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Waste and Material Flow Analysis in the End-of-Life Wind Energy System

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Abstract

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 is to quantify wind turbine (WT) material wastes and flows across the Champagne-Ardenne (CA) region from 2002 to 2020. To do so, a material flow analysis (MFA) model was used. It included three maintenance strategies used for onshore wind turbines. Results show that more 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. In this total, blades and composite EoL materials that need to be managed, account for more than 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 tons. When the concrete in foundation is not considered, 73% of an average wind turbine can

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

33

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

36

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

39 **Introduction**

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

53 removed concrete is left on site and the excavated concrete is disposed of elsewhere.
54 Moreover, wind farms are generally located in sites that are distant from main roads or
55 dismantling and recycling facilities, which makes logistics and dismantling costs higher.
56 Therefore, ways need to be found to maintain the tempo of wind energy systems' progress
57 and improve its sustainability.

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

78 To do so, a material flow analysis (MFA) is adopted in this study for accounting and assessing
79 EoL 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.
83 [17] used products and MFA to assess electronic waste management. Kim et al. in [18] also
84 used same method to assess hydrogen fluoride in domestic chemical industries. Liu et al. [19]
85 showed that aluminum stocks and flows set critical boundary conditions for future emission
86 pathways. **MFA was also used to assess wastes and flows in several processes [20] [21] [22]**
87 **[23] [24] [25] [26] [27] [28] [29] and cities (York) [30]**. It was also used in wind energy
88 systems to assess critical materials such as Dysprosium [31], Neodymium-iron-boron used in
89 wind turbine magnets [32] and blade wastes [33] [34]. In these last studies, Liu & Barlow and
90 Ma et al. showed that global annual blade waste would reach up to 2.9 Mt by 2050. Other
91 valuable materials used in wind energy, such as silver and gold, were also assessed by Kim et
92 al. [35]. Zimmerman et al. conducted in [36] an MFA resulting from large scale deployment
93 of wind energy in Germany. In this study, the authors considered a wind turbine lifetime of 20
94 years, as well as gearless technologies [37], these WT are common in Germany.

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

103 regional case study of CA, the windiest French region (wind class I locations) [38] [39].
104 French wind energy systems have undergone rapid expansion to meet the 2020 and 2050
105 renewable energy targets [2]. In France, onshore wind energy accounts for more than 12 GW
106 of installed capacity, with more than 20% of this capacity concentrated in the 4 counties
107 (Aube, Marne, H. Marne and Ardennes) of CA region [38] [39].

108 This rapid deployment of wind energy in CA [40] is supported by regional and national tax
109 incentives. It also involves significant material flows and stocks, including materials from
110 wind farm subsystems and cables connected to the grid. Our approach is based on CA
111 regional energy plans, which state that these flows are likely to continue at the same rate until
112 2020 [40]. However, to the best of our knowledge, no public studies have previously been
113 made to quantify wind energy material flows and wastes in France nor in CA.

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

118

119 **Data and methods**

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

121 The Champagne-Ardenne (CA) region is the windiest region in France [41], it also contains a
122 large variety of installed wind turbine sizes and capacities. Within this region, Marne county
123 has 413 installed (working) wind turbines, followed by Aube county with 319 installed wind
124 turbines, then Ardennes and H. Marne with 208 and 145 installed wind turbines, respectively.

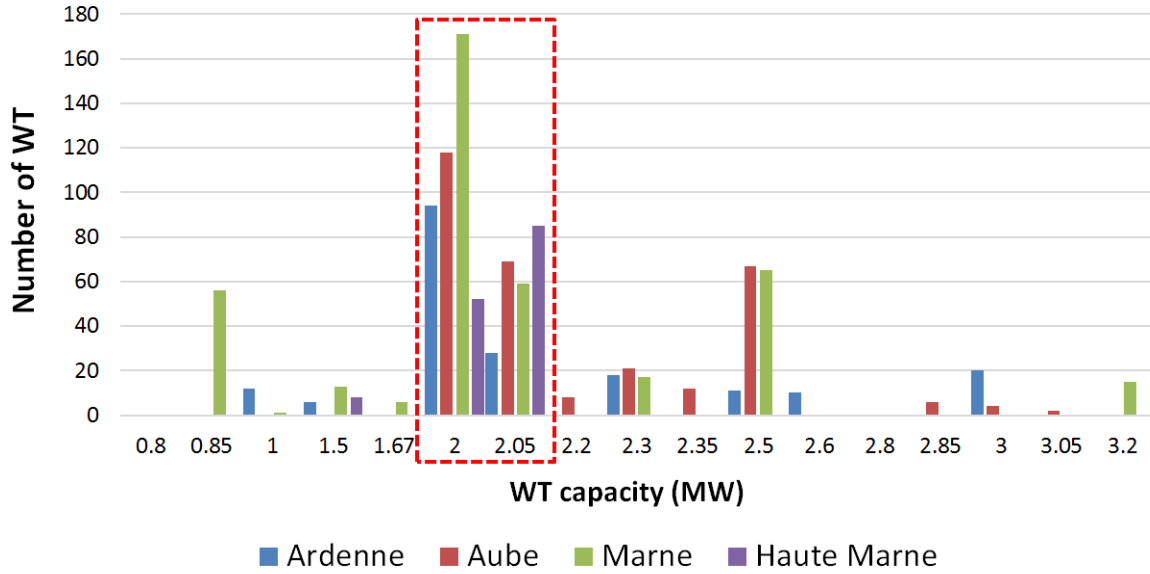
125 The main installed wind energy technology is geared wind turbines and the most common
126 models are Senvion (MM92), Vestas (V90-V100) and Nordex (N90-N100).

