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1 Exploring technologically, temporally and geographically-sensitive life
2 cycle inventories for wind turbines: a parameterized model for Denmark
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8 **Summary abstract**

9 In life cycle assessments of wind turbines and, more generally, of Renewable Energy Systems (RES), environmental
10 impacts are usually normalized by electricity production to express their performance per kilowatt-hour. For most RES,
11 manufacture and installation dominate the impacts. Hence, results are sensitive to parameters governing both impacting
12 phases and electricity production. Most available studies present the environmental performance of generic wind
13 turbines with assumed fixed values for sensitive parameters (e.g. electricity production) that often vary between studies
14 and fail to reflect specificities of wind farm projects. This study presents an approach to build a comprehensive
15 parameterized model that generates unique wind turbine life cycle inventories conditioned by technologically,
16 temporally and geographically-sensitive parameters. This approach allows for the characterization of the carbon
17 footprint of five sets of turbines in Denmark, where wind power is highly developed. The analysis shows disparities
18 even between turbines of similar power output, mostly explained by the service time, load factor and components
19 weights but also by background processes (evolution of electricity mix and recycled steel content). Project-specific
20 inventories with technologically, temporally and geographically-sensitive parameters are essential for supporting RES
21 development projects. Such inventories are especially important to evaluate highly-renewable electricity mixes, such as
22 that of Denmark.

23 *Keywords:* wind turbine, parameterized model, life-cycle assessment, spatio-temporal variability, carbon footprint.

24

25 1 Introduction

26 Increasingly competing with conventional energy sources, Renewable Energy Systems (RES) offer a way out of fossil
27 fuels dependency and allow to reduce greenhouse gas emissions (GHG) associated with the generation of electricity [1].
28 The latter, together with heat production, still represents 42% of the world GHG emissions in 2015 per the International
29 Energy Agency. The importance of RES is visible as the installed capacity of these systems increased by 30%
30 worldwide in the last 40 years. However, their development must be intensified and combined with energy efficiency
31 measures to reduce the GHG emissions at a global level, since the electricity demand has more than doubled during that
32 same period [2].

33 In parallel to this development, numerous Life Cycle Assessment (LCA) studies analyzed the performance of RES and
34 their increasing role in regional and national electricity mixes – see [3] in the context of Denmark – as well as at
35 worldwide level – see [4]. LCA has proven to be a relevant tool to analyze the performance of different electricity
36 generation systems [5–8]. LCA includes all the environmentally-relevant phases of the value chain of electricity
37 production system: from the capture and conversion of primary energy, via the construction, maintenance and disposal
38 of the plant to transform it, down to its distribution. As highlighted by Asdrubali et al. [9], the inclusion of all the phases
39 of an energy system is important. Unlike for conventional fuel-based technologies, the highest contribution to
40 environmental impacts of most RES corresponds to the *manufacture* and *installation* phases, while direct emissions
41 during the *use* phase (i.e. electricity production phase) remain limited.

42 Given the rapid deployment of RES as well as the establishment of LCA as an adapted tool for assessing energy
43 systems, this article suggests an approach to overcome current methodological issues in LCA applied to RES by
44 generating tailored life cycle inventories (LCI) of wind turbines.

45 As the supply share of RES becomes significant in a national energy mix – as illustrated, for example, by recent
46 statistics on gross electricity production and supply in Denmark [10] –, it seems paramount to use precise and correct
47 data for modeling the *manufacture* and *installation* inventory as well as the production output during the *use* phase.
48 Both elements strongly influence the end-results as the environmental performance of RES is usually expressed as the
49 sum of the impacts of the manufacture, installation, maintenance and end-of-life inventories normalized by the
50 electricity production. Zimmerman highlighted the importance of site specific parameters that can strongly influence the
51 environmental performance of wind turbine [11]. For that reason, there is a need to move away from generic inventories
52 and assumptions as they induce uncertainty in the results and fail to consider the diversity of designs and the effect of
53 time and geography on the environmental performances of RES on the market. Among RES, tailored wind turbine
54 inventories are notably worth to be developed, given the important spectrum of the market for the technology – for

55 example, more than 1,500 different wind turbine models have been marketed as of today – and the temporal and
56 geographical span over which they have been deployed. This diversity ideally calls for a differentiation in inventory
57 modeling for each plant within the fleet of a studied area, as differences in technologies and materials used may lead to
58 different end-results for some impact categories. This relates to the issue of parameter variability, affecting the
59 modeling of product systems that have different technological and geospatial parameters. Padey et al. [12] have shown
60 that such variables can have a considerable influence on the outputs of the LCA model of a wind turbine. In their review
61 of LCA studies on wind turbines, Lenzen and Munksgaard [13] underline the contribution of variables such as the
62 country of manufacture, the technology and the location of use on the overall energy intensity of the turbine. As they
63 point out, the country of manufacture and the used technology indirectly affect the content of recycled metals in the
64 turbines and its disposal options while the location of use (e.g. onshore or offshore) can affect the expected production
65 output. Another study from 2004 from Lenzen and Wachsmann [14] confirms this outcome showing that differences in
66 the background systems of two geographically-distinct economies (in this case, Germany and Brazil) could lead to a
67 fivefold difference in environmental impacts for the manufacture of a same wind turbine.

68 In addition to variability-related issues at the *manufacture* and *installation* phases, the environmental performances of
69 RES are also strongly influenced by the service conditions during their *use* phase. Indeed, the characterized emissions
70 are normalized over the electricity production over time. This relates to the issue of parameter uncertainty, which results
71 of the lack of knowledge on the conditions of use that affect the electricity production. Typical uncertain parameters for
72 RES during their use phase would be their service time and their capacity factor [12,13]. The service time of a RES can
73 be limited by harsh conditions of use. The capacity factor is generally function of wind speed distribution and the
74 corresponding power curve for wind turbines. LCA studies and other Environmental Product Declarations (EPD)
75 sometimes “guesstimate” the true value of such uncertain parameters and/or consider them fixed over time. For
76 example, studies such as [14–17] assume a theoretical value for the capacity factor of wind turbines while Schleisner
77 [18] leaves it simply unspecified. This can explain the spread in results found in meta-LCA studies, together with the
78 uncertainty due to methodological choices [9,19,20]. It also leads to a misalignment between the environmental
79 footprint theoretically calculated and the one observed *a posteriori*. The review work of Arvesen and Hertwich [21]
80 concludes that real conditions of use are different from the theoretical ones used in most LCAs and that both capacity
81 factors and service time of wind turbines are overestimated when characterizing their environmental performances.

82 Eventually, the use of simplifying assumptions for sensitive parameters at the different phases of the life cycle of the
83 RES inevitably leads to ignore the influence of technology, time and geography on the LCI and associated life cycle
84 impact results. The environmental performances calculated from generic inventories and production models likely
85 contrast with what is observed. Moreover, as assumptions considered in generic inventories may differ from one study

86 to another, generic studies cannot really offer a fair basis for comparison. Their usefulness for decision support is
87 limited in the context of, for example, wind farm project development. In such case, knowing precisely the
88 environmental gains expected from several alternatives for a project can foster its acceptance by the surrounding society
89 and authorities.

90 This article presents a parameterized model able to generate tailored wind turbine LCI. By differentiating the inventory
91 of each single RES according to the technological, temporal and geographical context of the product system, the
92 approach allows first to tackle the issue of uncertainty in inventories, and second to consider variability in plant designs
93 and in their electricity production over lifetime.

94 The LCI modeling approach presented in the next section allows for estimating the general material, energy and
95 environmental performance of a whole fleet of wind turbines while keeping an important level of detail. It also accounts
96 for the changes over time and space of certain background processes in the LCI, such as the evolution in material
97 recycling rates or the changes in the electricity mixes at the manufacture phase. The benefit of such parameterized
98 inventories is illustrated with the analysis of 1,401 cradle-to-grave LCI of wind turbines. Grouped in four categories of
99 nominal power output with a subdivision for offshore installations, these wind turbines belong to different
100 manufacturers, operate in distinct locations and are deployed at different points in time in Denmark. Their respective
101 environmental performances are thereafter analyzed through their carbon footprint.

102 Several comparable wind turbines with a similar nominal power output may have significantly different environmental
103 performances when the influence of technology, geography and time are considered in the LCI. The need for life cycle
104 practitioners and energy project developers to move away from generic models could thereby be justified.

