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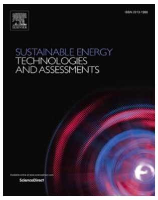

# Energy efficiency and environmental impacts of horizontal small wind turbines in Austria

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ABSTRACT

Small wind turbines (SWT) can contribute to the urgent need of transforming the energy system. Nevertheless, due to the heterogeneity of SWT technology, a high variety in environmental impacts of SWT exist. To evaluate whether the use of horizontal SWT can efficiently contribute to a renewable energy system, Life Cycle Assessments of two SWT, a commercial Schachner SW5 and a do-it yourself turbine in the Piggot Pig2F design, were conducted. The energy payback time was calculated using performance measurements from a rural and a suburban site in Austria. Results show that SWTs can reduce greenhouse gas emissions of the Austrian electricity production with calculated global warming potentials of 62 $gCO_2eq/kWh$ (SW 5) and 94 $gCO_2eq/kWh$ (Pig2F) respectively. For both SWTs, the sub-system *tower with foundation* contributes about half to their overall global warming potential as well as to the cumulative energy demand. An improved shaping of SWT technology is therefore exemplified by both SWTs. The analysis shows that 19 out of 20 considered impact categories can be reduced by using secondary (recycled) or re-used steel, especially for the tower. The rural and suburban use of horizontal SWT can potentially contribute to reduce the environmental impacts of Austrian electricity production. Nevertheless, it becomes evident that a more sustainable shaping of SWT technology is highly recommendable.

## Introduction

The reduction of GHG (greenhouse gas) emissions of the electricity system is an urgent need addressed in numerous scientific and political statements [1]. In this context, wind energy is planned to have a central role in the decarbonization of electricity generation [2]. While large wind turbines are highly efficient, they cannot be installed close to populated areas due to health and safety considerations (e.g. ice throw, falling parts, noise, [3]). Moreover, such turbines are typically feasible and economical in places where energy demand is minimal. Next to the use of photovoltaic systems, small wind turbines (SWT) may be an optional technology for decentralized renewable electricity production close to the consumer (households or industry).

The International Electrotechnical Commission defines SWT as wind turbines with max. 200 $m^2$ rotor swept area and a nominal capacity $<$ 50 kW [4]. However, the global average nominal capacity of a SWT is 1.1 kW. One million SWT are installed worldwide, with the majority of them having a nominal capacity of under 1 kW [5]. The market for SWTs, counting 330 manufacturers worldwide, features heterogeneous technologies. About 75% of them are selling turbines with a horizontal axis (HAWT), while 18% sell turbines with a vertical axis (VAWT) and 7% do sell both. About 80% of the manufacturers sell stand-alone applications for rural electrification or off-shore use [5]. This indicates that only a minor fraction of installed SWTs is located in urban areas. In 2017, when the last market overview was generated, about 350 SWT were installed in Austria, out of which 75% have a capacity in the range of 1 kW to 10 kW [6].

Even though the turbines are already on the market, determining questions of the environmental efficiency of their use often stay unaddressed. Some effort has already been made in assessing the environmental impact of SWT. For large wind turbines, reliable values on energy payback time and GHG emissions exist [7] and are provided by

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*Abbreviations:* CED, cumulative energy demand; GHG, greenhouse gas; GWP, global warming potential; HAWT, horizontal axis wind turbine; LCA, Life-Cycle Assessment; LCIA, Life-Cycle Inventory Assessment; Pig2F, small wind turbine type Piggott2F16P; SWT, small wind turbine; SW05, small wind turbine type Schachner05; VAWT, vertical axis wind turbine; WT, wind turbine.

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the manufacturer (e.g. [8]). In contrast, only few studies have been published regarding SWTs, reporting very different results for energy payback times and GHG emissions (see e.g. [9,10,11,12]).

Life Cycle Assessment (LCA) is a helpful method to evaluate the potential environmental impacts of a technology. In general, a LCA describes a Product System, the object of the analysis, which can be a product or a service, as a network of processes – activities which transform inputs into outputs. The inputs and outputs are typically materials and energy as well as emissions. Processes are often transformations of materials (e.g. Iron ore to Steel, Oil to Electricity) but can also describe transport of goods. Several processes may be aggregated into new processes when useful (different energy sources → EU energy mix). Typically, the connection of processes is done via a software tool which takes the necessary input and output data for processes from established data bases. The cumulated outputs can finally be assessed using environmental impact assessment methods, which transform the multitude of outputs into few descriptive parameters. The used software and database both need to support the chosen environmental impact assessment methods.

In a recent review focusing on LCAs of wind turbines, a wide range of potential environmental impacts of turbines in the $<$ 20 kW range was detected and a need for further assessments was determined [13]. The focus of recently made LCAs is usually on vertical axis turbines ([14,15,16]), while the most common type are horizontal axis turbines ([6]).

Furthermore, improvement assessment is rarely addressed explicitly (e.g. [11],) and no publications doing an analysis of technology shaping possibilities for small wind turbines could be identified. Assessments of off-grid-systems mostly identify batteries as relevant ([17]) and focus on system optimization (hybrid systems).

The present paper is addressing these missing information by conducting a LCA of two SWTs representing the range of design and installation sites of HAWT in Austria. The global warming potential (GWP) and energy payback times are the core of the present analysis. This study also presents 17 other impact categories which have also been analyzed to broaden the picture of the potential environmental impacts. Since LCAs of wind power systems are especially sensitive to the local site conditions, the focus of the present paper is on general technology aspects and possibilities for improved shaping of the current technology and design to reduce the impacts of the two HAWTs are assessed.

Although the precursory requirement of a renewable energy technology having low environmental impacts seems fundamental, studies show that there are SWTs on the market that do either not fulfil these requirements or for which no information on their environmental impact is available. For instance, a surprisingly high energy payback time of 160.9 years was calculated for a small HAWT in Taiwan [9],

**Fig. 1.** Small wind turbines Schachner05 (left) and Piggott2F16P (right) at their respective sites.

**Table 1**
Characterization of performance measurements for SW05 in Lichtenegg and Pig2F in Groß Enzersdorf.

| | SW05 | Pig2F |
|---|---|---|
| rotor diameter | 5.6 *m* | 2 *m* |
| rated power | 5 kW | 400 W |
| starting speed | 2.5 m/s | 3 m/s |
| maximum speed | 50 m/s | Unknown |
| rotational speed control | Rpm-dependent pitch | Furling system |
| location | Lichtenegg | Groß Enzersdorf |
| location type | Rural | suburban |
| average wind speed at installation height | 5.3 m/s | 3.6 m/s |
| Turbine installation height | 12 *m* | 6 *m* |
| time period measured | Jan-Dec 2019 | Jul 2018 - Jun 2019 |
| type of installation | grid connected | isolated operation/ battery connected |
| data measurement | kWh / 15 min | W / sec |
| calculated capacity factor | 0.15 | 0.08 |

whereas for large wind turbines, which are almost always HAWT, the payback time amounts to less than one year [7]. Another study calculated a payback time of 6.5 years for a 250 Watt turbine [10]. Even though this value is feasible within the life span of a wind turbine, which is assumed to be 15 to 20 years, the value still exceeds other technologies such as large wind turbines or photovoltaics [18]. These high and highly variable payback times are confirmed by other studies [10,15].

