Renewable Energy and Carbon Management in the Cradle-to-Cradle Certification Limitations and Opportunities

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1 Journal of Industrial Ecology

2 **Type of contribution: Research and analysis**

3

4 **Renewable energy and carbon management in the Cradle-to-Cradle**
5 **certification: Limitations and opportunities**

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7

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11 **Summary**

12 As part of the Cradle to Cradle® (C2C) certification program, the C2C certification criterion
 13 “Renewable Energy and Carbon Management” (RE&CM) focuses on use of electricity from RE
 14 and direct greenhouse gas offsets in the manufacturing stage and to a limited extent on the cradle to
 15 gate only at the highest level of certification. The aim of this study is to provide decision-makers
 16 with a quantified overview of possible limitations of that C2C certification requirement and
 17 potential gains by introducing a full Life Cycle Assessment (LCA) perspective to the scheme.
 18 Scenario analysis was used to perform an LCA of an aluminum can system representing different
 19 levels of the C2C certification criterion RE&CM, considering different strategies to achieve 100%
 20 RE in the manufacturing stage. The adoption of a broader life cycle RE perspective was considered
 21 through the implementation of electricity from renewable sources from cradle to grave. Our results
 22 show that compliance with the current RE&CM certification framework offers limited benefits, i.e.
 23 significant reduction for climate change but negligible reductions for other environmental impacts,
 24 e.g. particulate matter and acidification. However, increasing the share of RE in the primary
 25 aluminum production from a full life cycle perspective can greatly increase the environmental
 26 benefits brought up by the C2C certification, not only for climate change, but for the broader range
 27 of impact categories. In our striving towards environmental sustainability, which often cannot be
 28 approximated by climate change impacts alone, we therefore recommend decision-makers in
 29 industries to combine the C2C certification with LCA when they define strategies for the selection
 30 of renewable energy and raw materials suppliers.

31

32 **Keywords** (max 6): Life Cycle Assessment (LCA), aluminum, packaging, circular economy, C2C,
 33 decision support

34 <heading level 1> Introduction

35 With the current political and business emphasis on circular economy, defined as a restorative or
 36 regenerative industrial system by intention and design (EMF 2013; EC 2015), the Cradle-to-Cradle®
 37 (C2C) design framework has gained an increasing visibility in industry (Toxopeus et al. 2015). C2C
 38 is a design framework oriented towards product quality and innovation, aiming to maximize the
 39 overall benefits of products to ecological and economical systems by designing “eco-effective”
 40 solutions. C2C relies on three key principles: “waste equal food”, “use current solar income” and
 41 “celebrate diversity”(McDonough and Braungart 2002). Until now in the circular economy context,
 42 efforts have largely focused on implementing the former, i.e. attempting to shift from a waste
 43 paradigm to a resource one, where waste from some industries can serve as resources for others. To
 44 allow companies to monitor and market their progress in C2C compliance, a certification program
 45 known as the Cradle to Cradle Certified™ Product Standard was established and recently updated
 46 (Cradle to Cradle Products Innovation Institute 2016). Applicants have to comply with a series of
 47 requirements for five categories: material health (MH), material reutilization (MR), renewable
 48 energy and carbon management (RE&CM), water stewardship (WS) and social fairness (SF), each
 49 of them being scored on a 5-grade scaling system, i.e. basic, bronze, silver, gold and platinum,
 50 reflecting an increased stringency in the C2C requirements.

51 As already discussed in past studies (Bjørn and Hauschild 2013; Toxopeus et al. 2015), the trade-off
 52 between resource conservation and energy use is a weakness of the C2C design framework and
 53 therefore of the certification program. For all the grades but platinum in the scaling system, only
 54 electricity use and greenhouse gases (GHGs) emissions in the manufacturing stage of a product are
 55 thus considered. This means that for most of the grades the environmental impacts stemming from
 56 the raw materials extraction, production, construction, and decommissioning of the energy
 57 generation facilities are disregarded even though those stages may be important drivers of the
 58 environmental impacts. This is particularly relevant for energy production based on renewable

59 energy sources e.g. wind (Dolan and Heath 2012; Turconi et al. 2013; Asdrubali et al. 2015) or
60 solar power (Hsu et al. 2012; Turconi et al. 2013; Asdrubali et al. 2015), for which life cycle
61 assessment (LCA) showed relatively low environmental impacts in the use/operation stage
62 compared to their production and disposal stages. Moreover, the need to include a broader range of
63 impact categories than climate change to gauge the environmental sustainability when shifting
64 electricity production from the use of fossils to the use of renewables has been pointed out (Laurent
65 et al. 2012; Hertwich et al. 2014).

66 These gaps in the RE&CM requirement of the C2C certification can induce important biases in the
67 decision making process for companies, who might not be aware of such limitations and associated
68 uncertainties. In this study, we therefore aim to provide decision-makers in industry a quantified
69 overview of possible limitations of the RE&CM requirement and potential gains by introducing a
70 full LCA perspective, as well as recommendations to alleviate these shortcomings in decision-
71 making processes.