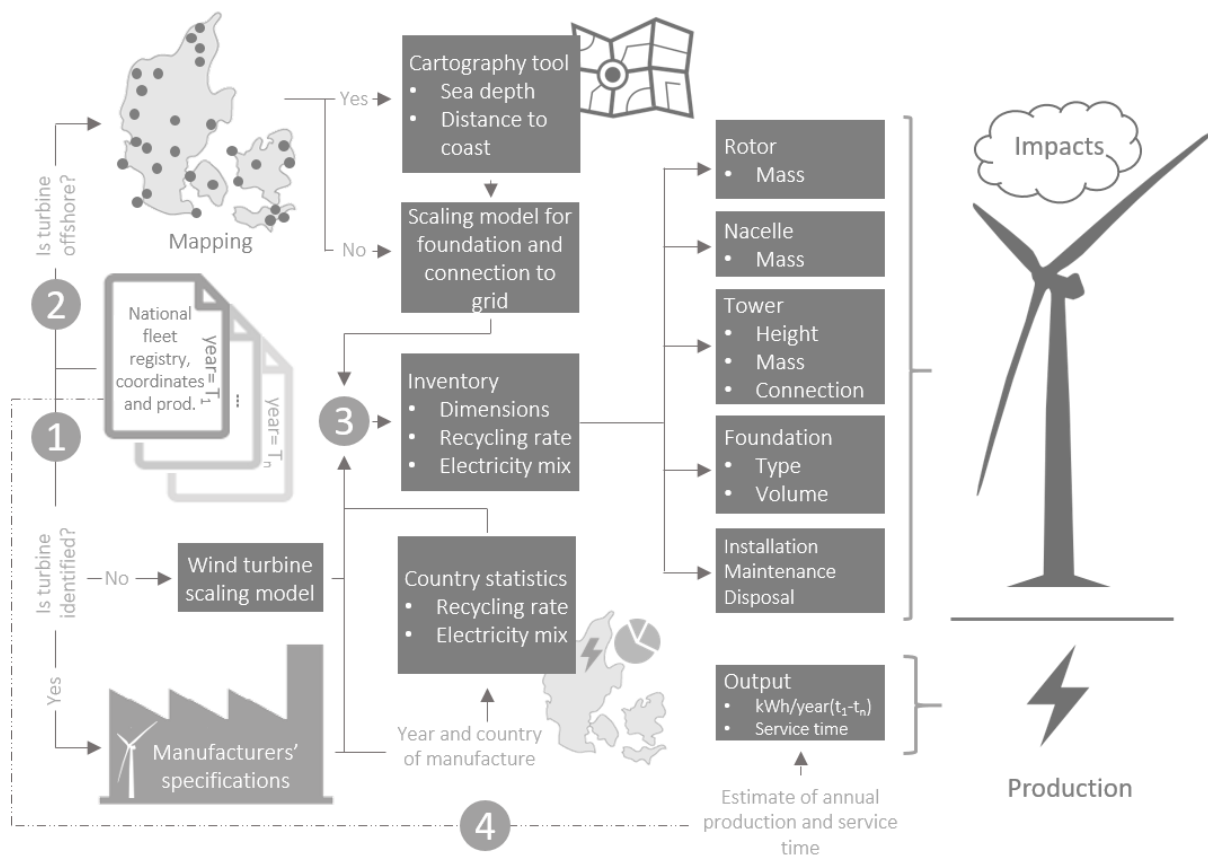
105 2 Method

106 This section describes the method used to generate individual cradle-to-grave LCI through a parameterized model
107 following a four-step sequence. The applicability of the parameterized model is demonstrated with five sets of wind
108 turbines in Denmark that have been operated before or until 2016.

109 The finality of the parameterized model developed in this study is to build wind turbine-specific inventories: it entails
110 the definition of the total material and energy requirements of each phase of the wind turbine life cycle from its
111 *manufacture* down to its *disposal* phase. As a first step, the method requires the acquisition of a fleet registry of wind
112 turbines including key information such as the brand, model and coordinates of wind turbines that are located in the
113 studied area, as well as their respective electricity production during their service time. Then, there is an attempt to
114 match the information from such fleet registry with manufacturers specifications to obtain mass and dimension

115 attributes. If a wind turbine cannot be matched with any manufacturer data, the method uses regression analysis to
 116 approximate mass and dimension attributes. As a second step, knowing the location of each wind turbine, the method
 117 can detect if the wind turbine is onshore or offshore. For offshore wind turbines, cartography tools are used to obtain the
 118 sea depth and distance to shore. These parameters are required to size the wind turbine foundation and the length of
 119 cables to connect to the national electricity grid. Third, knowing the size and mass attributes of the wind turbine, a
 120 specific supply, manufacture, installation, maintenance and disposal inventory is generated with the background support
 121 processes adjusted to the geographical and temporal context of the value chain, based on statistics of the appropriate
 122 geographical scope of analysis (i.e. regional, national or continental). At the last step, the method retrieves the
 123 registered electricity production and service time for the wind turbines already dismantled. For wind turbines currently
 124 in operation, their remaining service time is estimated based on the historical service time expectancy of past wind
 125 turbines (see Section 2.3). Additionally, their expected yearly electricity production is projected based on past registered
 126 production. The inventory of each wind turbine can be divided by the production output registered throughout its *use*
 127 phase to obtain its environmental burden in relation to a kWh of electricity produced. This four-step sequence adopted
 128 by the model is graphically summarized in Figure 1.

129



130

131 *Figure 1: Graphical representation of the 4-step approach used to estimate the life cycle inventory of a given wind turbine.*

132 The approach has been applied to a selection of individual wind turbines grouped into five sets that have been operated
 133 in Denmark until 2016 as per the national wind turbines registry [22]:

- 134 • A “100-kW” set that comprises 543 onshore wind turbines with a nominal power output of [90-110] kW,
- 135 • A “500-kW” set that comprises 230 onshore wind turbines with a nominal power output of [450-550] kW,
- 136 • A “1-MW” set that comprises 370 onshore wind turbines with a nominal power output of [0.9-1.1] MW,
- 137 • A “2-MW” set that comprises 154 onshore wind turbines with a nominal power output of [1.8-2.2] MW.
- 138 • And a “2-MW offshore” set that comprises 104 offshore wind turbines with a nominal power output of [1.8-
 139 2.2] MW.

140 These five sets, totaling 1,401 wind turbines and described in Table 1, include different manufacturers and turbine
 141 models. These models have been manufactured at different points in time and operated in distinct locations. Their
 142 respective electricity production and service time are entirely or partially known, depending on whether they still
 143 operate in 2016.

144 *Table 1: Sets of studied wind turbines.*

Set	100 kW	500 kW	1 MW	2 MW	2 MW offshore
Number of wind turbines	543	230	370	154	104
Number of manufacturers	20 (including 1 unidentified)	7	7 (including 1 unidentified)	3	2
Number of models	15 models (including 3 unidentified)	28 models (including 2 unidentified)	27 models (including 2 unidentified)	13 models (including 3 unidentified)	3
Start of service time	1980 to 2004	1989 to 2013	1993 to 2005	1996 to 2016	2000 to 2003
Operating in 2016	3.5%	95%	98%	93%	100%

145

146 A tailored cradle-to-grave LCI is built for each of these wind turbines with the parameterized model following the
 147 above-mentioned steps. These steps are detailed in the next sub-sections. The inventories are stored in a Python
 148 dictionary and the material and energy requirements are solved thereafter using the LCA framework Brightway [23].
 149 Finally, each inventory is characterized regarding the *global warming* impact category with a hundred-year time
 150 horizon and expressed as GHG emissions (mass of emissions of CO₂-eq.) using the characterization factors provided by
 151 the Intergovernmental Panel on Climate Change [24].

152 2.1 Modeling the foreground processes

153 The following sub-sections describe the inventory modeling of foreground processes included in the manufacture,
 154 installation, use, maintenance and disposal phases of the life cycle.