Early studies focusing on SWT GHG emissions demonstrated a 93% reduction compared to private household diesel generators [11]. Considering the existing high share of renewable energy sources in the European and especially the Austrian electricity production mix, more ambitious targets than lower environmental impacts than a diesel generator need to be defined. Some studies show that SWTs have a lower GWP than the local grid electricity mix: Glassbrook et al. [19] published a study on four SWTs with a nominal capacity of under 20 kW. These turbines showed shorter energy payback times and lower GWP than the Thai grid electricity, but higher levelized costs of electricity. This may partly be explained by Thailand's electricity mix, which consists of 75% fossil fuels. A recent study by Kouloumpis et al. [16] compared the use of VAWTs to the Polish grid electricity. At sites where the turbine production reached a capacity factor of at least 1.4%, the turbines exhibited a lower GWP/kWh than Polish grid electricity. The published results demonstrate how important the selection of appropriate sites is. Since the importance of siting is well-known, this topic will not be pursued further in relation to the performed LCAs.

Furthermore, the question arises what technological design and material-use leads to the most energy efficient utilization strategy. This question stays unaddressed in most studies. Kouloumpis et al. recently conducted LCAs of two VAWTs (1 kW and 3 kW) [16]. Aside from comparing the overall impact of electricity production to the grid electricity, they also analyzed which turbine parts contribute the most to the GWP. It is also noted that use of Steel and concrete for construction leads to highest contribution towards the GHG emission (60%). On the other hand, about 30% GWP correspond to transportation. To evaluate whether this finding can be confirmed for HAWTs as well, two fundamentally different types of HAWTs are analyzed in the present study. The analysis is not a comparison of the two turbines. This would not be eligible since the installation sites and types differ considerably. The turbines are chosen to show the current spectrum of designs and sites in Austria.

It is further evaluated, which components and materials show the highest energy demand and contribution to GWP and how this demand may be reduced by replacing selected construction materials. The present paper aims to answer the question: "What are the potential environmental impacts of SWTs at suburban and rural sites in Austria and how can they be improved?".

Furthermore, the following questions are addressed:

- Considering their whole life cycle, are the two turbines producing more energy than they consume at a suitable suburban/rural site (energy payback)?
- Are the turbines reducing GHG emissions compared to the Austrian electricity production mix (GWP)?
- Which components of the SWTs are hotspots considering the potential environmental impact?
- Which technological design adaptations may reduce energy demand as well as GHG emissions?

## Method

The methodical approach was chosen to be a combination of LCA and a performance analysis of two horizontal SWT: Schachner05 (SW05, Fig. 1 left) and Piggott2F16P (Pig2F, Fig. 1 right). The SW05 is the dominating SWT on the Austrian SWT market. It has a relatively high

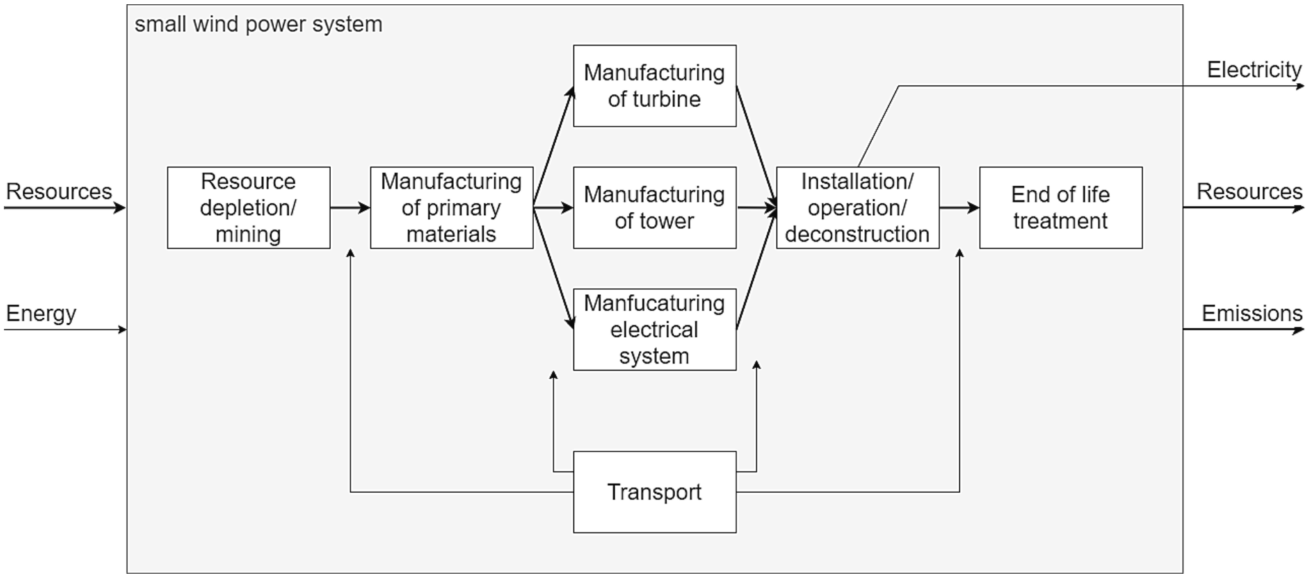

**Fig. 2.** System diagram of the conducted LCA. System boundaries include all processes directly related to manufacturing, the use and end-of-life treatment of a SWT.

**Table 2**
Results of LCIA [22,23] of the six most relevant categories for SW05 and Pig2F (functional unit one item SWT).

| Impact category | Unit | SW05 | Pig2F |
|---|---|---|---|
| Freshwater ecotoxicity | kg1,4-DCB | 1 496.25 | 607.06 |
| Human carcinogenic toxicity | kg1,4-DCB | 2 157.73 | 147.88 |
| Global warming potential | kgCO$_2$eq. | 8 576.51 | 494.10 |
| Land use | m$^2$a crop eq | 165.59 | 103.07 |
| Energy demand | kWh | 37 474 | 2 483 |
| Non-renewable energy demand | kWh | 35,518 | 2,137 |

nominal capacity compared to other SWT used in Austria (5 kW), while still undisputedly classified as SWT. The Pig2F is built according to the most used do–it–yourself concept worldwide and has a relatively low nominal capacity compared to other SWT (0.4 kW). The two systems are technologically mature SWTs and represent the range of design and size of HAWTs used in Austria. In the following, first the LCA methodology is described. Secondly an overview of the performance measurements on a rural site (SW05) and at a suburban site (Pig2F) is given (see Table 1). The last subsection describes the sensitivity analysis and shaping possibilities regarding the tower and the use of steel.