72 We build on the results of an existing LCA of aluminum beverage cans (termed “AIC system” in
73 the following) (Niero et al. 2016). We focus on (primary) aluminum production, which belongs to
74 those sectors, where energy consumption during manufacturing is an environmental hotspot of the
75 technologies and systems (EAA 2013) and is thus fully relevant from a life cycle perspective (Liu
76 and Müller 2012). Due to its rapid aluminum industry development in the last decade, China has
77 become the largest primary aluminum producer in the world and now faces urgent needs to reduce
78 associated environmental impacts (Sun et al. 2015). As a result, the longtime front-runner in
79 aluminum production, Europe, is today the second largest producer ([http://www.world-](http://www.world-aluminium.org/statistics/)
80 [aluminium.org/statistics/](http://www.world-aluminium.org/statistics/)). Chinese and European aluminum productions differ from each other with
81 regard to their supporting electricity mixes, which are mainly based on coal and hydropower,
82 respectively. In the current study, we therefore consider different can systems including either
83 China or Europe as aluminum-producing countries: (1) the AIC system as commonly in place
84 (baseline scenario), (2) the AIC system with implementation of the C2C certification requirement at

the highest grades for the RE criterion (i.e. gold and platinum) using alternative renewable energy sources, and (3) the AIC system with adoption of a broader life cycle RE perspective, i.e. implementation of electricity from renewable sources from cradle to grave.

88

89 <heading level 1> Materials and methods

Aluminum cans systems have recently been evaluated by means of LCA, e.g. van der Harst and colleagues (2015). We consider here an AIC system for beer containment in the UK market previously used to model 20 different scenarios complying to different degrees with two of the C2C certification requirements, namely RE and MR (Niero et al. 2016). We followed the requirements of the ISO 14040-44 standards (ISO 2006a, 2006b) and the technical guidance provided by International Reference Life Cycle Data System (ILCD) handbook (EC-JRC-IES 2010). We also used the approach from the product environmental footprint (PEF) guide (EC 2013) to model the end-of-life (EoL) as it is the one recommended in the context of policy support applications (Allacker et al. 2014).

99

100 <heading level 2> Goal and scope of the LCA

The goal of the LCA study is to compare different AIC systems, some representative of different level of compliance with the requirements of the C2C certification for the RE&CM criterion, and some going beyond C2C certification through the inclusion of RE in a life cycle perspective, considering the average primary aluminum production in either Europe or China. Since the aim of the LCA is to provide decision support related to product development, with small scale changes in the background system, i.e. in terms of energy supply and material supplier, then the decision context is a situation A type according to the ILCD Handbook, i.e. micro-level decision support (EC-JRC-IES 2010). The considered functional unit is “the containment of 1 hl of beer until the

109 expiry date”, in accordance with the draft version of the PEF category rules for beer published in
 110 the context of the beer PEF pilot (Technical Secretariat for the Beer Pilot 2015). In the case of 33 cl
 111 aluminum cans, with average weight of 13.5 g, 4.22 kg of material per functional unit is required
 112 (Niero et al. 2016). Only the primary packaging, i.e. the materials which come into direct contact
 113 with the product, is considered, being the object of the C2C certification. The product system under
 114 study includes the supply of raw materials, i.e. the aluminum alloys used for the lid (21% of the can
 115 weight) and the body (79% of the can weight), the manufacturing of the lid and body, as well as
 116 their assembly, the filling of the can and its final EoL. The system boundaries are presented in
 117 Figure 1: the main exclusions regard the distribution and use stages, since these are assumed
 118 identical for all compared systems. The influence of transports on the overall environmental impact
 119 of AIC systems cans is usually minor compared to the other life cycle stages, and the use stage, e.g.
 120 refrigeration of the beverage, is typically not included as it is assumed that the beverage is
 121 consumed shortly after the purchase (Amienyo and Azapagic 2016).

122

Figure 1. Life cycle stages of the aluminum can (AIC) system considered, with indication of main inputs and outputs; excluded processes are marked with dashed box.

<heading level 2> Data collection and system modelling

In line with the identified decision context situation A of the ILCD guidelines (see previous section), the Life Cycle Inventory (LCI) modelling framework chosen is attributional with the use of system expansion to model process multi-functionality (EC-JRC-IES 2010). The ecoinvent 3.1 database (attributional default) was used to build the LCI (Weidema et al. 2013), considering the avoided impacts from the average market situation to model recycling at the EoL (EC-JRC-IES 2010). The LCI model was built in the LCA software SimaPro v.8.0.4.30 (PRé 2013). The foreground system was modelled with primary data, e.g. using electricity and heat consumption data from the filling facilities (Niero et al. 2016), while secondary data were used for modelling the background system, i.e. primary aluminum production (Stichling and Nguyen-Ngoc 2009), can manufacturing (e.g. lacquering (Li and Qiu 2013)) and the EoL management, which includes recycling and landfilling (Stichling and Nguyen-Ngoc 2009). We considered the current recycling rate for aluminum cans in UK (65%) (EAA 2015), and an average % of recycled content of 67.8% (PE Americas 2010). We used the default ecoinvent 3.1 datasets to model the input materials, i.e. average primary aluminum production both in Europe and China, secondary aluminum production, lacquer composition and EoL treatment. We modelled the can components, i.e. body and lid, according to their actual aluminum alloy composition: AA5182 for the lid and AA3004 for the body, respectively, as suggested in Niero and Olsen (2016). We considered the maximum threshold values of alloying elements allowed for the two abovementioned alloys (The University of Liverpool 2015). The main modifications to the default datasets in the scenario analysis consisted of changed energy input, i.e. the electricity used during manufacturing, primary aluminum production and recycling.

