Impact assessment modelling of the matter-less stressors in the context of Life Cycle Assessment

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No matter – how? Dealing with matter-less stressors in LCA: the case of noise in wind energy systems

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Summary
The portfolio of impacts that are quantified in Life Cycle Assessment (LCA) has grown to include rather different stressors that require complex models. Some of these are still in a seminal phase of development, and have not yet been included in any LCA study. This the case for sound emissions and noise impacts, which have been the result of recent modelling that expands the scope of the existing noise impact assessment models in LCA. Sound emissions are a rather specific type of emissions that are matter-less, time-dependent and bound to the physical properties of waves. The way sound emissions and the relative noise impacts are modelled in LCA are paradigmatic for the way new or existing matter-less impacts can be dealt with. In this study, we analyse, through sound emissions, the specific features of other matter-less impacts that do not stem from the use of a kg of matter, nor are related to the emission of a kg of matter. We take as a case study the production of energy by means of wind turbines, contradicting the credo that windmills have no emissions during use. We show how to account for sound emissions in the Life Cycle Inventory (LCI) phase of the life cycle of a wind turbine, and then calculate the relative impacts using a noise Life Cycle Impact Assessment (LCIA) model.

Keywords
LCA; LCIA; LCI; wind turbine; matter-less stressors

1
Introduction

The list of impacts recommended back in 1992 by the report of Heijungs et al. (1992a, 1992b) has remained fairly constant over the years. However, discussions have always taken place on the best set of possible impacts to be considered in the Life Cycle Impact Assessment (LCIA) phase, with impact assessment methods under different methodological and conceptual assumptions being developed by several research groups around the globe (Bare 2010). The landmark ISO14040 series (ISO 2006) proposed standard principles, procedures and requirements for the LCA framework. The availability of such standard increased the methodological robustness of LCA, defining the criteria, according to which most of the later contributions and studies tried to adhere. Nevertheless, the standard did not provide a shortlist of impacts to use, but recommended impact categories and characterization models to be based on an international agreement or approved by an international institution (ISO, 2006). The LCA community has been trying in the last years to reach a consensus of best practices and best impact assessment models. According to Huijbregts (2013), the quest for a consensus entered a new phase with the ILCD report on recommended practice for life cycle impact assessment methods in a European context (Joint Research Centre 2011; Hauschild et al. 2013).

The European Commission tried, in fact, to define the best practice in the LCA scientific domain from a conceptual and methodological point of view (EC-JRC 2010a, 2010b, 2011). A total of 91 characterization models were short-listed and recommended as best practice within their impact categories, according to criteria such as scientific quality and applicability (Hauschild et al. 2013). Furthermore, the absence of other classes of impacts was indicated as one of the shortcomings of the current LCA framework (EC-JRC, 2011), since it may restrict the efficacy of LCA to act as a comprehensive environmental decision support tool. However, it has been claimed that not all impacts should be included in LCA (see e.g. Udo de Haes 2006), though as claimed by the ILDC handbook "an open mind" should be kept towards emerging impacts. Some impacts have high priority on the list, because they are related to emerging technologies (such as nano-materials), which will eventually penetrate the market, thus increasing the size of the related impacts and the number of humans and ecosystems exposed to them. The absence of certain impact categories may be due to the necessity of dealing with unusual LCI and LCIA methodologies.

Some of the impacts that should be developed in LCA or for which the modelling effort of developers should be increased regard matter-less impacts, thus impacts that are not related to the release of a quantity of matter. The case of noise (see Cucurachi et al. 2012 and Cucurachi and Heijungs 2014) is used in this study as a model-type to illustrate how to deal with matter-less emissions and impacts. We discuss, through the example of sound emissions and noise impacts, the specificities of emerging matter-less impacts that are relevant also for emerging technologies and their assessment.

We analyze the case of wind turbines to test the applicability of the noise-impact method and to further understand the importance of the analysis of emerging impacts in the field of LCA. While existing LCA studies show that only upstream processes in their life cycle contribute the most to emissions and impacts (see e.g. Dolan and Heath 2012), we show that it is now possible to quantify the noise impacts of wind turbines during their operation and during other phases of their life cycle phases that emit sound. The operation of this type of systems produces emissions that are not related to a release of matter, but do have, just like e.g. toxic emissions, an impact on the population living in the area surrounding a turbine.

2
The input, the output and the necessity for a shift of paradigm
2.1
Matter-less impacts
At the basis of LCA the assumption holds that only activities that are related to and affected by a functional unit should be included in the LCI, and then in the LCIA (Rugani et al. 2012). Originally, only impacts (and activities) related to physical extractions and emissions, thus to material inputs and outputs from a product system were modelled in LCA (Udo de Haes et al. 2004). During the last decade, however, researchers expanded the boundaries of LCA, allowing also other impacts to be included also in the cases in which the relationship to a functional unit is not mediated by the extraction/emission pattern.

A number of stressors (i.e. pressure on the environment) that are included or recommended for inclusion in the LCA framework are not substance-induced, nor directly related to emissions and physical exchanges of matter with the environment. Stressors such as noise or light pollution correspond to a matter-less emission, which cannot be directly taken in by e.g. respiration or food consumption. In particular, we define here as matter-less stressors those that are not related to a release of a certain quantity of matter (e.g. kg of carbon dioxide). Moreover, the damage such stressors determine involves a mix of physiological and psychological conditions of exposure that make their analysis rather specific. The process of modelling of such matter-less impacts has not developed as fast as that of the traditional substance-induced impact categories.

