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1	Waste and Material Flow Analysis
2	in the End-of-Life Wind Energy System
3	
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16 Abstract

17 In the specific case of French onshore wind farms, waste management of these systems has become an important factor of the wind energy industry's sustainability. The aim of this paper 18 is to quantify wind turbine (WT) material wastes and flows across the Champagne-Ardenne 19 (CA) region from 2002 to 2020. To do so, a material flow analysis (MFA) model was used. It 20 included three maintenance strategies used for onshore wind turbines. Results show that more 21 22 than 1 million tons of material will ultimately be generated at the EoL of CA wind farms. The main EoL materials are ferrous and non-ferrous metals, polymers, glass and concrete. The 23 main EoL materials are ferrous and non-ferrous metals, polymers, glass and concrete. In this 24 total, blades and composite EoL materials that need to be managed, account for more than 25 26 27,000 tons; there are 523,227 tons of steel and iron materials that need to be handled; 6,617 tons of copper, and 28,179 tons of aluminum flows. Landfill concrete accounts for 734,230 27 tons. When the concrete in foundation is not considered, 73% of an average wind turbine can 28

be recycled. With the first generation of WT reaching their EoL phase and taking into account
that no dismantling or recycling facilities of WT components have emerged in the French
territory, the potential of WT wastes available for treatment (recycle, incinerate, landfill etc.)
is still increasing.

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Keywords: wind energy, material flow analysis, End of Life, wind turbine wastes,
maintenance, recycling.

36

Abbreviations: Champagne-Ardenne (CA); Wind turbine (WT); End of life (EoL); Material
Flow Analysis (MFA)

39 Introduction

Wind energy has become one of the most promising and economically feasible sources of 40 41 renewable energy [1]. It is one of the fastest growing sources of renewable electricity in France and Europe, it represents 52% of renewable energy investments (including offshore 42 wind energy) with more than 42 billion € [2]. In 2017, there were ~15,680 MW of additional 43 44 wind energy facilities in Europe and more than 640 MW decommissioned wind farms [3]. Thus, end of life (EoL) wastes and material flows management, as well as environmental 45 impacts, have evolved as an emerging challenge of the wind energy industry. For instance, 46 blades, which are commonly made from glass or carbon fibers, cannot be recycled (used as a 47 substitute for raw materials). In addition, there are still issues regarding the EoL treatment of 48 49 concrete. For instance, in France, the ICPE reform [4] established the restoration guidelines of wind farm sites after the dismantling of their turbines. This measure includes the removal of 50 site components and a limited excavation of foundations. Thus, according to the size of the 51 52 wind turbine, a 30 cm to 2-meter depth of foundations has to be replaced by farm land. Nonremoved concrete is left on site and the excavated concrete is disposed of elsewhere. Moreover, wind farms are generally located in sites that are distant from main roads or dismantling and recycling facilities, which makes logistics and dismantling costs higher. Therefore, ways need to be found to maintain the tempo of wind energy systems' progress and improve its sustainability.

There have recently been several studies on environmental impacts of wind energy 58 59 technologies. Industrial companies, such as Vestas corp. published case studies about their wind turbines, these studies assessed the environmental impacts of wind farms and are mainly 60 based on life cycle assessment (LCA). Some of these studies are available in [5] [6] [7]. 61 62 Moreover, Arvensen and Hertwich in [8] assessed the life cycle environmental impacts of wind turbines and discussed the main variations in the reviewed literature. Haapala and 63 Prempreeda in [9] presented comparative life cycle environmental impacts of two 2.0 MW 64 wind turbines. Other studies in literature are also based on LCA when assessing the 65 sustainability of wind turbine technologies [10] [11] [12]. These studies used different 66 67 versions of LCA and assessed different technologies of wind turbines. LCA results may also differ from one study to another according to the assumptions made during the life cycle of 68 the system [13]. For instance, it can be seen that maintenance assumptions in these studies are 69 70 limited, and were only based on manufacturer's data. Furthermore, EoL issues raised in the LCA state of art method are limited. Indeed, only EoL environmental impacts were 71 considered in previous studies and material stocks and flows were not taken into account, nor 72 their chronological availability for treatment. Besides, the previous studies cover only single 73 wind energy systems and do not assess the global environmental impact of regional or 74 national wind energy systems. Consequently, they did not consider wastes and flows 75 accounting for territorial wind energy systems. We will therefore address this issue in the 76 77 present paper.