149 <heading level 2> The C2C requirement for RE&CM

150 The intention of the RE&CM category of the C2C certification program is “*to provide a*
 151 *quantitative measure of the percentage of renewably generated energy that is utilized in the*
 152 *manufacture of the product. Purchased electricity and direct on-site emissions associated with the*
 153 *final manufacturing stage of the product, as well as embodied energy associated with the product*
 154 *from Cradle to Gate, are considered, depending on the level of certification*” (Cradle to Cradle
 155 Products Innovation Institute 2016). The product under analysis is indeed graded based on
 156 quantitative parameters, e.g. the proportion of electricity coming from renewable sources (termed
 157 “% RE” in the following) and the proportions of direct GHGs emissions which are offset (named
 158 “% GHGs offset” in the following), and qualitative ones, e.g. the development of strategy for
 159 energy use and carbon management. Direct GHG emissions in scope for this requirement are those
 160 that are either emitted directly during the product’s final manufacture or on-site treatment of process
 161 wastes or associated with purchased heat (Cradle to Cradle Products Innovation Institute 2016). We
 162 focus here on the quantitative aspects and consider the highest levels for the RE&CM criterion, i.e.
 163 gold (G) and platinum (P), which are achieved if the manufacturing stage of the product (see Fig.
 164 1), meets the two following conditions: (i) 50% (for gold) and 100% (for platinum) of purchased
 165 electricity is renewably sourced or offset with renewable energy projects, and (ii) the same
 166 proportions of direct on-site GHG emissions are offset (Cradle to Cradle Products Innovation
 167 Institute 2016). For the platinum level additional requirements apply that comprise the supply chain,
 168 and therefore a “cradle to gate” perspective (see Fig. 1): iii) the accounting of the embodied GHG
 169 emissions; (iv) the definition of a strategy to optimize the embodied GHG of the product; (v) the
 170 coverage of at least 5% of the embodied energy associated with the product (cradle to gate) by
 171 offsets or other mechanisms, e.g. projects with suppliers, product re-design, savings during the use
 172 phase (Cradle to Cradle Products Innovation Institute 2016).

173

174 <heading level 2> Scenarios definition

175 In the development of the scenarios we refer to the % RE in the electricity mix used for the life
 176 cycle stages included in the C2C certification up to platinum level, i.e. body and lid manufacturing
 177 and filling, as well as the stages included only partially in the platinum level, i.e. primary aluminum
 178 production and excluded from the certification, i.e. the EoL, as shown in Fig. 1. Since can
 179 manufacturing and filling are assumed to take place in the UK, the electricity mix for UK was used
 180 taking the default ecoinvent 3.1 unit processes as a starting point. In the C2C certification program,
 181 renewable electricity that is already a standard part of the grid mix does not count toward this
 182 requirement, *“unless the applicant is participating in a voluntary green pricing program or the*
 183 *applicant has verified that their utility is delivering renewable electricity that may be claimed by the*
 184 *utility customer without being double-counted elsewhere in the system”* (Cradle to Cradle Products
 185 Innovation Institute 2016). For the AIC system under study we assumed that the applicant is
 186 involved in a voluntary green pricing program. To take into account of the variability in renewable
 187 energy sources different scenarios, including different mixes of renewable electricity, were
 188 considered for the highest certification level, i.e. platinum. In terms of direct GHGs we accounted
 189 only for those associated with purchased heat by the utility during the manufacturing stage (Fig. 1)
 190 and deducted their contribution from the climate change impact category, according to the
 191 requirements set by the certification level (i.e. 50% for gold and 100% for platinum). No impacts
 192 generating from the actions undertaken to provide the offset are considered, therefore the case
 193 modelled represents the best case scenario. Table 1 provides an overview of all scenarios assessed
 194 in the study. The details of the datasets used in the LCI modelling for the electricity from RE,
 195 primary aluminum production and heat (from natural gas) are reported in Table S1, in the
 196 Supplementary Information (SI).

197

Table 1 Summary of the 16 scenarios considered for the aluminum can (AIC) system, where EU refers to manufacturing in Europe and CN in China, respectively. The detail of the ecoinvent datasets used is reported in Table S1, in the Supplementary Information (SI).

