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1 **Evaluating climate change pathways through a building's lifecycle based on**
2 **Dynamic Life Cycle Assessment**

3

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20 Abstract:

21 Climate change impact of a building was evaluated through a Dynamic Life Cycle Assessment (DLCA)
22 methodology with the aim at demonstrating the feasibility of DLCA and the usefulness of such approach in the
23 building sector. The methodology uses dynamic thermal simulation for energy consumption, databases for the
24 building sector, a new developed database for temporal parameters of buildings, DyPLCA tool for dynamic LCI
25 calculation. Climate change indicators were obtained in function of time for 500 years time span: radiative forcing,
26 cumulated radiative forcing and global mean temperature change. Results revealed that each building component
27 has its own climate footprint from which mitigation actions can be deduced. Results should always be placed in
28 the climate context, in this case, the critical period 2030-2050, a turning point for limiting the temperature increase
29 at 1.5°C, with an objective of zero net emission beyond 2050. Dynamic indicators are well adapted for accounting
30 the effect of biogenic CO₂ and can be used to simulate strategies for GHGs neutralization. The main outcome of
31 the comparison DLCA – LCA is that the results can be greatly different, especially when biogenic carbon is present
32 (case of bio-based materials): i) the ranking and proportion of the contributors can change according to the time
33 horizon for a given dynamic indicator (cumulative radiative forcing and global mean temperature change), ii) the
34 ranking and proportion of the contributors can be different between the considered indicators, demonstrating the
35 need of a more detailed assessment in the context of the imminent climate target.

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39 Keywords:

40 Dynamic Life Cycle Assessment, climate change impact, biogenic carbon dioxide

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42 Highlights :

- 43 • A full dynamic LCA for buildings was demonstrated through a case study
- 44 • The evolution in time of the building and its components was quantified
- 45 • Temporal LCI was calculated for all foreground and background processes
- 46 • Dynamic indicators bring out rich information for climate mitigation decisions
- 47 • Bio-based systems promise near net zero effects for dynamic climate indicators

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50 **Nomenclature**

51	CF	Characterization factor
52	COP	Coefficient of Performance
53	CRF	Cumulative Radiative Forcing
54	DHW	Domestic Hot Water
55	DLCA	Dynamic Life Cycle Assessment
56	DLCI	Dynamic Life Cycle Inventory
57	DLCIA	Dynamic Life Cycle Impact Assessment
58	DTS	Dynamic Thermal Simulation
59	DyPLCA	Dynamic Process Life Cycle Assessment
60	EPD	Environmental Product Declaration
61	F&EC	Façades and exterior carpentry
62	F&I	Foundations and Infrastructure
63	GHG	Greenhouse Gas
64	GMTC	Global Mean Temperature Change
65	GWP	Global Warming Potential
66	H&MEWS	Highways and Miscellaneous External Works
67	HVAC	Heating, Ventilation and Air Conditioning
68	IPCC	Intergovernmental Panel on Climate Change
69	LCA	Life Cycle Assessment
70	LCI	Life Cycle Inventory
71	LCIA	Life Cycle Impact Assessment
72	P&IC	Partitioning, lining, suspended ceiling, interior carpentry
73	PVC	Polyvinyl Chloride
74	RE	Renewable Energy
75	RF	Radiative forcing
76	S&M	Superstructures and Masonry

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82 **1. Introduction**

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84 With a current contribution of 39% of global CO₂ emissions, the building (28%) and construction (11%) sectors
85 represent a major source of greenhouse gases (GHGs) [1]. In the context of urgent climate risks, transition
86 pathways for limiting global warming are challenging. The latest IPCC report [2] mentions that the global mean
87 temperature increase is ‘likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate.’
88 Therefore, GHG mitigation efforts in the building sector need to be implemented as early as possible for both the
89 renovations of existing buildings and new construction projects. Moreover, the necessity of limiting the global
90 temperature increase to 1.5°C through 2100 requires decreasing CO₂ emissions by approximately 45% by 2030
91 compared to 2010 and reaching net zero emissions by approximately 2050, according to the same report.

92 Despite its recognized usefulness and exhaustive use in all activity fields, the Life Cycle Assessment (LCA)
93 method faces some limitations including the lack of a temporal dimension of the inventory and of the impact
94 indicators. In the building sector, the time scale is an important parameter given the long lifetimes of buildings
95 (greater than 50 years); however, the conventional LCA method (guided by ISO 14040–14044 [3,4]) doesn’t
96 dispose of adapted tools (software, databases) for a relevant temporal analysis of the environmental performances
97 (e.g., [5]) and fails to consider the temporal evolution of the system under study, the temporal discrepancies of
98 activities and their associated emissions and the dynamic characteristics of the environmental impacts.

99 An extended analysis of the temporal aspects of buildings and the temporal dimension in LCAs of buildings
100 (temporal LCA elements and building’s temporal characteristics) was presented in a previous study [6]. The
101 identified key dynamic characteristics of buildings were related to i) construction products, e.g. performance
102 degradation over time, replacement and use of new technologies; ii) energy equipment, e.g. performance
103 degradation and the use of new technologies for renewable resources; iii) occupant behaviour, e.g. the occupancy
104 typology and thermal comfort; iv) the energy mix, e.g. its evolution following national strategies; v) end-of-life
105 technologies, e.g. material elimination versus reuse and recycling; and vi) carbon uptake/emission (the case of
106 biogenic carbon).

