 Emissions payback and Future Intensity

Carbon payback period represents the time period of energy generation from micro-wind or solar PV that must take place to offset the losses incurred in the installation period (i.e. the lifecycle emissions). Renewable energy sources offset their embedded CO_2e by replacing electricity generation from a carbon intensive source (e.g. fossil fuels). The carbon payback period for micro-wind and solar PV replacing grid electricity are calculated.

The number of years required to offset the embedded carbon of a technology at a specific site is given by equation (6):

$$T = \frac{E_{CO_2}}{I_{grid} \cdot a_i} \qquad (6)$$

Where T = time to payback CO_2e (years); E_{CO_2} = Embedded CO_2e of the turbine (kg CO_2e) ; I_{grid} = intensity of the UK electricity grid (kgCO_2e/kWh); a_i = average annual generation at the installation site given an average annual wind speed of i (kWh/year).

The carbon intensity of the UK electricity grid mix in 2009 is used and assumed to be maintained throughout the years of payback (0.494 kg CO_2e/kWh); [3232]. Note that the annual generation for solar PV has been calculated to reflect panel efficiency degradation with time. This creates a time dependence factor in the sum of annual generation.

Carbon payback period for micro-wind and solar PV at different wind speeds and annual irradiance respectively are given in Table 5.

Average annual wind velocity (*i*)	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s
Turbine A– 1.5 kW	8	4	2	2	1	1	1
Turbine B – 2 kW	25	12	7	5	4	3	2
Turbine C – 6 kW	14	7	5	3	2	2	2
Solar PV: Annual irradiance (I_j)	-	700 kWh/m^2	800 kWh/m^2	900 kWh/m^2	1000 kWh/m^2	1100 kWh/m^2	-
Solar panel– 3 kWp	-	9	8	7	6	6	-

Table 5 : Carbon payback time (years) required for sites of varying average annual wind speed and annual irradiance

The embodied carbon, and hence carbon to pay back, will vary depending on the design and material composition of the technology. Output capacity and site conditions will influence the carbon payback time. Taking a direct comparison between turbines B and C reveals the higher the output capacity, the shorter the payback period, especially in less favourable conditions. At low wind speeds it could take up to 25 years to offset the carbon from infrastructure requirements of wind turbines compared to just a year or two at sites with high wind speeds. The variation is less for the solar sites modelled ranging between 6 - 9 years.

3.4 Uncertainty and Future Emissions

According to the methodology outlined in section 2.5, scenario analysis of the lifecycle analysis results has been conducted to establish the potential impact of improvements in the carbon intensity of electricity used to produce the technology.

3.4.1 Solar Scenario

Figure 10 provides the results for the scenarios in 2030 showing the carbon intensity of production in comparison to the level of annual irradiance. The scenario analysis suggests that by 2030, assuming no improvements in generation efficiency, solar PV would be produced with a carbon intensity 10 % lower than 2012. Further savings in carbon intensity are therefore highly dependent on future generation efficiency improvements and decarbonisation of the electricity grid, in the UK or elsewhere. To achieve the lower carbon intensity figure shown here (50% reduction by 2030) would require an almost complete decarbonisation of electricity generation to 50g of CO_2e/kWh. Figure 10 highlights that attention should be given to the placing of solar PV installations so that the maximum irradiation possible can be received to ensure carbon intensity is minimised.