The reasons behind this slower pace of development reside in the difficulty of modelling the stressors in a way that accommodates the computational structure of LCA (see Heijungs and Suh, 2002), or in the level of knowledge of the mechanisms that determine their impacts (see Cucurachi et al. 2014).

Examples of matter-less stressors, for which methodological attempts have already been made, include land-use (Milá i Canals et al. 2012; de Baan et al. 2013; Brandão and Milá i Canals 2013), noise (Althaus 2009a,b; Cucurachi et al. 2012; Cucurachi and Heijungs 2014) and thermal pollution (Verones et al. 2010). In other cases, matter-less impacts have been related to the exchange of a certain quantity of matter between the ecosphere and the biosphere. This is the case of the introduction of exotic species by means of freight transport of goods in Hanafiah et al.(2013), and the impacts of ionizing radiation due to the release of radioactive substances in Frischknecht et al. (2000).

Though the modelling assumptions behind each model are different, general considerations can guide future developments of new models for those categories that are still outside LCA, and for the improvement and adaptation to the specific structure of LCA of models that have already been tackled by modelers. Such considerations will be further clarified in the case study of a wind turbine.

2.2
The inventory analysis and the relationship to a functional unit

In LCA, the study of a life cycle of a product system scales all inputs to the functional unit that best represent the goal and scope of the system under analysis. The usual way to proceed in the Life Cycle Inventory analysis (LCI) phase is to detail the conversion of inputs (e.g. products, waste, and resources) into outputs (e.g. products, waste, residuals to the environment; Curran 2012). Practitioners have matured a great deal of experience in treating emissions that are related to the release of a quantity of matter, or, alternatively, to the depletion of a certain quantity of a natural resource. However, for some unit processes and/or stressors, the relationship between inputs and outputs is not immediately paramount. We show that, in some cases, before an emission can be recorded in the inventory table it is necessary to define a further emission-specific conversion factor that allows for similar emissions across the life cycle to be compared. The necessity of adding extra steps to the already complicated and time-consuming LCI phase is particularly relevant for the case of matter-less impact categories.

In general, the LCI phase deals with the representation of the relationship between flows of inputs and outputs and unit processes. Using a simple representation one could describe a unit process as in Figure 1:

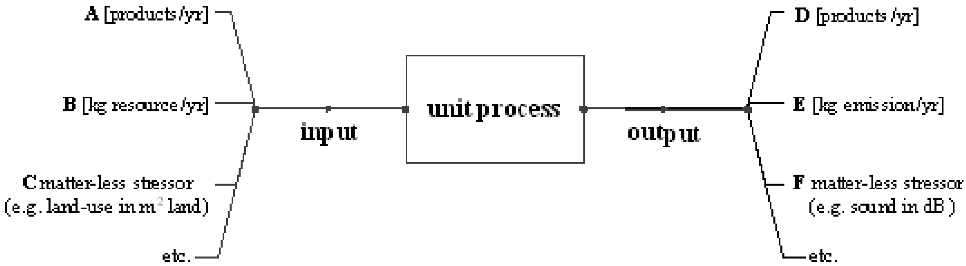

Figure 1. Inputs and outputs of a unit process in the LCI phase. The flows are here including a "per year" property, in contrast to the usual LCA practice where the flows are written as amounts ("kg", "product", etc.).

If we follow the notation introduced in Figure 1, to express all resource inputs and emissions per unit of product the process must be multiplied by a scaling factor $1/D$. Mind that this scaling factor has the dimension of time. It can be interpreted as the time it takes for the unit process operating at full production volume to produce 1 unit of product (Heijungs and Suh 2002). The resource input then becomes $B \times 1/D$ and the emission $E \times 1/D$. These results are in kg. For the case of C, and considering as in the example a land-use input, we would proceed by calculating $C \times 1/D$, thus with the dimension m² $\times\ yr$ (Brandão and Milá i Canals 2013). So far, this works fine, because products, mass and area are aggregatable quantities. Let us consider a matter-less output, see e.g. F in Figure 1. If we consider the example of sound, the output is typically expressed in dB, which, in contrast, may not be aggregated by simple addition. Thus, the non-linear dB is inconvenient for the purely linear aggregations and additions that are common in LCA. It should be first converted into an energy unit (the Joule) to be aggregatable. The amount of sound, thus, becomesg$(F) \times 1/D$, where $g(F)$ is a transformation function (Cucurachi et al. 2012; Cucurachi and Heijungs 2014). This result is in $W \times yr$, which corresponds to J.

The crucial element of this whole discussion is in the function g, which transforms a non-material elementary flow that is non-aggregatable into an aggregatable one. The transformation function g is defined according to the local conditions of the system under study and to the specific properties (i.e. physical or otherwise) of the matter-less emission under consideration. Several local parameters (e.g. production rate of a system, speed of a vehicle) may be needed according to the type of matter-less emission under consideration. This counts also for emissions related to electromagnetic or light emissions, which are associated through the physics of waves with the transportation of energy, but not with that of matter (see Georgi and French 2007 for a detailed analysis of the physics of waves).

2.3
Life Cycle Impact Assessment

Once the LCI phase is concluded, if enough information has been stored in the LCI, a modeler dealing with the definition of a suitable impact assessment model for a matter-less stressor would have to take into account in the modelling process a series of emission-specific properties, and solve all potential non-linearities. The impact score for that specific impact category under consideration would be obtained simply by multiplying it by the relative inventory item. For some matter-less impacts that are highly localized (e.g., that depend on population density or the ambient pH), time-specific (e.g., that depend on the time of the day or the year), property-specific (e.g. that depend on the frequency or polarization) a system of characterization factors may be needed to represent all possible conditions of fate, effect, exposure, and damage. 3

The life cycle of a wind turbine

In the previous sections we have dealt with the specific considerations needed to include matter-less stressors in LCA. In the following, the example of the life cycle of wind turbines is considered to show a practical example of how the matter-less sound emissions may be accounted for in LCA.