### *Life Cycle assessment*

In this study, the software openLCA 1.10.3 [20] with the database ecoinvent 2.2 [21 22] is used and the impact categories of ReCiPe midpoint (H) 2016 [23] as well as the cumulative energy demand (CED) and the non-renewable energy demand were applied (described in detail in section 2.1.4). LCA-processes will be identified in the text by the names used in the database and written in italics. A more detailed description of used LCA-processes will be given where necessary.

The LCA is conducted in four steps according to ISO 14044 [24]:

1) Definition of goal and scope.
2) Inventory assessment.
3) Impact assessment.
4) Interpretation.

The next sub-chapters are following this structure.

### *Goal and scope*

The present LCA study aims to evaluate whether the use of SWTs at rural and suburban sites in Austria is energy efficient, compared to the Austrian grid electricity consumption mix considering the potential environmental impacts of electricity production. A further goal is to evaluate which components of the system contribute most to GHG emissions (hot spots) to identify how a better shaping of SWTs can be achieved in order to reduce the potential environmental impacts the most. A HAWT with 5 kW nominal capacity (SW05) as well as a HAWT with 400 W nominal capacity (Pig2F) were examined including the turbine itself, the tower as well as the electric/electronic system. For technical details of the turbines see Table 1.

Both SWT systems were divided into three sub-systems: The *wind turbine* itself, the *tower with foundation*, and the *electric/electronic system*, including inverter, control unit and cables. For all components of the system, production, manufacturing, end-of-life treatment and transport are considered.

The system diagram, shown in Fig. 2, depicts the different processes, which are considered in the LCA. Material use, transport and construction were assessed according to information provided by the manufacturers. Values of material and energy flows considering mining, manufacturing of primary materials, construction processes and end-of-life treatments were taken from the ecoinvent 2.2. database [22]. Operation phase and thereby all energy and materials needed for maintenance, were neglected in the present LCA.

### *Inventory assessment Schachner05*

The SW05 is a 5 kW (nominal power) system produced by an Austrian manufacturer, which has been on the market since 2010 and is EN1400-2 certified. The turbine of the SW05 system consists of steel and glass-fiber-reinforced composites and a permanent magnet generator using NdFeB alloy magnets. For the inventory analysis the turbine is divided into three sub-processes: generator, nacelle and rotor. The generator weighs 118 kg, which is mainly steel, followed by copper (15 kg). The magnets are made from 4.8 kg Nd$_2$Fe$_{14}$B and some components are covered in linen. The nacelle as well as the rotor comprise mainly steel and further brass and copper. The blades are made of glass fiber reinforced composites filled with polyurethane foam.

The electronic system comprises cables, the control cabinet, the inverter and a control unit. For these components comparable existing datasets [22] were used.

The manufacturing of *tower with foundation* was divided into the two sub-processes tower and foundation. The tower of the SW05 system is made of 750 kg steel. The reinforced concrete foundation is made from 12 906 kg concrete and 50 kg steel. For all steel elements the input and output values according to the LCA-process *steel, low-alloyed, at plant* provided by the ecoinvent database [22] was used, describing the representative manufacturing process for low alloyed steel types in the EU without transport to the facility manufacturing the turbine ("at plant").

For economic reasons, turbine and tower are produced in China and transported to Austria by freight ship. The transport ways are included in the manufacturing LCA-(sub-)processes. Values from the processes *transport, lorry > 16 t, fleet average*, representing the transport by a lorry with a load capacity>16 t from an average fleet of transport vehicles, and *transport, transoceanic freight ship*, representing transport with a large freight ship (50 000 t carrying capacity, 65% load factor), provided by the ecoinvent database were used.

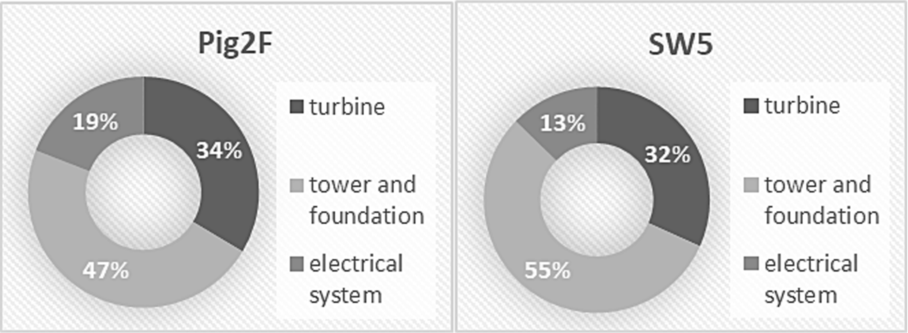

**Fig. 3.** Contribution to GWP over the whole lifecycle of Pig2F (left) and SW05 (right) sub-systems.

### *Inventory assessment Piggott2F16P*

The Piggott SWT is an open access technology originally developed by Hugh Piggott in Scotland [25]. The design is used worldwide and has been improved by different organizations and research institutes over the past 20 years [26] and is mainly used for rural electrification [27]. For the present LCA the Piggott turbine Pigott2F16p (Pig2F) as built in the workshops of the Austrian company PureSelfMade is used. This version of the turbine has a diameter of 2 m, 400 Watt nominal capacity, uses ferrite magnets and its generator consists of 16 poles (magnets) and 12 coils [28].

The frame of the generator as well as the nacelle are made of steel. The generator consists of ferrite magnets and copper coils cast in epoxy resin. The wooden blades are made from Austrian plywood and acrylic varnish. The tower is made of steel. Similar to the LCA for the SW05, the input and output data as provided by the ecoinvent-process *steel, low-alloyed, at plant* [22] were used for all steel elements. The electronic system is divided into cables, the inverter and a control unit. Different pre-existing ecoinvent-processes for electronic components were used for the control unit and cables. For the inverter the ecoinvent-process “*inverter, 500 W, at plant*.” was used [22].

Transport was assumed to be exclusively by lorry. The ecoinvent-process “*lorry > 16 t, fleet average*” [22] was therefore used for all transport routes.

### *Impact assessment*

The impact categories GWP and energy demand are in focus of the present analysis. Therefore, cumulative energy demand and non-renewable energy demand were analyzed using openLCA. The non-renewable energy demand includes the use of fossil and nuclear energy as well as the use of primary forest. Energy payback times for both SWT were further calculated considering a 20-year lifetime. The chosen three sub-systems (*turbine*, *electronic system* and *tower with foundation*) were analyzed to identify the hot spots for GWP and CED.