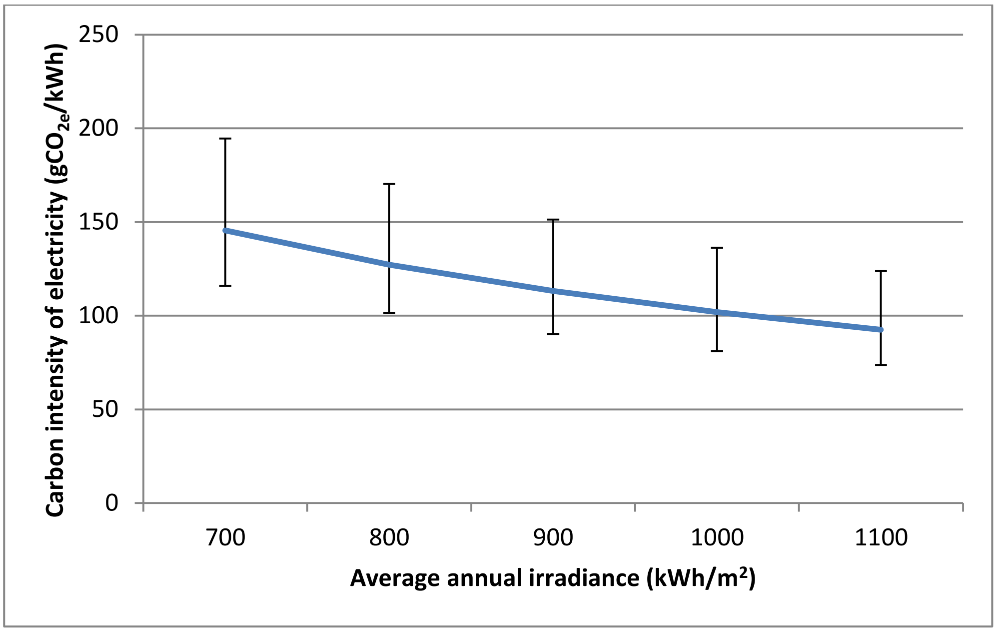

Figure 10: Solar PV: Three scenarios (low/central/high electricity carbon intensity) for the carbon intensity of a 3 kWp solar PV installation in 2030.

3.4.2 Wind Scenario

A similar situation can be seen for wind (Figure 11), where again high levels of electricity decarbonisation are needed to achieve the lower carbon intensity figures. Wind turbines have the added challenge that they are predominately made from steel or aluminium. Allwood (2012) [33] provides compelling evidence of the difficulty in achieving significant gains in the carbon intensity of steel and aluminium production.

In addition to the limited opportunities for carbon intensity improvements, the decarbonisation rates of the electricity sector are very ambitious and more closely reflect ambitions of EU countries as opposed to emerging economies. Both solar PV and wind turbines are global markets with high levels of production in China, where electricity generation is heavily dependent on coal. Therefore, the more modest reductions presented in the scenarios demonstrate a more feasible outcome. This makes future performance efficiency gains of solar PV technology essential to achieving a target of 50 gCO_2e/kWh.

For wind turbines this is clearly heavily dependent on average wind speed and this factor remains as the most important variable that dictates the carbon intensity of small scale wind turbines.

