Performance and life cycle assessment of a small scale vertical axis wind turbine

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Abstract

Wind energy is one of the most popular renewable energy technologies that is considered indispensable in any low carbon energy mix. Small scale wind technologies that occupy less space and can supply electricity directly to their owners are thought to be more environmental friendly than the large turbines and therefore attract less criticism. Based on these, smaller scale renewables especially micro wind turbines should be the ideal solution but this might be just a leap of logic. The aim of this paper is to investigate whether it is worth developing smaller scale vertical axis wind turbines (VAWT) as a solution towards mitigating climate change. A real case of a H-Rotor 5 kW Darrieus vertical axis wind turbine in Poland is investigated for its performance using actual generation data. More importantly, a life cycle assessment (LCA) is undertaken, by compiling a very detailed life cycle inventory based on primary data and two scenarios were examined for the end-of-life treatment, including recycling and incineration. The performance assessment results show that the actual performance is very poor mainly due to the low wind speed. For this reason a series of hypothetical capacity factors were used to facilitate comparison with other studies. Using the CML impact assessment methodology, eleven environmental impact categories are assessed. The results show that the majority of the impacts are accredited to the supporting infrastructure - especially the mast and the foundations - rather than the turbine itself, which in the case of the Global Warming Potential (GWP) accounts for only 30%. Although the specific VAWT cannot achieve a generation that could reduce the environmental impacts to the level of the existing wind energy in Poland, a feasible capacity factor of 1.4% could make the GWP lower than the average low voltage electricity mix in Poland. The environmental performance is very sensitive to the fluctuations of the capacity factor and recommendations are given for appropriate siting, recycling of the metals and integration of the turbine on existing building structure.

Keywords: Vertical axis wind turbine, Small scale wind system, Life cycle assessment, Sustainable energy

1. Introduction

When designing a low carbon electricity mix, wind turbines are considered as one of the most important technologies to include. Although life cycle greenhouse gas (GHG) emissions are usually much lower for wind turbine than existing fossil fuel technologies, the range of the reported values in various life cycle assessment (LCA) studies is wide (Allen, 2011). These life cycle assessment (LCA) studies tend to focus on the mainstream horizontal axis wind turbines (HAWT) of medium and large capacity (i.e. above 500 kW and reaching up to 8 MW for onshore applications (Siemens Gamesa Renewable Energy, 2019)) and not on the Vertical Axis Wind Turbines (VAWT), whose capacity is usually small and ranges between 0.11 to 500 kW and in very rare occasions up to 1.6 MW (Rashedi et al., 2013). Despite their smaller capacity, the interest for VAWT has risen due to their suitability to be installed in an urban environment. The most recent literature (Möllerström et al., 2019) suggests that although the gap between VAWTs and HAWTs is wider than ever, the VAWT concept continues to be explored and that there have been several revivals of attempts to commercialize VAWTs.

In Europe alone, according to a catalogue of European urban wind turbine manufacturers published under the WINEUR EU Project, 33 companies are listed, one third of which include VAWT with capacities ranging from 0.11 to 100 kW in their portfolio (European Cities Wind Turbine Network, 2005). The main reason is that they are omni-directional and can accept wind from any direction and can therefore be situated at places where the wind is turbulent and where the wind direction changes often (Eriksson et al., 2008). Another reason is that they are less noisy than the HAWT, and that they can be mounted on a building roof, lowering the actual footprint and allowing them a better integration with the environment. Even when they are not mounted on a building roof and a mast is required, the height is usually 10 to 30 meters above the ground. This is much lower than the 60, 80 or 150-meter towers the HAWT require (ENERCON GmbH, 2016; Siemens AG, 2015; Vestas Wind Systems, 2008). The HAWT height can create visual impact issues as examined in the literature (Kokologos et al., 2014) and sparkle opposition from the locals. Based on these characteristics, as well as the fact that they can be deployed easier and faster in myriad locations they should have constituted a significant share in the energy mix and enjoyed the popularity of other small-scale renewables such as the photovoltaics, but this is not the case. One of their major problems, is their inability to perform adequately in low speed conditions (Tummala et al., 2016) which leads to low levels of electricity generation. According to (Kumar et al., 2018), “further research is crucial in making VAWTs a viable, dependable, and affordable power solution”. Their low performance has a very negative effect to their potential environmental impacts as well when these will be calculated against the actual kWh of electricity generated. A number of studies have been published the last ten years that investigate these impacts following a life cycle perspective (Kadiyala et al., 2017; Lombardi et al., 2018; Rashedi et al., 2013; Riley et al., 2011; Tremeac and Meunier, 2009; Uddin and Kumar, 2014). These studies present some common characteristics such as considering the same lifetime of 20 years, the use of aluminium, even partly, in manufacturing, the use of hypothetical electricity generation data and the low nominal capacity. An exception to sharing the same low capacity characteristic is the case where inventory data for a 1.6 MW Sandia VAWT are utilised to evaluate a 50 MW wind farm and compare them to two HAWT ones (Rashedi et al., 2013). Unfortunately, the use of Eco-indicator impact assessment method and Ecopoints as the unit used for the presentation of the results does not make this study easily comparable to others and only the outcome of the comparison, which shows that the VAWT has the lowest impacts, can be recorded. Another study which can neither be used for comparison is a cradle-to-gate LCA comparison of two 1 kW capped Savonius type VAWTs with blades made of stamped aluminium or injection moulded polypropylene (Riley et al., 2011). The study does not investigate the operation and end of life stages and the comparison gives a quite wide range of carbon footprints for the manufacturing only but conveys a very useful message about the benefits of using 100% recycled aluminium. The study about the characterization of the life cycle greenhouse gas emissions from wind electricity generation systems from (Kadiyala et al., 2017) only mentions the results from another work on the LCA of a 250 W VAWT from Tremeac and Meunier. Their work (Tremeac and Meunier, 2009) is one of the three studies that include a full LCA on VAWT and the inventory is based on manufacturer data of a 0.3 kW helix shaped turbine manufactured in Finland and installed in France. Using the Impact 2002+ impact assessment method, the small turbines with an intensity of 46.4 g CO_2-eq/kWh are presented as an excellent environmental solution for isolated sites compared to the alternative of generating power from diesel engines. They are also presented as a good solution for integration in low energy building, provided that there is adequate local wind resources. The authors suggest that the efficiency, we calculated as having a capacity factor of 5.48%, needs to improve and that recycling during decommissioning is an important step in order to reduce the environmental impacts. The other two cradle to grave LCA studies refer to a H-Rotor Darrieus type turbine and include both landfill and recycling scenarios and utilise the CML-2001 impact assessment method. In the first study, (Uddin and Kumar, 2014) analysed the energy, emissions and environmental impacts of a 300 W turbine for three different sites in Thailand, the wind conditions of which result in three different electricity generation profiles with capacity factors of 4.30%, 5.33% and 20.51% and the best of which gives a Global Warming Potential of 13.5 g CO_2-eq/kWh. The most recent of these studies (Lombardi et al., 2018), refers to two micro VAWTs of 1 and 3 kW nominal capacity manufactured and installed in Italy. The assumption they make about the wind distribution and shape factor results in two capacity factors of 9.1% and 9.2%, which give a GWP of 225 and 177 g CO_2-eq/kWh respectively. These studies are helpful and set the basis of including the VAWT in a low-carbon energy mix design. Nevertheless, their results are based on theoretical calculations and not on actual electricity generation data. Therefore, it becomes evident that there is a need for a LCA that uses actual electricity generation data from a VAWT that is installed and operating on a specific location so that the real world problems and restrictions of such an implementation can be studied and analysed. In order to bridge that gap, we have undertaken a cradle to grave LCA of a small VAWT for which we used data for the real manufacturing and for the actual generation recorded at the point of installation for three consecutive years. We compared the results with the ones that would be produced if a hypothetical capacity factor of 9% was used which is the average of the 5 capacity factors used in the cases studied in the available three LCA studies mentioned before. To facilitate the comparison we also included an end-of-life scenario, which combines recycling and incineration. Another reason that motivated this research is to highlight the contribution of the ancillary infrastructure required for the turbine to operate such as the mast and the foundation. It is mandatory to design and produce strong mast and foundation to avoid the collapse of the turbine. The infrastructure requires a lot of different materials, processing and transportation and this paper can provide future developers and consumers with highly useful information on many design and deployment parameters.