Designation	Scenario description (In brackets the C2C certification level)	Primary Al alloy production	Manufacturing	
			Electricity mix	GHGs offset
1-B-EU	Baseline AIC system in Europe	Default Europe	Current (2015) UK el. mix (21% RE) ^a	-
1-B-CN	Baseline AIC system in China	Default China		
2-C2C/G-EU	AIC in Europe (Gold)	Default Europe	Current (2015) UK el. mix adjusted to 50% RE ^b	50% GHGs from heat
2-C2C/G-CN	AIC in China (Gold)	Default China		
3-C2C/P(2015UK)-EU	AIC in Europe (Platinum) with current UK mix	Default Europe	Current (2015) UK el. mix adjusted to 100% RE ^c	100% GHGs from heat
3-C2C/P(2015 UK)-CN	AIC in China (Platinum) with current UK mix	Default China		
4-C2C/P(solar)-EU	AIC in Europe (Platinum) with 100% solar energy	Default Europe	100% solar energy (single-Si)	100% GHGs from heat
4-C2C/P(solar)-CN	AIC in China (Platinum) with 100% solar energy	Default China		
5-C2C/P(wind)-EU	AIC in Europe (Platinum) with 100% wind energy	Default Europe	100% wind energy (on-shore >3MW)	100% GHGs from heat
5-C2C/P(wind)-CN	AIC in China (Platinum) with 100% wind energy	Default China		
6-LC(2015 UK)-EU	AIC in Europe, current UK mix (100%RE) + life cycle perspective for RE	Europe with 100% RE ^d	Current (2015) UK el. mix adjusted to 100% RE ^c	100% GHGs from heat
6-LC(2015 UK)-CN	AIC in China, current UK mix (100%RE) + life cycle perspective for RE	China with 100% RE ^e		
7-LC(solar)-EU	AIC in Europe, (100% solar) + life cycle perspective for RE	Europe with 100% RE ^d	100% solar energy (single-Si)	100% GHGs from heat
7-LC(solar)-CN	AIC in China, (100% solar) + life cycle perspective for RE	China with 100% RE ^e		
8-LC(wind)-EU	AIC in Europe, (100% wind) + life cycle perspective for RE	Europe with 100% RE ^d	100% wind energy (on-shore >3MW)	100% GHGs from heat
8-LC(wind)-CN	AIC in China, (100% wind) + life cycle perspective for RE	China with 100% RE ^e		

201

202 ^a Based on UK-DECC (2014)

203 ^b Based on the current (2015) mix distribution (UK-DECC 2014), but adjusted with 50% RE, i.e. wind
204 (34%), heat and power co-generation from biogas (12%) and biomass (2%), hydro (2%)

205 ^c Based on the current (2015) mix distribution, but with adjusted with 100% RE, i.e. wind (67%), heat and
206 power co-generation from biogas (23%) and biomass (5%), hydro (5%).

207 ^d Modelled considering 80% hydropower and 20% wind power

208 ^e Modelled considering 10% hydropower and 90% wind power

209

210

211 <heading level 3> Baseline scenarios

212 For the baseline scenarios (1-B-EU, 1-B-CN) we considered the current UK electricity mix for the
213 manufacturing processes based on the reference scenario described by the UK Department of
214 Energy and Climate Change (UK-DECC 2014). This leads to the following distribution: hard coal
215 (35%), natural gas (26%), nuclear (17%), oil (1%), wind (14%), heat and power co-generation from
216 biogas (5%) and biomass (1%), hydro (1%). Overall, the share of RE is equal to 21%.

217

218 <heading level 3> Gold scenarios

219 For the scenarios representing gold certification (2-C2C/G-EU, 2-C2C/G-CN), the relative
220 distribution of each renewable and non-renewable energy source as in the current electricity mix
221 were kept and adjusted so that the aggregated contributions of RE and non RE sources amount to
222 50:50% of the modelled electricity mix, respectively. Therefore, the electricity mix considered is:
223 hard coal (22%), natural gas (16.4%), nuclear (11%), oil (0.6%), wind (34%), heat and power co-
224 generation from biogas (12%) and biomass (2%), hydro (2%).

225

226 <heading level 3> Platinum scenarios

227 With regard to platinum certification, corresponding to 100% RE, different scenarios were built
228 using: the current UK RE mix (for scenarios 3-C2C/P(2015UK)-EU and 3-C2C/P(2015 UK)-CN);
229 100% RE from solar energy (for 4-C2C/P(solar)-EU and 4-C2C/P(solar)-CN), represented by the
230 single-Si panel technology (choice subject to limited data availability) and 100% RE from wind
231 source (5-C2C/P(wind)-EU; 5-C2C/P(wind)-CN), assuming on-shore wind technology, which
232 currently is more mature and is foreseen to support a larger share of electricity generation than off-
233 shore wind power technology (IEA 2013). The selection of wind and solar power was motivated by
234 their relatively lower reported environmental impacts, their anticipated role in future electricity
235 generation landscapes and their contribution to energy security (Asdrubali et al. 2015;

Hosenuzzaman et al. 2015). Moreover, to model the offset of 5% of the embodied energy associated with the product, we reduced by 5% the electricity used in the manufacturing stage.