To do so, a material flow analysis (MFA) is adopted in this study for accounting and assessingEoL wastes and flows.

80 MFA is an analytical tool useful for quantifying flows, stocks and substances [14], it is also 81 helpful in supporting environmental policies [15] [16]. MFA has been widely used as an 82 environmental tool for EoL and waste resources management. For instance, Vadoudi et al. [17] used products and MFA to assess electronic waste management. Kim et al. in [18] also 83 84 used same method to assess hydrogen fluoride in domestic chemical industries. Liu et al. [19] showed that aluminum stocks and flows set critical boundary conditions for future emission 85 pathways. MFA was also used to assess wastes and flows in several processes [20] [21] [22] 86 87 [23] [24] [25] [26] [27] [28] [29] and cities (York) [30]. It was also used in wind energy systems to assess critical materials such as Dysprosium [31], Neodymium-iron-boron used in 88 wind turbine magnets [32] and blade wastes [33] [34]. In these last sudies, Liu & Barlow and 89 Ma et al. showed that global annual blade waste would reach up to 2.9 Mt by 2050. Other 90 valuable materials used in wind energy, such as silver and gold, were also assessed by Kim et 91 92 al. [35]. Zimmerman et al. conducted in [36] an MFA resulting from large scale deployment of wind energy in Germany. In this study, the authors considered a wind turbine lifetime of 20 93 years, as well as gearless technologies [37], these WT are common in Germany. 94

95 However, this last state-of-art on using MFA in wind energy did not discuss either the lifetime 96 or maintenance scenarios adopted for these systems. Thus, this can result in an incomplete 97 understanding of wind turbine EoL material flows, which, in turn, could alter the efforts made 98 to enhance the sustainability of wind turbines. Finally, it is necessary to assess waste flows 99 from different lifecycle stages.

100 The aim of this paper, therefore, is to quantify all wastes and flows, including maintenance 101 inputs, taking into account EoL issues. The flows for all Champagne-Ardenne (CA) wind 102 turbines installed from 2002 to 2016 were taken into account. In fact, this study focuses on a regional case study of CA, the windiest French region (wind class I locations) [38] [39].
French wind energy systems have undergone rapid expansion to meet the 2020 and 2050
renewable energy targets [2]. In France, onshore wind energy accounts for more than 12 GW
of installed capacity, with more than 20% of this capacity concentrated in the 4 counties
(Aube, Marne, H. Marne and Ardennes) of CA region [38] [39].

This rapid deployment of wind energy in CA [40] is supported by regional and national tax incentives. It also involves significant material flows and stocks, including materials from wind farm subsystems and cables connected to the grid. Our approach is based on CA regional energy plans, which state that these flows are likely to continue at the same rate until 2020 [40]. However, to the best of our knowledge, no public studies have previously been made to quantify wind energy material flows and wastes in France nor in CA.

This paper is presented as follows: section "Data and methods" presents the collected data and methodology used to calculate the EoL materials generated by the CA wind farms. Section "Results and Discussion" shows results generated by the MFA methodology. We end with a conclusion, general remarks and future works.

118

Data and methods

120 1) Wind energy systems of Champagne-Ardenne (CA) region in France

The Champagne-Ardenne (CA) region is the windiest region in France [41], it also contains a large variety of installed wind turbine sizes and capacities. Within this region, Marne county has 413 installed (working) wind turbines, followed by Aube county with 319 installed wind turbines, then Ardennes and H. Marne with 208 and 145 installed wind turbines, respectively. The main installed wind energy technology is geared wind turbines and the most common models are Senvion (MM92), Vestas (V90-V100) and Nordex (N90-N100). The authors combined data from [38] [39] [41] to quantify all wind farms installed in CA.
this data is presented in Table 1, this region has more than 1000 wind turbines installed from
2002 to 2016. National and regional policies allowed this rapid deployment over the period.