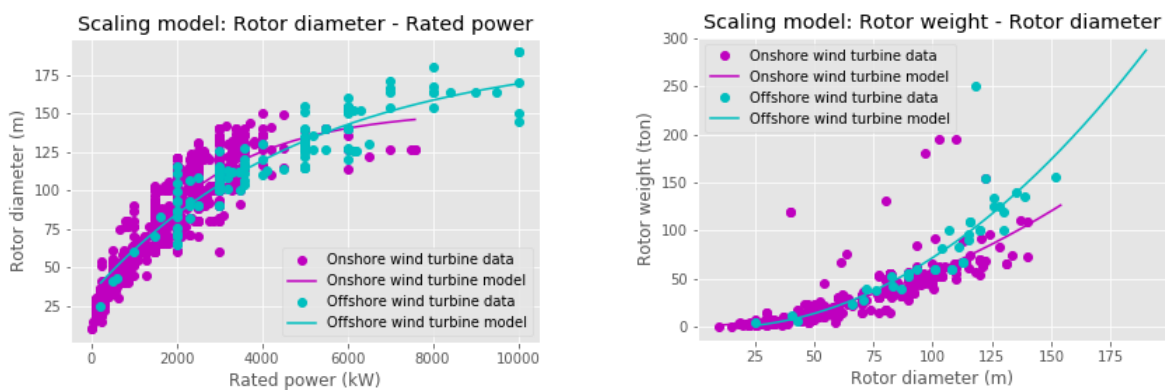
155 2.1.1 Components specifications: manufacturers data and scaling models

156 The model considers onshore and offshore wind turbines as a group of components to be assembled: the tower, the
 157 nacelle, the rotor (including the hub and the blades), the transformer and the connection to the substation. Onshore
 158 plants have a concrete-based foundation while offshore plants are assumed to be connected to the sea bed by a steel-
 159 made monopile foundation – which equips 70 to 80% of the offshore installations in Denmark [25] – via a transition
 160 piece.

161 Almost all the wind turbines in the studied sets have been identified and linked to manufacturers data, from which
 162 precise dimensions and weights of the different components are obtained. The dimensions of the remaining few wind
 163 turbines that the model could not identify are estimated using a set of scaling models based on correlations between
 164 attributes of the turbine components that are presented below.

165 2.1.2 Scaling models: from wind turbine nominal power to mass and size attributes

166 The approach described in [12] is adapted to build a series of scaling models for onshore and offshore plants against the
 167 mechanical and physical specifications of 1,525 unique models provided by *The Wind Power* database [26]. Based on
 168 observed physical correlations between components, the scaling models estimate a set of dimensions and masses for the
 169 foundation, tower, nacelle and rotor using the nominal rated power of the wind turbine as input. Details on the
 170 correlations between the nominal power output and the different components of a wind turbine are available in the
 171 Supporting information document. To illustrate the idea behind the correlations used by the scaling models, Figure 2
 172 shows the sequence used to obtain the rotor weight of an unidentified wind turbine. The rotor diameter is first estimated
 173 based on the nominal power output of the wind turbine, since the correlation between the two parameters is statistically
 174 significant (i.e. a Pearson correlation coefficient superior to 0.75). Once the rotor diameter is known, it can be used to
 175 obtain its mass.



176 *Figure 2: Correlation between nominal power and rotor diameter (left)*
 177 *and correlation between rotor diameter and rotor weight (right).*

178 2.1.3 Sizing the offshore foundation

179 For offshore wind turbines, the parameterized model uses an additional model built from a technical project description
180 report on offshore installations in Denmark [25]. A schematic representation of an offshore installation as considered in
181 this study is available in the Supporting information document. The scaling model returns the material and energy
182 requirements for the supply and installation of a steel-made monopile foundation with the transition piece, including the
183 grouting between the foundation and the transition platform, the casting of concrete at the bottom and the use of rocks
184 to prevent degradation from scouring. The overall monopile height is modelled as being equal to the part inserted in the
185 sea bed (conditioned by the nominal power output of the wind turbine and its weight), the part between the sea bed and
186 the surface (a cartographic tool is used to return the sea depth for the location of each offshore installation) and the part
187 between the surface and the transition platform (assumed to be 9 meters above the surface, regardless of other
188 parameters).

189 2.1.4 Sizing the electric connection to the national electricity grid

190 Additionally, the model estimates the amount of materials necessary to connect wind turbines to the national electricity
191 grid considering both cables and power transformers. For offshore wind turbines, the amount of cable necessary to
192 connect to the coast is calculated considering a typical grid connection scheme found in Horns Rev wind farms, off the
193 western coast of Jutland (Denmark) with a 33 kV inter-array cabling voltage and a shore connection voltage of 150 kV
194 – or directly at 33 kV if the wind farm power output is lower than 30 MW [27]. The assessed cable sections are based
195 on the transport capacity of Nexans 33 kV and 150 kV copper-based product range [28,29]. The cable length depends
196 on the distance between the wind turbine and the central transformer of the farm (which is roughly assumed to be
197 positioned at the centroid of the farm) and the distance between the farm and the coastline. Based on such distance,
198 requirements in terms of copper for cabling and the energy for laying the cable – with ship consumption figures from
199 the company [30] – are approximated. It is important to note that this estimation may differ from reality for at least two
200 reasons. First, there is a tendency to use higher voltage or HVDC technology when distance increases. Second, the
201 inter-array cabling and the central transformer location also strongly depend on topology and aluminum-based cables
202 are sometimes used instead of copper. Additionally, the model considers a medium voltage power transformer for each
203 wind turbine to reach the intra-array voltage of 33 kV and a high voltage power transformer for the wind farm to reach
204 the shore connection voltage of 150 kV. Inventories for power transformers are based on ABB Environmental Product
205 Declarations [31,32]. Fugitive emissions of sulfur hexafluoride, an extremely potent greenhouse gas often used in
206 circuit breakers for its exceptional electrical insulation properties, have not been accounted for in the model. This choice
207 is justified by the fact that even if SF₆ emissions are strongly underestimated, the impacts on climate change remains
208 negligible compared to the GHG emissions from wind power as detailed in the SI document. Moreover, there are

209 important uncertainties regarding the nature of the gas used with some alternatives being developed [33,34] and the
210 amount of gas used in circuit breakers and the leakage rate over the lifecycle have been strongly reduced over time
211 [35,36]. The size of each medium power transformer depends on the corresponding wind turbine nominal power, while
212 the size of the high-voltage transformer depends on the total nominal power of the wind farm. In coherence with the
213 EPD, the lifetime of the shore connection infrastructure is 35 years for the power transformer and 40 years for the
214 cables. Regarding onshore wind turbines, they connect to the national grid at medium voltage. For this reason, a
215 medium voltage power transformer associated to each turbine is also considered, as well as a cable with a length
216 conditioned by the nominal power output of the wind turbine it connects to.

217 2.1.5 Estimating mass distribution of wind turbine components according to the nominal 218 power

219 The detailed material and assembly inventories of six wind turbine models (33 kW, 150 kW, 600 kW, 800 kW and two
220 2 MW) provided by [37] are used to obtain the materials percentage distribution by mass for the different wind turbine
221 components (e.g. ratio glass fiber-epoxy in the blades). The calculated mass ratios are used by the model to estimate the
222 unknown quantities of the different materials necessary to produce the wind turbine components. These quantities are
223 obtained by interpolating between the known ratios. For the material and energy flows that are not significantly
224 correlated to the mass of the components, the model extrapolates their quantities based on the nominal power output of
225 the wind turbine. For example, based on the provided inventories, 0.5 kWh of electricity per kg of material is needed to
226 assemble the wind turbine components together. Once all the quantities for the different flows of material and energy
227 are calculated, they are linked to corresponding supply market datasets in the ecoinvent 3.3 LCI database [38]. Market
228 datasets in ecoinvent provide “cradle-to-supply” inventories for commodities for a specific regional area. The
229 environmental burden that relates to the geographical variation in production technology and modes of distribution
230 within that area is considered based on the respective market share of countries that supply these commodities. The
231 specific mapping between inventory flows and the ecoinvent market datasets can be consulted in the section 1.4 of the
232 Supporting information document.

233 2.1.6 Installation, maintenance and disposal

234 Requirements for specific activities such as road construction for onshore installations or sea bed drilling and the
235 hammering of the monopile for offshore installations are interpolated based on the nominal power output of the wind
236 turbine which correlates rather well with its mass and dimensions. Background processes associated to the assembly
237 operations are provided by the ecoinvent 3.3 LCI database [38]. Furthermore, regular maintenance is considered with
238 the change the lubrication oil in the gearbox and transport of technicians. However, exceptional maintenance involving

239 material replacement has not been accounted due to lack of data. Finally, different disposal options are considered
240 depending on the nature of the materials. While concrete, fiberglass and aggregates are disposed in landfills, steel
241 (excluding reinforcing steel), thermoplastics and copper cables are supplied to the corresponding scrap markets. This
242 study follows the *polluter pays* principle: the environmental burden associated to the treatment of waste materials is
243 accounted for. These operations are further described in the Supporting information document.

244 2.2 Adjusting background processes

245 The model also adjusts the background processes in the inventory of the wind turbines in function of the location and
246 time of manufacture. This was relatively simple in this case study since all the wind turbines have been manufactured
247 by medium and large manufacturers in Denmark that rely on supplies from neighboring countries, for which data and
248 background inventory datasets are abundant.