To evaluate whether technology shaping to reduce GWP or energy demand show negative effects on other environmental impact categories, the life cycle impact assessment (LCIA) was calculated using the 18 impact categories according to ReCiPe midpoint (H) 2016 [23], as well as the CED and non-renewable energy demand. Selected examples of impact categories are shown in Table 2. These 18 categories, called midpoint indicators in the ReCiPe framework, are characterized as “low uncertainty and difficult to interpret” [23]. The results in the individual categories are further modified by the time frame for which an effect is assumed (e.g. global warming potential over 100 years – GWP100). Of the three available versions, the so called hierarchist perspective (H) is chosen since it “is based on scientific consensus with regard to the time frame and plausibility of impact mechanisms” [23]. According to the hierarchist perspective, the GWP values are calculated as GWP100 and thereby show the estimated GWP over a time period of a 100 years [23].

Regarding data actuality, a sensitivity analysis was conducted since some data used from the database ecoinvent 2.2. are older than 10 years. It has been analyzed how the GWP from electricity production mix as well as steel manufacturing has changed from 2006 to 2020 and how much these processes contribute to the total CED.

### *Interpretation*

For interpretation six impact categories are chosen: CED, non-renewable energy demand as well as GWP are in the focus of the analysis. Further land use change, freshwater ecotoxicology and human carcinogenic toxicity [23] have been chosen since the results in these categories differ strongly to the results of the other three core impact categories. The GWP is compared to the current average GWP of the Austrian grid electricity and other renewable energy technologies as well as values for SWTs from literature and the Austrian label for renewable electricity “Grüner Strom” (green electricity). Further, it is analyzed which of the three sub-systems is the greatest contributor to GWP. The CED and measured production data are used to calculate the energy payback time according to equation (1).

$$\boldsymbol{energypaybacktime} = \frac{E_{demandtotal}}{E_{annual}} \tag{1}$$

With $E_{\text{demand total}}$ being the overall energy demand and $E_{\text{annual}}$ the average annual energy production of the SWT.

### *Performance assessment*

Performance data are measured at two different sites characterized in Table 1. The Pig2F is installed at a suburban site (Groß-Enzersdorf) close to Vienna and data of power production and wind speeds were collected between July 2018 and June 2019. The average wind speed at the hub height of 6 m above ground was 3.6 m/s. The annual production of the Pig2F was 263 kWh.

The SW05 is installed in Lichtenegg, a rural site with an average wind speed of 5.3 m/s at 12 m above ground (hub height). Wind and performance data have been collected by Technikum Vienna. In 2019 the SW05 produced 6926 kWh electricity.

### *Sensitivity analysis considering data actuality*

The values for the electricity consumption and production mixes in the used data base ecoinvent 2.2 date back to 2006. Within the last 15 years energy production changed significantly. Therefore, a sensitivity analysis of three used processes for electricity mixes (Austrian grid electricity mix, Swiss electricity mix, Chinese electricity mix) on the LCA results is conducted.

### *Sensitivity analysis and shaping possibilities in steel use*

The LCA results are also used to place them in the broader context of a technology assessment. [29] The impact of changes in steel consumption for the SWT system, especially regarding the tower, on the environmental impacts of the assessed SWT are investigated, in order to find out whether improvements in shaping SWT technology are possible. The use of different types of steel was assessed to identify the possible changes in the overall environmental impacts. In a first step the GWP of steel production between the years 2000 and 2020 is analyzed and in a second step is compared to the GWP of secondary steel production. The impact of the overall environmental impact of the two small wind turbines by using a different type of steel was assessed by different alternative scenarios related to the different manufacturing processes of the two turbines. The SW05 is produced in serial production. Instead of the EU steel mix, which is made from 63% primary and 37% secondary steel, only secondary steel is used. No more changes are made in the production system. The sensitivity to the environmental impact categories land use, global warming, human carcinogenic toxicity and freshwater ecotoxicity are discussed. The Pig2F is a self-built turbine, so instead of new manufactured primary or secondary steel, also directly reused steel (e.g. reused steel pipes) can be used in the manufacturing process. Therefore, for the Pig2F the sensitivity of GWO to changing the used steel from EU steel mix to directly reused steel is assessed.

**Table 3**
Total energy demand and energy payback time of the two studied SWT systems calculated using the cumulative energy demand.

| | SW05 | Pig2F |
|---|---|---|
| total energy demand (kWh) | 37 474 | 2 483 |
| non-renewable energy demand (kWh) | 35 518 | 2 137 |
| nominal capacity (kW) | 5.00 | 0.40 |
| annual production (kWh) | 6 926 | 263 |
| energy payback time (yr) | 5.41 | 9.43 |

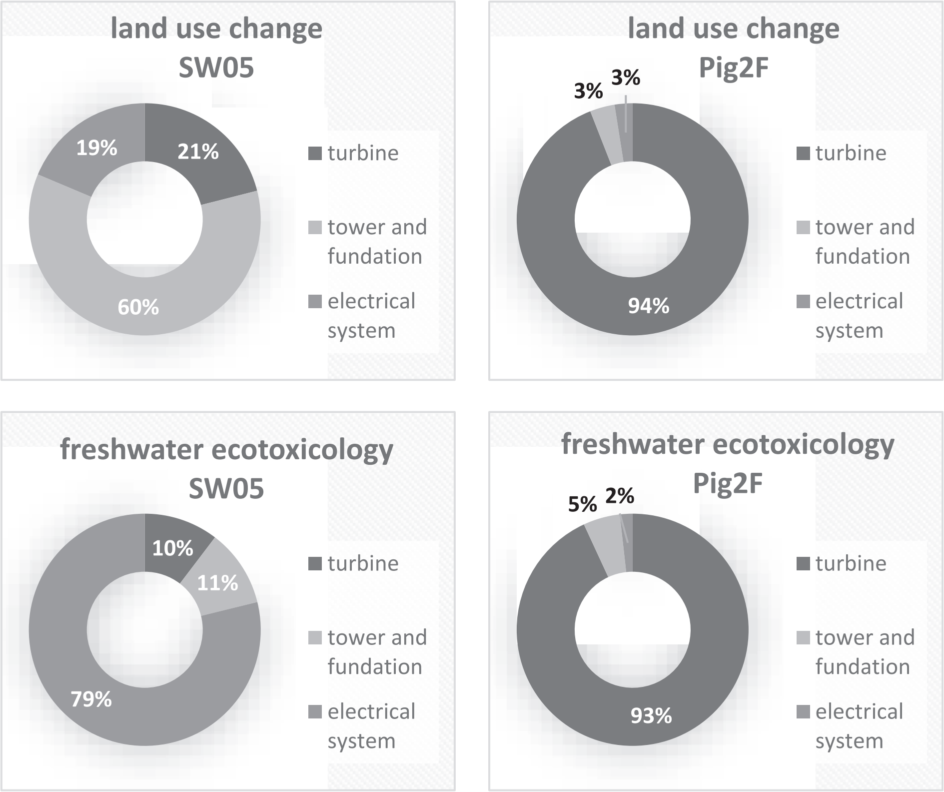

**Fig. 4.** Contribution to land use change and freshwater ecotoxicology over the whole lifecycle of SW05and Pig2F sub-systems.