Table 1. Installed wind turbines (WT) in CA from 2006 to 2016, data extracted from [38]

131

[39] [41]

County: Ardennes (5 220 km ²)			County: Auba (6.004 km^2)		County: Marma (8, 160 km²)		County:				
Year	WT number	Σ Capacity (MW)	Year	WT number	Σ Capacity (MW)	Year	WT number	Σ Capacity (MW)	Year	WT number	Σ Capacity (MW)
2002	-	-	2002	-	-	2002	1	1.50	2002	-	-
2003	-	-	2003	-	-	2003	-	-	2003	-	-
2004	-	-	2004	-	-	2004	-	-	2004	-	-
2005	-	-	2005	6	12.00	2005	54	57.70	2005	-	-
2006	-	-	2006	12	6.00	2006	12	21.00	2006	-	-
2007	-	-	2007	24	48.00	2007	22	29.50	2007	-	-
2008	3	6.90	2008	-	-	2008	17	37.52	2008	6	12.00
2009	16	32.00	2009	43	92.40	2009	-	-	2009	14	24.30
2010	32	64.00	2010	48	97.50	2010	47	109.70	2010	103	209.95
2011	19	38.95	2011	17	34.00	2011	18	45.00	2011	-	-
2012	6	18.00	2012	57	128.65	2012	23	46.00	2012	6	12.00
2013	41	103.50	2013	6	12.30	2013	16	32.30	2013	-	-
2014	21	46.45	2014	15	31.95	2014	74	150.55	2014	10	20.00
2015	32	65.20	2015	46	112.10	2015	47	107.15	2015	6	12.00
2016	38	76.00	2016	45	120.95	2016	82	185.95	2016	-	-
Total	208	451	Total	319	695,85	Total	413	823,87	Total	145	290,25

132

When considering wind turbine capacities, we can see that these vary from 0.8 MW to 3.2 MW over the period of data extraction of Table 1. Moreover, as seen in Figure 1, wind turbines with a capacity between 2 MW and 2.5 MW represent more than 75% of the total installed wind turbines over the studied period. The main reason is that this range of wind turbines are the most commercially available [2], they also have a grid code that fits most countries.



Figure 1. Capacity of wind turbines (WT) installed in CA

In addition, most wind turbines in the region are geared wind turbines. Gearless wind turbines represent less than 10% of the total. Thus, geared configuration will be chosen as the main configuration in the present study. Gearless wind turbines flows will be presented separately (see supporting information document) and only blade replacement will be considered for this technology.

- 146 2) Material consumption of studied wind turbines
- 147 When assessing all installed wind turbines, and taking into account industrial and scientific
- data [5] [6] [7] [10] [39] [41] [42], the following list of materials that constitute wind turbines,
- and the assumptions considered in this study are presented in Table 2.
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Table 2. Material assumptions

Materials	Assumptions
Steel and iron materials	Including all types of steel and cast iron. If the wind turbine ferrous material is unknown, it will be considered to be made from iron

Aluminum	10% of this material is not recyclable. It will go to landfill.
Copper	EoL assumptions about this material category consider that only 90% of copper will be recycled, the rest will be sent to landfill [5] [6] [7]
Polymer materials (plastics)	Includes all thermoplastic and thermosetting resins.
Lacquers, adhesives and sealants	Includes all materials used in gluing and polishing processes
Glass and ceramic	It is assumed in this study that all the wind turbines' blades, hubs and nacelles are made from fiberglass
Concrete	Concrete is either disposed on site or in landfill elsewhere in France. We consider in this study that all concrete will be disposed on site
Electronics	This category contains all electronics, electrics and magnets (e.g. printed circuit board and information)
Lubricants and coolant	All flows used in operation and maintenance activities

All these material deposits will be assessed for the studied wind turbines. In addition, to 153 154 reflect reality, other wind farm subsystems, such as cables and site switchgear, were incorporated in this study. In fact, at the end of life of the wind farm project all these 155 subsystems are dismantled so that the site is returned to its original state. Table 3 presents an 156 157 example of material quantities for a wind farm containing one WT (example of 2MW WT, material in tons). It is based on combined data from Table 1, material consumptions were 158 extracted from available LCAs [5] [6] [7] [10] [37] [43]. If data of a specific wind turbine 159 160 size or technology were not available, extrapolation to the nearest size was considered using cross multiplication rules. For 2MW wind turbines, Vestas turbine's material breakdown was 161 selected since it represents the most frequent size and technology installed in CA region. 162