249 2.2.1 Geographically-adjusted supply markets

250 The model is designed to be as location-specific as possible, resorting to global supply markets last. First, the supply of
251 energy and materials is geographically-adjusted: electricity and heat are supplied by the Danish market, ferrous and
252 non-ferrous metals are supplied by the German market, plastics components by the European market and the materials
253 that cannot be supplied by a local market are eventually supplied by the global market.

254 2.2.2 Time-adjustment of the background electricity supply

255 To reflect the influence of time on the manufacture and assembly inventories, the model adapts specific energy-
256 intensive background processes to the year of manufacture. It is the case with electricity. Danish-average electricity mix
257 datasets with supplying technologies, imports and network losses are built to the year of manufacture of each wind
258 turbine. The electricity mixes are based on historical time series provided by the Danish Ministry of Energy [10]. The
259 time series of electricity supply mix are available in the Supporting information document.

260 2.2.3 Time-adjustment of the background steel supply

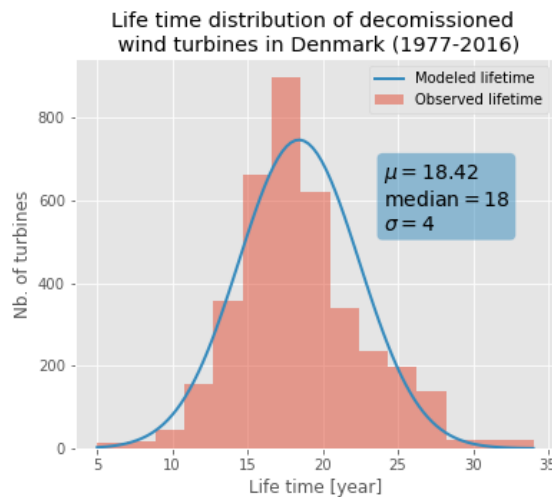
261 The provision in primary and secondary (recycled) low-alloyed steel for the manufacture of the tower and the different
262 components inside the nacelle is also adjusted. Germany, the main supplier of steel in Europe, has been selected as the
263 primary supplier of steel, since Denmark does not have any domestic production. As secondary steel has a lower
264 embodied energy than primary steel, the recycling rate for steel has been adjusted to the year of manufacture of the
265 wind turbine to reflect the evolution in terms of recycling in the steel industry over time [39]. The time series of primary
266 and secondary steel supply mix are available in the Supporting information document.

267 2.3 Modeling the electricity production

268 The two following sub-sections describe the approach used to model the electricity production during the life cycle use
269 phase of the wind turbines.

270 2.3.1 Estimation of the service time for operating turbines

271 There are no clear correlations between the service time observed on dismantled wind turbines and any of their
272 technical specifications (brand, model, nominal power, installation date, etc.). Also, the 40 years of data from the
273 Danish wind turbines registry did not suffice to detect a statistical pattern in that regard. The service time of a turbine
274 seems to be conditioned by the relation between the marginal cost of maintenance and the electricity price of the
275 supplied area, as indicated by a report commissioned by the Danish Ministry of Energy on the topic [40]. The plant
276 owner tends to operate the wind turbine if the marginal cost of maintenance is inferior or equal to the marginal income
277 of production. Variable maintenance costs for the turbines are not known to the authors and future electricity prices
278 remain difficult to predict. Regardless of the characteristics, the wind turbines still in operation in 2016 are given a
279 service time in line with what has been observed on the 3,121 turbines that have been decommissioned to date: a
280 random value comprised within a normal distribution centered around 18-19 years with a standard deviation of 4, see
281 Figure 3.



282

283 Figure 3: Distribution of the service time of decommissioned turbine in Denmark up to 2016.

284 2.3.2 Estimation of the remaining production for operating turbines

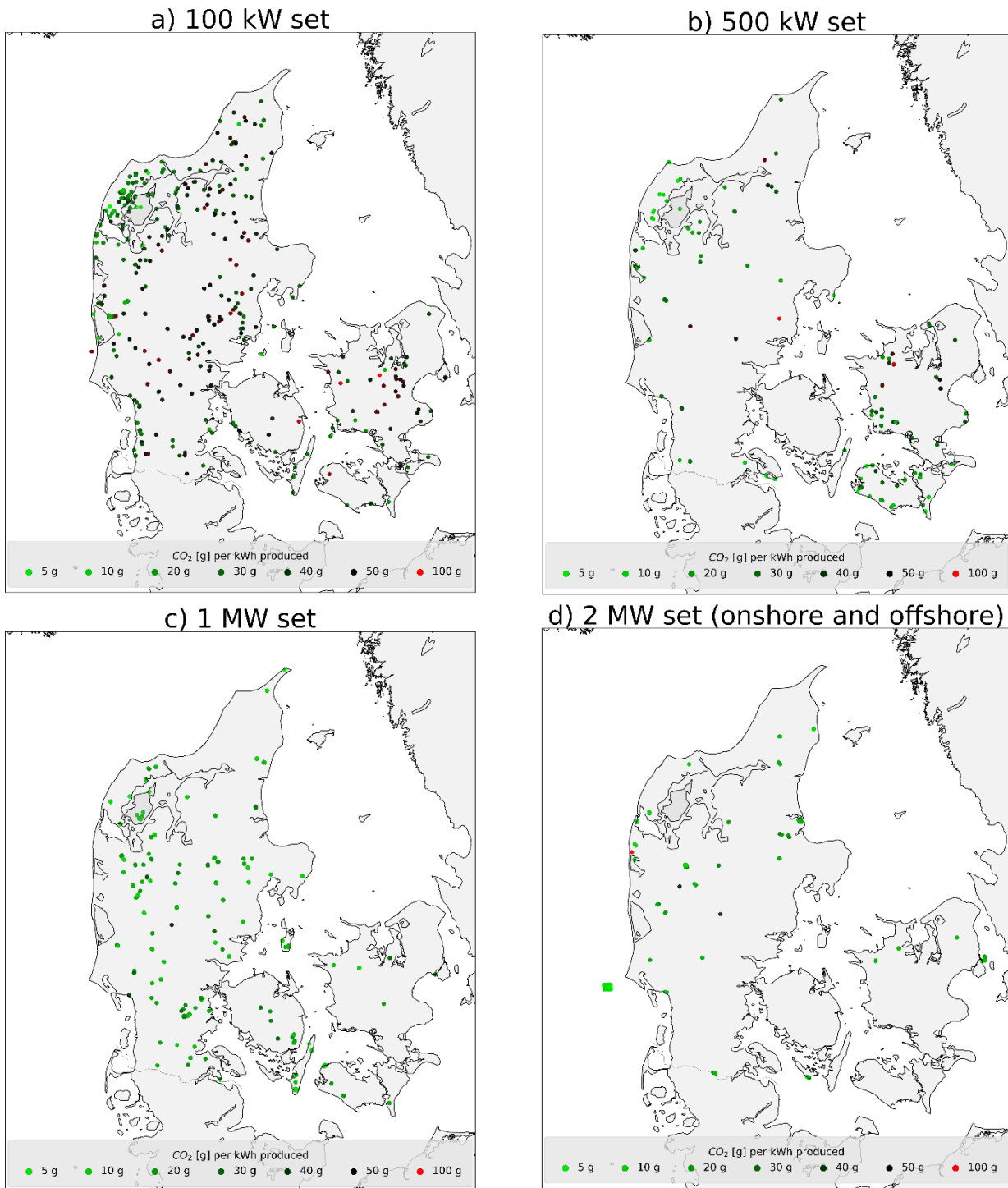
285 The electricity production registered for the wind turbines that are already decommissioned is used. As described in
286 Table 1, it is worth underlining that most of the wind turbines in the studied sets are still operating in 2016. The
287 parameterized model needs to estimate the remaining electricity production of the wind turbines still active in 2016.
288 With a service time estimated as per Section 2.3.1, the overall electricity production during the *use* phase is obtained by

289 adding the product between the median value of the registered production and the estimated remaining years of service
290 time to the production that has already been registered. The median annual production value is used instead of the
291 average value to avoid considering the first year of production. Indeed, the first year of production may return a much
292 lower production figure than the following years if the wind turbine started operating towards the end of the year.

293 3 Results and discussion

294 Thanks to the parameterized model generating tailored onshore and offshore wind turbines LCI, it is now possible to
295 analyze the environmental performances of the 1,401 wind turbines studied in regard to the global warming impact
296 category as presented in Figure 4 hereunder.