127 The authors combined data from [38] [39] [41] to quantify all wind farms installed in CA.
 128 this data is presented in Table 1, this region has more than 1000 wind turbines installed from
 129 2002 to 2016. National and regional policies allowed this rapid deployment over the period.

130 Table 1. Installed wind turbines (WT) in CA from 2006 to 2016, data extracted from [38]
 131 [39] [41]

County: Ardennes (5,229 km ²)			County: Aube (6,004 km ²)			County: Marne (8,169 km ²)			County: H. Marne (6,211 km ²)		
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
 133 When considering wind turbine capacities, we can see that these vary from 0.8 MW to 3.2
 134 MW over the period of data extraction of Table 1. Moreover, as seen in Figure 1, wind
 135 turbines with a capacity between 2 MW and 2.5 MW represent more than 75% of the total
 136 installed wind turbines over the studied period. The main reason is that this range of wind
 137 turbines are the most commercially available [2], they also have a grid code that fits most
 138 countries.



139

140

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

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

146 2) Material consumption of studied wind turbines

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

150

151

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

152

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

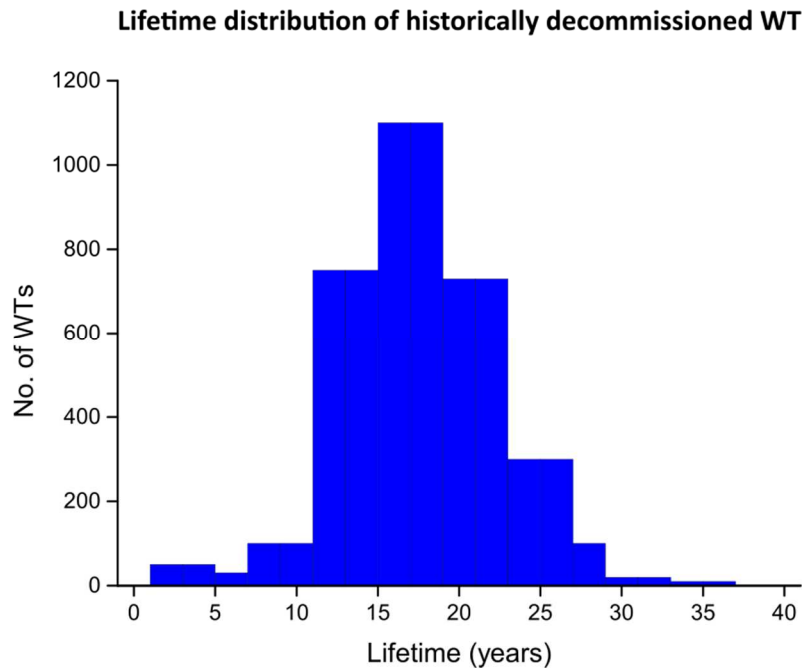
164 Table 3. Example of Vestas 2MW wind turbine material consumption (materials in tons) [6]

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

165

166 3) Wind turbine service

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



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 lifetime
 182 is equal to the feed-in tariff contract duration [45].

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

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

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

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

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

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

224 4) EOL and material treatment assumptions

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

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

239

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

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

251 5) MFA and flow mapping

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

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

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

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

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

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

278 **Results and Discussion**

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

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

County	Total mass in tons (turbine + foundations) from 2002 to 2016
--------	---

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

283

284 As seen in Table 6, the Aube and Marne counties account for more than 80% (about 890,000
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
287 has so far been dismantled. Thus, we are looking at an overview of the quantity of wastes that
288 this region will need to manage. Moreover, as seen in Table 1, 230 wind turbines were
289 installed as late as 2010. This was the year with the highest installation rate. The turbines are
290 expected to operate for 15 years (feed-in tariff contracts) and to be dismantled in 2025. The
291 next section deals with the future EoL of the 2010 wind turbines.