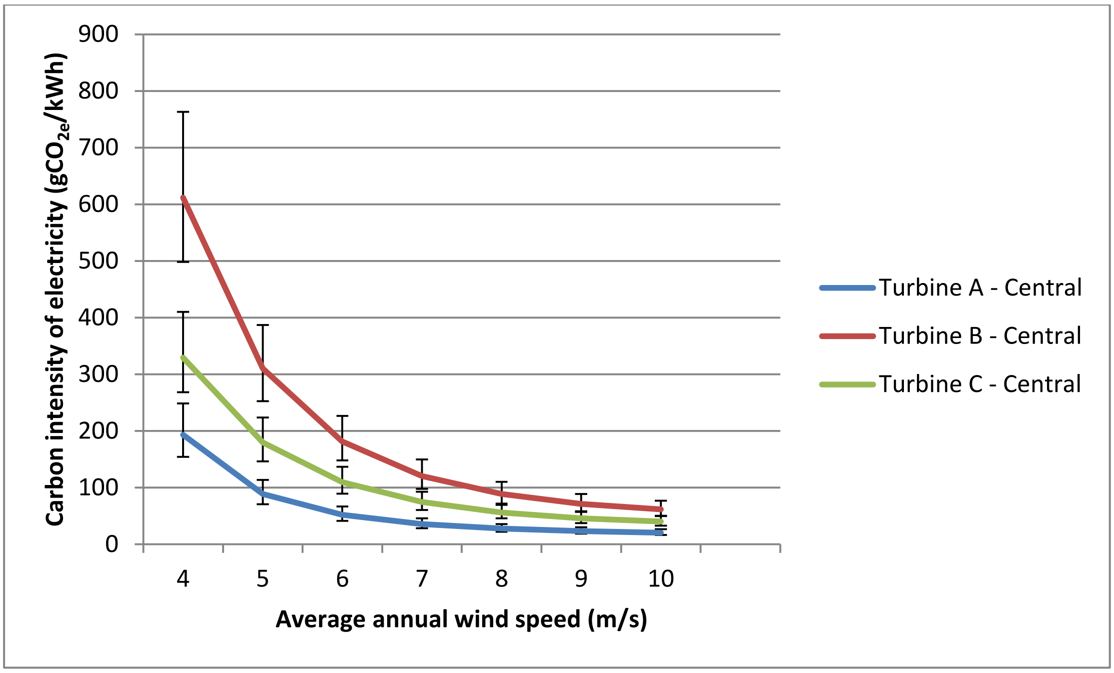

Figure 11: Micro-wind: Three scenarios (low/central/high electricity carbon intensity) for the carbon intensity of turbines A, B and C in 2030.

4 Discussion

Technologies such as micro-wind and solar PV could be thought of as infrastructure technologies which enable the capture of renewable resources. Their impacts are generated through their production, installation and maintenance rather than in their operation. It is therefore essential to account for these when assessing the carbon intensity of electricity generation to offer an accurate comparison with fossil fuel alternatives. Here, the use of the integrated hybrid LCA methodology has resulted in lifecycle emissions that are in the higher-end or exceed the ranges given in the IPCC Special Report shown in Table 1. Whilst the hybrid method captures emissions that would otherwise have been lost to truncation error, methodological diversity and inconsistent boundary setting makes it difficult to determine the reason for differences between studies. The fact that the considered case studies are at the micro-scale further adds to the higher carbon intensities. However the results clearly indicate the importance of accounting for the full lifecycle emissions of these technologies, particularly at the micro-scale, to ensure carbon savings are achieved through their deployment.

Choosing the most efficient technology is primarily determined by the installation site conditions and resource requirements. Micro-wind is favourable in areas with high average wind speed (greater than 7 or 8 m/ s) where the carbon payback period becomes only a few years. However, sites with these higher wind speeds are extremely rare. At more realistic wind speeds of around 6 m/s carbon intensities are comparable to nuclear and fossil fuels with carbon capture and storage and when wind speeds are less than 5 m/s carbon intensities of micro-wind even become comparable to some estimates of fossil fuels, such as gas. There is less variation in solar across the considered levels of irradiation, with solar PV being preferable to wind (and significantly preferable to fossil fuels) in areas where wind is less powerful or frequent. At the optimum level of irradiation in the UK the carbon payback period of solar PV is about six years.

Current FiT policy does not discriminate between technologies on the basis of the renewable resource at an installation site. To achieve a lower carbon intensity of electricity, however, would require prioritisation of more favourable sites. Criteria to ensure technologies are only deployed in favourable sites would incentivise appropriate use and move the UK closer to reaching a decarbonised electricity system.

Further consideration should be given to the role of policy mechanisms for influencing supply chain decisions such as the material composition of products or their manufacturing locations. As the electricity intensity of different nations begins to change the supply chain of technologies will become crucial in determining which scenario of electricity carbon intensity will apply.

5 Conclusions

The lifecycle emissions of technologies provide a significant challenge to meeting electricity generation carbon intensity targets of 50g CO_2e/kWh by 2030. A complete re-assessment of the target should be undertaken based upon the full lifecycle impacts of technologies. Alongside this there must be a comprehensive accounting system that considers the impacts of policies to discourage perverse technology choices that do not offer the required carbon savings.

In line with this, there is a need for complete and impartial assessment of the lifecycle emissions of technologies. Techniques such as the integrated hybrid LCA used here have the capacity to pick up impacts that would otherwise be lost to the truncation error inherent in process LCA methods. Further research is required to develop these methodologies for wider use.

The extent of the role for micro-generation in the UK electricity mix is still unclear but its ability to offer carbon reductions, make use of otherwise untapped renewable energy resource, and offer resilience to future communities is already apparent. However, policies such as FiTs need to ensure that installations are only incentivised where there are genuine carbon savings to be made. Lack of inclusion of lifecycle emissions, combined with the significant variation in performance of micro-generation technologies, provides an overly optimistic interpretation of the contribution of these technologies to decarbonisation targets.