297

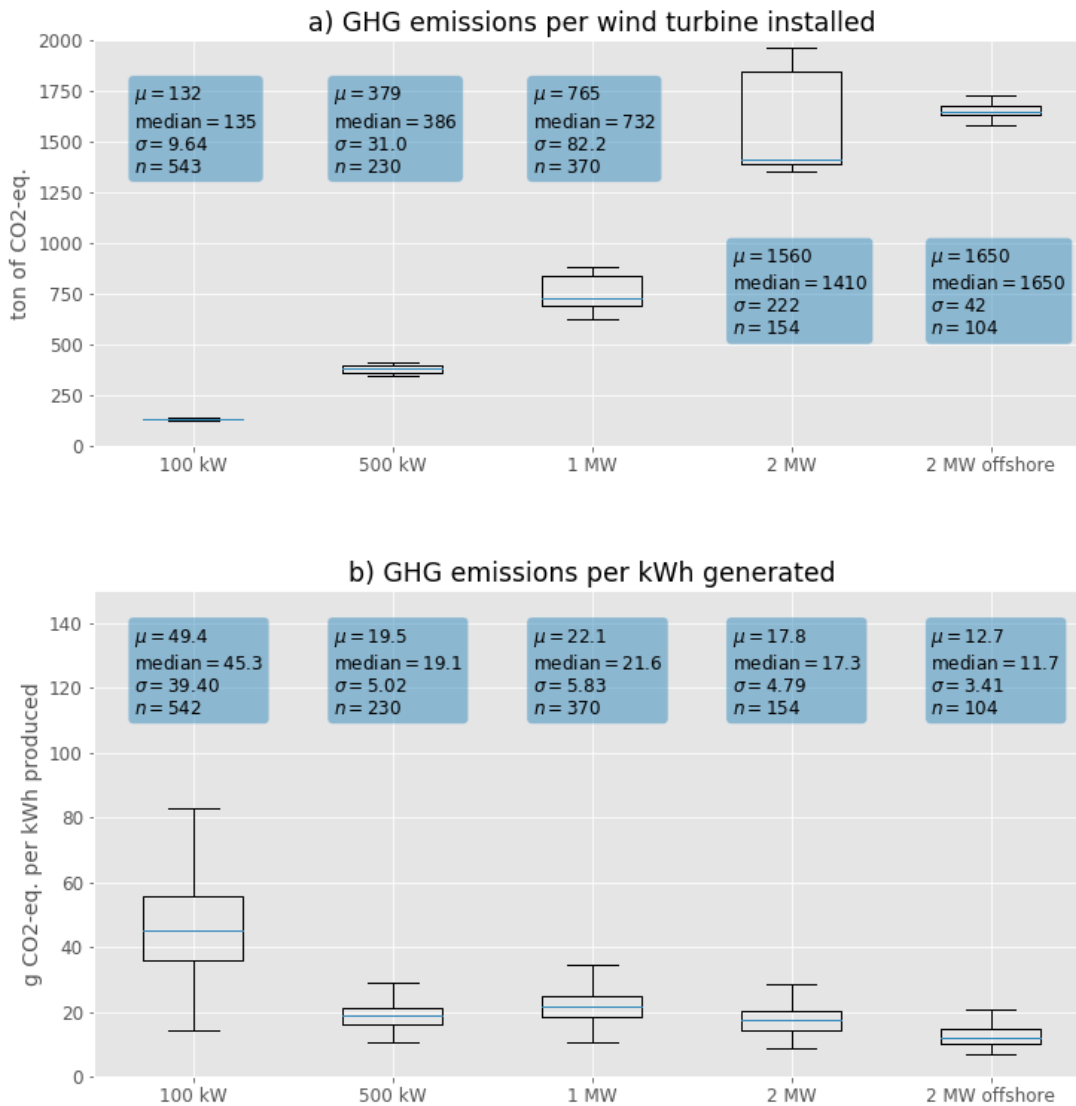


298

299 *Figure 4: Map of the studied wind turbines and associated GHG emissions per kWh. Wind turbines with GHG emissions per kWh*
 300 *above 100 grams are not displayed (27 wind turbines of 100 kW)*

301 The GHG emissions of wind turbines are conditioned by their material and energy requirements all along the life cycle.
 302 These requirements are particularly dependent on the nominal power output and dimensions of the wind turbine.
 303 Figure 5.a shows economies of scale where GHG emissions are marginally decreasing as the nominal power of the wind
 304 turbine increases: progress in terms of design and technology allowed reaching higher nominal power outputs while
 305 increasing the energy and material efficiency. While the nominal power output is multiplied by 20 between the wind
 306 turbines that belong to the 100-kW and 2-MW sets, the median GHG emissions per life cycle are only 10 times as

307 important. For 2-MW systems, offshore wind turbines emit slightly more GHG than most onshore wind turbines during
 308 the manufacture and installation phase due to heavier foundations. However, some 2 MW onshore wind turbines have a
 309 larger rotor to increase the turbine production, which leads to a higher impact than that of the offshore ones. This
 310 increased impact is associated with the higher and heavier tower required to support the larger rotor. These aspects are
 311 further discussed in Section 3.1.



312 *Figure 5: Statistical distribution of wind turbines GHG emissions per power category expressed as: a) emissions per life cycle and*
 313 *b) emissions per kWh produced. The blue horizontal line is the median value. Vertical rectangles represent 50% of the distribution.*
 314 *Vertical black intervals represent 90% of the distribution. Outlying values are computed but not displayed.*

315 When considering GHG emissions per kWh of electricity produced, there are two combined effects: on the one hand,
 316 increased power output leads to increased electricity production and, on the other hand, material and energy
 317 requirements per kW decrease for wind turbines with higher power output (that is, material and energy requirements do
 318 not increase linearly with power output). According to the results shown in Figure 5.b, these effects lead to a reduction

319 of the GHG emissions per kWh produced as the nominal power output of the wind turbine increases. However, the
320 GHG emissions reduction between the sets is marginally decreasing as the nominal power output increases. While such
321 reduction is significant between the 100-kW and 500-kW sets, it is less so between sets of wind turbines with larger
322 nominal power outputs. The statistic relation between nominal power output and electricity production is later discussed
323 and graphically described in Figure 8. A lower carbon footprint for offshore wind turbines explained by a better wind
324 resource is observed, as described in Section 3.3.

325 There is a high variance in the results of the 100-kW set due to an important variability of electricity production that can
326 be partly explained by technological improvements as these turbines were the first to be developed and installed in
327 Denmark. Additionally, some wind turbines with outlying performances heavily weight on the average value of the
328 100-kW set distribution that exceeds 3,000 grams CO₂-eq. per kWh. This is not representative of the actual performance
329 of the set (i.e. unfairly high, in that case) and it is due to wind turbines that have served as prototypes and have
330 produced very few electricity or that presented serious defects. The median value, unaffected by outlying values, is a
331 more useful statistic in this case. The distribution is narrower for the four other sets, but their standard deviation values
332 remain important: at best, the standard deviation value represents a fourth of the average value for the 1-MW set, with a
333 min-max interval going from 10 to 56 grams of CO₂-eq. per kWh produced. As wind power can compete for investment
334 with other “low-carbon” technologies (e.g. hydro, solar, nuclear), such spread in the results is meaningful and
335 understanding its cause is important. The variance is believed to find roots in the model parameters that are of
336 technological, temporal and geographical nature, as the next subsections discuss.