## Results and discussion

In this section, the results of the LCA and energy payback time calculations and the results of the sensitivity analysis regarding the input data are presented. The impact categories GWP and CED are discussed in detail.. Furthermore, considerations on a better shaping of the technology due to changes in steel use are substantiated and design adaptations are discussed. In every section, the results of the present work are directly compared to further results from literature. In Table 2, the overall results of the six relevant LCIA categories for both SWTs are presented.

Toxicology categories are calculated in hazard-weighted increase equivalent to the increase by 1 kg of 1,4-Dichlorobenzene (kg 1,4-DCB), global warming potential is calculated as equivalent to the warming by

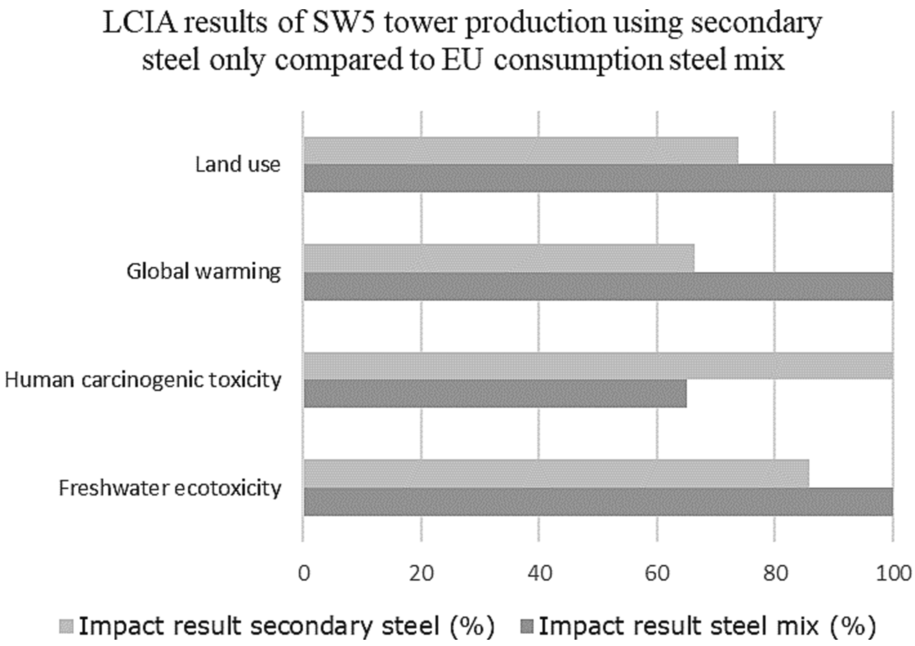

**Fig. 5.** LCIA results of SW05 tower production using secondary steel only compared to the use of EU consumption steel mix.

1 kg $CO_2$ (kg $CO_2$ eq.), land use as change in square meters and years of crop production equivalent ($m^2$a crop eq) and energy demand categories in units of energy (kWh).

### *Global warming potential*

Over their lifetime, The SW05 and the Pig2F turbines emit about 8 577 $kgCO_2$eq. and 494 $kgCO_2$eq respectively. Fig. 3 shows the contribution to the GWP by sub-systems. In both cases tower and foundation are responsible for about half of the total emissions: 47% for the Pig2F and 55% for the SW05. Similar to the calculations for VAWTs [16], HAWT tower and foundation are the most relevant contributors to the overall GHG emissions.

The emission intensities ($GWP_{rel}$), which is the GWP per produced unit of energy, for the two analyzed turbines at their specific sites were calculated as described in equation (2).

$$GWP_{rel} = \frac{GWP_{total}}{LT^{*}E_{annual}} \tag{2}$$

The $GWP_{total}$ is the GWP of the total emissions of the turbine in the assumed lifetime (LT) in years, and $E_{annual}$ is the annual production of the SWT. The SW05, installed on a rural site emits 62 $gCO_2$/kWh. The Pig2F, installed on a suburban site exhibiting acceptable wind conditions, emits 94 $gCO_2$/kWh.

Mendecka and Lombardi [13] recently published a review article on LCA of wind turbines. The overall median value of onshore wind turbines was found to be 9.7 $gCO_2$eq/kWh. A total of 14 SWTs with nominal capacity of under 20 kW were part of the review. In these cases, the authors describe GHG emissions between 43 and 560 $gCO_2$eq/kWh. According to them, SWTs show a broad range of emission values mainly due to high variability in design, geometric description, and site selection. Nevertheless, even the lowest value for a SWT (43 $gCO_2$eq/kWh) is roughly five times higher than the median for onshore wind turbines. The results of the present analysis fit in with these observations. The GWP of the Pig2F at the rural site fits the median, while the GWP of the SW05 at a rural site lies within the lower quartile of the review and thereby has less emissions than most of the assessed SWTs. When comparing to large wind turbines, it has to be taken into account that the power delivered by the wind to a turbine increases with the squared rotor radius and the third power of the wind speed, which again generally increases with tower height.

In 2019 the Austrian production mix (high voltage) showed emissions of 140 $gCO_2$eq/kWh [30]. Thus, both SWTs meet the goal of reducing the emission of the current consumption mix of electricity production. However, both analyzed SWTs, as well as all analyses on SWTs found in literature, are not able to meet the threshold of 16 $gCO_2$eq/kWh of the Austrian label for renewable electricity production “Grüner Strom” (lit. “green electricity”). For example all 14 SWTs analysed in [13] are in a range of 43–560 $gCO_2$eq/kWh. For comparison, the same source gives a median value for (large) onshore wind turbines of 10 $gCO_2$eq/kWh.

Annual power production has a significant effect on the calculation of the GWP of power production. Since wind speed is the most important factor in power production of a wind turbine ($P = \frac{1}{2}\rho v^3 A[W]$ [32]), it is a crucial parameter when calculating GWP related to power production. Hence, the presented values for GWP heavily depend on site-specific parameters and are therefore not directly comparable. The great influence of the average wind speed is also shown in an SWT LCA study considering four different impact categories including GWP [14].

A further publication assessed a 6 kW wind turbine, which showed a GWP of 48 $gCO_2$eq/kWh, close to the lowest value reported for SWTs [33]. Wind speeds were assumed to be 5 m/s in average resulting in a capacity factor of 14.8%. This assumption as well as the system boundaries are comparable to the present analysis of the SW05. The higher emissions of the SW05 are caused by transportation due to being manufactured in China.