292 1) 2010 wind farms EoL

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

297

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

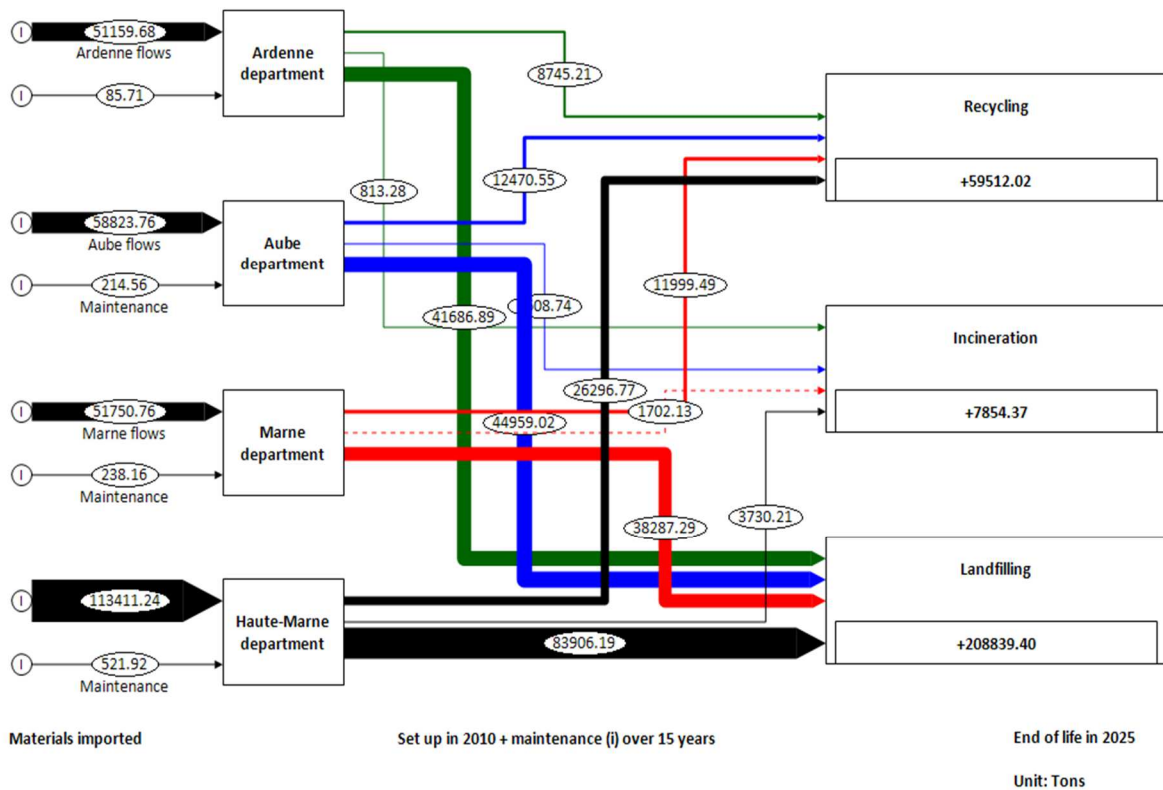
Materials	Medium scenario case		
	Recycling	Incineration	Landfill
Steel and iron materials	70,046	0	7,783
Concrete	0	0	194,547
Al	4,968	0	552
Cu	1,392	0	152
Polymer materials (plastics)	0	5,321	5,321

Glass	0	3,076	3,076
-------	---	-------	-------

299 unit: tons

300 As seen in Table 7, EoL materials are categorized into 3 possible scenarios: recycling;
 301 incineration, and landfilling. From the 2010 wind turbines' materials, recycling and
 302 landfilling flows were the highest. This is mainly explained by the high rate of ferrous and
 303 non-ferrous materials recycling (up to 90% of materials are recycled). Landfill flows are
 304 211,431 tons, including 194,547 tons of concrete. The other maintenance scenarios are
 305 provided in supplementary materials (supporting information document).