In the next section, we present the materials and methods used for the LCA we undertook and the section that follows that discusses the results of this modelling and comparison with other alternatives. This paper concludes with recommendations for future reference.

2. Materials and method

This research is mainly a LCA augmented by an assessment of the performance of the specific VAWT installed at the BUT campus. The overall methodology is shown in Figure 1 to facilitate understanding in the steps involved in this study.

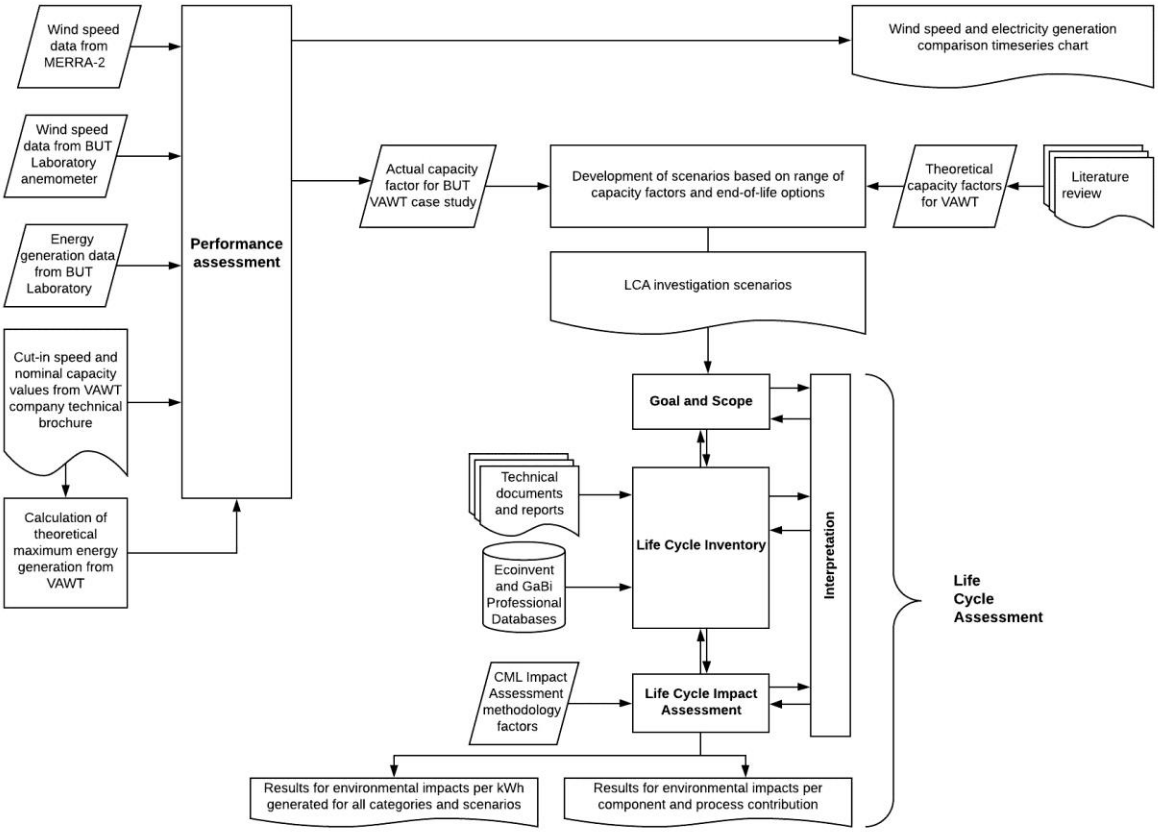

Figure 1 Research methodology flowchart

As can be seen in Figure 1, the performance assessment provided a standalone wind speed and electricity generation comparison timeseries chart but the main reason for undertaking it was to calculate the actual capacity factor of the specific VAWT. This actual capacity factor, along with the theoretical capacity factors found in the literature, are the basis of the scenarios used in the LCA. All the elements depicted in Figure 1 are analysed in the following subsections. First, we briefly describe the VAWT system and report its real-world performance at a demonstration site. This is followed by details of the LCA, which include goal and scope definition, compilation of the Life Cycle Inventory (LCI) and the Life Cycle Impact Assessment (LCIA) method used.

2.1. System description

The main device of the system under study is an H-Darrieus three-blade VAWT with a diameter of 3.5 m, blade height of 3 m and nominal capacity of 5 kW. The VAWT was commercially developed and manufactured in Poland (Polbud, 2013) by a company that is no longer in business and produced very few wind turbines during its lifetime. Therefore, this VAWT is a prototype rather than an established commercial product. It was erected on a mast with a height of 15.6 m on the west side of a building at the campus of the Bialystok University of Technology (BUT), Poland in 2015. The main components of the VAWT system, including the turbine, mast, foundation, cabling, earthing system and inverter, are shown in Figure 2.

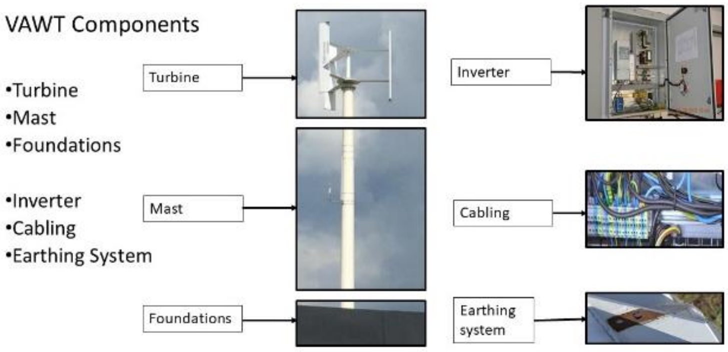

Figure 2. Main components of the Windkop 5kW Vertical Axis Wind Turbine system

2.2. Field trial and performance assessment

Technical performance is the primary concern for small-scale renewable energy system developers, mainly due to the need for financial sustainability of a project. Achieving sufficient electricity generation is also critical for environmental sustainability. The lower the generation, the lower the net energy the system will produce and the higher carbon footprint of the electricity generated will be.

The amount of electricity generated from the VAWT system over its lifetime can be calculated using the following equation

$$\boldsymbol{E_{Lifetime} = NY \cdot 8760 \cdot CN \cdot CF}$$

where, $E_{Lifetime}$ is the amount of electricity generated during the VAWT system lifetime [kWh], *NY* is the life time of the system [years], 8760 is the number of hours in a year, *CN* is the nominal capacity of the system [kW] and *CF* is the capacity factor [%].

We assume that the VAWT has a lifetime of 20 years because the majority of the components have a lifetime of 20-25 years. Therefore, this should be considered as a conservative assumption as the actual lifetime might be longer. In addition, we use 20 years because this is also used in similar studies (Lombardi et al., 2018; Tremeac and Meunier, 2009; Uddin and Kumar, 2014), which enables direct comparisons of our results with theirs.

The nominal capacity is 5 kW and the capacity factor need to be determined. The capacity factor represents the amount of electricity actually produced divided by the theoretical maximum amount that can be generated if the system was operating at 100% of the time at the nominal capacity. For this VAWT the maximum amount of electricity that could theoretically be generated is 8760 hours · 5 kW = 43,800 kWh annually. All of the previous VAWT LCA studies found in the literature calculated the electricity generated using the wind speed profiles of the sites and the technical characteristics of the wind turbines (e.g., cut-in speeds). For example, the estimated capacity factors range from 5.48% to 20.51% in three LCA studies (Lombardi et al., 2018; Tremeac and Meunier, 2009; Uddin and Kumar, 2014). Based on them we managed to estimate a hypothetical capacity factor of 9%, which is the average of the five capacity factors used in them.