A further LCA study assessed a 500 W HAWT installed on rooftops in Thailand [34]. A GWP of 90 $gCO_2$eq/kWh was calculated and even though the authors assumed significantly higher wind speeds, the result is close to the Pig2F in this analysis.

A further LCA on a Piggott turbine calculated 54–140 $gCO_2$eq/kWh considering different ways of maintenance [35]. Even though the final values correspond to the present analysis, the contributions of the subsystems differ. This is mainly due to different system boundaries: While in the present study the electronic system is integrated in the analysis, Troullaki [35] did not integrate the electronic system, but integrated intensive maintenance procedures, which are neglected in the present study.

### *Energy demand and payback times*

Since the power of the analysed SWTs differs by approximately one order of magnitude, the results for the CED also differ considerably. The SW05 system showed an overall energy demand of 37 474 kWh, of which 95% originates from non-renewable energy sources. The Pig2F system showed a total energy demand of 2 483 kWh, of which 2 137 kWh (86%) are non-renewable. These results as well as the nominal capacity and the annual production of the turbines are presented in Table 3.

Installed at Lichtenegg (rural site), the SW05 system shows an energy payback time of 5.41 years, while the Pig2F installed at Groß Enzersdorf (suburban site) has an energy payback time of 9.43 years. This again demonstrates the great impact of the specific location and thereby the dependency on the average wind speed. Nevertheless, both systems pay back within lifetime, even though the payback times are much higher than for large wind turbines which achieve payback times of less than a year [7].

### *Land use and freshwater ecotoxicology*

The results of the impact categories land use and freshwater ecotoxicology differ considerably from the results from GWP and CED regarding the contributions of the three sub-systems, *turbine*, *electronic system* and *tower with foundation.* The results of the impact category land use in “occupation and time-integrated transformation” [23] is quantified as equivalent to the use as crop land (*$m^2$a crop eq)*. Thus, the impact category “land use (change)” quantifies the amount of land not available for crop farming due to effects of the analysed system, e.g., through soil sealing or mining activities. Both turbines cause land use change of a similar magnitude: 166 $m^2$a crop eq for the SW 05 turbine and 104 $m^2$a crop eq for the Pig2F. While the contributions of SW05 sub-systems are comparable to the GWP contributions, the results of the Pig2F differ strongly. About 94% of land use are caused by manufacturing of the turbine. This is related to the use of plywood for manufacturing the blades.

For the impact category freshwater ecotoxicology in “hazard-weighted increase in fresh waters” an equivalent to 1 kg of 1,4-Dichlorobenzene (*kg 1,4-DCB*) [23] is used. The contributions of the three subsystems differ heavily between the two turbines. Considering the SW05, the electronic system contributes 79% of a total of 1497 *kg 1,4-DCB*, while in the Pig2F 93% of the total 630 *kg 1,4-DCB* are related to the turbine. In both cases, the main contributor in the sub-processes is copper. In both turbines, copper coils are used in the generator. The high contribution of the electrical and electronic system to freshwater ecotoxicity of the SW05 can be explained by the longer and thicker copper cables used to connect the turbine to the electrical system. Fig. 4 gives a graphical representation of the results.

### *Sensitivity analysis considering data actuality*

The GWP of the Austrian grid electricity consumption mix in ecoinvent 2.2 is 402 $gCO_2eq/kWh$ and was last updated in 2004. In 2019 the GWP of the Austrian electricity consumption mix is 258 $gCO_2eq/kWh$ [36], whereby it needs to be taken into account that the calculation method is slightly different than in ecoinvent. For all manufacturing processes conducted in Austria, in the present LCA study the impact values provided by the ecoinvent process *electricity mix AT* are used. Its contribution to the CED of the Pig2F is 0.38% and 0.02% for the SW05. Therefore, even though the value changed considerably, the contribution of the process to the overall result is small enough to neglect the differences.

The Swiss electricity mix has some relevance for the LCA results since some of the used sub-processes of the ecoinvent database are based on Swiss data, resulting in a fraction of the total CED of 0.28% for the Pig2F and 1.15% for the SW05 respectively. The Swiss consumer electricity mix changed from 106 $gCO_2/kWh$ to 128 $gCO_2/kWh$ from 2004 to 2018 [37,38]. It has to be considered, that the Swiss emission intensity is largely dependent on the amount of imported energy and thus varies significantly between single years. Regarding the SW05, 1.51% relate to the Chinese electricity mix, due to mining and material production in China. Here, the emission intensity decreased by 37% from 2004 to 2019 [39].

Still, the impact of the electricity mixes is comparatively small, so that the deviation in GWP from the values used in this analysis compared to the current state of art is accepted. Especially for the Pig2F the total change of GHG emissions per kWh is only −0.08%, for the SW05 it is −0.32%. A general conclusion from this analysis is, that for the Pig2F even a switch to a full renewable energy mix for input materials would reduce total emissions only by approximately 0.5%, while for the SW05 a reduction in the range of 2.5% would be conceivable.

The values related to the steel manufacturing did not change significantly since 2006. Energy efficiency in steel production strongly improved before 2000, but nearly no change occurred between 2000 and 2020 [40]. The share of secondary steel in global steel production is currently 42% [41], which represents a small increase compared to the data of ecoinvent 2.2. (37%). The use of a more current database would therefore lead to a slightly lower and more accurate result in GWP of the two SWTs, but no relevant difference can be expected.

### *Sensitivity analysis considering lifetime and site conditions*

Since lifetime of a system and the annual production are the most influential input parameters for a LCA of an energy conversion technology, a simple estimation of the impact of these parameters was done. For the SW05 the manufacturer describes in the technical datasheet an annual production of up to 10000 kWh [42], corresponding to 2000 full load hours per year. At the test site, an annual production of 6926 kWh was measured, so a maximum possible increase at optimum conditions to 144% annual production can be assumed. For the Pig2F no manufacturer information is available. However, the generator is specified for 400 W capacity, which results in a maximum annual production of 1000 kWh if equally 2000 full load hours are assumed. Thus, an increase to 304% production can be assumed for this estimation. Further, an increase of the assumed lifetime to 25 years is within technically feasible range for both systems, given sufficient maintenance.

From these factors a new, minimum value for the GHG emission intensity can be calculated, using the inverse product of the relative increase factors For the SW05 the emission intensity is approximately halved (34.3 gCO2eq/kWh). For the Pig2F this results in 24.7 $gCO_2eq/kWh$, close to the Austrian reference value for green electricity of 16 g/kWh [31]. It has to be considered, that the assumptions for these estimations represent the maximum conceivable results and are highly unlikely to be achieved under practical conditions.