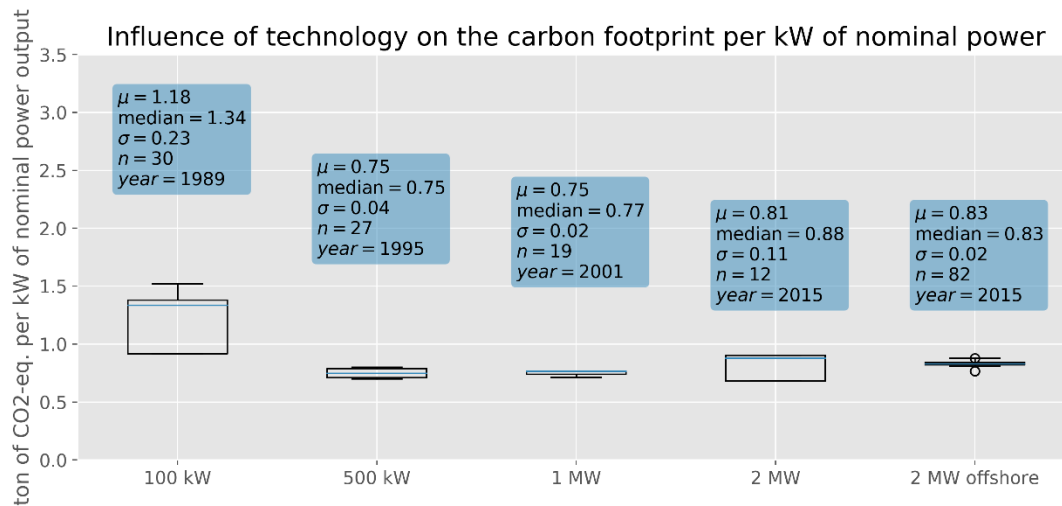
337 3.1 Technological influence

338 This section looks at how the choice of design and technology affects the material and energy-efficiency of wind
339 turbines. In this case, GHG emissions are expressed per kW of nominal power output for each set of wind turbines
340 produced at a given year of manufacture. Setting a fixed year of manufacture in reference to a kW of nominal power
341 output, as opposed to a kWh of electricity produced, allows testing the influence of technological parameters while
342 keeping spatial and time-related parameters fixed. Parameters that relate to technological aspects, such as the design and
343 the intended application (onshore, offshore) of the wind turbine seem to affect the use of materials and energy and
344 consequently, the amount of GHG emissions per kW of power output. Average and median GHG emissions per kW for
345 each set of turbines are shown in Figure 6. The results seem very sensitive to technological parameters, notably for the
346 smaller wind turbines contained in the 100-kW set.

347 As the wind turbine industry developed, the models on the Danish market became fewer along with the number of
348 producers. But the models increased in power and size. This led to less material required and less variance in terms of

349 impacts associated to the *manufacture* phase per kW of nominal power output. Indeed, the effect of design and material-
350 intensity is visible on early models with a low nominal power output, explained by a wider spectrum of designs and
351 technologies. For example, the amount of low-alloy steel needed for the wind turbines in the 100-kW set is about 150
352 kg per kW of nominal power output, with large variations around that value. For the wind turbines in the 2-MW set, this
353 value decreases down to approximately 100 kg of steel per kW on average. It is also the case in regard to the design of
354 blades and the amount of glass fiber-reinforced plastics required for their manufacture: while an average of 9 kg of
355 reinforced plastics are needed per m² of swept area on wind turbines from the 100-kW set (with a total swept area of
356 320-350 m²), that figure goes down to 5.5 kg for the wind turbines that belong to the 2-MW set (with a swept area of
357 5000-7000 m²). As illustrated by Figures 5.a and 6, 2 MW wind turbines show a relatively wider dispersion than 500
358 kW and 1 MW wind turbines that is explained by differences of rotor size and tower height within this set. Two thirds
359 of those turbines have rotor diameters of 70-80 m, tower heights between 60-80 m weighting about 160 t and impacts of
360 1400 tCO₂-eq, approximately. Wind turbines belonging to the other third have larger rotor diameters of 85-100 m,
361 which logically involve higher tower heights of 75-110 m weighting between 200-270 t and higher impacts close to
362 1800 tCO₂-eq. This higher impact is compensated by a higher load factor when expressing the environmental
363 performance in terms of gCO₂-eq/kWh produced (see Section 3.3).

364 Regarding offshore wind turbines, they have a higher global warming impact per kW of nominal power output during
365 the installation phase and the supply of the foundation than equivalent onshore wind turbines (i.e. with similar rotor
366 dimension). For instance, the characterized LCI of the offshore version of the VESTAS V80 model results in higher
367 GHG emissions per kW of nominal power output than its onshore counterpart (0.83 tCO₂-eq/kW against
368 0.70 tCO₂-eq/kW, on average). These assertions are discussed in the next sections where the environmental impacts are
369 expressed in relation to the effective production of electricity to reflect the influence of wind availability and service
370 time. The material and energy requirements related to underwater foundations (between 130 and 190 tons of steel
371 supply for the monopile foundation mostly) bear a higher environmental burden than the onshore alternative (350 cubic
372 meters of in-situ concrete, 27 tons of reinforcing steel, 8,000 meter-year of road and associated handling operations).
373 This difference becomes increasingly important as the sea depth increases. In relation to a sea depth of 10 meters, the
374 GHG impact of an offshore VESTAS V80 installed in the Horns Rev wind farm would approximately increase by 1%
375 per additional meter of sea depth. Upcoming floating platforms may in the future further increase this difference with
376 onshore installations, despite better wind resources found away from the coastline, according to [41]. However, floating
377 platforms will be less sensitive to sea depth and allow installation of wind turbines in deeper seas.



378

379 *Figure 6: Statistical distribution of wind turbine carbon footprint per kW of nominal power per power category. The*
 380 *blue horizontal line is the median value. Vertical rectangles represent 50% of the distribution. Vertical black intervals*
 381 *represent 90% of the distribution. Outlying values are computed but not displayed.*
 382

383 3.2 Temporal influence

384 3.2.1 The year of manufacture

385 In this section, the influence of adjusting the background processes (electricity and steel) at the *manufacture* phase to
 386 the year of manufacture on the GHG emissions of wind turbines is assessed. To do so, the GHG emissions of a unique
 387 wind turbine model are plotted in reference to a kW of nominal power output for different years of manufacture. This
 388 allows disregarding the influence of technology (as only one model is considered) or location of use and wind
 389 availability (as the GHG emissions are expressed regarding one kW of nominal power output). Figure 7.a shows the
 390 GHG emissions per kW of nominal power output obtained according to the parameterized model for the VESTAS V80,
 391 produced from 1995 to 2015 with the same manufacture inventory. In parallel, the figure also shows with a base 100
 392 Index in 1996 the relative change in the GHG emissions for the supply of Danish electricity and German steel used for
 393 the manufacture of the wind turbine. The GHG emissions per kW of nominal power output decreased by 11% during
 394 the analyzed period, exclusively due to the evolution of electricity and steel background processes. The GHG emissions
 395 associated with Danish electricity decreased in the same period by almost 80% and the German steel by 5%.

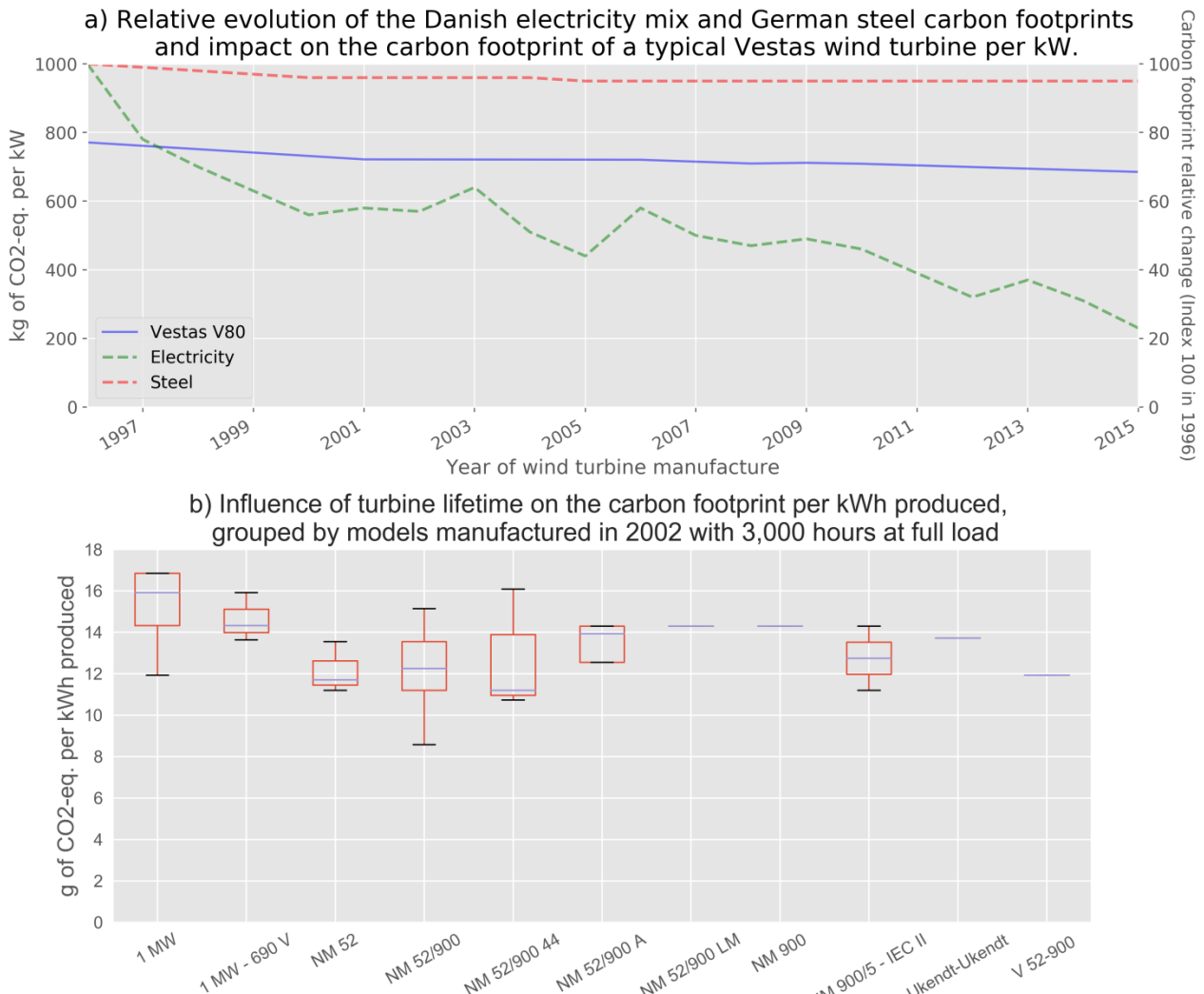


Figure 7: Graphical depiction of the temporal influence on the GHG emissions of wind turbines.