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



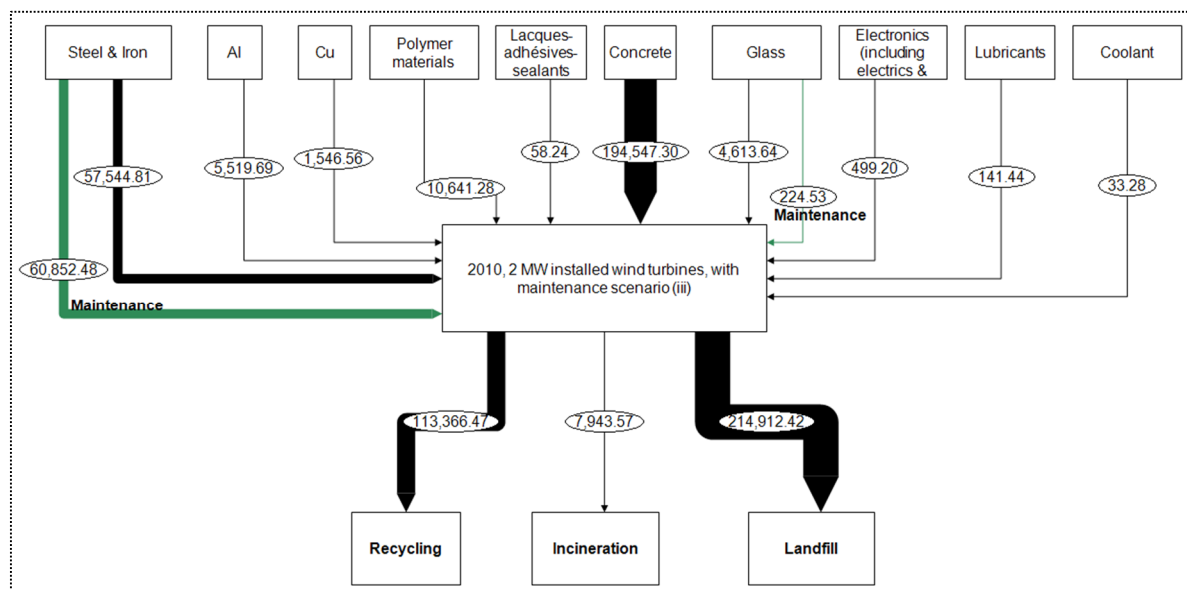
309

310 Figure 3. Flows generated for 2010 installed wind turbines under maintenance scenario 1 (low

311

case scenario)

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

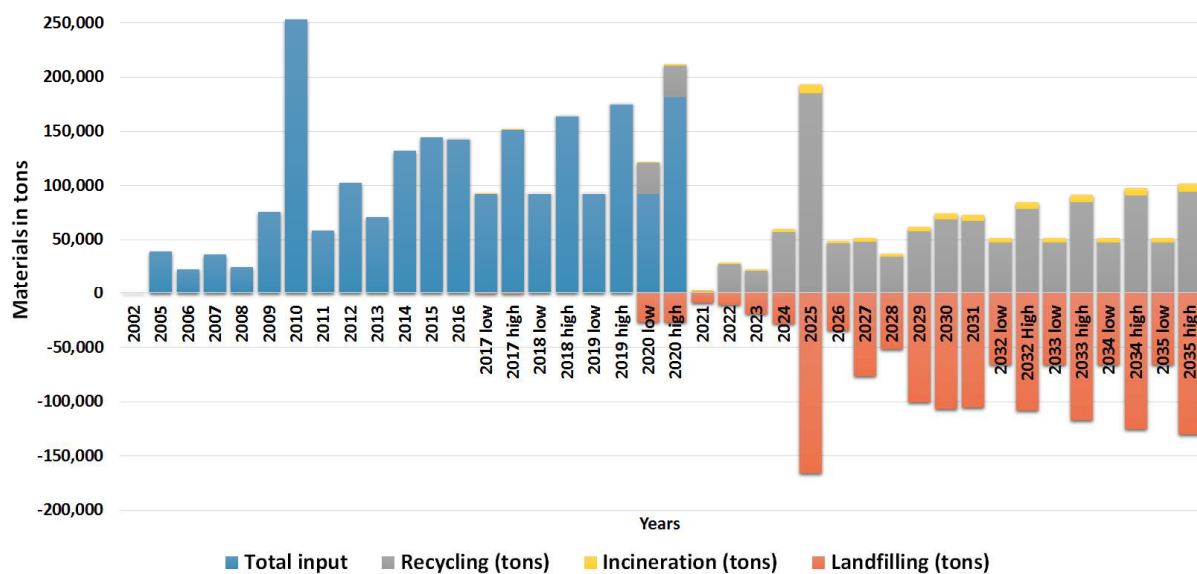


321
 322 Figure 4. Flows generated for 2010 installed wind turbines under the highest maintenance
 323 scenario (with material specifications), flows in tons.

324 Figure 4 shows the main materials mobilized for the 2010 wind farms. Concrete and steel
 325 represent the highest fractions of these flows (194,547 and 118,397 tons, respectively). The
 326 next section presents more generalized results about wind turbines' material wastes and flows.

327 2) Waste chronology of 2002-2016 installed wind turbines.