The 5kW VAWT system installed at BUT was operated and monitored for a period of three years (April 2015 – March 2018) and the actual electricity generated is shown in Figure 3 (see Appendix 1 for the numerical data). The total amount of electricity generated was 658.3 kWh or 219.4 kWh annually, resulting in a capacity factor of 0.50% (219.4 kWh / 43,800 kWh). This is very small comparing to the capacity factors of other wind turbines (Lombardi et al., 2018; Tremeac and Meunier, 2009; Uddin and Kumar, 2014). In order to investigate this, wind speed data for the BUT site were acquired from two sources: i) the anemometer positioned on the wind turbine mast and ii) from Modern-Era Retrospective analysis for Research and Applications (MERRA) MERRA-2 by NASA (Gelaro et al., 2017) for a location situated 15 km away from the BUT site. Figure 2 also shows the average monthly wind speed for the two locations, the cut-in wind speed according to the company specifications, and the actual energy generated (measured in kWh) using the vertical axis on the right side of the graph. The two wind speed datasets seem to follow a similar trend but wind speeds at the BUT site are consistently lower (1.74 m/s lower on average and 2.5 m/s or by 53% lower at times). This difference was never below 1.26 m/s or 26% and this is not insignificant given that the cut-in speed stated in the technical brochure was 1.5 m/s.

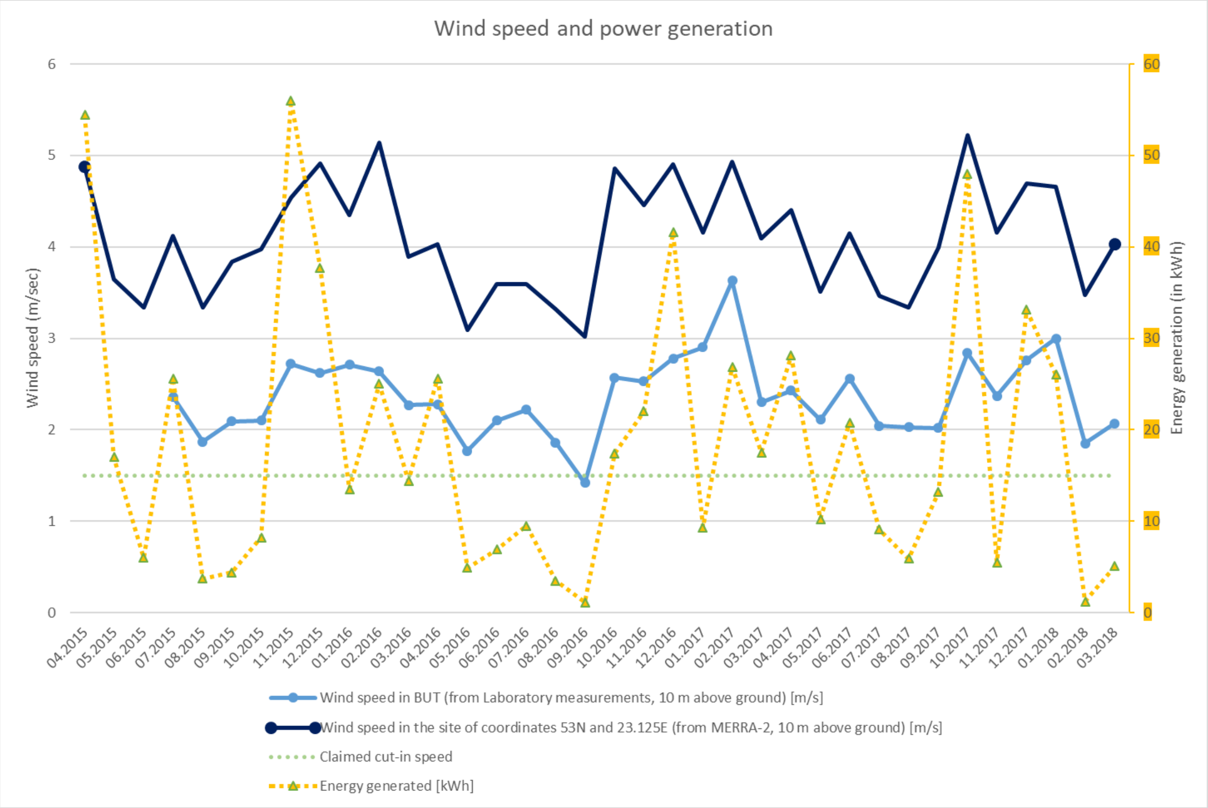

Figure 3. Wind speed and energy generation of the 5kW VAWT system installed at BUT

The technical brochure of the VAWT presented a cut-in speed of 1.5 m/s but the actual cut-in speed might be higher than what the company claimed. We could not perform any tests and experiments to confirm whether the parameters of the turbine provided by the company were correct and as the company is not active anymore it was not possible to confirm them. Regardless, the relatively low wind speeds at the BUT site could be an explanation of the low energy generation achieved by the system. In order to understand why the wind speeds at the site were low, we obtained the satellite image of the site (see Figure 4) from Google maps (Google Maps, 2019). The thick red circle near the centre of the image shows the location of the VAWT and the numbered polygons indicate the buildings nearby (1 – dormitories, 2 – auxiliary service building, 3 – Faculty of Civil and Environmental Engineering, 4 – Faculty of Electrical Engineering, and 5 – Faculty of Mechanical Engineering). The fact that the site was surrounded by buildings from three directions could be a reason for the low wind speeds. As far as the trees shown in Figure 4 are concerned, it is worth noting that the highest tree is around 10 m tall. This is lower than any of the buildings which range from approximately 12 m (buildings in cluster number 2) to 35 m (buildings in cluster number 1). The existence of the trees in urban sites in Poland (and especially the region where VAWT is installed) is very common and it is possible that these trees can affect wind speed and/or make wind more turbulent. However, in the case under study, the wind speed is not expected to be affected significantly by the trees in the future because the specific trees species have a very low annual height increment.

Another reason for the low electricity generation could be the interconnection of the turbine to the inverter. As the turbine is a prototype it was mandatory to adjust the loading characteristics and a few other parameters of the inverter in order to maximize the energy uptake. This can only be done experimentally and such a process can take a lot of time.

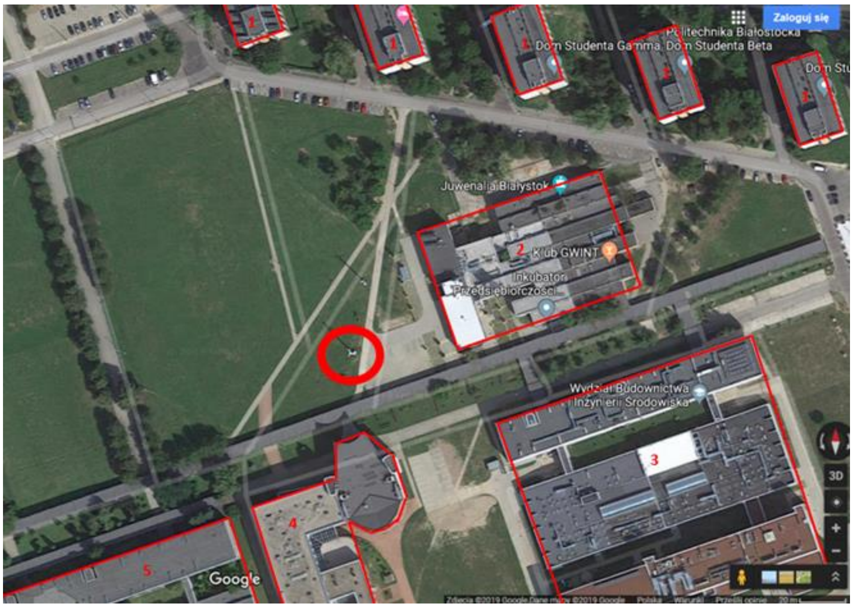

Figure 4 Google map view of VAWT in BUT Campus

Ideally, the actual generation of the VAWT should be measured for the whole lifetime but the three years of generation data should allow a reasonable LCA study. It is expected that the actual capacity factor of 0.5% observed could result in high environmental impact results. In order to produce results that are comparable to those from other studies, a hypothetical capacity factor of 9%, the average of the values found in the literature (Lombardi et al., 2018; Tremeac and Meunier, 2009; Uddin and Kumar, 2014), is also used to illustrate the effect of installing the VAWT at a site with much better wind speeds.