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8 Appendix

A. Solar PV Transportation Data

Table A.1 details the assumed transportation distances and weight (tkm) of products transported during the manufacture of a solar PV installation. It is assumed that the cells are manufactured within Germany.

Transport stage	Contribution (tkm)
Components to inverter factory	45.7
Components to cell factory	1.83
Components to panel factory	11.05
Components & personnel to installation site	848.3
TOTAL	906.88

Table A.1: Solar PV transportation assumptions

B. Micro-Wind Transportation Data

Table A.2 details the assumed transportation distances and weight (tkm) of products transported during the manufacture of the case study micro-wind turbines. It is assumed that turbine A is manufactured within the UK and turbines B and C are manufactured in Europe (as appropriate)

Turbine Model	A	B	C
Transport stage	Contribution (tkm)	Contribution (tkm)	Contribution (tkm)
Materials to turbine factory	22.5	272.5	503.4
Turbines to installation site	35	695.6	1364.5
Installer transport impact	1.2	6.4	40
TOTAL	58.7	974.5	1921.3

Table A.2: Micro-wind transportation assumptions

C. Scaling Factors for Data Approximation

For turbine B the data has been scaled up from turbine A by the ratio of the weights of the two turbines. Table A.3 details the the scaling factor used:

Turbine A (1.5kW) total weight	115 kg
Turbine B (2 kW) total weight	595 kg
Weight ratio / scaling factor	5.17

Table A.3: Scaling Factors used to approximate data for Turbine B (2 kW).

The technical specifications for turbines B and C indicated that the increase in capacity between the turbines does not result in an equal increase in mass of the materials. Each section of the turbine increased by different proportions. The scaling factors were calculated for the different sections independently and used to scale the data up where necessary. These scaling factos are outlined in the Table A.4.

	Scaling factor
Superior Rotor Tube and Blades	1.62
Mast (9 m)	2.33
Mechanical Parts	1.79
Electronic Components	1.14

Table A.4: Scaling Factors used to approximate data for Turbine C.

D. Solar PV lifecycle inventory

Table A.5 details the lifecycle inventory used to conduct the LCA analysis for a typical monocrystalline silicon solar PV panel. This data has been taken from the ecoinvent v.2.1 (2009) database and censored according to confidentiality restrictions for the database. X's represent digits within the data.

	[G2030] [P1653] inverter, 2500W, at plant[RER] (-)[RER] (unit)	[P2880] photovoltaic cell, single-Si, at plant[RER] (-)	[P2889] photovoltaic panel, single-Si, at plant[RER] (-)	[P1647] 3kWp slanted-roof installation, single-Si, panel, mounted, on roof[CH] (-)
[G5] copper, at regional storage[RER] (kg)	-x.xx	0	-x.xxx	0
[G7] steel, low-alloyed, at plant[RER] (kg)	-x.x	0	0	0
[G27] sheet rolling, steel[RER] (kg)	-x.x	0	0	0
[G54] polystyrene foam slab, at plant[RER] (kg)	-x.x	0	0	0
[G101] transport, lorry >16t, fleet average[RER] (tkm)	-x.x	-x.xxx	-x.xx	-xxx
[G103] transport, transoceanic freight ship[OCE] (tkm)	-xx.x	-x.xxxx	0	-xxx
[G133] transport, freight, rail[RER] (tkm)	-x.xx	-x.xx	-x.xx	0
[G146] electricity, medium voltage, production UCTE,	-xx.x	-xx.x	-x.xx	0