396
397

398 Virtually all wind turbine models rely on the extensive use of steel and electricity for manufacture. Hence, the
 399 decarbonization of support systems (i.e. electricity, heat) and materials play a major role in reducing the GHG
 400 emissions associated to the life cycle of wind turbines. In fact, in the case of Danish electricity, the reduction of 80% of
 401 its GHG emissions within the last 20 years is to a large extent due to the expansion of wind power in the national supply
 402 mix over the use of coal. The GHG emissions reduction for steel of 5% over that same period is comparatively more
 403 modest, as recycling rates evolve at a slower pace. The scrap steel to be reconditioned as secondary steel takes some
 404 time to return to the electric steel furnaces as the service time is generally long. However, steel is extensively used in
 405 the manufacture of wind turbines – up to 500 tons can be required on a 9 MW model. Therefore, small increments in the
 406 recycled content rate lead to significant potential reduction of GHG emissions.

407 3.2.2 The service time

408 In this section, the sensitivity of the length of service time on the GHG emissions *per kWh produced* of the different
 409 wind turbine models contained in the 1-MW set is tested while the technological and spatial parameter values are kept

410 fixed. All the models presented are manufactured in 2002 – the year where most wind turbines in that set were
411 manufactured – and benefit from an assumed value for wind availability at full load of 3,000 hours, which corresponds
412 to the current average wind load in Denmark [42]. The only varying parameter value in each group of wind turbine
413 models is the duration of the service time.

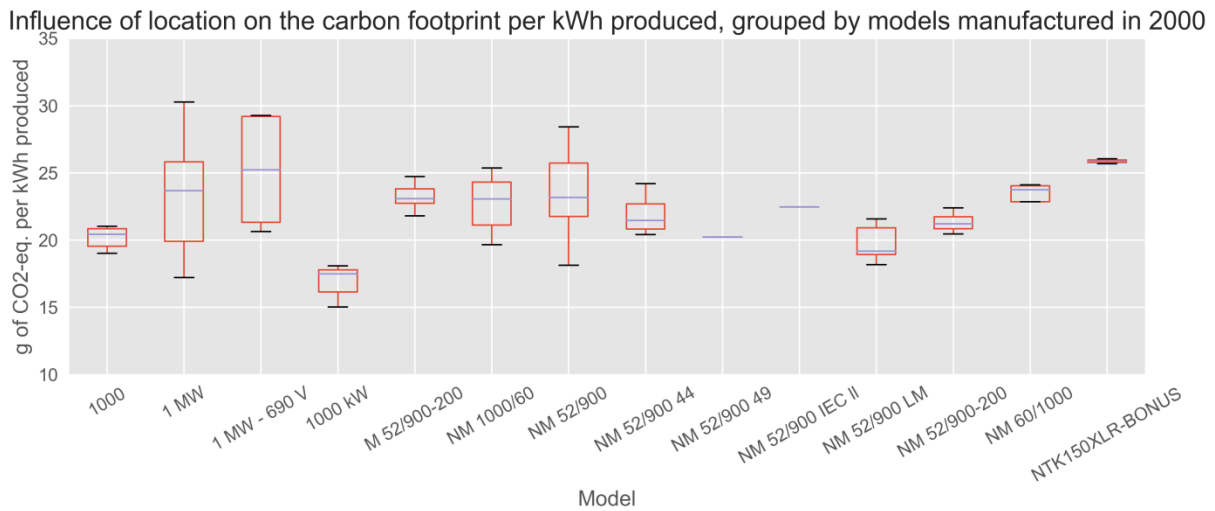
414 The results shown in Figure 7.b confirm that the length of service time has a major influence on the GHG emissions per
415 kWh produced. In fact, for some wind turbine models, the most extreme variation in the service time leads to a 100%
416 difference in terms of GHG emissions per kWh produced between the best and worst performing wind turbines (see
417 model “NM 52/900”).

418 3.3 Geographical influence

419 Considering the measured electricity production allows highlighting two important efficiency-related aspects:

- 420 - i) the efficiency of the transformation of the wind kinetic energy into electrical power, which refers to the
421 technological ability of wind turbines to reach a certain power output at different wind speeds. This efficiency
422 is determined by the power curve.
- 423 - ii) the productivity, which is conditioned by the previously presented power curve and the local wind resource.
424 This productivity can be represented by the number of equivalent hours of wind at a speed that allows the
425 turbines to operate at full load. This is also synonymous to the notion of capacity factor.

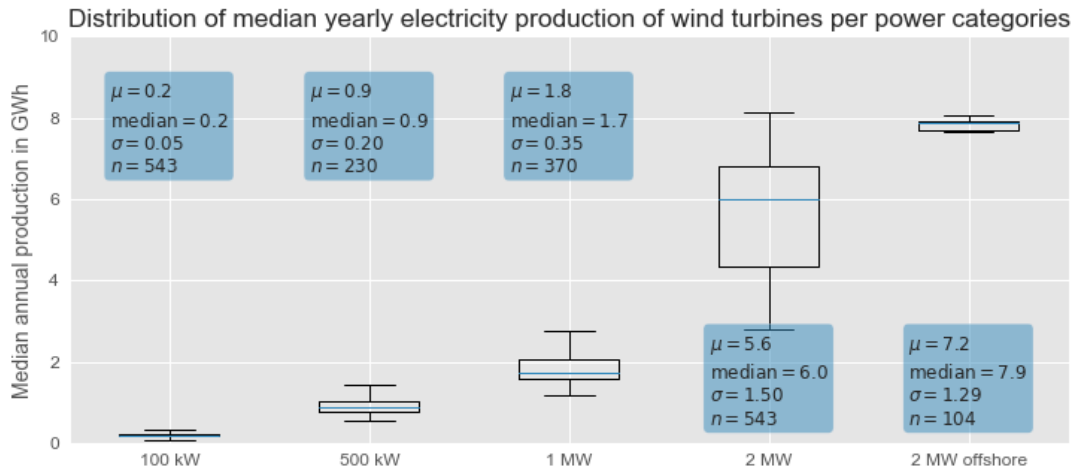
426 Figure 8 shows the sensitivity of parameters associated to the location of the wind turbine during the *use phase* (i.e.
427 during the electricity production phase) on the GHG emissions of the different wind turbine models contained in the 1-
428 MW set. All the models presented are manufactured in 2002 with a service time of 20 years and an annual electricity
429 production that equals their respective median registered production value, to reflect exclusively the influence of local
430 wind availability. As explained in section 2.3, the median value has been considered to exclude extreme non-
431 representative value such as the first year of production for a wind turbine installed in December. This allows for
432 keeping technological and temporal parameters fixed to assess the sensitivity of spatial parameters (the annual number
433 of hours of available wind at full load, essentially) on the results. The amount of electricity produced over the service
434 time of the wind turbine is influential on the GHG emissions per kWh produced, as depicted in Figure 8. The 90%
435 distribution interval is significantly spread for some wind turbine models.