3.1
Wind energy, wind turbines and their impacts in LCA

Wind turbines are classified as promising "sustainable" energy sources for our energy supply portfolio, and have become one of the most often cited source of electricity generation to address e.g. climate change issues (Doblinger and Soppe 2013; GWEC 2013). With the exception of direct solar heat and light, wind energy is believed to have the least adverse environmental impacts of all renewable energy technologies (Tabassum-Abbasi et al. 2014). Though these features of wind power are promising, the use of kinetic energy for the production of power does not come free of impacts.

7

Within the field of LCA, Dolan and Heath (2012) identified 240 LCA studies that have investigated the environmental impacts of electricity from onshore and offshore wind farms. To our knowledge, none of these studies accounted for the impacts of wind turbines in the use-phase of their life cycle, apart from the impacts related to the maintenance and lubrication of components, which assumes that wind turbines do not have any direct measurable environmental impact related to their operation. However, a variety of potential environmental effects have been related to wind turbines. These include noise, electromagnetic interference, visual impacts, impacts on wildlife, and, the more recently investigated, impacts on local weather and surface temperature (Boyle 2004; Walsh-Thomas et al. 2012; Zhou et al. 2012; Tabassum-Abbasi 2014; Vautard et al. 2014).

The current list of stressors covered by existing impact assessment methods keeps the aforementioned impacts, related to the use-phase of wind turbines, outside the study of their life cycle. However, for the case of the noise impacts, recent developments in LCIA allow to deal with sound emissions related to any sound emitting source, including static sources (e.g. a wind turbine), and mobile sources (e.g. transportation means) in all life cycle stages (Cucurachi et al. 2012; Cucurachi and Heijungs 2014). Noise has not been considered in any LCA study on wind turbine, though it is admittedly the most claimed issue related to the setting up of a wind farm (Tabassum-Abbasi 2014). The life cycle of a wind turbine provides a perfect opportunity to hold the model of Cucurachi and Heijungs (2014) to the test.

3.2
Goal and scope of the study

The goal of the current study is to evaluate the impacts of sound emissions from resource extraction to operation next to commonly measured impacts. We complement the inventory of the recent study by Caduff et al. (2013) with inventory data regarding the emission of sound and with the background data provided by the ecoinvent database version 2.2 (Frischknecht et al. 2005). A variety of wind turbine configurations are compared to show how prone to variability sound emissions and impacts are, depending on the local conditions under study. The LCA software CMLCA version 5.2 (Heijungs 2013) was used to model the different configurations and perform the analysis and calculations.

3.3
System definition and relationship to the functional unit

The model defined by Caduff and co-authors (2013) uses scaling and size equations to identify the relationship between a certain configuration of wind turbine and the elementary flows (e.g. used materials and assembly of a component of the generator). Basic wind power equations are used to calculate the produced electricity per year (i.e. in kWh/year) at different nominal powers and similar hub heights and diameters. A functional unit of 1 kWh was selected.

In the current study, we adopt a similar system definition as in Caduff et al. (2013) and include in the analysis the following phases of the life cycle: resource extraction, material manufacturing and processing, production of the components, transport to the erection site, turbine maintenance and disposal, and turbine operation (see Figure 2 below).

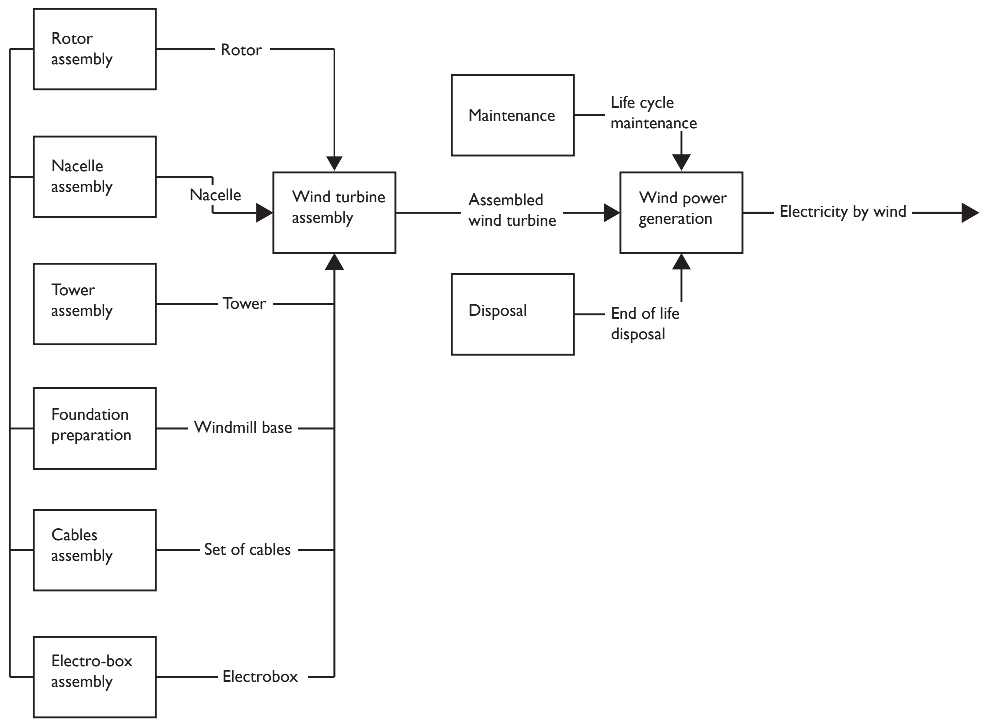

Figure 2. System flowchart: definition of elementary flows and input/output relationships. Boxes represent processes, arrows represent products.