2.3. LCA Goal and Scope

Following the LCA framework in the ISO 14040 guidelines (International Standard Organization, 2006), we first define the goal and scope of the study and then compile the life cycle inventory (LCI) and proceed with the life cycle impact assessment (LCIA). The goal of our study is to evaluate the life cycle environmental impacts of electricity generated from the VAWT and the functional unit is defined as 1 kWh of electricity generated. The GaBi software version 9.2.0.58 (Thinkstep AG, 2019) is used to perform the LCA.

The system boundary is from cradle to grave and covers key life cycle stages including acquisition of raw materials, manufacturing and transportation of the VAWT components (foundation, mast, turbine, inverter, cabling and earthing system), installation, operation and maintenance, and end-of-life treatment (see Figure 5). The junction box which includes the protection relays, switches and electricity meter is shared with another wind turbine and three PV panels and excluded as the allocation would be difficult. The electricity generated is fed into a small grid at BUT and rather than the national grid. Therefore, transmission and distribution activities were not included in the system boundary.

The VAWT is still in operation and it is difficult to predict the end-of-life treatment. Therefore, we considered two scenarios, one being no specific action and the other a combination of recycling and incineration. The following section describes in detail the way the LCI was compiled and the Life Cycle Environmental Impacts were assessed.

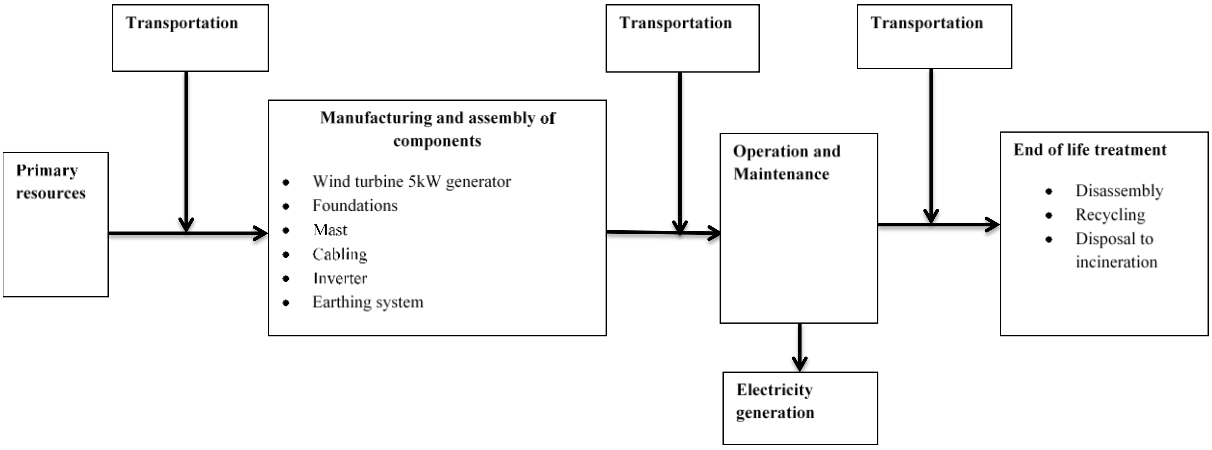

Figure 5 Life Cycle system boundaries of Vertical Axis Wind Turbine electricity generation

2.4. Life Cycle Inventory

The foreground data for the LCI was collected through the field trial. The dimensions and weights of the components were measured, supplementing the information readily available from the technical specifications documents. Communication with people involved in the development of this VAWT system allowed us to obtain more detailed information and data so that our LCI includes not only the direct material inputs but also the processes involved in their manufacturing and transportation where possible. The foreground data collected was then matched with the relevant background datasets that were available in Ecoinvent v3.4 (Wernet et al., 2016) and GaBi Professional database (schema 8007). When actual material and processing data was not available, assumptions were made. In addition, two different life cycle model plans were created in GaBi to represent the two main scenarios for the end-of-life treatment (do nothing and recycling in combination with incineration). Within these two main scenarios, we used three sub-scenarios with capacity factor of 0.5%, 9% and 20.5%, so that the actual as well as the maximum and average capacity factors found in the literature can be investigated. The following subsections describe the characteristics of and data collection and management for each one of the six components.

2.4.1. Wind turbine 5 kW generator

H-rotor wind turbines like the one under study have a simple blade profile and do not require a yaw mechanism. They also use a direct drive mechanism, which means that they do not require a gearbox thereby reducing the probability of a breakdown and the need for maintenance (Eriksson et al., 2008). Their simpler design enables the separation of the two main sets of components: i) the permanent magnet generator and ii) the main body and arms. The permanent magnet generator is made up of magnetic, resin and copper components. More specifically, the permanent magnet component refers to 56 pieces of tile-shape neodymium magnets each with dimensions of 80 mm × 40 mm × 15 mm and a weight of 360 g. These magnets were made in China and imported to Poland by ENES company ("ENES Magnesy - Hurtownia magnesów, uchwytów, separatorów magnetycznych," n.d.). We assume that they were transported by air from Zhejiang, which is approximately 8000 km away from Bialystok (Made-in-China.com, n.d.). Additional processes involved in their manufacturing such as wire drawing and energy and auxiliary inputs for the metal working factory and machines were taken into account. The copper components refer to 18 kg of copper used for the generator windings with a diameter of 1.4 mm. The resin components are 14 kg of polyester resin Polimal 109-32 (Polimal, 2018) used for the insulation of the generator windings. The windings consist of a number of coils that are connected in series formed from the wire whose ends are connected to the output terminals. The main body and the 12 arm rods are made of 272 kg of steel and the 3 blades, 6 arms and upper and lower covers are made of 126 kg of aluminium. The dimensions of these parts were available so it was possible to calculate the surface that had to be powder coated. This manufacturing process together with the sheet rolling and other metal working steel product manufacturing processes were included. The resin, steel, aluminium and copper parts are produced in Poland and a 400 km distance between their producers and the manufacturer of the turbine was assumed. The finished turbine was transported from the manufacturer to the BUT campus by lorry covering a distance of 150 km.

2.4.2. Foundations

The foundations that support the structure are consisted of an underlay, the footing and the reinforcement. The underlay is made of 2450 kg of type C12/15 gravel concrete and protected against ground water/humidity with ABIZOL P (Tytan professional, 2018a) and ABIZOL R (Tytan professional, 2018b) bitumen sealants. The footing is built with approximately 19 tonnes of C20/25 ready mix concrete reinforced by approximately 530 kg of type A-IIIN B500SP reinforcing steel. The concrete is produced in Bialystok and the ironworks is located in South of Poland, approximately 10 km and 500 km away from the BUT site where the turbine is installed, respectively. We also assumed that a 3m^3 diesel concrete mixer had to operate for 3 hours (US EPA, 2010). These distances and weights were taken into account and the transportation was assumed to be performed by 16-32 metric ton lorries.

2.4.3. Mast

The mast is a 15.6 m high welded tube made of 5 mm thick steel sheets cut and cold rolled with convergent cross-section along the height. The total weight of the mast is approximately 1.2 tonnes and its diameter is 450 mm at the top and 700 mm at the bottom. The tubes were fillet welded inside and outside and the total length of the weld is 90 m. The mast is coated both inside and outside using epoxy for the base layer and polyurethane for the external layer. The coat has white colour and a total thickness of 160 μm. Before painting the mast was sandblasted to achieve Sa 2,5 degree of purity (according to ISO 12944-4). As shown in Figure 6, the mast has two platforms, one at the top used for the attachment of the wind turbine body and one at the bottom used for basing the mast onto the foundation. Both platforms have holes for connection with the other components and ribs that are welded to them and the tube. At the bottom there is an additional opening with a cover for the cabling. We obtained data for the dimensions and were able to estimate the additional processes of drilling and laser machining required. In addition, we took into account the electricity, compressed air and lubricating oil required for the steel sheet stamping and bending. The ironworks is located in South Poland approximately 500 km away from the BUT site where the turbine is installed. These distances and weights were taken into account and the transportation was assumed to be performed by 3.5-7.5 metric tonnes lorries.