### *Technology shaping considering the use of steel*

The results of the impact category GWP showed that the sub-system *tower with foundation* is responsible for about half of the total emissions for both SWTs. Therefore, the potential for an alternative shaping of the SWT technology at least concerning the steel material used for the tower manufacturing is scrutinized. Steel is the main material used for manufacturing the tower. Hence, the steel type was changed in an alternative scenario, which also influences environmental impacts stemming from steel production. For the SW05, instead of the EU steel mix from 2006 as used in ecoinvent 2.2., which is made from 63% primary and 37% secondary steel, only secondary steel is used. Secondary steel needs about 56% of the energy demand needed to produce primary steel [43]. Fig. 5 shows the results for the study's impact categories in percent, comparing the EU mix scenario with the alternative secondary steel only scenario for the sub-system *tower with foundation*. For the tower of the SW05, in 17 out of 18 impact categories the exclusive use of secondary steel shows a significant improvement of 34% in GWP (from 2993 to 1986 $gCO_2eq$), 26% inland use (from 46 to 34 $m^2a$ crop eq) and 14% in freshwater ecotoxicity (from 142 to 122 kg 1,4-DCB). An overview of all impact categories is included in the Appendix. Only the impact category human carcinogenic toxicity shows a reverse effect: The use of only secondary steel would increase the impact by 35% (from 1153 to 1770 kg 1,4-DCB), which can be explained by the manufacturing processes of secondary steel, emitting more carcinogenic substances than the production of primary steel. This result demonstrates that the type of steel used in the manufacturing of SWTs has a strong effect on all impact categories for the sub-process *tower with foundation*.

Regarding the Pig2F SWT system, it is possible to use re-used steel instead of newly produced steel, because it is made from commonly used steel pipes. Re-used steel does not go through a special treatment process, while secondary steel is made from scrap iron, which has to be molten and treated before further use. Since not only the tower can be made from re-used steel pipes, but also components of the turbine, the contribution to the GWP of all steel components is calculated. In total 59% of the total GWP of 292 $kgCO_2eq$ is related to the manufacturing of steel elements: 45% relate to the tower with foundation, 5% to steel elements in the generator and 9% are related to manufacturing of steel elements used in the nacelle. By only using re-used steel the GWP could be reduced even further than by using only secondary steel. Regarding the impact category energy demand, the results are comparable. The use of re-used steel has great potential to reduce the GWP as well as the CED and energy payback of the Pig2F. Assessing the actual reduction would require to include the previous (unknown) use of the re-used steel and accounting for it accordingly. The potential of using re-used materials instead of newly manufactured materials in SWTs is also proposed by Uddin and Kumar [34].

A current LCA study on VAWTs also identified steel and concrete to be the materials with the highest impact in terms of GHG emissions [14]. Due to this high contribution of steel, the question arises whether other materials with lower environmental impacts could be used for the tower. One alternative are wooden towers, which already exist on the market. Further research is necessary considering the use and the impact of other tower materials.

## Conclusion

At sites with acceptable wind conditions the two analysed SWTs, a Schachner SW05 at a rural site and a Piggot 2F at a sub-urban site, are able to meet their intended goal of producing more energy than they consume. The GWP was lower than the current GWP of the Austrian grid electricity production mix. While the Austrian grid shows a GWP of 0.256 g/kWh, the Pig2F has a GWP of 0.094 g/kWh, the SW05 a GWP of 0.062 g/kWh. However, this will not hold in a future perspective, when the decarbonisation of the energy system makes significant progress. Energy payback times are much higher compared to other renewable energy sources, even at sites with good wind conditions. For the renewable energy certification "Grüner Strom" for example, a GWP of

0.016 g/kWh is needed – nine times less than Pig2F and six times less than SW05. Sensitivity analysis shows, that only under ideal conditions, which are unlikely to be practically attained, results close to this value could be achieved. Therefore, an improved shaping of SWT technology is mandatory.

In the contribution analysis, steel use could be identified as major contributor to the overall GWP – 59% of all GHG emissions can be attributed to steel production for the Pig2F turbine. The sub-system *tower with foundation* is identified to be a hot spot in CED and GWP for both investigated SWTs. The use of only secondary steel instead of the European steel mix for producing the SW05 tower, could reduce the impact of 17 out of 18 impact categories. The GWP in particular could be reduced by 34%, from 2993 to 1986 kg$CO_2$eq. Energy payback time as well as GWP of the Pig2F turbine could even be reduced further by using re-used steel. Nevertheless, even so the change in steel can reduce the emissions up to 60%, they would still be higher than needed for renewable energy certification. The use of wooden towers can be expected to result in further reductions.

SWTs are able to reduce the environmental impact of electricity production. Only changing the material will not reduce the emissions enough to meet the renewable energy certification values, it needs the right combination of a good site, low impact materials and a reliable construction is chosen. The present analysis showed that there are shaping possibilities for improving the environmental impact of SWTs. Changing the materials used in construction, especially considering the tower would greatly reduce the potential environmental impacts. Additional research regarding different tower materials would therefore be needed to further investigate this potential.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The authors do not have permission to share data.