436

437 *Figure 8: Dispersion of the GHG emissions per kWh produced due to the local wind availability for different wind turbine models*
 438 *manufactured in 2002.*

439 This is also confirmed by looking at the median yearly electricity production for the five sets of wind turbines, as shown
 440 in Figure 9. It can be seen that the 90% distribution interval of the 500-kW and 1-MW sets overlap. This indicates that a
 441 well-located 500 kW wind turbine can potentially produce as much as a 1-MW wind turbine for which the location has
 442 not been ideal. Moreover, the 90% distribution interval of the 2-MW set indicates that a well-located wind turbine may
 443 produce more than twice as much than a similar wind turbine not ideally located. It is worth noting that 2 MW onshore
 444 wind turbines with larger rotors generally produce more than 6 GWh/year with an average load factor of 38% compared
 445 to the 27% value for wind turbines with a rotor diameter lower or equal to 80 m. Using larger rotors enables capturing
 446 more kinetic energy from the moving air and producing more power at a given wind speed. Despite a higher impact
 447 caused by a heavier tower to support the larger rotor, the increase of the electricity output generally more than
 448 compensates the difference. However, while locations with optimal wind availability are ideal, they are usually limited
 449 within an area such as Denmark. Hence, placing wind turbines in sub-optimal locations still present an environmentally
 450 superior alternative to fossil-based energy technologies as it helps to improve the overall electricity supply mix.
 451 Usually, offshore locations benefit from a more stable and abundant wind resource, as illustrated in Figure 9. Although
 452 in this case, the narrowness of the distribution may also be partially explained by the fact that 80 of the 104 wind
 453 turbines are operated in the same wind farm. This section demonstrates that the electricity production can vary
 454 dramatically even between wind turbines of a same model sharing a similar power curve. It underlines the importance
 455 of the spatial parameters, notably the productivity (or capacity factor), in shaping electricity production and ultimately
 456 affecting the environmental performances of wind turbines.



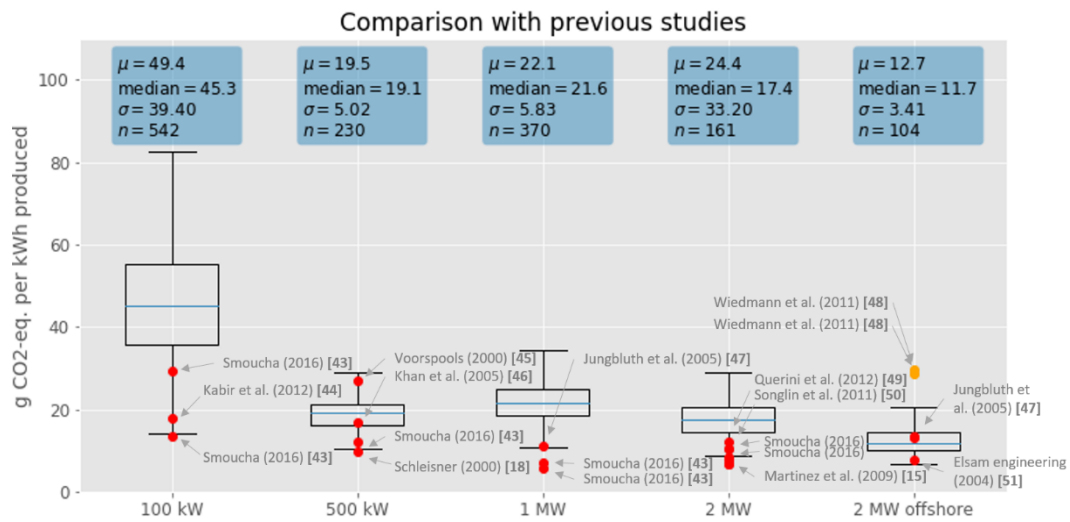
457

458 *Figure 9: Dispersion of median yearly electricity production of wind turbines per power categories. The blue horizontal*
 459 *line is the median value. Vertical rectangles represent 50% of the distribution. Vertical black intervals represent 90% of*
 460 *the distribution. Outlying values are computed but not displayed.*

461 Figure 4, located at the beginning of the results section presents four maps of the selection of wind turbines studied in
 462 this article associated to their carbon footprint per kWh produced. As pointed out throughout Sections 3.1 and 3.2, one
 463 may notice that wind turbines installed close to one another may not necessarily have similar corresponding GHG
 464 emissions per kWh as technology and time-related parameters probably have as much influence on the end-results as
 465 parameters related to location. It is important to understand that associating generic values to such parameters inevitably
 466 leads to incorrect results and may mislead the decision-maker. It is however certain that the worst-performing wind
 467 turbines emit less GHG than conventional fossil fuel-based technologies [9], aside from exceptional manufacture
 468 defects or accidents associated to extreme natural events (e.g. storms, lightning strike) that could shorten the service
 469 time of the wind turbine unexpectedly.

470 4 Comparison with previous studies

471 A review of existing studies on wind turbine systems is done considering both process-based LCA and hybridized forms
 472 of LCA to position the results obtained for the five sets of wind turbines, expressed as GHG emissions per kWh in
 473 Figure 10. The emissions dispersion intervals for the five sets of wind turbines are similar to what has been presented in
 474 Figure 5.b. As argued in the Introduction section, most LCA studies of wind turbine systems, and RES in general,
 475 cannot be fairly compared because of differing model-related assumptions, among others. Hence, this comparison is not
 476 an attempt to explain the difference between the results of this study and what has been published previously
 477 [15,18,51,43–50], but rather to confirm that they fall within acceptable ranges.



478

479

Figure 10 Comparison with previous studies expressed as GHG emissions per kWh

480

481 In Figure 10 two outliers for the 2 MW offshore turbines are worth discussing – see the orange dots. These values are
 482 more than twice the average GHG emissions per kWh obtained for the corresponding set of wind turbines. They are
 483 obtained by combining Multi-Regional Input-Output (MRIO) tables with process-based LCA, also called hybrid LCA.
 484 Such observation is coherent with the findings of Wiedmann et al. [48] who underlined that hybrid LCA for wind
 485 turbines return impacts that are consistently higher than those obtained with a purely process-based LCA approach. This
 486 seems to confirm here once again. The authors argued that process-based LCA may lead to truncate a significant part of
 487 the inventory and to ultimately underestimate emissions. However, the current resolution of most common MRIO can
 488 restrain the possibilities to distinguish specific materials within the inventory, limiting oneself to families of products.
 489 For example, low-alloy and stainless steel, two steel products extensively involved in the inventory of wind turbines,
 490 are two materials with significantly different environmental impacts (approximately 2 kgCO₂-eq./kg of low-alloy steel
 491 against 5 kgCO₂-eq./kg of stainless steel according to [38] using IPCC’s GWP100a characterization factors). Such
 492 MRIO as Exiobase v.3 [52] would treat both steel products indifferently as “*Basic iron and steel and of ferro-alloys and*
 493 *first products thereof*”. It is therefore not hard to imagine that what is gained in completeness could potentially be lost
 494 as increased inaccuracy due to the coarse resolution of the MRIO data. Nevertheless, the use of a hybrid approach based
 495 on MRIO could add completeness to the present method and should be considered a potential direction for future
 496 research.

497

498 5 Conclusion

499 This study highlights the importance of considering the variability and uncertainty induced by parameters of
500 technological, spatial and temporal nature in LCA models of RES in general, illustrated with a significant sample of
501 wind turbines in Denmark. Great variability in results has been found within sets of wind turbines with a similar
502 nominal power output. Looking at the causes of such variability, diversity of designs (material intensity), intended
503 applications (onshore and offshore use), wind availability, service time and the year of manufacture have a major
504 influence on the environmental performances of wind turbines. Instead of generic models provided by common LCI
505 databases or EPD, one should welcome more complex parameterized inventories that embrace technological,
506 geographical and temporal variability, limit uncertainty and allow the comparison of different models on equal grounds.
507 If LCA is to gain in precision for assessing potential wind turbine farms, there is a need in the future for models that
508 generate LCI tailored to specific projects. They would ideally allow including the specificities associated to the wind
509 turbine models considered and the context and location of use.

510 Access to such parameterized models would support better-informed decisions as wind power cannot be reduced to one
511 single wind turbine installed in generic conditions. It would also produce a more accurate reporting of GHG emissions
512 associated to wind power generation in general. At the national level, there is a need for developing nation-wide wind
513 turbine fleet inventories to improve the environmental assessment of electrical systems with a high share of renewable
514 energy. It is precisely the purpose of LCA_WIND_DK, an online LCA tool under development that will rely on the
515 parameterized model presented in this study to provide detailed environmental statistics on all past, current and future
516 wind turbines in Denmark.

517 Such methodology developed along the four-step sequence could be applied, for example, to other RES and/or to other
518 areas at regional and national level. Finally, the approach seems suitable for a large range of energy systems, especially
519 for RES for which most of the material and energy requirements occur during the *manufacture* and *installation* phases:
520 photovoltaic panels, geothermal heat pumps, tidal and wave energy converters.

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525 the LCA framework used in this study.

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