Figure 6. Views of the VAWT parts: bottom platform of the foundation (left), top platform (centre), welding lines between two segments and along two parts of one segment (right)

2.4.4. Cabling

For the cabling 110 m of YKY 5×16 mm^2 weighing 131 kg and 20 m of NSHTOU 5×6 mm^2 weighing 16 kg were used and an analytical description is available in the technical brochures from their manufacturers (HELUKABEL, 2018; NKT cables, 2018). For both types, the activities for the production of copper, rolling and wire drawing were taken into account as well as the activities for the production of their plastics parts. For their transportation, we assume 3.5-7.5 t lorries were used and the distances were 600 km for the Polish supplier and 821 km for the German supplier.

2.4.5. Inverter

The 5 kW inverter was supplied by TWERD company from Torun and the total weight and analytical drawings for the circuit and its components were available. It consists of a main case EATON CS-75/250, a controller MFC710ACR, a reactor ED1W, a sinusoidal filter CNW933/24, a radio frequency interference (RFI) filter RFI FLD 3030, contactors, disconnectors and other minor parts like wires, resistors and terminals. From the weights and descriptions of the components and other relevant information gathered from the companies' websites, assumptions were made about the types and shares of materials used. We estimated that overall the 52.5 kg inverter is made up of 29.1 kg of steel, 10.8 kg of copper, 11.6 kg of electronics and 1 kg of cables. Using these foreground data a new process was created in GaBi using background data from the Ecoinvent database. Although a dataset for the production of a 500 W inverter for a photovoltaic plant is available in the Ecoinvent database, we chose to create this simplified process that can be further analysed in the end-of-life scenarios. TWERD is situated at a distance of approximately 400 km and the transportation of the inverter is assumed to be done by a small commercial vehicle.

2.4.6. Earthing system

The system for the mast consists of a tape/earthing conductor FeCu 30×4 type and its length and weight are 26 m and 27.5 kg, respectively. For the allocation of the weights of the two materials (copper and steel) the ratio of their volumes was calculated using data from the technical brochure of a Polish supplier (CBM Technology, 2018). The 26 m tape with dimensions 30 mm × 4 mm is made of steel coated by copper with a thickness of 0.07 mm. Using the volume ratio, the density of these materials and the total weight, we estimated that the steel used was 26.88 kg and the copper 0.62 kg. We have taken into account the production of these materials and the sheet rolling processes as well as energy and auxiliary inputs for the metal working factory and machines used. The earthing system manufacturer is situated in Poland at a distance of approximately 400 km and the transportation is assumed to be done using a 3.5-7.5 t lorry.

2.4.7. Operation and maintenance

The type of the bearings used in the turbine do not require any lubrication during the turbine lifetime and they should be substituted by new ones, if deteriorated. The turbine is not designed for a regular maintenance. In fact, access to the lower bearing is very difficult and requires the disassembly of the turbine. Any screw tightening required is done manually. Based on this information, we did not include any material or energy inputs for the operation and maintenance phase.

2.4.8. End of life treatment

Based on communications with relevant stakeholders, we investigated two possible options for the end-of-life treatment. The first one is a ‘do nothing’ scenario, where the system is preserved at the BUT campus to serve as an exhibit for educational purposes. In the second scenario all of the components of the system are treated apart from the foundation and the permanent magnets of the generator. The foundation would remain in the ground while the magnets might still be used elsewhere though no data is available for the exact way of their reuse, recycling or refurbishing. The treatments of the other components mainly include the recycling of the metals (steel, copper and aluminium) and the incineration of the plastics and electronics together with a small fraction of the metals that is lost during the recycling process. The electronics and the paint in particular need to go through treatment as hazardous wastes. Table 1 shows the amounts of and the types of treatment for the materials mentioned.

Table 1. End of life material treatment

Materials type	Disposed mass [kg]	Recycled mass [kg]	Incinerated mass [kg]	Treatment as hazardous waste mass [kg]
Copper	120	108	12	-
Aluminium	126	120	6	-
Steel	1,530	1,377	153	-
Plastics (excluding paint)	71	-	71	-
Electronics	-	-	-	13
Paint	-	-	-	16
Foundation materials (Concrete, steel, bitumen)	No disposal			
Permanent magnets	No disposal			

In this scenario, the processes required for the recycling or incineration of the components are considered such as aluminium refining, electrolytic refining of copper scrap etc. The recycling process requires additional energy and material consumption, which burdens the system but at the same time, the recycling process also leads to production of secondary metals. Since we assumed that only virgin metals were used in the manufacturing stage, we can assume that the metals that are produced after the recycling can result in avoiding to use virgin metals in the future. Therefore, the impacts for the production of virgin metals should be taken into account as an environmental credit to the system. More specifically, the outcome of the recycling processes credits the system for avoiding to produce approximately 1245 kg of steel, 111 kg of aluminium and 82 kg of copper.

2.5. Life Cycle Impact Assessment method

Based on the LCIs for the system under the four scenarios, the LCIA results were calculated in GaBi using the CML2001 - Jan. 2016 (UL-IES, 2012) method. This LCIA method is one of the most widely used and it was chosen because the results can be compared to other studies found in the literature that used the same method. In addition, this method provides transparency, by keeping the results for 11 life cycle environmental impact categories disaggregated and does not assign weights. The 11 impact categories include Abiotic Depletion Potential – elements (ADP elements), Abiotic Depletion Potential – fossil (ADP fossil), Acidification Potential (AP), Eutrophication Potential (EP), Freshwater Aquatic Ecotoxicity Potential (FAETP), Global Warming Potential (GWP), Human Toxicity Potential (HTP), Marine Aquatic Ecotoxicity Potential (MAETP), Ozone Layer Depletion Potential (ODP), Photochemical Oxidant Creation Potential (POCP) and Terrestrial Ecotoxicity Potential (TETP).

The interpretation phase that included the results of the LCA and communication with the suppliers and stakeholders are presented in the following section.

3. Results and discussion

In this section we present the results for all the 11 environmental impact categories for the scenarios we used and which fall into two main categories: Scenarios A (three Sub-scenarios: Scenario A1, Scenario A2, Scenario A3) that assume that the components are not treated in any way after the end of life, and Scenarios B (three Sub-scenarios: Scenario B1, Scenario B2, Scenario B3) that assume that after the end of the lifetime in 20 years the components are treated as described in Section 2.4.8. Within each one of these two main scenarios, we considered the three sub-scenarios as described above and shown in Table 2. These sub-scenarios consider the three different capacity factors of 0.5%, 9% and 20.50% and the corresponding electricity generation based on the 5 kW nominal capacity and 20 years of lifetime.

Table 2. Scenario analysis

	Scenario A No End of Life treatment			Scenario B End of Life treatment included		
	Scenario A1	Scenario A2	Scenario A3	Scenario B1	Scenario B2	Scenario B3
Capacity factor [%]	0.5	9	20.5	0.5	9	20.5
Lifetime [years]	20	20	20	20	20	20
Energy generated [kWh]	4,380	78,840	179,580	4,380	78,840	179,580

The results are first compared to the impacts of the Polish national grid mix for low voltage electricity and the Polish wind electricity using datasets available in the Ecoinvent database as benchmarks. Then the contribution of each system component is analysed and presented for all environmental impact categories.

3.1. Results per kWh delivered for all scenarios

The graph in Figure 7 presents the results for each set of three sub-scenarios (A1-A3) and (B1-B3) compared against the Polish national grid mix and Polish wind electricity. The results shown are percentages normalised against the highest value for each impact and the absolute values are provided in a table at the appendix 1.