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

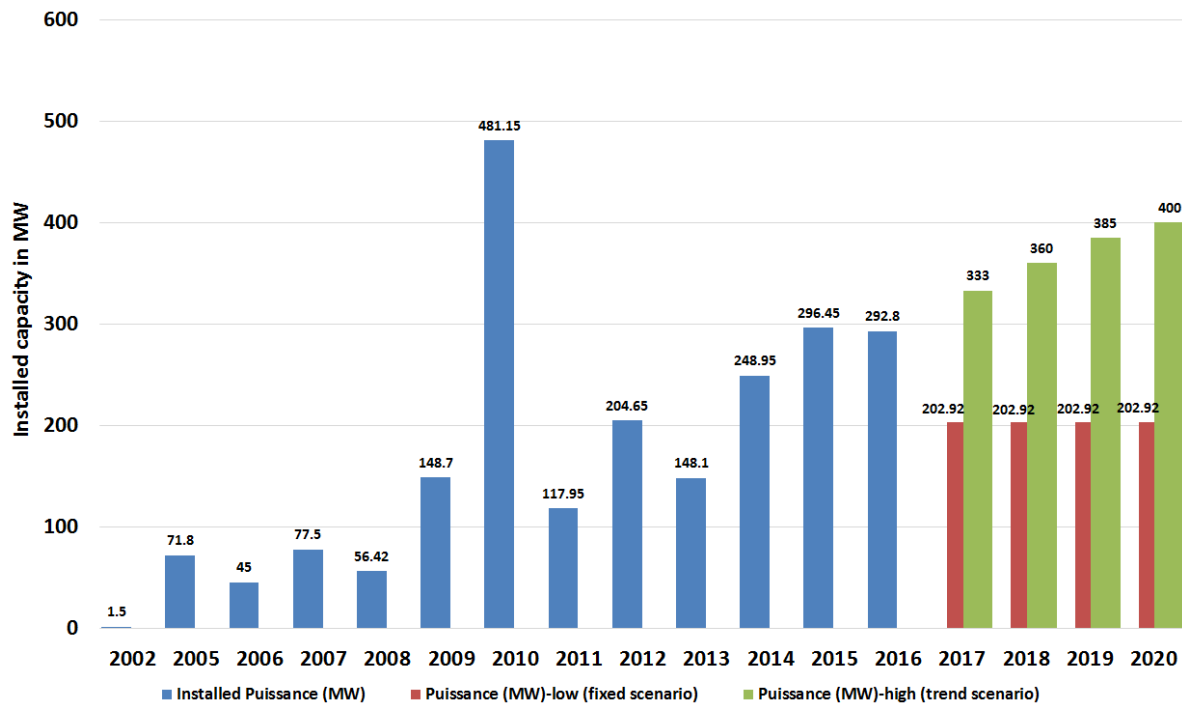


337
338 Figure 5. Chronological EoL flow materials generated in CA region under the high
339 maintenance scenario case

340 The same results are generated with a focus on wind turbine materials, and taking into
341 account other maintenance scenarios (see supplementary data in the *online supporting*
342 *information*). These results could also be generated for every individual wind farm location in

343 the CA region, which could eventually lead to an optimization of recycling or disassembling
344 factories under constraints of logistic or environmental costs.