Materials	Turbine	Foundation	Site cable	Site switchgear
Steel and Iron Materials	205.32	38.28	0.00	0.20
Al	4.20	0.00	22.20	0.00
Cu	1.68	0.04	4.40	0.08
Polymer materials	10.44	0.12	40.6	0.00
Lacquers-adhesives-sealants	0.28	0.00	0.00	0.00
Glass-ceramic	19.08	0.00	0.04	0.00
Concrete	0.00	750.88	0.00	0.00
Electronics (Electronics-Electrics-Magnets)	2.40	0.00	0.00	0.00
Lubricants	0.68	0.00	0.00	0.00
Coolant	0.16	0.00	0.00	0.00

164 Table 3. Example of Vestas 2MW wind turbine material consumption (materials in tons) [6]

166 3) Wind turbine service

Wind turbines are designed, in general, for a lifetime of 20-25 years. A lifetime duration of 20 167 years is often considered by wind turbine manufacturers [5] [43], or in scientific literature 168 [32]. Another study by O'Sullivan [44] showed that Danish wind turbine technologies lifetime 169 170 follows a lognormal distribution with a mean of 15 years. This distribution is presented in Figure 2. In France, where the economic lifetime is considered more than the technological 171 one, wind turbines are generally decommissioned when the feed-in tariff contract expires 172 [45]. In this feed-in tariff contract [45], the lifetime clause is up to 15 years. Furthermore, 173 according to our exchanges with CA wind farm managers, it will not be economically feasible 174 to pursue the operation of the wind farm after the feed-in tariff contract expires. Thus, the 175 most likely and economically feasible scenario after 15 years of operation is to dismantle the 176 wind farm and probably repower it. Thus, it can be considered that the above-mentioned 177 Danish and French sources for wind turbine lifetime duration are equivalent. 178

163

Lifetime distribution of historically decommissioned WT



179

180 Figure 2. Lifetime distribution of Danish decommissioned wind turbines (WT) [44]

181 To resume, a 15-year lifetime was considered for CA wind turbines in this paper, this lifetime182 is equal to the feed-in tariff contract duration [45].

183 In addition, three types of maintenance scenarios were introduced to include wastes from operation and maintenance activities. The maintenance scenarios are spread over the wind 184 turbine lifetime and are defined considering wind turbine manufacturers [6], reliability 185 assessment of wind turbines subsystems [46] [47], and recent studies about components EoL 186 [33] [48]. The objective of considering three maintenance strategies is in order to be as 187 accurate as possible when dealing when maintenance flows, compared to previous studies [6] 188 [33] [36] [48]. These scenarios were listed according to the quantity of materials used in 189 maintenance activities. Thus, we consider three levels of maintenance strategies: (i) low, (ii) 190 medium and (iii) high. 191

(i) Low scenario (Reliability assessment of wind turbines subsystems): wind turbines
 critical subsystems rarely achieve their reliable lifetime interval [15; 20 years], they
 are replaced several times during the lifetime of the wind farm. According to

reliability assessment studies of wind energy systems [46] [47], gearbox and blades are the wind turbine's subsystems that frequently fail. Statistical data showed that 5% of the total population of wind turbines get a gearbox replacement over their lifetime, and 3% of the total wind turbines get a blade replacement as well.

(ii) Medium scenario (Wind turbine manufacturers): it is generally considered that
 either the gearbox or the generator, and one blade is completely replaced once during
 the wind turbine lifetime. LCA studies [5] [6] [7] [43] take into account one gearbox
 and one blade replacement during the wind turbine lifetime, assuming that the gearbox
 is generally heavier than the wind turbine generator [7]. It is also assumed in these
 studies that the wind turbine gearbox represents 40% of total steel and iron in the

206 (iii) High scenario (recent studies about wind turbines subsystems EoL): Other studies in literature deal with specific turbine components replacement & EoL scenarios. The 207 main studies focused on gearbox replacement, since that represents a critical 208 component of wind turbines, and also considered blades, since their EoL scenarios 209 represent uncertainties about recycling their materials. Thus, Ragheb et al. [48] 210 assumed that gearbox is replaced on average 3 times over the total wind turbine 211 lifetime. Gearboxes are observed to fail within an operational period of 5 years and 212 their failure rates are one of the most critical among wind turbines subsystems. 213 214 Similarly, Liu and Barlow in [33] conducted a study about wind turbine blade waste over its lifetime. In this study, blade waste is distributed over routine maintenance, 215 accident repairs and blade upgrades after the first decade of operation. These flows 216 217 represent 0.146 of the total blade weight. Thus, only gearbox and blade replacements were taken into account in this scenario over the turbine lifetime, which represent 3 218 gearbox replacements and 14.6% of a blade replacement. 219

220 Maintenance scenarios are summarized in Table 4. As for gearless wind turbines, only blade

221 replacements were considered.