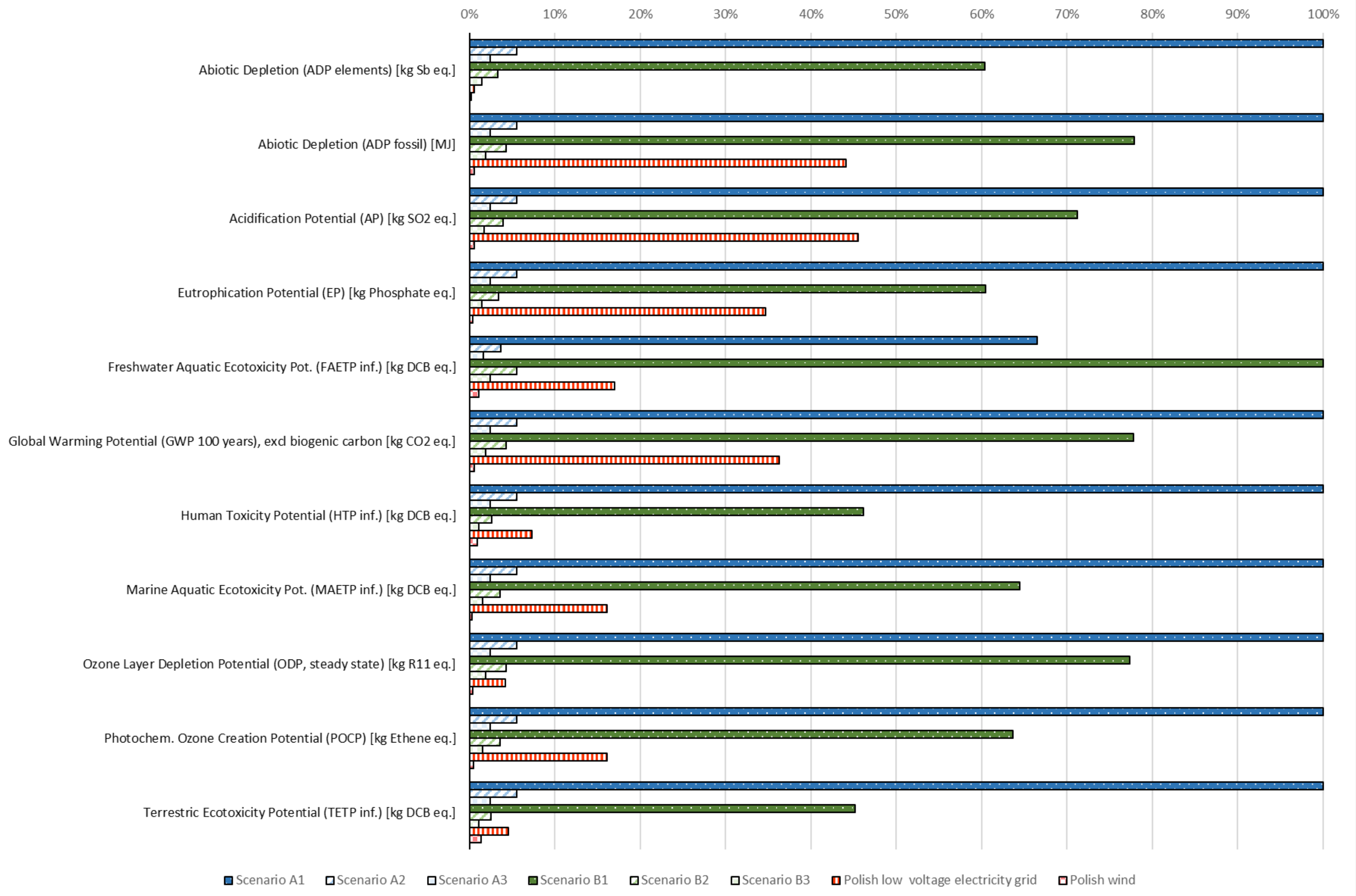

Figure 7. Comparison of scenarios results against Polish low voltage grid and wind electricity

From the graph (Figure 7), it is evident that the scenarios A1 and B1 score the highest values for all the environmental impact categories, regardless of the recycling of the materials or not. This is expected because these are the scenarios where the actual electricity generation capacity factor of 0.5% is used and that results in the lowest electricity generation and thus to higher impacts per kWh. Likewise, when we use the average capacity factor found in the literature (9%) the electricity generation increases and the impacts per kWh drop and that has as a consequence the better performance of the VAWT system against the Polish low voltage electricity grid. More specifically, the impacts for both A2 and B2 scenarios are lower than that of the Polish electricity grid but higher than the Polish wind for all environmental impact categories except the ADP elements, ODP and -for scenario A2 only- the TETP. Our investigation included the use of the highest capacity factor we could find in the literature for VAWT (20.5%) and as in the previous case, the resulting increase of the generated electricity improved the environmental performance. In particular, the impacts for both A3 and B3 scenarios are lower than that of the Polish electricity grid for all environmental impact categories except the ADP elements. When compared to the Polish wind, both scenarios score higher and only in the case of the TETP the scenario B3 has lower environmental impacts. One more observation is that Scenario A always scores higher than Scenario B apart from the case of FAETP. This could be justified by the fact that in Scenario B the components of the VAWT are treated which includes mainly recycling and incineration of the remaining smaller fraction and the gains from the recovered materials lowers the impacts while the incineration of copper and steel increases the impact on the freshwater aquatic ecotoxicity. Since one of the main reasons for supporting renewables is to tackle climate change it is worth highlighting that under the actual capacity factor, the GWP is more than double than the average Polish mix for low voltage electricity generation even when recycling happens at the end of life. This may seem controversial because the Polish electricity mix has a high carbon footprint due to the high share of fossil fuels and in these particular scenarios (A1 and B1) the results show that energy from wind could potentially contribute more to climate change than the combustion of a fossil fuel based mix. This should not be used as a generalisation that wind energy does not help tackle climate change but more like a warning that a minimum capacity factor should be guaranteed before VAWTs are installed. The rest of the results show that a capacity factor increase can lower the impacts to a point where the VAWT system can become more environmental friendly than the Polish mix and not only for the case of GWP. When compared to the Polish wind, which uses more efficient larger scale HAWT and has a GWP of approximately 15 g CO_2-eq/kWh the VAWT cannot compete as the lowest GWP it can get is approximately 55 g CO_2-eq/kWh in scenario B3. If the VAWT system was to play a role in the Polish energy mix, it would be good to know what performance could lead to lowering its environmental impacts to the level of the electricity sources currently used. For this reason, we investigated what should be the capacity factor threshold that could make the system equal to the Polish mix and Polish wind energy as shown in Table 3.

Table 3. Capacity factor investigations

	Scenario A No End of Life treatment		Scenario B End of Life treatment included	
	Capacity factor to equalise with Polish low voltage electricity	Capacity factor to equalise with Polish wind	Capacity factor to equalise with Polish low voltage electricity	Capacity factor to equalise with Polish wind
Abiotic Depletion Potential (elements)	84%	211%	51%	127%
Abiotic Depletion Potential (fossil)	1%	88%	1%	69%
Acidification Potential	1%	86%	1%	61%
Eutrophication Potential	1%	134%	1%	81%
Freshwater Aquatic Ecotoxicity Pot.	2%	29%	3%	44%
Global Warming Potential	1%	97%	1%	76%
Human Toxicity Potential	1%	97%	1%	75%
Marine Aquatic Ecotoxicity Pot.	7%	56%	3%	26%
Ozone Layer Depletion Potential	3%	172%	2%	111%
Photochem. Ozone Creation Potential	12%	141%	9%	109%
Terrestric Ecotoxicity Potential	3%	100%	2%	64%

Based on the results presented in table 3, it is not easy for the current VAWT to achieve low impact scores equivalent to the ones of the current Polish wind regardless of the end of life treatment scenario. Apart from the categories FAETP and the MAETP, for all the other categories the capacity factors should exceed 60% and in some cases (ADP elements, ODP and POPC) more than 100% which is not possible. For the FAETP, it might be possible if the capacity factor reaches 29% in scenario A and for the MAETP it might be possible if the capacity factor reaches 26% in scenario B. Although these capacity factors are possible to achieve for other types of wind turbines, no evidence in the literature was found to support that this has been achieved for this type of VAWT.