at grid[UCTE] (kWh)				
[G464] corrugated board, mixed fibre, single wall, at plant[RER] (kg)	-x.x	0	-x.x	0
[G465] disposal, packaging cardboard, 19.6% water, to municipal incineration[CH] (kg)	-x.x	0	0	0
[G631] disposal, polystyrene, 0.2% water, to municipal incineration[CH] (kg)	-x.xx	0	0	0
[G805] disposal, polyethylene, 0.4% water, to municipal incineration[CH] (kg)	-x.xx	0	0	0
[G826] polyvinylchloride, at regional storage[RER] (kg)	-x.xx	0	0	0
[G846] aluminium, production mix, cast alloy, at plant[RER] (kg)	-x.x	0	0	0
[G1532] section bar extrusion, aluminium[RER] (kg)	-x.x	0	0	0
[G1539] wire drawing, copper[RER] (kg)	-x.xx	0	-x.xxx	0
[G2047] styrene-acrylonitrile copolymer, SAN, at plant[RER] (kg)	-x.xx	0	0	0
[G2048] printed wiring board, through-hole, at plant[GLO] (m2)	-x.xxx	0	0	0
[G2049] connector, clamp connection, at plant[GLO] (kg)	-x.xxx	0	0	0
[G2050] inductor, ring core choke type, at plant[GLO] (kg)	-x.xxx	0	0	0
[G2051] integrated circuit, IC, logic type, at plant[GLO] (kg)	-x.xxx	0	0	0
[G2052] transistor, wired, small size, through-hole mounting, at plant[GLO] (kg)	-x.xxx	0	0	0
[G2053] diode, glass-, through-hole mounting, at plant[GLO] (kg)	-x.xxx	0	0	0
[G2054] capacitor, film, through-hole mounting, at plant[GLO] (kg)	-x.xxx	0	0	0
[G2055] capacitor, electrolyte type, > 2cm height, at plant[GLO] (kg)	-x.xxx	0	0	0
[G2056] capacitor, Tantalum-, through-hole mounting, at plant[GLO] (kg)	-x.xxx	0	0	0

[G2057] resistor, metal film type, through-hole mounting, at plant[GLO] (kg)	-x.xxx	0	0	0
[G2058] metal working factory[RER] (unit)	-x.xxE-09	0	0	0
[G2059] fleece, polyethylene, at plant[RER] (kg)	-x.xx	0	0	0
[G2060] disposal, treatment of printed wiring boards[GLO] (kg)	-x.x	0	0	0
[G152] nitric acid, 50% in H2O, at plant[RER] (kg)	0	-x.xxxx	0	0
[G388] sodium hydroxide, 50% in H2O, production mix, at plant[RER] (kg)	0	-x.xxx	0	0
[G394] ammonia, liquid, at regional storehouse[RER] (kg)	0	-x.xxxxx	0	0
[G396] solvents, organic, unspecified, at plant[GLO] (kg)	0	-x.xxxxx	0	0
[G405] argon, liquid, at plant[RER] (kg)	0	-x.xxxx	0	0
[G427] calcium chloride, CaCl2, at regional storage[CH] (kg)	0	-x.xxxx	0	0
[G433] nitrogen, liquid, at plant[RER] (kg)	0	-x.xx	0	0
[G434] oxygen, liquid, at plant[RER] (kg)	0	-x.xxx	0	0
[G437] hydrochloric acid, 30% in H2O, at plant[RER] (kg)	0	-x.xxxx	0	0
[G438] titanium dioxide, production mix, at plant[RER] (kg)	0	-x.xxE-06	0	0
[G439] sodium silicate, spray powder 80%, at plant[RER] (kg)	0	-x.xxxx	0	0
[G441] hydrogen fluoride, at plant[GLO] (kg)	0	-x.xxxx	0	0
[G525] phosphoric acid, fertiliser grade, 70% in H2O, at plant[GLO] (kg)	0	-x.xxxxx	0	0
[G526] isopropanol, at plant[RER] (kg)	0	-x.xxxx	0	0
[G562] disposal, waste, Si waferprod., inorg, 9.4% water, to residual material landfill[CH] (kg)	0	-x.xxx	0	0
[G565] tetrafluoroethylene, at plant[RER] (kg)	0	-x.xxxxx	0	0
[G570] silicone product, at plant[RER] (kg)	0	-x.xxxxx	-x.xxx	0
[G571] natural gas, burned in industrial furnace low-NOx >100kW[RER] (MJ)	0	-x.xx	-x.xx	0