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



358

359

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

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

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

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

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400 **References**

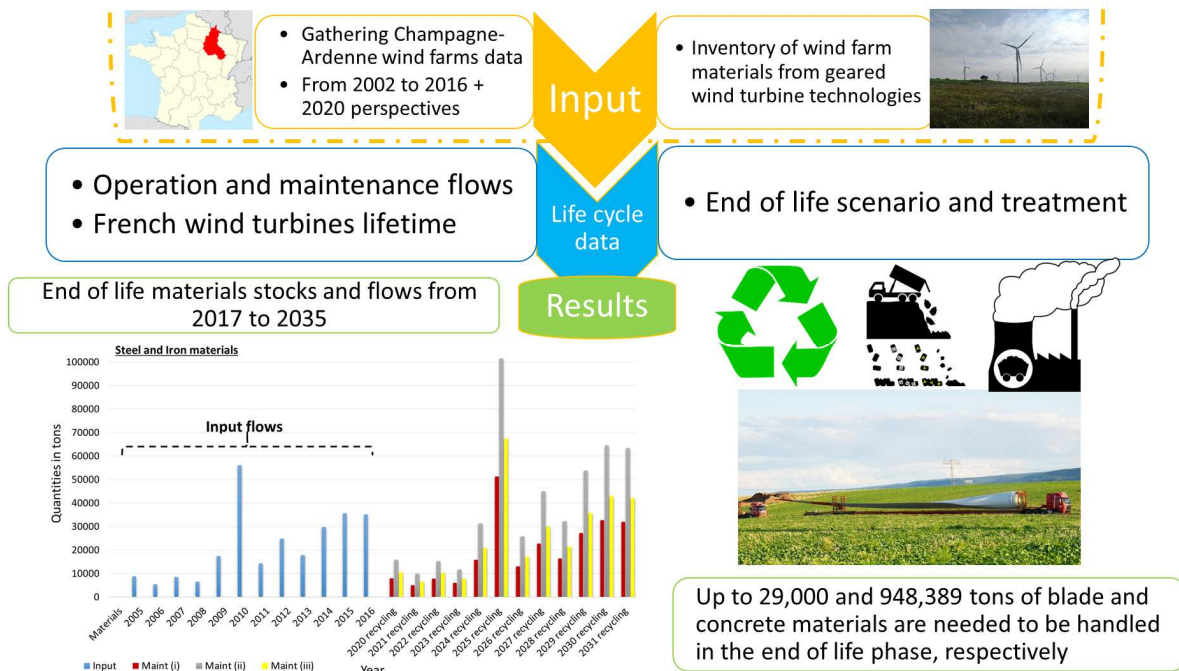
- [1] E. Denny and M. O'Malley, "Quantifying the total net benefits of grid integrated wind," *IEEE Transactions on Power Systems*, vol. 22, no. 2, pp. 605-615, 2007.
- [2] GWEC, "Global Wind Report 2017," Global Wind Energy Council, Brussels, 2017.
- [3] D. Fraile and A. Mbistrova, "Wind in power 2017. Annual combined onshore and offshore wind energy statistics," WindEurope, Brussels, Belgium, 2018.
- [4] N. Tazi, E. Châtelet, Y. Bouzidi and R. Meziane, "Tazi, N., Chatelet, E., Bouzidi, Y., & Meziane, R. (2017) Wind farm topology-finding algorithm considering performance, costs, and environmental impacts," *Environmental Science and Pollution Research*, pp. 1-9, 2017.
- [5] Vestas, "Life cycle Assessment of a wind turbine (3MW)," Vestas, Denmark, 2006.
- [6] Vestas, "Life cycle assesement of electricity production from a V90-2.0 MW gridstreamer wind plant," Vestas, Denmark, 2011.
- [7] Vestas, "Life cycle assessment of electricity produced from onshore sited wind power plants based on Vestas V82-165 MW turbines," Vestas, Denmark, 2006.
- [8] A. Arvensen and E. G. Hertwich, "Assessing the life cycle environmental impacts of wind power: A review of present knowledge and research needs," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 8, pp. 5994-6006, 2012.
- [9] K. R. Haapala and P. Prempreeda, "Comparative life cycle assessment of 2.0 MW wind turbines," *International Journal of Sustainable Manufacturing*, vol. 3, no. 2, pp. 170-185, 2014.
- [10] B. Tremeac and F. Meunier, "Life cycle analysis of 4.5 MW and 250W wind turbines," *Renewable and Sustainable Energy Reviews*, vol. 13, no. 8, pp. 2104-2110, 2009.
- [11] E. Martinez, E. Jimenez, J. Blanco and F. Sanz, "LCA sensitivity analysis of a multi-megawatt wind turbine," *Applied Energy*, vol. 87, no. 7, pp. 2293-2303, 2010.
- [12] R. H. Crawford, "Crawford, R. H. (2009). Life cycle energy and greenhouse emissions analysis of wind turbines and the effect of size on energy yield," *Renewable and Sustainable Energy Reviews*, vol. 13, no. 9, pp. 2653-2660, 2009.
- [13] I. Bhat and R. Prakash, "LCA of renewable energy for electricity generation systems—A review," *Renewable and Sustainable Energy Reviews*, vol. 13, no. 5, pp. 1067-1073, 2009.