7

Due to lack of specific data, we excluded from the analysis the energy for the assembly of components and for the decommissioning of the wind turbine (see Caduff et al. 2013). Inventory data for resource extraction, transportation of components, material manufacturing, disposal and land use was associated to each of the components of the wind turbine (i.e. rotor, nacelle, tower, foundation, cables, electro-box) according to the indication of Caduff et al. (2013).

In this study, we selected a number of representative configurations based on the availability of sound emissions data for models of wind turbines analyzed in Caduff et al. (2013). Different local conditions were defined in order to stress the influence on sound emissions of different local conditions of wind speeds and revolutions per minute (RpM), also for systems with the same nominal power, but different hub heights and diameters. The defined configurations are reported in Table 1 and were used to calculate the total potentially produced electricity following the engineering approach detailed in Caduff et al. (2013).

The sound power is the amount of sound energy a source emits, by converting a different kind of energy (e.g. mechanical) into sound energy, with the loudness of the sound depending on how rapidly such a conversion takes places (see Blackstock 2000 for a thorough study). Therefore, sound power is a measure of the sound energy produced versus time, thus it has units of Joules per second, i.e. Watt. The sound power level of a source is expressed in decibels (dB) relative to a reference sound power of 1 picowatt (i.e. 10-12 Watt). We obtained sound power levels from the study of Zanetta (2008), in which sound power levels are provided for a variety of configurations of wind turbine.

Table 1. Configurations of wind turbine considered in this study. Local and technical specifications determine the effective electricity produced by each system.

Configuration	Nominal Power [a] [kW]	Wind speed [m/s]	Diameter [m]	Revolutions per minute [1/min]	Hub height [m]	Produced electricity per year [kWh/yr][b]
[A1]	500	8	37	30	56	6.25E+06
[A2]	500	8	40.3	38	65	1.02E+07
[A3]	500	10	40.3	38	65	8.16E+06
[A4]	600	8	44	34.5	78	1.74E+07
[A5]	600	9.5	44	34.5	65	1.22E+07
[A6]	600	8	44	34.5	65	1.45E+07
[A7]	600	8	46	25	56	1.49E+07
[A8]	600	9.5	46	25	56	1.26E+07
[A9]	600	8	42	28.2	56	1.04E+07
[A10]	600	8	48	23	56	1.77E+07
[A11]	800	5	48	29.5	56	2.83E+07
[A12]	800	6	48	29.5	56	2.36E+07
[A13]	800	7	48	29.5	56	2.02E+07
[A14]	800	8	48	29.5	56	1.77E+07
[A15]	800	9	48	29.5	56	1.57E+07
[A16]	800	10	48	29.5	56	1.42E+07
[A17]	1500	10	70	19	65	7.43E+07
[A18]	1500	8	66	22	67	7.57E+07
[A19]	1500	10	70.5	20	65	7.64E+07
[A20]	1500	8	70.5	20	65	9.56E+07
[A21]	1500	8	77	18	100	2.09E+08
[A22]	1500	10	70	19	65	7.43E+07

[A23]	1500	9	70.5	20	56	7.32E+07
[A24]	1500	8	70.5	20	65	9.56E+07
[A25]	1500	8	77	18	56	1.17E+08
[A26]	1500	8.4	77	18	56	1.12E+08
[A27]	1500	10	70	19	65	7.43E+07
[A28]	1500	8	64	17.3	80	7.99E+07
[A29]	1500	8	72	17.3	64	1.02E+08
[A30]	1500	7.7	82	14.4	93.6	2.62E+08
[A31]	1500	8.3	70	19	114	1.57E+08
[A32]	1500	10	70	19	56	6.40E+07
[A33]	1650	8	82	14.4	93.6	2.52E+08
[A34]	2000	6	71	20	64	1.29E+08
[A35]	2000	8	71	20	64	9.68E+07
[A36]	2000	9	71	20	64	8.60E+07
[A37]	2000	10	71	20	64	7.74E+07
[A38]	2000	6	82	19	85	3.05E+08
[A39]	2000	7	82	19	85	2.61E+08
[A40]	2000	8	82	19	85	2.29E+08
[A41]	2000	7	82	17.1	80	2.46E+08
[A42]	2000	7.6	92.5	15	80	3.67E+08
[A43]	3000	8	104	15.3	56	3.90E+08

[a] The nominal power indicates maximum power that can be safely dissipated by the wind turbine.

[b] The output electricity produced by the wind turbine is calculated based on the engineering equations reported in Caduff et al. (2013).

3.4 Process data and assumptions

Given the emphasis of the current study on introducing sound emissions and noise impacts in a LCA study, we focus on adding inventory data relating to sound to the existing life cycle inventory from Caduff and co-authors (2013) rather than refining its existing LCI data. We use the modelling principles reported in the main body and supplementary information to that study to define the configurations of interest reported in Table 1. The analysis of the use-phase of all the 43 configurations of wind turbine was complemented in the current study with their relative sound emissions.

Based on the investigation of the specialist literature we consider that each system has a sufficient amount of wind to operate for 30% of the time (see e.g. Boccard 2009, 2010), thus only for a fraction of the 8760 hours considered in Caduff et al. (2013). The matter of the influence of the capacity factor on the results of LCA studies of wind turbines

7

is discussed with detail in Arvesen and Hertwich (2012). The assumption relates to an onshore site with good wind availability, considering that the average capacity factor (i.e. long-term wind intensity) for Europe is currently of ~22% (Boccard 2010). Further assumptions related to the physical relationships (e.g. efficiency factors and losses) between engineering parameters and the inventories were maintained.