<heading level 3> Life cycle scenarios

For including the life cycle perspective from cradle to grave in the AIC system we considered additional sets of scenarios, built on the platinum certification level, but assuming an increase of RE for electricity in the raw materials extraction and production (i.e. prior to the manufacturing stage) and EoL stages (see Fig. 1). Primary aluminum production is very energy intensive, and hence the location of production plants is often determined by access to large amounts of cheap electricity, which often results in an electricity mix that is different from the general grid mix of the countries where the production plants are located, thus aluminum industry specific electricity markets were used (Moreno Ruiz et al. 2014). Therefore, we modified the electricity mix used in primary ingot production, as well as in the primary liquid aluminum production (including bauxite mine operations, Al hydroxide, Al oxide). We assumed that the current fraction of non-renewable energy (termed “non-RE” in the following) in the aluminum specific electricity markets, i.e. 20% for Europe and 90% for China, can be substituted with the most competitive RE source, i.e. on-shore wind power (IEA 2013). An extension to 100% RE from hydropower is not deemed realistic due to the already high exploitation of hydropower capacity in these regions, e.g. hydropower is already extensively developed and with little further expansion potential left in Europe (IEA 2012). This leads to electricity mixes of 80:20% and 10:90% hydropower (current share):wind power sources throughout primary aluminum production in Europe and China, respectively. These grid mixes, in particular that of China, should be regarded as explorative mixes as a share of 90% wind power in the electric mix in China would imply effective grid management systems including storage capacity, which are not encompassed in this study due to lack of data.

<heading level 2> Life Cycle Impact Assessment and sensitivity analysis

262 The life cycle impact assessment (LCIA) was performed using the ILCD 2011 recommended
 263 methodology v1.05 (Hauschild et al. 2013) as embedded in SimaPro LCA software (PRé
 264 Consultants, 2015). The covered impact categories include climate change (CC), stratospheric
 265 ozone depletion (OD), human toxicity, considering both cancer effects (HT-c) and non-cancer
 266 effects (HT-nc), particulate matter (PM), ionizing radiation impacting human health (IR-HH),
 267 photochemical ozone formation (POF), acidification (Ac), terrestrial eutrophication (TE),
 268 freshwater eutrophication (FE), marine eutrophication (ME), freshwater ecotoxicity (FET), water
 269 use (WU), land use (LU) and resource depletion (RD), including mineral, fossil and renewable
 270 resources. To assess water use, significant advances have been made since the review of the
 271 methods leading to the ILCD recommendations was conducted; the water scarcity index (WSI)
 272 method developed by Pfister and colleagues (2009) was thus considered instead. Furthermore, given
 273 the focus on the energy aspect we considered the non RE Cumulative Energy Demand (CED) v1.09
 274 (Frischknecht et al. 2007) as an LCI indicator since it has been proven to provide insights for
 275 product comparison in the beverage packaging sector (Scipioni et al. 2013). To illustrate the
 276 differences observed between the different scenarios for each impact category, we performed
 277 ‘division-by-baseline’ internal normalization, i.e. dividing results obtained for a given impact
 278 category for each scenario by the corresponding impact results of the baseline scenario (thus taken
 279 as a reference) (Laurent and Hauschild 2015). This enables to quantify the impact reductions
 280 brought by the implementation of the different scenarios compared to the baseline scenario. We
 281 assumed a cut-off of 10% to identify a significant difference among the alternatives, following e.g.
 282 Humbert et al. (2009); this cut-off was arbitrarily defined and does not necessarily reflect the actual
 283 uncertainty assessment. As a sensitivity check at the impact assessment level, a different LCIA
 284 methodology, i.e. ReCiPe 2008 midpoint, hierarchist v.1.11 (Goedkoop et al. 2009) was
 285 additionally used.

286

287 <heading level 1> Results and discussion

288 The detailed characterized impact scores for the aluminum can system are reported in Table S2 and
 289 S3 for Europe and China, respectively in the SI. Table 2 reports the normalized results of the
 290 progression from the baseline to the C2C gold and platinum grades and “life cycle” scenarios (as
 291 defined in Table 1) for 4.22 kg of aluminum cans manufactured in the UK with primary aluminum
 292 produced in Europe. Normalized impact results for China are reported in a similar way in Table S4
 293 in the SI.

294 **Table 2 Normalized impact scores for the aluminum can system (indexed based on the**
 295 **baseline scenario) according to different C2C certification levels and scenarios defined in**
 296 **Table 1 (Europe). The color coding is used to indicate the ranking of the scenarios, where the**
 297 **option with higher environmental impact are marked with red and the one with the lower**
 298 **environmental impact are marked with green, according to the following legend: above 1.10**
 299 **(dark red); 1.00-1.09 (red); 0.90-0.99 (orange); 0.80-0.89 (dark yellow); 0.70-0.79 (yellow);**
 300 **0.60-0.69 (light green); 0.50-0.59 (green); below 0.49 (dark green). Results for China are**
 301 **provided in Table S4.**