The results are more encouraging for the comparison against the Polish national low voltage electricity mix. Excluding the ADP elements, where a capacity factor of 84% and 51% is required for scenarios A and B respectively, the other impact categories can be lower if the VAWT achieves a capacity factor of more than 12%. For almost half of the environmental impact categories (ADP fossil, AP, EP, GWP and HTP), the capacity factor could be lower by achieving a 1% capacity factor which is just two times the actual one. Achieving a capacity factor of 3% which is still less than the lower capacity factor found in the literature could cover these as well as the FAETP, ODP, TETP and (for scenario A only) MAETP categories. Finally, achieving a capacity factor of 9% for scenario B and 12% for scenario A, which cannot be excluded based on the current literature would render the VAWT system an environmental friendlier option than the Polish national low voltage electricity mix (excluding the ADP elements category). The difference in these values for the required capacity factors and the fact that very small changes could lead to great improvements highlight the sensitivity of the environmental performance of the VAWT system to the changes in the actual generation performance.

3.2. Analysis of component and processes contributions

This subsection presents the contribution of the six components of the VAWT to the environmental impacts including the extraction of raw material, manufacturing, transportation and installation and excluding the end of life treatment (see Figure 8). This corresponds to scenario A but it does not take into account the electricity generation achieved so it is independent of the capacity factor and the specific conditions of the site. A table with the percentage contribution of VAWT components to life cycle environmental impacts excluding end-of-life stage is provided at the appendix 2.

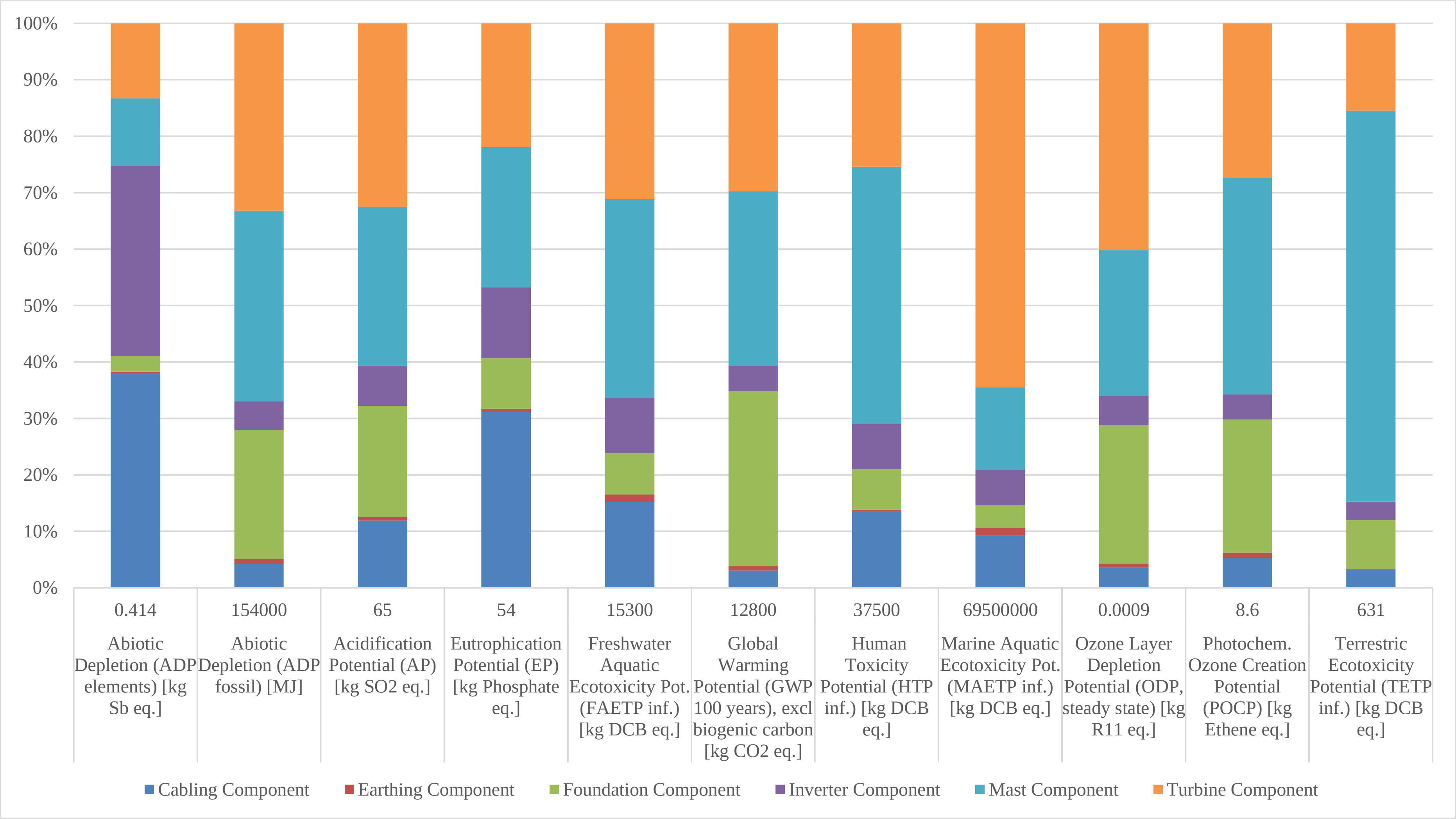

Figure 8. Life Cycle environmental impacts of the VAWT per component

Apparently, the turbine itself is not the main contributor, except in the case of MAETP, ODP and AP, and in most cases it accounts for about one third (33.3%) or less. The other two main contributors are the mast (for ADP fossil, FAETP, GWP, HTP, POCP and TETP) and cabling for ADP elements and EP. The foundations may not be the main contributor in any category but they contribute equally high with the mast to GWP and approximately to 20% or more to ADP fossil, AP, ODP and POCP. Similarly, the inverter who is not a main contributor still has a high share of 33.6% to the ADP elements which is close to the cabling components share of 37.9% for that category. Especially for the GWP, it is worth noting that the components used for the physical support of the turbine i.e. the mast and the foundation account for more than 60%. That is because of the use of concrete and steel, which are carbon intensive materials and this could be an incentive to explore other ways of supporting the turbine such as mounting them on the roof. However, the roof should be of appropriate strength and the installation should be further investigated because the VAWT resonance frequency is quite low and this could cause vibration that can be shared along the building structure.

As far as the contribution of the stages is concerned, the extraction of raw materials and their production before reaching the factory for further processing accounts for 70% to 94% of the impacts, their further processing (e.g. laser machining, welding, etc) for 3% to 22% and the transportation for 0% to 14% depending on the environmental impact category. On top of that, the end-of-life stage which includes both the recycling and the incineration as described in scenario B, can reduce the impacts from 22% to 55% depending on the environmental impact category with the exception of the FAETP where the impacts are increased by 50%. A table with the percentage contribution of life cycle stage to total life cycle environmental impacts excluding end-of-life stage is provided at the appendix 3.

3.3. Limitations

Because of technical and economical limitations, it is only possible to deal with one particular turbine and investigate the performance and environmental impacts of the technology that was applied. For a LCA, studying only one turbine or one type of turbine may be sufficient, but for the performance assessment, it would have been better to compare a few turbines or types of turbines ideally at sites with different wind conditions. To overcome this limitation, it is suggested that more than one VAWT should be installed on the campus to facilitate comparison of the performance and LCA of a variety of VAWT designs.

Another limitation of this study is that the site where the turbine is installed had many obstacles and quite weak wind conditions which led to an inadequate capacity factor that could potentially undermine the results. However, our analytical investigation on the capacity factors helped to tackle this issue. Results from this unfavorable siting provide a unique opportunity to highlight these concerns over establishing small wind turbines in urban areas (close to residential and/or commercial buildings) to potential customers and installers.

Last but not least, the relatively short duration for testing the turbine operation poses another limitation to this study. However, there are not many small scale VAWT systems commissioned and tested in real conditions for a longer time. In order to overcome this, monitoring of the wind speed and electricity generation will continue so that data can be collected over a longer period.

4. Conclusions

Based on the results of this study, it is suggested that great attention should be given in the specific location the VAWTs are deployed. An appropriate analysis of the wind speed profile and selection of the sites that exceed the stated cut-in speed is necessary so that a good performance is achieved. A combination of appropriate siting, recycling of the metals and mounting the turbine on a roof instead of using a steel mast and concrete foundations could render VAWT an environmental friendly technology for electricity generation compared to a fossil fuel dominated electricity mix. These findings together with the real and analytical data for the LCI have been the strong points of this study.