[G606] acetic acid, 98% in H2O, at plant[RER] (kg)	0	-x.xxxxx	0	0
[G623] water, completely softened, at plant[RER] (kg)	0	-xxx	0	0
[G681] light fuel oil, burned in industrial furnace 1MW, non-modulating[RER] (MJ)	0	-x.xx	0	0
[G769] polystyrene, expandable, at plant[RER] (kg)	0	-x.xxxxxx	0	0
[G2065] photovoltaic cell factory[DE] (unit)	0	-x.xxE-07	0	0
[G2875] ethanol from ethylene, at plant[RER] (kg)	0	-x.xxxxxx	0	0
[G2964] single-Si wafer, photovoltaics, at plant[RER] (m2)	0	-x.xx	0	0
[G2970] metallization paste, front side, at plant[RER] (kg)	0	-x.xxxx	0	0
[G2971] metallization paste, back side, at plant[RER] (kg)	0	-x.xxxxx	0	0
[G2972] metallization paste, back side, aluminium, at plant[RER] (kg)	0	-x.xxxx	0	0
[G2973] phosphoryl chloride, at plant[RER] (kg)	0	-x.xxxx	0	0
[G2974] treatment, PV cell production effluent, to wastewater treatment, class 3[CH] (m3)	0	-x.xxx	0	0
[G69] disposal, plastics, mixture, 15.3% water, to municipal incineration[CH] (kg)	0	0	-x.xx	0
[G71] tap water, at user[RER] (kg)	0	0	-xx.x	0
[G72] lubricating oil, at plant[RER] (kg)	0	0	-x.xxxxx	0
[G140] disposal, used mineral oil, 10% water, to hazardous waste incineration[CH] (kg)	0	0	-x.xxxxx	0
[G172] disposal, municipal solid waste, 22.9% water, to municipal incineration[CH] (kg)	0	0	-x.xx	0
[G399] nickel, 99.5%, at plant[GLO] (kg)	0	0	-x.xxxxx	0
[G577] methanol, at regional storage[CH] (kg)	0	0	-x.xxxxx	0
[G614] acetone, liquid, at plant[RER] (kg)	0	0	-x.xxx	0

[G648] vinyl acetate, at plant[RER] (kg)	0	0	-x.xxxxx	0
[G656] treatment, sewage, from residence, to wastewater treatment, class 2[CH] (m3)	0	0	x.xxxx	0
[G835] brazing solder, cadmium free, at plant[RER] (kg)	0	0	-x.xxxxx	0
[G1223] solar glass, low-iron, at regional storage[RER] (kg)	0	0	-xx.x	0
[G1224] tempering, flat glass[RER] (kg)	0	0	-xx.x	0
[G1410] aluminium alloy, AlMg3, at plant[RER] (kg)	0	0	-x.xx	0
[G1925] polyethylene terephthalate, granulate, amorphous, at plant[RER] (kg)	0	0	-x.xxx	0
[G2073] photovoltaic panel factory[GLO] (unit)	0	0	-x.xxE-06	0
[G2074] ethylvinylacetate, foil, at plant[RER] (kg)	0	0	-x	0
[G2076] disposal, polyvinylfluoride, 0.2% water, to municipal incineration[CH] (kg)	0	0	-x.xx	0
[G2079] glass fibre reinforced plastic, polyamide, injection moulding, at plant[RER] (kg)	0	0	-x.xxx	0
[G2900] 1-propanol, at plant[RER] (kg)	0	0	-x.xxxxx	0
[G2969] photovoltaic cell, single-Si, at plant[RER] (m2)	0	+1	-x.xxx	0
[G2978] polyvinylfluoride film, at plant[US] (kg)	0	0	-x.xx	0
[G33] electricity, low voltage, at grid[CH] (kWh)	0	0	0	-x.xx
[G279] transport, van <3.5t[CH] (tkm)	0	0	0	-xx.x
[G2030] inverter, 2500W, at plant[RER] (unit)	+1	0	0	-x.x
[G2031] electric installation, photovoltaic plant, at plant[CH] (unit)	0	0	0	-x
[G2035] photovoltaic panel, single-Si, at plant[RER] (m2)	0	0	+1	-xx.x
[G2041] slanted-roof construction, mounted, on roof[RER] (m2)	0	0	0	-xx.x
[G2018] 3kWp slanted-roof installation, single-Si, panel, mounted, on roof[CH] (unit)	0	0	0	+1

Table A.5: Lifecycle inventory of a monocrystalline silicon solar PV panel

Unfortunately a corresponding table cannot be provided for the micro-wind case studies due to a restricted publishing agreement with the manufacturer.