Impact category	1- B -EU	2- C2C/G -EU	3- C2C/P (2015UK) -EU	4- C2C/P (solar) -EU	5- C2C/P (wind) -EU	6- LC (2015UK) -EU	7- LC (solar) -EU	8- LC (wind) -EU
Climate change (CC)	1.00	0.78	0.54	0.54	0.53	0.47	0.47	0.46
Ozone depletion (OD)	1.00	0.99	0.97	0.99	0.96	0.91	0.93	0.90
Human toxicity, cancer (HT-c)	1.00	1.00	1.01	1.00	1.00	1.01	1.01	1.00
Human toxicity, non cancer (HT-nc)	1.00	0.99	0.98	1.01	0.99	0.97	1.00	0.98
Particulate matter (PM)	1.00	0.99	0.96	0.98	0.95	0.86	0.87	0.84
Ionizing radiation, human health (IR-HH)	1.00	0.94	0.83	0.84	0.82	0.62	0.62	0.61
Photochemical Ozone Formation (POF)	1.00	0.98	0.94	0.94	0.92	0.87	0.87	0.85
Acidification (Ac)	1.00	0.97	0.93	0.93	0.91	0.84	0.85	0.82
Terrestrial Eutrophication (TE)	1.00	0.98	0.95	0.92	0.90	0.87	0.85	0.82
Freshwater Eutrophication (FE)	1.00	0.99	0.98	1.00	0.98	0.89	0.91	0.89
Marine eutrophication (ME)	1.00	1.00	1.01	0.91	0.89	0.93	0.83	0.81
Freshwater Ecotoxicity (FET)	1.00	1.02	1.05	1.00	0.99	1.04	0.99	0.98
Land Use (LU)	1.00	1.05	1.14	0.93	0.92	1.13	0.92	0.91
Resource depletion (RD)	1.00	1.00	1.01	1.06	1.00	1.01	1.06	1.01
Non Renewable Cumulative Energy Demand (Non-RE CED)	1.00	0.97	0.91	0.92	0.90	0.82	0.83	0.81
Water Scarcity Index (WSI)	1.00	1.04	1.10	1.01	0.93	1.07	0.98	0.90

302

303 <heading level 2> What environmental impact reductions can C2C certification achieve?

304 Only considering the scenarios relating to the C2C certification, i.e. scenarios 2-5, a common trend
 305 across the different certification scenarios can be identified for the impact categories in Table 2,
 306 which can be divided in three groups. A first group includes IR-HH and CC, which present
 307 significant reductions among scenarios 2-5, i.e. 22% for gold and ca 45% for platinum. A second
 308 group includes OD, PM, POF, Ac, TE, FE, ME, non RE CED which shows a slightly decreasing
 309 but not significant reduction in impact scores from the baseline towards gold and platinum
 310 certification (i.e. below 10%). The third group includes the toxicity related and resource-related
 311 impact categories, i.e. HT-c, HT-nc, FET, LU, RD and WSI, which show a slightly increasing
 312 difference (maximum 14% for LU) towards the higher certification levels, except for the last
 313 platinum scenario (i.e. number 5).

314 The marginal impact reduction (except for CC and IR-HH) across the C2C certification scenarios
 315 can be explained by the contribution analysis per life cycle stage for the baseline scenario (Fig. 2a),
 316 the gold certification scenario (Fig. 2b), and the platinum certification scenario considering 100%
 317 wind energy during manufacturing (i.e. the platinum scenarios with lower impacts; Fig. 2c). The
 318 positive contribution of the electricity use to environmental impacts during manufacturing, i.e. the
 319 one included in the C2C certification, is negligible compared to the contributions from heat during
 320 manufacturing and from lid and body alloys production, which include all the upstream processes
 321 such as alumina refining and electrolysis. These three life cycle stages thus represent the hotspots
 322 across all impact categories, as reported in the most recent LCA of primary aluminum production,
 323 which identified electricity and thermal energy as the factors responsible for the large contribution
 324 of alumina refining and electrolysis to GHGs emissions (Nunez and Jones 2015). The negative
 325 values observed in Fig. 2 refer to the End-of-life phase, namely to the avoided environmental
 326 impacts due to recycling.

327

328 **Figure 2 Contribution analysis for a selection of scenarios relative to Europe A) 1-B**
329 **(baseline); B) 2-C2C/G; C) 5-C2C/P (wind); D) 8-LC (wind). Lid and body alloys production**
330 **include all the upstream processes, as presented in Figure 1.**

331

332 **<heading level 2> Importance of including a full life cycle perspective in RE&CM criterion**

333 The normalized impact results for scenarios 6-8 indexed on the baseline scenario are presented in
 334 Table 2 (for EU) and Table S4 in the SI (for CN). They reflect the changes when including a full
 335 life cycle perspective, i.e. from cradle to grave, for electricity use in the AIC systems. The same
 336 trends can overall be identified for EU and CN, with some discrepancies. Significant deviations of
 337 the environmental impacts from the baseline (i.e. higher than 10%) are generally observed, with the
 338 exceptions of OD and HT-nc (for EU), for which the decrease is below the cut-off, and HT-c, FET,
 339 RD and LU (except 6-LC(2015UK)-EU), for which relatively negligible increases in the
 340 environmental impacts can overall be observed. For RD, the increase is mainly due to an increased
 341 metal extraction specific to PV, as confirmed by the sensitivity analysis performed with ReCiPe,
 342 which distinguishes between fossil and metal depletion, see Tables S5 and S6. For WSI, the
 343 inclusion of renewable energy highly based on hydropower in the primary Al production (scenarios
 344 6) causes an increase of the environmental impact compared to the other scenarios with lower
 345 shares of hydropower (i.e. scenarios 7 and 8).