For the specific VAWT model, an energy generation peformance that corresponds to a capacity factor of more than 1.4% is enough to guarantee a lower GWP than that of the Polish low voltage grid electricity. On the same note, a capacity factor higher than 12% is enough to reduce all the environmental impacts (except ADP elements) to the same as or lower than those of the grid electricity. Since the results are very sensitive to the fluctuations of the capacity factor values, it is recommended to achieve a higher value than the one that makes them equal.

Althgouh VAWT is found to be less environmental friendly than the mainstream Polish wind energy technologies based on our field experiment, it should be noted that this conclusion is specific to the VAWT model tested and the site. It therefore does not suggest that VAWT technologies necessarily have poor environmental performance. It would be ideal to investigate future types of VAWT technology as they come into the market and improve on this study.

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APPENDICES

Appendix 1. Wind speed and electricity generation historical data

Appendix 2. Life Cycle Assessment results per kWh generated by VAWT under all scenarios and from Polish low voltage grid and wind electricity

Appendix 3. Contribution of VAWT components to life cycle environmental impacts excluding end-of-life stage

Appendix 4. Contribution of life cycle stage to total life cycle environmental impacts excluding end-of-life stage

Appendix 1. Wind speed and electricity generation historical data

MM.YYYY	Energy generated [kWh]	Wind speed in BUT (from Laboratory measurements, 10 m above ground) [m/s]	Wind speed in the site of coordinates 53N and 23.125E (from MERRA-2, 10 m above ground) [m/s]	Claimed cut-in speed [m/s]
04.2015	54.4		4.88	1.5
05.2015	17		3.65	1.5
06.2015	6		3.34	1.5
07.2015	25.6	2.36	4.12	1.5
08.2015	3.7	1.87	3.34	1.5
09.2015	4.4	2.09	3.84	1.5
10.2015	8.2	2.1	3.97	1.5
11.2015	56	2.72	4.54	1.5
12.2015	37.7	2.62	4.91	1.5
01.2016	13.5	2.71	4.35	1.5
02.2016	25	2.64	5.14	1.5
03.2016	14.4	2.27	3.89	1.5
04.2016	25.6	2.28	4.03	1.5
05.2016	4.9	1.77	3.09	1.5
06.2016	6.9	2.1	3.59	1.5
07.2016	9.5	2.22	3.59	1.5
08.2016	3.5	1.86	3.32	1.5
09.2016	1.1	1.42	3.02	1.5
10.2016	17.4	2.57	4.86	1.5
11.2016	22	2.53	4.46	1.5
12.2016	41.6	2.78	4.9	1.5
01.2017	9.3	2.9	4.16	1.5
02.2017	26.9	3.63	4.93	1.5
03.2017	17.5	2.3	4.09	1.5
04.2017	28.1	2.43	4.4	1.5
05.2017	10.2	2.11	3.51	1.5
06.2017	20.8	2.56	4.15	1.5
07.2017	9.1	2.04	3.46	1.5
08.2017	5.9	2.03	3.34	1.5
09.2017	13.2	2.02	3.99	1.5
10.2017	48	2.84	5.22	1.5
11.2017	5.5	2.37	4.16	1.5
12.2017	33.1	2.76	4.69	1.5
01.2018	26	3	4.66	1.5
02.2018	1.2	1.85	3.47	1.5
03.2018	5.1	2.07	4.03	1.5

Appendix 2. Life Cycle Assessment results per kWh generated by VAWT under all scenarios and from Polish low voltage grid and wind electricity

	Scenario A1	Scenario A2	Scenario A3	Scenario B1	Scenario B2	Scenario B3	Polish low voltage electricity grid	Polish wind electricity
Abiotic Depletion (ADP elements) [kg Sb eq.]	9.45E-05	5.25E-06	2.31E-06	5.71E-05	3.17E-06	1.39E-06	5.65E-07	2.24E-07
Abiotic Depletion (ADP fossil) [MJ]	3.52E+01	1.95E+00	8.58E-01	2.74E+01	1.52E+00	6.68E-01	1.55E+01	0.199
Acidification Potential (AP) [kg SO2 eq.]	1.48E-02	8.21E-04	3.60E-04	1.05E-02	5.85E-04	2.57E-04	6.72E-03	8.59E-05
Eutrophication Potential (EP) [kg Phosphate eq.]	1.23E-02	6.84E-04	3.00E-04	7.44E-03	4.13E-04	1.82E-04	4.27E-03	4.58E-05
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	3.49E+00	1.94E-01	8.52E-02	5.25E+00	2.92E-01	1.28E-01	8.95E-01	0.0595
Global Warming Potential (GWP 100 years), excl biogenic carbon [kg CO2 eq.]	2.92E+00	1.62E-01	7.13E-02	2.27E+00	1.26E-01	5.55E-02	1.06E+00	0.0151
Human Toxicity Potential (HTP inf.) [kg DCB eq.]	8.56E+00	4.76E-01	2.09E-01	3.95E+00	2.19E-01	9.63E-02	6.27E-01	0.0766
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	1.59E+04	8.82E+02	3.87E+02	1.02E+04	5.68E+02	2.49E+02	2.56E+03	46.2
Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	2.16E-07	1.20E-08	5.27E-09	1.67E-07	9.28E-09	4.08E-09	9.13E-09	7.68E-10
Photochem. Ozone Creation Potential (POCP) [kg Ethene eq.]	1.95E-03	1.09E-04	4.77E-05	1.24E-03	6.91E-05	3.03E-05	3.15E-04	9.78E-06
Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	1.44E-01	8.00E-03	3.51E-03	6.51E-02	3.61E-03	1.59E-03	6.54E-03	0.002

Appendix 3. Contribution of VAWT components to life cycle environmental impacts excluding end-of-life stage

	Cabling Component	Earthing Component	Foundation Component	Inverter Component	Mast Component	Turbine Component
Abiotic Depletion (ADP elements) [kg Sb eq.]	37.9%	0.3%	2.8%	33.6%	12.0%	13.3%
Abiotic Depletion (ADP fossil) [MJ]	4.2%	0.8%	23.0%	5.0%	33.9%	33.3%
Acidification Potential (AP) [kg SO2 eq.]	11.9%	0.7%	19.6%	7.1%	28.1%	32.5%
Eutrophication Potential (EP) [kg Phosphate eq.]	31.2%	0.6%	8.9%	12.6%	24.9%	21.9%
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	15.1%	1.4%	7.3%	9.7%	35.2%	31.0%
Global Warming Potential (GWP 100 years), excl biogenic carbon [kg CO2 eq.]	3.0%	0.8%	30.9%	4.5%	30.9%	29.7%
Human Toxicity Potential (HTP inf.) [kg DCB eq.]	13.6%	0.3%	7.2%	7.9%	45.6%	25.4%
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	9.2%	1.5%	4.0%	6.2%	14.7%	64.5%
Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	3.5%	0.8%	24.5%	5.1%	25.8%	40.2%
Photochem. Ozone Creation Potential (POCP) [kg Ethene eq.]	5.3%	0.9%	23.6%	4.4%	38.4%	27.3%
Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	3.3%	0.1%	8.6%	3.2%	69.3%	15.5%

Appendix 4. Contribution of life cycle stage to total life cycle environmental impacts excluding end-of-life stage

	Raw material and parts production	Manufacturing and assembly	Transportation
Abiotic Depletion (ADP elements) [kg Sb eq.]	96%	3%	1%
Abiotic Depletion (ADP fossil) [MJ]	77%	16%	7%
Acidification Potential (AP) [kg SO2 eq.]	81%	15%	4%
Eutrophication Potential (EP) [kg Phosphate eq.]	89%	10%	1%
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	78%	22%	1%
Global Warming Potential (GWP 100 years), excl biogenic carbon [kg CO2 eq.]	80%	14%	6%
Human Toxicity Potential (HTP inf.) [kg DCB eq.]	91%	8%	1%
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	80%	20%	0%
Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	70%	16%	14%
Photochem. Ozone Creation Potential (POCP) [kg Ethene eq.]	85%	12%	3%
Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	94%	6%	0%