- [14] P. H. BRUNNER and H. RECHBERGER, "Practical handbook of material flow analysis," *The International Journal of Life Cycle Assessment*, vol. 9, no. 5, pp. 337-338, 2004.
- [15] S. Bringezu, S. Moll, M. Fisher Kowalski, R. Kleijn and V. Palm, "Regional and National Material Flow Accounting, 'From Paradigm to Practice of Sustainability'," in *Proceedings of the 1st ConAccount Workshop 21–23 January, at Leiden. Wuppertal Institute*, Wuppertal, Germany, 1997.
- [16] R. Kleijn, R. Huele and E. Van der Voet, "Dynamic substance flow analysis: the delaying mechanism of stocks, with the case of PVC in Sweden," *Ecological Economics*, vol. 32, no. 2, pp. 241-254, 2000.
- [17] K. Vadoudi, J. Kim, B. Laratte, S. J. Lee and N. Troussier, "E-waste management and resources recovery in France," *Waste Management & Research*, vol. 33, no. 10, pp. 919-929, 2015.
- [18] J. Kim, Y. Hwang, M. Yoo, S. Chen and I. M. Lee, "Hydrogen fluoride (HF) substance flow analysis for safe and sustainable chemical industry," *Environmental Science and Pollution Research*, vol. 24, no. 32, pp. 25137-25145, 2017.
- [19] G. Liu, C. E. Bangs and D. B. Muller, "Stock dynamics and emission pathways of the global aluminium cycle," *Nature Climate Change*, vol. 3, no. 4, pp. 338-342, 2013.
- [20] K. Pivnenko, D. Laner and T. F. Astrup, "Material cycles and chemicals: dynamic material flow analysis of contaminants in paper recycling," *Environmental science & technology*, vol. 50, no. 22, pp. 12302-12311, 2016.
- [21] J. Zhang, S. Chen, J. Kim and S. Cheng, "Mercury flow analysis and reduction pathways for fluorescent lamps in mainland China," *Journal of Cleaner Production*, vol. 133, pp. 451-458, 2016.
- [22] K. Matsubae-Yokoyama, H. Kubo, K. Nakajima and T. Nagasaka, "A material flow analysis of phosphorus in Japan," *Journal of Industrial Ecology*, vol. 13, no. 5, pp. 687-705, 2009.
- [23] S. Ziemann, D. B. Müller, L. Schebek and M. Weil, "Modeling the potential impact of lithium recycling from EV batteries on lithium demand: a dynamic MFA approach," *Resources, Conservation and Recycling*, vol. 133, pp. 76-85, 2018.
- [24] M. Gusukuma and R. Kahhat, "Electronic waste after a digital TV transition: Material flows and stocks," *Resources, Conservation and Recycling*, vol. 138, pp. 142-150, 2018.
- [25] H. P. Tran, T. Schaubroeck, D. Q. Nguyen, V. H. Ha, T. H. Huynh and J. Dewulf, "Material flow analysis for management of waste TVs from households in urban areas of Vietnam," *Resources, Conservation and Recycling*, vol. 139, pp. 78-89, 2018.
- [26] K. Nakajima, I. Daigo, K. Nansai, K. Matsubae, W. Takayanagi, M. Tomita and Y. Matsuno, "Global distribution of material consumption: nickel, copper, and iron," *Resources, Conservation and Recycling*, vol. 133, pp. 369-374, 2018.
- [27] Z. Cao, L. Shen, L. Liu, J. Zhao, S. Zhong, H. Kong and Y. Sun, "Estimating the in-use cement stock in China: 1920–2013," *Resources, Conservation and Recycling*, vol. 122, pp. 21-31, 2017.

- [28] G. Meylan and B. K. Reck, "The anthropogenic cycle of zinc: Status quo and perspectives," *Resources, Conservation and Recycling*, vol. 123, pp. 1-10, 2017.
- [29] L. Ciacci, F. Passarini and I. Vassura, "The European PVC cycle: In-use stock and flows," *Resources, Conservation and Recycling*, vol. 123, pp. 108-116, 2017.
- [30] J. Barrett, H. Vallack, A. Jones and G. Haq, "A material flow analysis and ecological footprint of York," Stockholm Environment Institute, Stockholm, 2002.
- [31] A. Elshkaki and T. E. Gradel, "Dysprosium, the balance problem, and wind power technology," *Applied Energy*, vol. 136, pp. 548-559, 2014.
- [32] K. Habib, P. K. Schibye, A. P. Vestbø, O. Dall and H. Wenzel, "Material flow analysis of NdFeB magnets for Denmark: a comprehensive waste flow sampling and analysis approach," *Environmental science & technology*, vol. 48, no. 20, pp. 12229-12237, 2014.
- [33] P. Liu and C. Y. Barlow, "Wind turbine blade waste in 2050," *Waste Management*, vol. 62, pp. 229-240, 2017.
- [34] Y. Ma, D. Kim, M. S. Wu, L. Bai, X. Gao, B. Qing, J. He, X. Li, S. R. Nutt and B. Liang, "Processing and performance of recyclable composites for wind turbine blades," in *11th Annual TechConnect World Innovation Conference and Expo, Held Jointly with the 20th Annual Nanotech Conference and Expo, and the 2017 National SBIR/STTR Conference*, Washington; United States, 2017.
- [35] J. Kim, B. Guillaume, J. Chung and Y. Hwang, "Critical and precious materials consumption and requirement in wind energy system in the EU 27," *Applied Energy*, vol. 139, pp. 327-334, 2015.
- [36] T. Zimmermann, M. Rehberger and S. Gößling-Reisemann, "Material Flows Resulting from Large Scale Deployment of Wind Energy in Germany," *Resources*, vol. 2, no. 3, pp. 303-334, 2013.
- [37] T. Zimmermann, "Parameterized tool for site specific LCAs of wind energy converters," *The International Journal of Life Cycle Assessment*, vol. 18, no. 1, pp. 49-60, 2013.
- [38] FEE, "Onshore wind energy (Eolien Terrestre)," 2017. [Online]. Available: <http://fee.asso.fr/politique-de-leolien/eolien-terrestre/>. [Accessed 10 10 2017].
- [39] TheWindPower, "Wind Energy market intelligence," 2017. [Online]. Available: https://www.thewindpower.net/country_fr_1_france.php. [Accessed 10 10 2017].
- [40] SER, "French onshore wind energy production costs (Etat des coûts de production de l'éolien terrestre en France)," Renewable Energy syndicate, Paris, 2014.
- [41] Observ'ER, "French onshore wind farms atlas (Atlas des parcs éoliens en France)," *Le journal de l'Eolien*, pp. 38-47, 07-08 2016.
- [42] T. Zimmermann and S. Gößling-Reisemann, "Recycling potentials of critical metals-analyzing secondary flows from selected applications," *Resources*, vol. 3, no. 1, pp. 291-318, 2014.
- [43] P. Razdan and P. Gerrett, "Life cycle assessment of electricity production from an onshore V100-2.0 MW Wind Plant," Vestas, 2015.