3.4.1
Inventory of sound emissions

Across several phases of any life cycle it is possible to attribute sound emissions to processes, based on the time each unit process is working to obtain the desired output. In the life cycle of each wind turbine, data availability allowed to associate sound emissions to the following processes in the life cycle: transportation of components by freight train and by lorry, transportation by passenger car of a technician to maintain the turbine, excavation of the foundations of the wind turbine, and actual operation of the system.

As recommended in Cucurachi and Heijungs (2014), we collected for each of the relevant sound-emitting phases of the wind turbine life cycle the respective sound power levels. Sound power levels were differentiated where possible in octave bands and expressed in the logarithmic decibel scale. In order to obtain a sound energy in joule, the following transformation function was applied (Cucurachi et al. 2012):

$$m = \left(10^{-12} \times 10^{\frac{Lw}{10}}\right) \times t \qquad (1)$$

where m represents the sound energy in Joule to be inventoried at the LCI stage, Lw represents the sound power level in decibel, and t represents the time in second in which a certain process is working for the output under study (thus implicitly for the functional unit) at a certain time of the day and location. Emissions are recorded at a specific center-frequency band, time of the day, and location. The sound power level Lw depends only on the center-frequency band and does not change according to the time of the day and location. The time t is calculated based on the input/output rate of production of the process under study and varies per time of the day and location. The factor 10^{12} has a unit of Watt.

Transportation

At different phases during the life cycle of a wind turbine a variety of basic components need to be transported e.g. from the production site to the assembly site. This study included transportation by freight train, lorry and passenger vehicle. Sound power levels for each transportation mode were calculated using the indication of the reference report on Common Noise Assessment Methods in Europe and attributed to the transportation modes used in the study (CNOSSOS-EU; Kephalopoulos et al. 2012).

Transport demands from Caduff et al. and ecoinvent were used. The process of transportation of goods has in the ecoinvent database the unit of tonne-kilometer (tkm) or person-km (pkm), which represents the transport of one tonne of goods/person by a given transport mode over a distance of one kilometer. For each of the different transport modes different assumptions and calculations were necessary to associate to a tkm/pkm the relative time t necessary to transport a certain good/person for the functional unit under analysis (i.e. 1 kWh). Details of the calculations are reported in the Supporting Information. All the calculated values of sound energy in joule were associated as environmental extensions to the operation of each transportation mode in CMLCA.

Excavation of foundations

In the process of excavation of the foundation work for the wind turbine, the time to calculate corresponds to the time necessary for a hydraulic digger to excavate the material for the foundation. The process of excavation by hydraulic digger was selected from the ecoinvent database. The sound power level for the hydraulic excavator was defined according to the council directive 2005/88/EC of the European Commission (EU 2005) and represents the permitted maximum allowed sound power level for excavator loaders. A combined sound energy of 9.064×10^{-01} J/m^3 was calculated and associated in CMLCA to the environmental extensions related to the excavation process.

Use-phase of the wind turbine

During the use-phase in the life cycle of a wind turbine, sound is emitted by the functioning of the mechanical components (e.g. yaw motors), and by the aerodynamic flow of air around the blades and tower (Pedersen and Waye, 2004). The dominant component is usually in the range of 500 to 1000 Hz, and, while the mechanical sound emissions have been over the years curbed by manufacturers, aerodynamic sound emissions determining a "whooshing" sound are highly variable and dependent upon the technical features of the wind turbine and upon the local atmospheric conditions (e.g. wind speed, RpM). Both the mechanical and aerodynamic specifications contribute to the sound power levels reached by the wind turbine (Pedersen and Waye 2004).

We selected the 43 configurations reported in Table 1. For the configuration of 3000 MW (i.e. identified with number 43 in Table 1) we assumed similar sound power levels as for the 3600 MW configuration reported in Zanetta (2008). In order to measure the time necessary for the wind turbine to produce 1 kWh, the total produced electricity over the 20 years lifetime of the wind turbine was calculated for each configuration. Time in seconds per 1 kWh was then obtained, and the respective sound energy per octave-band center frequency were recorded as environmental extensions of each wind turbine during the use-phase (see Supporting Information). Sound energy values were recorded at an unspecified time of the day and unspecified location.

Inventory of other elementary flows

Other processes in the life cycle were selected from ecoinvent based on the indications in Caduff et al. Calculations are reported in the Supporting Information. A lifetime of 20 years was assumed for all components of the wind turbine: nacelle, rotor, tower, foundation, cables and electronic box. The total electricity produced per year, and per lifetime of the generator was calculated using standard equations of wind power systems (see Caduff et al. 2013; Table 1, page 4727).3.5

Characterization of the inventory

The latest update of CML-IA database of midpoint characterization methods was considered (Van Oers 2013). Inventory data was characterized (ISO, 2006) using the CML-IA characterization factors. We complemented the CML-IA method with the noise impact assessment method for the quantification of the impacts of noise on humans and characterization factors as provided by Cucurachi and Heijungs (2014), which means a list of characterization factors to characterize sound emitted at specific frequency bands, time of the day and locations. In this study, we used the characterization factors needed to characterize the sound inventoried according to the definition earlier reported. It was not possible to define at the time of the analysis a specific country of installation of the wind turbine, therefore only archetypical locations of emissions (and exposure) were considered. Other inventory items were characterized according to the CML-IA list. 4

Results

4.1

Analysis of noise impacts on humans

The noise results after characterization are expressed in units of *person × pascal × second,* and indicate at the midpoint level the amount of sound pressure each person exposed to a certain sound power would receive per second, integrated over the full life cycle. The results links, according to the traditional ISO 14044 characterization scheme (ISO, 2006), the inventory item $m_{i,c,f}$ specified at the inventory stage with the specific characterization factors $CF_{i,c,f.}$ The subscripts i, c, and f represent, respectively, the center-frequency band, time of the day, and location of emission.