346 For the remaining impact categories, the deviations from the baseline are different between EU and
 347 CN scenarios. For EU, the impact categories PM, POF, Ac, TE, FE, ME and non RE CED show a
 348 moderate reduction (up to 20%) in impact scores from the baseline towards the “LC scenarios”,
 349 meanwhile for CN the decrease is up to 40-60%. For CC the decrease from P-scenarios to LC-
 350 scenarios is negligible (i.e. less than 10%) for EU, but relevant for CN (i.e. around 50%). This
 351 decrease is due to the contribution of the GHGs offset for the thermal energy, which is comparable
 352 in magnitude to the CC impact score from cradle to grave for CN, but not for EU. For IR-HH a
 353 consistent decrease of the impact score is shown for EU, but no differences can be detected for CN
 354 due to the absence of nuclear energy in the electricity mix considered for Chinese primary
 355 aluminum production. No strong influence in terms of RE electricity source used can be detected

356 with regard to the manufacturing stage, since the impact deriving from the other life cycle stages is
 357 much higher.

358 The trend reported in Table 2 confirms the importance of considering a broader range of
 359 environmental impacts alongside climate change, already reported for the specific UK case by
 360 Kouloumpis and colleagues (2015) and also at the global scale by Laurent and Espinosa (2015).
 361 Kouloumpis and colleagues (2015) concluded that in the UK case a decarbonisation of electricity
 362 supply to meet the 2050 carbon targets would lead to a reduction in the majority of the life cycle
 363 impacts by 2070, including climate change, with the exception of resource depletion, which would
 364 increase by 4–145 times on today’s value, and health impact from radiation which would increase
 365 four-fold if nuclear power is used and electricity demand grows strongly (Kouloumpis et al. 2015).
 366 Moreover, the selection of the RE source could have some implications on the potential for impact
 367 reduction, even though in our case the deviations across platinum scenarios and “LC scenarios” are
 368 below 10%. The sensitivity analysis performed using a different LCIA method, i.e. ReCiPe 2008
 369 (midpoint, hierarchist v.1.11), confirmed the results obtained with the ILCD recommended method
 370 for all impact categories (see detailed explanation in Table S5 in the SI)

371 When switching from the baseline to the LC-scenarios, the reduction in terms of non RE CED is not
 372 significant for EU and moderate for CN (see Tables 2 and S4). Figure 3 represents the CED results
 373 for renewable and non-renewable energy results for the 16 scenarios analyzed, in the case of
 374 primary Al from Europe (Fig. 3a and 3c) and China (Fig. 3b and 3d).

375

376

377 **Figure 3 Contribution analysis in terms of Cumulative Energy Demand (CED) for the AIC**
378 **systems according to the scenarios presented in Table 1, with distinction between renewable**
379 **energy for (A) EU and (B) CN and non-renewable energy for (C) EU and (D) CN.**

380

381 The contribution analysis displayed in Fig. 3 shows that a considerable share of non RE comes from
382 the heat used in the manufacturing stage. Despite the use of electricity from RE in the primary Al
383 production in the LC scenarios, the share of non-renewable energy still dominates the CED, due to
384 the contribution from the non-fossil component (e.g. natural gas and coal) used for heating and in
385 the background processes, both for EU and CN. However, the switch to electricity from RE in the
386 primary aluminum production can considerably contribute to the reduction of the non RE CED in
387 the case of CN, where the current electricity mix used for aluminum production is mainly based on
388 non RE sources.

389

390 <heading level 1> Conclusions and recommendations

391 The outcomes of the LCA-based scenario analysis showed that compliance with the current
392 RE&CM C2C certification requirement offers limited benefits in terms of reduced environmental
393 impacts for the AIC system considered. Although there are slight differences between the EU and
394 CN scenarios, the observed trends are the same: with the exception of CC impacts, the reduction in
395 potential environmental impacts that can be achieved at the highest certification levels (gold and
396 platinum) is negligible compared to the potential for reduction that the LC perspective can bring.
397 The recently-updated RE&CM criterion includes a partial life cycle perspective – only at the
398 platinum level – and has limited minimum requirements, i.e. coverage of at least 5% of the
399 embodied energy associated with the product from cradle to gate. Even though our modelling was
400 incomplete and did not include all background processes (see Section “Life cycle scenarios”), we
401 showed that increasing the share of electricity from RE in a cradle to grave perspective can greatly
402 exceed the environmental benefits brought up by the C2C certification, not only for CC, but for the
403 broader range of impact categories. The impacts from thermal energy are currently dealt in terms of
404 direct on-site GHGs emissions, which need to be offset to achieve the highest C2C certification

level. In our study we have not modelled the impacts originating from the offset activities, which could further limit the benefits in terms of environmental impacts reduction from the baseline to the C2C certification scenarios and potentially also lead to increases of impacts.