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## References

[1] EC, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee of the Regions: A policy framework for climate and energy in the period from 2020 to 2030, (2014).
[2] Republic of Austria. Federal Ministry for Sustainability and Tourism, Integrated National Energy and Climate Plan for Austria 2021–2030. Vienna: Austria; 2019. https://ec.europa.eu/energy/sites/ener/files/documents/at_final_necp_main_en.pdf.
[3] Zajicek L. Probabilistic Safety Analysis for Small Wind Turbines. University of Natural Resources and Life Sciences Vienna; 2017. Master Thesis,.
[4] IEC, IEC 61400-2:2013 Small wind turbines, (2013).
[5] Pitteloud J-D, Gsänger S. 2017 Small Wind World Report summery. Bonn, Germany: World Wind Energy Association; 2017. https://issuu.com/wwindea/docs/swwr2017-summary.
[6] Leonhartsberger K, Peppoloni M, Hirschl A. Kleinwindkraftreport Österreich 2018. Wien: FH Technikum Wien; 2018. https://www.technikum-wien.at/kleinwindkraftreport/.
[7] Bonou A, Laurent A, Olsen SI. Life cycle assessment of onshore and offshore wind energy-from theory to application. Appl Energy 2016;180:327–37.
[8] Vestas, Life Cycle Assessment of Electricity Production from an onshore V150-4.2 MW Wind Plant, (2022).
[9] Wang W-C, Teah H-Y. Life cycle assessment of small-scale horizontal axis wind turbines in Taiwan. J Clean Prod 2017;141:492–501.
[10] Tremeac B, Meunier F. Life cycle analysis of 4.5MW and 250W wind turbines, Renew. Sustain Energy Rev 2009;13:2104–10.
[11] Fleck B, Huot M. Comparative life-cycle assessment of a small wind turbine for residential off-grid use. Renew Energy 2009;34:2688–96.
[12] Allen SR, Hammond GP, McManus MC. Energy analysis and environmental life cycle assessment of a micro-wind turbine. Proc Inst Mech Eng Part J Power Energy 2008;222:669–84. https://doi.org/10.1243/09576509JPE538.
[13] Mendecka B, Lombardi L. Life cycle environmental impacts of wind energy technologies: A review of simplified models and harmonization of the results. Renew Sustain Energy Rev 2019;111:462–80. https://doi.org/10.1016/j.rser.2019.05.019.
[14] Lombardi L, Mendecka B, Carnevale E, Stanek W. Environmental impacts of electricity production of micro wind turbines with vertical axis. Renew Energy 2018;128:553–64.
[15] Matveev A, Shcheklein S. Life cycle analysis of low-speed multi-blade wind turbine. Int J Renew ENERGY Res 2015;5.
[16] Kouloumpis V, Sobolewski RA, Yan X. Performance and life cycle assessment of a small scale vertical axis wind turbine. J Clean Prod 2020;247:119520.
[17] Aberilla JM, Gallego-Schmid A, Stamford L, Azapagic A. Design and environmental sustainability assessment of small-scale off-grid energy systems for remote rural communities. Appl Energy 2020;258:114004. https://doi.org/10.1016/j.apenergy.2019.114004.
[18] S. Schlömer, T. Bruckner, L. Fulton, E. Hertwich, A. McKinnon, D. Perczyk, J. Roy, R. Schaeffer, R. Sims, P. Smith, R. Wiser, Annex III: Technology-specific cost and performance parameters. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on ClimateChange., (2014).
[19] Glassbrook KA, Carr AH, Drosnes ML, Oakley TR, Kamens RM, Gheewala SH. Life cycle assessment and feasibility study of small wind power in Thailand, Energy. Sustain Dev 2014;22:66–73.
[20] GreenDelta GmbH, openLCA – the Life Cycle and Sustainability Modeling Suite, Berlin, 2020. https://www.openlca.org/ (accessed October 23, 2020).
[21] Frischknecht R, Jungbluth N. Overview and Methodology Data v2.0, Swiss Centre for Life Cycle Inventories. Dübendorf; 2007.
[22] Weidema B, Hischier R. ecoinvent data v2.2: the,version of the most comprehensive and most popular public LCI database. St. Gallen: Swiss Centre for Life Cycle Inventories; 2010. p. 2010.
[23] Huijbregts MAJ, Steinmann ZJN, Elshout PMF, Stam G, Verones F, Vieira M, et al. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int J Life Cycle Assess 2017;22:138–47. https://doi.org/10.1007/s11367-016-1246-y.
[24] ICS, ISO 14044:2006 + Amd 1:2018 D Environmental management – Life cycle assessment – Requirements and guidelines, (2018).
[25] Piggott H. A Wind Turbine Recipe Book. Scoraig, Scotland: Scoraig Wind Electric; 2013.
[26] Sumanik-Leary J. Small wind turbines for decentralised rural electrification: case studies in Peru, Nicaragua and Scotland. University of Sheffield; 2013. PhD Thesis,.
[27] J. Leary, L.S. To, A. Alsop, Briefing paper 2: Is there still a role for small wind in rural electrification programmes?, (2018).
[28] J. Schreiber, Handout zum Kleinwindrad Selbstbau-Workshop: 2F 16p Windrad Design, (n.d.).
[29] Liebert W, Schmidt JC. Towards a prospective technology assessment: challenges and requirements for technology assessment in the age of technoscience. Poiesis Prax 2010;7:99–116.
[30] E. Moreno-Ruiz L. Valsasina D. FitzGerald F. Brunner A. Symeonidis G. Bourgault et al. Documentation of changes implemented in the ecoinvent database v3.6, ecoinvent Association 2019 Zürich, Switzerland.
[31] Bundesministerium für Klimaschutz Umwelt Energie Mobilität Innovation und Technolo, Verein für Konsumenteninformation - Team Umweltzeichen, eds., Richtlinie UZ 46: Grüner Strom, (2021). https://www.umweltzeichen.at/file/Richtlinie/UZ%2046/Long/Uz46_R5.2a_Richtlinie_Gruener%20Strom_2018.pdf.
[32] Hau E. Windkraftanlagen, Springer, Berlin Heidelberg, Berlin. Heidelberg 2014. https://doi.org/10.1007/978-3-642-28877-7.
[33] Greening B, Azapagic A. Environmental impacts of micro-wind turbines and their potential to contribute to UK climate change targets. Energy 2013;59:454–66. https://doi.org/10.1016/j.energy.2013.06.037.
[34] Uddin MS, Kumar S. Energy, emissions and environmental impact analysis of wind turbine using life cycle assessment technique. J Clean Prod 2014;69:153–64. https://doi.org/10.1016/j.jclepro.2014.01.073.
[35] A. Troullaki, Locally Manufactured Small Wind Turbines: Sustainability Assessment integrating Life Cycle Assessment and Multi-Criteria Decision Analysis, Master Thesis, Technical University of Crete, 2018.

[36] UBA, THG-Emissionen – Übersicht, (2019). https://secure.umweltbundesamt.at/co2mon/co2mon.html (accessed August 13, 2020).

[37] Jungbluth N., R. Frischknecht, Steiner R., Graue Treibhausgas-Emissionen der Schweiz 1990-2004. Erweiterte und aktualisierte Bilanz, Hrsg. Vom Bundesamt Für Umw. BAFU. (2007) 152.

[38] Krebs L, Frischknecht R. Umweltbilanz Strommixe Schweiz 2021;2018. https://www.bafu.admin.ch/dam/bafu/de/dokumente/klima/fachinfo-daten/Umweltbilanz-Strommix-Schweiz-2018-v2.01.pdf.download.pdf/Umweltbilanz-Strommix-Schweiz-2018-v2.01.pdf.

[39] climate-transparency.org, Country Profile China 2019, n.d. https://www.climate-transparency.org/wp-content/uploads/2019/11/B2G_2019_China.pdf (accessed April 27, 2022).

[40] worldsteel association, Fact sheet: Energy use in the steel industry, (2019).

[41] World Steel Recycling 2014 - 2018: Steel Scrap – a Raw Material for Steelmaking. 10th Edition, (2019).

[42] Schachner Wind GmbH, Schachner Wind GmbH Product Folder, Schachner Bewegt. (n.d.). http://www.kleinwind.at/assets/php/download.php?file=dXBsb2FkL2dyYXBoaWNzL1dpbmRyYWQxMGtXL1BERi9XaW5kcmFkRm9sZGVyXzIwMTVfV2ViLnBkZg== (accessed April 27, 2022).

[43] Xylia M, Silveira S, Duerinck J, Meinke-Hubeny F. Weighing regional scrap availability in global pathways for steel production processes. Energy Effic 2018; 11:1135–59. https://doi.org/10.1007/s12053-017-9583-7.