Thus, the human-noise impact (HN) was obtained by:

$$HN = \sum_i \sum_c \sum_f m_{i,c,f} \times CF_{i,c,f} \quad (2)$$

where HN is the impact of noise on humans, per frequency band i, per time of the day c, and location *f*. The resulting human-noise impacts ranged between 18600 and 55500 *person* × *Pascal* × *second*, respectively the total noise impact values for configuration [A37] and [A10] (see Figure 3 below). The lowest score was obtained for the configuration at a nominal power of 2000 kW, with a wind speed of 10 m/s, a diameter of blades of 71 m, a height of the hub of 64 m and a total speed of 20 RpM. Conversely, the highest score was obtained for the wind turbine with a nominal power of 600 kW, a wind speed of 8 m/s, speed of 25 RpM, a height of the hub of 56 m, and a diameter of the wind turbine of 48 m.

The results do not suggest a clear pattern that links the noise impacts to specific values of nominal power, hub heights RpM or size of the blades. The calculation of the Pearson correlation coefficient between noise impacts and the remaining set of parameters did not highlight any strong correlation for the data representing the 43 configurations.. The correlation between the noise impacts and the time necessary for a certain configuration to obtain 1 kWh of wind electricity resulted in a value of 0.53, thus a lower total time determined in general lower noise impacts. The measure of time typically provides a combined measure of the efficiency of the combination of configuration-parameters in producing a functional unit.

The analysis of the structure of the wind turbine life cycle and the relative contributions in CMLCA allowed identifying the most relevant processes in contributing to the noise impacts for each configuration. In all cases, the results indicate that the operation phase contributes the most to the impacts of noise to produce a functional unit of 1 kWh of energy (see Figure 3 below). The transportation of components by freight train and by lorry contributed for the remaining of the impacts for all configurations. The combined contribution of transportation determined 50% of the overall impact for configuration [A11]. Frequencies in the lower range of the spectrum contributed to the total noise impact, particularly those between 250 and 1000 Hz, with the highest contributions (in the range 6-38%) determined by sound emitted at 500 Hz. This finding is in line with the typical spectrum of sound emitted by wind turbines.