222

Table 4. Maintenance scenarios of wind turbines (WT) considered in this paper

Maintenance Scenario	Gearbox replacement	1*Blade replacement
(i) (low)	5% of total WT installed	3 % of total WT installed
(ii) (medium)	1 time over WT lifetime	1 time over WT lifetime
(iii) (high)	3 times over WT lifetime	0.146 time over WT lifetime

223

4) EOL and material treatment assumptions

At the end of service of all CA wind turbines, these facilities are dismantled and the land they 225 occupied is restored according to the ICPE reform (facilities classified in view of protecting 226 227 the environment-translated from French "Installations Classées pour la Protection de l'Environnement") [4]. Thus, used wind turbine components are not renovated or reinjected 228 in the present or future wind farms in the area. Thus, these components are either recycled, 229 incinerated, or sent to landfill. According to [5] [6] [7] [10], 90% of the ferrous and non-230 ferrous materials from wind turbines are collected and recycled. The last 10% are sent to 231 landfill. Up to 50% of other materials such as polymer materials and fiber glass are 232 incinerated [43]. In fact, plastic and composite wastes are difficult to manage, and the 233 composite and polymer separation process are often expensive in time, money and 234 environmental impact. Lubricants and coolants are generally used to feed concrete industry 235 furnaces. Other materials such as concrete are assumed to be sent to landfill sites. Table 5 236 resumes EoL material treatment assumptions considered in this paper. 237

238

Table 5. EoL assumptions based on the literature [5] [6] [7] [10] [43]

Materials	Treatment
Steel	90% recycled + 10 % landfill
Al	90% recycled + 10 % landfill
Cu	90% recycled + 10 % landfill

Polymer materials	50% incinerated + 50% landfill
Lubricants	100% incinerated
All other materials (including concrete)	100% landfill

Nowadays, some new studies consider a better rate of recycling for concrete, polymer materials and composites. For instance, Andersen et al. in [49] consider another scenario based on the authors' analysis of information from companies. In this scenario [49], blades are either disposed for recycling or landfilling with a recycling/disposal rate of 95%. In the same study, up to 64% of concrete is landfilled, the rest is used as filling material. Fox in [50] studied the feasibility of recycling blade composite material as an aggregate in concrete. However, these scenarios are still experimental and not applied in France.

Another assumption made in this study is the non-consideration of waste flows from the manufacturing and logistic processes, since they are negligible compared to operation, maintenance and EoL wastes. Below, the software tool used to conduct the MFA study is presented.

251 5) MFA and flow mapping

MFA is often used as a concept of building stock models in a specific location during a certain period of time. It operates on the principle of physical balance, which comes from the first law of thermodynamics on matter (and energy) conservation. By applying this principle to a specific location during a certain period of time, we obtain the following equation (1):

256
$$\sum_{i=1}^{n_{input}} f_i = \sum_{o=1}^{n_{output}} f_o + \sum_{s=1}^{n_{stock}} f_s$$
(1)

Where "{i,o,s}" are the input, output and stock flows respectively and "f" represents the flow or flux. MFA can be used for different systems, flows and matters. It is the systematic reconstruction of an element through its life cycle [51]. For instance, Kytzia [52] used this MFA as a tool for sustainable management of the built environement. In this study, material,

energy and money flows were represented. Bertram et al. [53] modeled aliminium stocks and 261 262 flows using a dynamic MFA. Agamuthu et al. [54] assessed e-waste flows and their EoL in universities. The main results generated were the in-house recycling and disposal flows and 263 stocks. Klinglmair et al. in [55] showed how assumptions and choices made by practitioners 264 can influence regional MFA regional results. Makarichi et al. in [56] used a combined MFA 265 and a multi-criteria decision analysis model for waste management decision making. This 266 combination also showed the effectiveness of MFA as a tool for assessing waste management 267 systems. In fact, it allows us to retrace wastes and emissions to their generation points. It can 268 thus be linked to life cycle assessment by identifying weak points and inefficiencies in all the 269 elements' life stages. This link also allows us to set priorities, and define strategies to 270 minimize wastes and emissions. 271

In this paper, the MFA describes wind farms of the CA region installed from 2002 to 2016. In each case presented, flows (in tons) are injected either into the CA region or into one of its 4 counties (Ardennes, Aube, Marne and H. Marne).