- [44] C. O'Sullivan, "Assessing the dynamics of materials demand associated with future implementation of wind energy in Denmark (Master thesis report)," University of Southern Denmark, Odense, 2017.
- [45] Legifrance, "Décret n° 2017-676 du 28 avril 2017," [Online]. Available: https://www.legifrance.gouv.fr/affichTexte.do;jsessionid=AC95496EB3DFA5EE908D6DEA49628B72.tpdila10v_1?cidTexte=JORFTEXT000034517272&dateTexte=&oldAction=rechJO&categorieLien=id&idJO=JORFCONT000034514987. [Accessed 04 09 2018].
- [46] N. Tazi, E. Chatelet and Y. Bouzidi, "Using a hybrid cost-FMEA analysis for wind turbine reliability analysis," *Energies*, vol. 10, no. 3, p. 276, 2017.
- [47] E. Lantz, "Operations Expenditures: Historical Trends and Continuing Challenges," in *Proceedings of the AWEA wind power conference*, Chicago, 2013.
- [48] A. Ragheb and M. Ragheb, "Wind turbine gearbox technologies," in *Nuclear & Renewable Energy Conference (INREC)*, Amman, 2010.
- [49] P. D. Andersen, A. Bonou, J. Beauson and P. Brondsted, "Recycling of wind turbines. p. 91-97," DTU International Energy Report, 2014.
- [50] T. R. FOX, "Recycling wind turbine blade composite material as aggregate in concrete," Iowa State University, 2016.
- [51] P. Baccini and P. H. Brunner, *Metabolism of the Anthroposphere*, London: Springer, 1991.
- [52] S. Kytzia, "Material Flow Analysis as a Tool for Sustainable Management of the Built Environment," in *The Real and Virtual Worlds of Spatial Planning*, Springer, 2004, pp. 281--298.
- [53] M. Bertram, H. R. G. Ramkumar, C. Rombach, K. Bayliss, D. Martchek and G. Liu, "A regionally-linked, dynamic material flow modelling tool for rolled, extruded and cast aluminium products," *Resources, Conservation and Recycling*, vol. 125, pp. 48-69, 2017.
- [54] P. Agamuthu, K. Pearson and A. Nurul, "E-waste flow among selected institutions of higher learning using material flow analysis model," *Resources, Conservation and Recycling*, vol. 105, pp. 177-185, 2015.
- [55] M. Klinglmair, O. Zoboli, D. Laner, H. Rechberger, T. Astrup and C. Scheutz, "The effect of data structure and model choices on MFA results: A comparison of phosphorus balances for Denmark and Austria," *Resources, Conservation and Recycling*, vol. 109, pp. 166-175, 2016.
- [56] L. Makarichi, K. Techato and W. Jutidamrongphan, "Material flow analysis as a support tool for multi-criteria analysis in solid waste management decision-making," *Resources, Conservation and Recycling*, vol. 139, pp. 351-365, 2018.
- [57] O. Cencic and H. Rechberger, "Material flow analysis with software STAN," *Journal of Environmental Engineering and Management*, vol. 18, no. 1, p. 3, 2008.

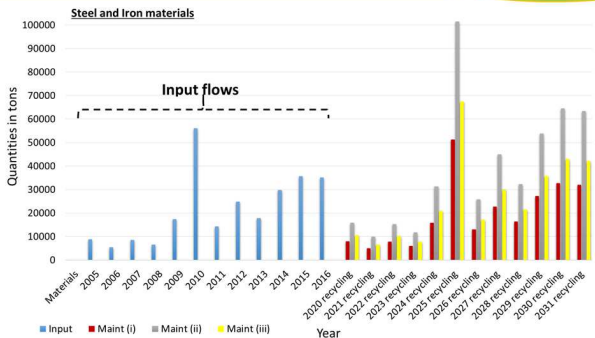
Graphical Abstract



• Operation and maintenance flows
• French wind turbines lifetime

• End of life scenario and treatment

End of life materials stocks and flows from 2017 to 2035



Up to 29,000 and 948,389 tons of blade and concrete materials are needed to be handled in the end of life phase, respectively