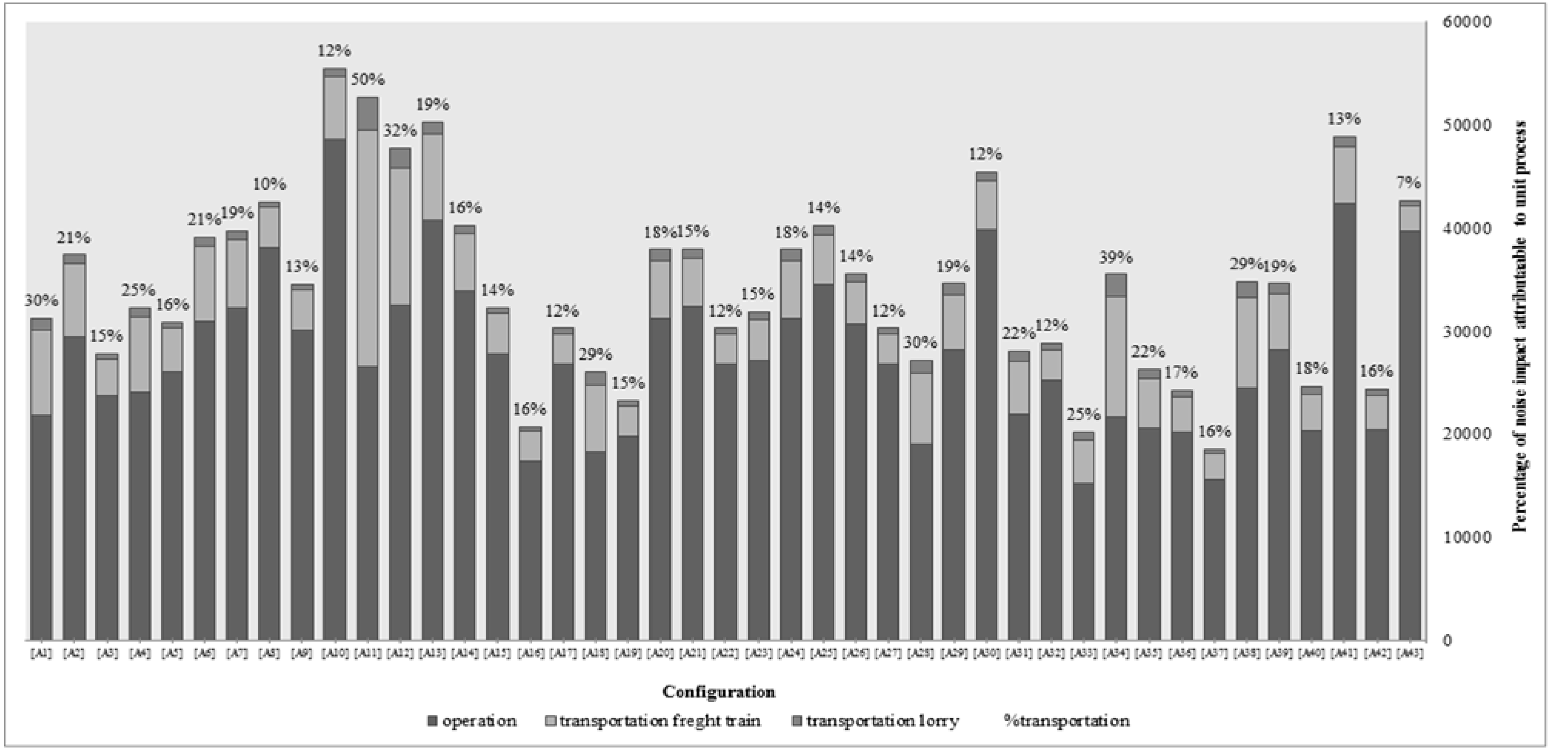

Figure 3. Noise impacts on humans under all configurations considered. Share of the impacts determined by the cumulative sum of transportation by means of freight train, and transportation by means of lorry is reported in the graph. Other sources of noise accounted for less than 1% of the total and are not reported in the figure.

4.2
Analysis of other impacts

The results obtained applying the CML-IA impact categories to the configurations are reported in detail in the Supporting Information. We focus here on the performance of a selection of configurations, representing one configuration per each class of nominal power. The worst and best performers in terms of noise impacts (i.e. [A38] and [A8]) are also included. Table 2 reports the results for this selection of configurations.

Table 2. Selection of CML-IA impacts for a number of configurations.

Power [kW]	500	600	800	1500	1650	2000	3000	
Configuration	[A1]	[A8]	[A11]	[A17]	[A33]	[A38]	[A43]	Unit [per KWh]
FSET[c]	1.92E-01	8.10E-02	**4.63E-01**[a]	6.18E-02[b]	8.78E-02	1.57E-01	7.38E-02	kg
GW20a	5.27E-02	2.64E-02	**1.57E-01**	1.81E-02	2.58E-02	5.96E-02	1.71E-02	kg
GW100a	4.71E-02	2.37E-02	**1.41E-01**	1.62E-02	2.31E-02	5.34E-02	1.54E-02	kg
TAE	1.16E-05	8.73E-06	**4.64E-05**	5.38E-06	7.65E-06	1.82E-05	3.17E-06	kg
MAE	4.19E-02	1.94E-02	**1.09E-01**	1.49E-02	2.12E-02	3.77E-02	1.60E-02	kBq
FAE	8.28E-02	3.61E-02	**2.05E-01**	2.79E-02	3.97E-02	7.00E-02	3.17E-02	kg
OD	2.39E-09	1.95E-09	**1.02E-08**	1.06E-09	1.52E-09	3.24E-09	8.47E-10	kg
HT	2.44E-01	9.40E-02	**5.11E-01**	6.63E-02	9.43E-02	1.74E-01	1.08E-01	kg
Low NOx PO (Europe)	1.48E-05	5.81E-06	**3.59E-05**	4.80E-06	6.82E-06	1.51E-05	4.35E-06	kg
High NOx PO (Europe)	1.66E-05	8.41E-06	**4.85E-05**	6.33E-06	9.01E-06	1.87E-05	5.13E-06	kg
Malodours air (Global)	8.05E+02	3.45E+02	**2.06E+03**	2.73E+02	3.87E+02	8.66E+02	2.40E+02	kg
Ionising radiation (Global)	1.65E-10	8.95E-11	**5.02E-10**	5.68E-11	8.08E-11	1.80E-10	5.82E-11	kg
Depletion of abiotic resources (Global)	-3.42E-04	-1.72E-04	-1.01E-03	-1.18E-04	-1.68E-04	-3.77E-04	**-1.08E-04**	kg

[a] In bold highest values in the selection

[b] In italic lowest values in the selection

[c] Correlation of results per configuration to the relative noise impacts. d List of acronyms used in the table: FSET: Freshwater sedimental ecotoxicity (measured with the global freshwater sedimental ecotoxicity potential with a time horizon of 20 years); GW: Global warming (measured with the global warming potential with a time horizon of 20 years); TAE: Terrestrial ecotoxicity(measured with the global terrestrial ecotoxicity potential with a time horizon of 20 years); FAE: Freshwater aquatic ecotoxicity (measured with the global freshwater aquatic ecotoxicity potential with a time horizon of 20 years); OD: ozone layer depletion (measured with the global ozone depletion potential with a time horizon of 20 years); HT: Human toxicity (measured with the global human toxicity potential with a time horizon of 20 years); low NOx PO: Photochemical oxidation low NOx.

7

In the selection of CML-IA impact categories reported in Table 2, we see that the configuration with the highest nominal power, [A43], results as the best performer for the majority of impact categories (see the Supporting Information for further details on the other configurations). The worst performer per functional unit is the configuration with a nominal power of 800 kilowatt. The results suggest the difference in local conditions (i.e. different wind speed, hub height, RpM, and diameter) may alter the trend suggesting that smaller wind turbines carry higher impacts. The score of the contributions to the global warming impact are in line with those found in the review by Arvesen and Hertwich (2012). No strong correlations were found between noise impacts and the other impacts reported in Table 2.

5
Concluding remarks

LCA deals with a number of emissions and impacts that are matter-less. Impact assessment models for some of these impact categories have been developed and proposed by developers, but are seldom considered by practitioners in LCA studies. A reason for this is due to the absence of suitable inventory data to deal with these matter-less impacts, to their absence in the LCA software in use, or to an insufficient knowledge of the mechanisms and procedures that would allow to clearly define the inputs and outputs of the system under study, also from the point of view of the interpretation of the relative impact scores. The decision to include or exclude an impact category from an LCA study is, in fact, left to the one conducting the study. Most guidebooks, in fact, tell that a practitioner should include a complete set of impacts, while most case studies take a selection that is dictated by the available databases and software. The a priori exclusion of a certain impact category may influence the usability of results, since important aspects of the study of a life cycle may be inadvertently neglected.