In order to estimate and map all wind turbine materials of the CA region, a software tool "STAN" (substance flow analysis) was used [57]. The used software supports the performance of MFA using fluid graphical modelling tools.

278 **Results and Discussion**

When grouping data from CA wind farms from 2002 to 2016, a figure of more than 1 million
tons of embodied materials can be reached. These materials are spread over the 4 CA counties
as follows (see Table 6).

282

Table 6. Total mass embodied from all wind turbines installed in the CA region

IFOM 2002 to 2016

Ardennes	282,013
Aube	404,435
Marne	487,369
H. Marne	157,454
TOTAL	1,331,271

As seen in Table 6, the Aube and Marne counties account for more than 80% (about 890,000 284 285 tons) of the total quantity of materials mobilized for CA wind farms. Taking into account the 286 lifetime expectancy of installed wind farms since 2002, currently no wind farm in the region has so far been dismantled. Thus, we are looking at an overview of the quantity of wastes that 287 this region will need to manage. Moreover, as seen in Table 1, 230 wind turbines were 288 installed as late as 2010. This was the year with the highest installation rate. The turbines are 289 expected to operate for 15 years (feed-in tariff contracts) and to be dismantled in 2025. The 290 next section deals with the future EoL of the 2010 wind turbines. 291

292 1) 2010 wind farms EoL

In CA region, 2010 was the year where 230 wind turbines were installed. Thus, when injecting these wind turbines' materials and considering the previous maintenance scenarios, one can predict the main flows of 2025 wastes as presented in Table 7 (medium scenario case):

297

Table 7. 2025 EoL flows from 2010 installed wind turbines (using the medium case scenario)

Matarials	Medium scenario case			
Waterials	Recycling	Incineration	Landfill	
Steel and iron	70.046	0	7 792	
materials	70,040	0	7,785	
Concrete	0	0	194,547	
Al	4,968	0	552	
Cu	1,392	0	152	
Polymer materials (plastics)	0	5,321	5,321	

	Glass	0	3,076	3,076
299				unit: tons

As seen in Table 7, EoL materials are categorized into 3 possible scenarios: recycling; incineration, and landfilling. From the 2010 wind turbines' materials, recycling and landfilling flows were the highest. This is mainly explained by the high rate of ferrous and non-ferrous materials recycling (up to 90% of materials are recycled). Landfill flows are 211,431 tons, including 194,547 tons of concrete. The other maintenance scenarios are provided in supplementary materials (supporting information document).

When incorporating this data into STAN software, one can get the total flows of wind turbine materials and their EoL issues. Figure 3 represents the MFA flows of 2010 wind turbines EoL, taking into account the first maintenance scenario (low case scenario).



309



Results presented in Figure 3 show that the recycling potential of 2010 wind turbines is up to 312 59,500 tons, and the landfill materials 208,800 tons. The H. Marne county regroups the 313 biggest share of potential EoL material wastes generated in 2025. Besides, the output flows 314 are equivalent to the input flows (county flow + maintenance flow) since the conservation of 315 mass has to be respected in the MFA. In this figure, wind turbine material flows are 316 incorporated into input and maintenance flows for every county. Then, after a service time of 317 15 years, the wind turbine is dismantled and materials are distributed over recycling, 318 incineration and landfill EoL scenarios. Figure 4 shows detailed information about each 319 material flow. 320



Figure 4. Flows generated for 2010 installed wind turbines under the highest maintenance
scenario (with material specifications), flows in tons.

Figure 4 shows the main materials mobilized for the 2010 wind farms. Concrete and steel represent the highest fractions of these flows (194,547 and 118,397 tons, respectively). The next section presents more generalized results about wind turbines' material wastes and flows. 327 2) Waste chronology of 2002-2016 installed wind turbines.