Our findings show that for product systems where most of the environmental impacts come from raw material extraction and production, the RE share in the upstream processes need to be taken into account in the product optimization strategy, not only in terms of electricity but also thermal energy production, which has a significant contribution in terms of non RE CED (see Fig.3c and Fig. 3d). From a company perspective, this means that the knowledge of the raw material supplier location is crucial for achieving better environmental performances and higher certification levels. However, when the C2C certification refers to a specific market, knowing the location at country level might be insufficient, e.g. for China, where the different Chinese provinces present a wide range of grid mixes and disparities in GHG emission intensities from primary aluminum production (Hao et al. 2015). If the location of the plant is known, the recommendation is thus to adjust the level of details during data collection to be able to model the local energy mix, if relevant, e.g. considering ecoinvent v3.2, which includes electricity production at the province level for China (Moreno Ruiz et al. 2015). Moreover, a huge margin for reducing the electricity consumption for aluminum production, is provided by the use of secondary aluminum (Hao and colleagues 2015), since only 5% of the energy used for primary aluminum is required to make secondary aluminum (EAA 2013). Particularly for Chinese Al production, GHG mitigation strategies should be based on developing secondary aluminum industry, improving energy mix and optimizing resource efficiency of production (Liu et al. 2016). Therefore, an increase in the recycled content of aluminum products (measured in terms of MR requirement in the C2C certification) could positively affect the RE criterion (Niero et al. 2016).

According to the C2C certification program, all eligible renewable energy sources , i.e. solar, wind, hydropower, biomass (when not in competition with food supplies), geothermal and hydrogen fuel cells, are given the same preference although these renewable energy sources differ in their

431 environmental performances, see e.g. Asdrubali et al. (2015). In the case of aluminum cans, due to
 432 the negligible contribution of electricity during manufacturing, no significant differences between
 433 the different RE sources were detected (see results for the different platinum scenarios). However,
 434 in other settings the selection of an energy source might be influential on the overall environmental
 435 performances of the system; such influences need to be further investigated. In the decision making
 436 process, the limitations of the LCA results should not be overlooked, e.g. the uncertainty associated
 437 to results due to assumptions made and to the LCIA characterization models.

438 As shown by Haas and colleagues (2015) in their assessment of material flows, waste production,
 439 and recycling in the European Union and the world in 2005, reducing the consumption of fossil
 440 energy carriers is necessary to further raise the degree of circularity of the economy. Our results
 441 confirm that the role of an energy transition from fossil to renewable energy resources should not be
 442 neglected in shifting towards a circular economy. Decisions at the company level present
 443 repercussions on the global scale: switching from fossil to renewable energy sources for aluminum
 444 production could induce effects on electricity infrastructures and other industrial sectors, and
 445 potentially lead to burden shifting due to the constrained supply of renewable energy. The
 446 environmental consequences of such a large scale change should therefore be assessed by means of
 447 a broader LCA incorporating the changes with structural market implications beyond the
 448 foreground- system, considering decision context situation B of the ILCD guidelines. Deploying
 449 renewable energy sources to produce electricity and heat for use at industrial scale is in the long
 450 term the only possible solution to implement the ideal C2C platinum scenario, with 100%
 451 renewable energy use. The possibility to use green certificates to achieve the C2C requirement
 452 stimulates the demand for renewable energy, but this is not a consistent long term solution to put
 453 into practice the use of “current solar income” principle. The selection of the perspective on the use
 454 of renewable energy is crucial to avoid burden shifting and assure a true environmental impact
 455 reduction, although the technical challenges at large production scale should be incorporated in the
 456 decision making process. In the case of products, such as aluminum cans, where most of the

environmental impacts do not originate from the manufacturing stage of the final products, but from the raw material extraction and production, the efforts should be directed to the upstream processes. This conclusion can be extended for all products where raw materials extraction is the most impacting life cycle stage, e.g. laminated carton containers (Scipioni et al. 2013), plastic containers (Madival et al. 2009), stainless steel building components (Ibbotson and Kara 2013), metallic furniture (Babarenda Gamage et al. 2008), etc.

LCA allows modeling the consequences of decisions not only at the product level but also on a large scale, e.g. through consequential LCA. Moreover, since the overall environmental performances of a product depend not only on the manufacture of the product itself, but on the whole life cycle, see e.g. the impact from refrigeration of beverages in certain geographical contexts, the limited focus of the C2C certification on the product can therefore benefit from the inclusion of a broader life cycle perspective. There has recently been a discussion whether C2C certified products are better from an environmental point of view, see Llorach-Massana and colleagues (2015) and the rebuttal by Kausch and Klosterhaus (2015). The primary aim of the C2C design framework is to provide guidelines for product quality and innovation, and not strictly to communicate the environmental issues associated with a product. However, considering that the C2C certification program is used also as a means of marketing towards consumers, caution is needed when communicating the environmental performances of C2C certified products. We believe that the current focus of the RE&CM criterion on the CC impact is too narrow for modelling the actual environmental impact deriving from the use of renewables. Our results confirmed that GHG emissions could not be used as a single indicator to represent the environmental performance of a system or technology (Turconi et al. 2013; Laurent et al. 2012).

Even though the use of LCA in a C2C certification context is constrained by the limited availability of datasets representing future energy technologies, therefore preventing the modelling of long term forecasting scenarios, our main recommendation is to combine the C2C certification with LCA to make the second C2C principle operational. The adoption of scenarios analysis in an LCA context

483 can support the C2C certification program with a tool to compare the environmental performances
 484 of alternative improvement strategies which can be implemented in the progression towards higher
 485 certification levels.

486

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492

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