We have presented a detailed analysis of the case study of wind turbines, which includes for the first time the evaluation of the impacts of sound emissions across all phases of the life cycle of a wind turbine. Through the test-case of the wind turbine we have showed in detail how sound emissions may be attached to a variety of processes in a life cycle, from extraction of resources to operation, and how these can be modelled. The results show that it is now possible to compare the human-related noise performance of systems with a similar functional unit and similar definitions. The study of the single configurations of wind turbine indicated that in the case of sound emissions also the local conditions considered for the modelled configurations, i.e. wind speeds, are relevant to obtain a significant result. In all cases it was the operation phase of the life cycle that contributed the most to noise impacts. For other impacts, the local conditions do not seem to have a strong influence on the entity of the impacts and the conclusion of Caduff et al. (2013) holds, thus bigger wind turbines have lower impacts per functional unit (see the review of Arvesen and Hertwich 2012).

Previous studies of noise in the context of LCA focused on the transportation sector (see e.g. Althaus et al. 2009a, b). In the current study, we showed that also the sound emissions (and the relative noise impacts) of other phases in a life cycle of a product system may be accounted for. Such approach allows bringing the study of noise impacts in LCA in line with other impact categories. Characterisation factors for noise impacts quantified in a variety of archetypal contexts could now be potentially included in LCA databases (e.g. Ecoinvent) and regularly used in case studies.

The selection of the life cycle of a wind turbine allowed dealing with the impacts of an emerging technology, on which a great deal of hope is put in future energy scenarios (see e.g. Krewitt et al. 2009 and SSREN 2011). We show that it is important to also include in the analysis those impacts that are related to the operation phase of the life cycle. Similar conclusions may be drawn for other emerging technologies (e.g. electric cars), which are claimed to have negligible impacts during their use. Some of these impacts will prove to be non-negligible when a suitable method becomes available to quantify them.

The limits of the currently available LCA studies of wind turbines are amply discussed by Arvesen and Hertwich (2012) and are outside the scope of the current study. We only note that particular attention should be given to the modelling of an accurate capacity factor that best represents the location when the system operates. Selecting too high capacity factors does influence the meaning of results. The inventory of the wind turbine configurations was composed using data already available in the study of Caduff et al. (2013), and, therefore, similar uncertainties and limitations may be assumed for the current study. For the case of sound emissions, the quality of data varied. The availability of a report specifically oriented at the operation phase of wind turbines allowed for an accurate modelling of sound power levels at specific local conditions, but limited the number of considered configurations to just a set of 43. For other configurations, a case-by-case analysis would be needed. For the phase of sound emissions from different transport modes, it was possible to use the CNOSSOS reference report (Kephalopoulos 2012), which also allowed for an accurate modelling of sound power levels. For the phase of excavation of the foundations the data found was not detailed in terms of frequency bands, thus it was not possible to give this extra nuance in the specification of the characterization of the emission data. The selection of the sound power level as a measure of sound emissions proved to be a reasonable modelling expedient, which simplifies the collection of sound emission data.

The results after characterization are presented at a midpoint level. A transition to the human health area of protection in units of years, or disability-adjusted-life-years (DALY) is proposed in Cucurachi and Heijungs (2014). In that study, we assumed a linear transition from midpoint to endpoint by means of a conversion factor linearly translating the midpoint unit person × Pascal × second to DALY. The multiplication of the score obtained in the current study with that in Cucurachi and Heijungs (2014) yields a damage score per functional unit ~0.002 DALY/KWh. Further investigations and modelling efforts are needed to evaluate the linearity of the midpoint-endpoint transition and the additional uncertainty that one may encounter when moving from the midpoint to the endpoint level of the impact pathway.

From a methodological standpoint, the criteria used for the inventory of sound emissions may reveal to be exemplary for the handling of other types of matter-less physical impacts in LCA that do not stem, just like sound and noise, from the extraction or release of a kg of matter. The process of linearization and inventory of sound emissions by means of a time-based factor provides indications on how other physical impacts may be analogously modelled. In order to open-up the LCA framework to new impacts that do not have the traditional extraction/emission features, these indications may come handy to approach the modelling phase, especially in the case of matter-less emissions and impacts. LCA, however, should not aim to measure all possible impacts and guidelines should be followed on which impacts to include and to which to give priority (see Cucurachi et al. 2014). For an assessment, especially at a very local level of detail, other decision-support tool in the environmental sciences would be more suitable and would provide less uncertain results.

The on-going modelling effort to provide LCA with a growing level of spatial detail (see e.g. Mutel et al. 2011) and temporal detail (Tessum et al. 2012) will certainly help giving the LCA framework the possibility to portray a wide variety of local conditions of emission and exposure. However, this current study shows how difficult it is to model geographical differences when no specific information is available on the location in which certain emissions took place. In principle, the model by Cucurachi and Heijungs (2014) provides spatially-explicit characterization factors for the EU. The use of such factors in the current study was of limited interest since it was not possible to specifically relate emissions to a certain location. In future studies, if extra information on the specific location of a wind turbine is available to the practitioner, those location-specific characterization factors may be used. However, even then we should check the balance between the added value of a regionalized approach and the added efforts to do the analysis (cf. Heijungs, 2012).

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7