In this section, all installed wind turbines in the CA region from 2002 to 2016 were 328 considered. Figure 5 presents a summary of the chronological flows for the 4 counties of CA 329 under maintenance scenario (iii). In figure 5, wind turbine materials were generated from 330 2002 until 2016. With 15 years of wind turbine operations, the first material flow outputs are 331 generated from 2018. Positive histograms are the cumulative recycled and incinerated 332 materials, respectively, whereas negative histograms represent material flows from 333 landfilling. Figure 5 also shows a peak of input and output material flows generated in 2010 334 and 2025, respectively. These peaks are related to the high installation rate of wind turbines 335 during 2010 and their subsequent EoL management in 2025. 336



338Figure 5. Chronological EoL flow materials generated in CA region under the high

339

maintenance scenario case

The same results are generated with a focus on wind turbine materials, and taking into account other maintenance scenarios (see supplementary data in the *online supporting information*). These results could also be generated for every individual wind farm location in the CA region, which could eventually lead to an optimization of recycling or disassemblingfactories under constraints of logistic or environmental costs.

However, this study does have some limitations. In fact, no precise future set ups were 345 346 considered. One of the main reasons behind this is that the CA region is becoming more and more saturated, and most windy locations have already been identified and used. Figure 6 347 represents two scenarios for future trends of wind turbine installations. These future scenarios 348 349 are: (i) a high trend scenario that assumes the extension of the linear distribution of installed turbines during previous years; (ii) a low trend scenario that represents available data from the 350 regional department of the promotion of wind energy [40]. The Chronological EoL flow 351 352 materials generated using these two trend scenarios is presented in the "online supporting information". It should be noted that it was assumed that all stock and flows generated from 353 maintenance activities during the wind turbine lifetime remain in stock, and are not processed 354 until the end of 15 years of operation. This assumption cannot always be true, since stock and 355 deposit management can be expensive and space consuming. However, it can produce a cost 356 357 optimization as well, since wind farms are generally located far from each other.





Figure 6. Future trends of wind turbine installation

360 Conclusion

361 In this paper, a material flow analysis (MFA) was conducted for the Champagne-Ardenne (CA) wind farms region. The study quantified all end of life (EoL) material flows from 2002 362 to 2016, with an extension of installed wind farms according to regional energy plans until 363 2020. The present study considers the French wind turbine's economic lifetime (15 years). 364 The main results showed that, taking into account the highest maintenance scenario, more 365 than 1,614,216 tons of EoL materials would be generated from 2002 to 2016 installed wind 366 turbines. These flows are distributed inter-alia as following: 556,830.5 tons of steel and iron 367 materials; 25,602 tons of aluminum; 7,480 tons of copper; 49,290 tons of polymer materials 368 (plastics); 268 tons of lacquers and adhesives; 23,233 tons of glass and composite, and 369 948,389 tons of concrete. CA wind turbines represent more than 20% of all French onshore 370 wind farms. Since this region welcomed the first wind turbines installed in France, it will be 371 the first to face the problem of wind farms EoL. Thus, considering the wind turbine 372

population in France (without the concrete of the foundation), 73% of the wind turbine isrecyclable and 10% of the total material goes for incineration.

This paper has also analyzed and provided the amount of future EoL wind turbine materials 375 until 2035. However, it has several limitations. The main limit concerns the French wind 376 turbine's lifetime (considered equal to 15 years). In fact, we consider that the lifetime of the 377 turbine is equal to the feed-in tariff contract duration. Even if this assumption is quite specific 378 to the French wind industry case, this assumption needs to be overcome and a French wind 379 turbine lifetime distribution should be explored. The second limit is about the non-380 consideration of scarce materials. The present analysis should be extended in order to take 381 382 into account rare earth materials. The last limitation concerns the recyclability rate of materials. It was assumed in this study, for instance, that 90% of ferrous and non-ferrous 383 materials will be collected and recycled, which an assumption is taken from LCA studies. 384 Since the objective of this paper is to provide accurate data of the potential wind farms 385 wastes, more effective EoL assumptions will need to be explored in order to evaluate the 386 quantities of materials available for recycling, rather than what is actually recycled. To do so, 387 a first investigation about the quality and type of wind turbine materials should be carried out 388 in order to assess their recyclability rate. 389

Having quantified the amount of wind energy wastes in the CA region, the next steps of the current study are to generalize it to the whole French territory, and develop an optimization algorithm for dismantling and recycling facilities for French wind energy. This future work should also take into account maintenance and EoL uncertainties, and will be based on a geographic information system to localize all input and output flows and wastes. Finally, EoL options such as reuse of materials or repowering will be also explored.

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402

Graphical Abstract