107 Dynamic LCA applied to building is new [7] and, according to the literature, the temporal aspects already included
108 in LCA of buildings are limited to either the Life Cycle Inventory (LCI) or to Life Cycle Impact Assessments
109 (LCIA) steps, or related to both LCI and LCIA but limited to parts of the studied systems [5]. Moreover, these
110 aspects concern only the foreground part or a few background processes, primarily related to variations in energy
111 consumption or production. Energy consumption in the use stage of buildings, as well as the grid composition,
112 have been extensively studied via hourly resolution simulations of the related inventory (e.g., [8–15]). Such
113 dynamic simulations allowed for extremely detailed energy consumption calculation, which was then translated

114 into climate change impacts using the GWP100 (kg CO₂-eq) method. Even if GWP100 was calculated at each
115 point in time, the impact result obtained cannot be considered as a temporal climate change indicator due to the
116 lack of dynamic modelling of climate perturbation.

117 Carbon emissions from the life cycle stages of a building (separated by embodied carbon emissions and operational
118 energy contributors) have also been evaluated [16,17] but without considering the dynamics of the processes and
119 supply chains; in other words, the inventory was calculated for four periods and discounting factors were applied
120 for late emissions. The same approach was used by Gimeno *et al.* [18] including the consideration of refrigerant
121 leakages and electricity mix periods (in accordance with regulations).

122 In the above-cited studies, the dynamics of all processes and the timings of the supply chains were not considered
123 nor were the (combined) effect of different interventions occurring at different moments in the lifetime of the
124 building (especially in the background part) taken into account. Concerning the LCIA, in most studies, only CO₂,
125 CH₄ and rarely N₂O have been considered for the global warming potential (GWP) calculation and no effective
126 dynamic assessment has been performed.

127 Recently, temporal characterization factors for global warming assessments have been developed and used in the
128 LCA of a wood-based building [19]; however, only a limited part of the LCI was considered. The current proposed
129 methodologies for dynamic LCAs applied to buildings (e.g., [20]) lack operational calculation tools (models,
130 software and coherent temporal databases) that could be used by practitioners for any building case study.

131 On a broader scope, dynamic LCA (DLCA) is still at the beginning of its development and very few calculation
132 tools exist [21]. The first studies proposing temporal inventories dealt only with the foreground part of the life
133 cycle and focused on several GHG emissions in the foreground processes [22–24]. These studies did not propose
134 a structured model for dynamic LCI (the emissions were ‘manually’ distributed in time). A first method was
135 proposed based on a temporal characterization of the processes and elementary flows [25]. The time distribution
136 of the LCI was calculated using a convolution operation between the distributions of two linked processes. A case
137 study was presented on domestic hot water production [26] with temporal differentiation for only the foreground
138 system (energy production/consumption). Pinsonnault *et al.* [27] applied this same framework to 22% of total
139 processes included in the ecoinvent 2.2 database, for which the authors defined the temporal characteristics
140 according to the sector of the activity (e.g. infrastructure or forestry). However, only significant intermediary and
141 elementary flows were selected for the calculation based on their contribution to global warming. This first model
142 for dynamic LCI calculations, however, lacked a structured database and a clear definition of process dynamics
143 and supply chain dynamics through physical, temporal parameters. Cardellini *et al.* [21] proposed a tool for
144 performing DLCA based on a graph search algorithm combined with a convolution operation between the
145 distribution functions of two linked processes, inspired by the previous method [25]. The dynamic LCI was
146 coupled with GWP characterization factors for climate change. However, this method also lacked the same
147 operational aspects mentioned above.

148 Another method was recently proposed [28] that calculates the temporal LCI by considering the complex supply
149 chains and processes that compose the life cycle system of both foreground and background processes. The
150 calculation tool, called DyPLCA ([29]; <http://dypzca.pigne.org/>), delivers the LCI distributed through time.
151 Moreover, this dynamic LCI can be calculated based on a conventional LCA database (e.g. ecoinvent), which
152 facilitates its use by LCA practitioners. A complementary temporal database is included in DyPLCA, containing
153 the time-dependent parameters of the processes and supply chains associated with the datasets existing in ecoinvent
154 3.2. The results provided by DyPLCA can be used with adapted LCIA dynamic models [29].

155 Concerning the LCIA, in particular climate change, Levasseur *et al.* [22] proposed a method based on the
156 calculation of characterization factors (CFs) for one-year time steps. This dynamic model uses radiative forcing
157 as a physical parameter, and no fixed time horizon is needed. However, the huge number of CFs calculated for
158 each time step and each substance could prove difficult to manipulate. In a recent study [30–32], a dynamic global
159 warming model (from IPCC [33]) and a dynamic toxicity model (based on Refs. [34,35]) were adapted and applied
160 to three case studies via a coupling with a dynamic LCI.

161 The present study applies the methodology proposed by Negishi *et al.* [6] to an existing building. The approach
162 provides a temporal, complete LCI (based on the DyPLCA tool), combined with dynamic global warming
163 indicators. DLCA could provide complementary and useful information (as testified by previous studies, several
164 of which are cited above) on the impact timing and variation (the short- and long-term effects) and on the role
165 played by biogenic CO₂ emissions and capture. However, at the same time, a dynamic approach will require
166 additional steps and calculation efforts and the obtained results will be more complex and difficult to interpret. In
167 this context, the objectives of the present study are i) to demonstrate the feasibility of a complete dynamic DLCA
168 applied to buildings, at the level of foreground and background LCI (considering process and supply chains
169 dynamics and future scenarios) and at the level of LCIA (using a methodology previously presented [5]) by an
170 actual building case study, and ii) to identify the benefit of such an approach when compared to conventional LCA,
171 in the case of buildings.

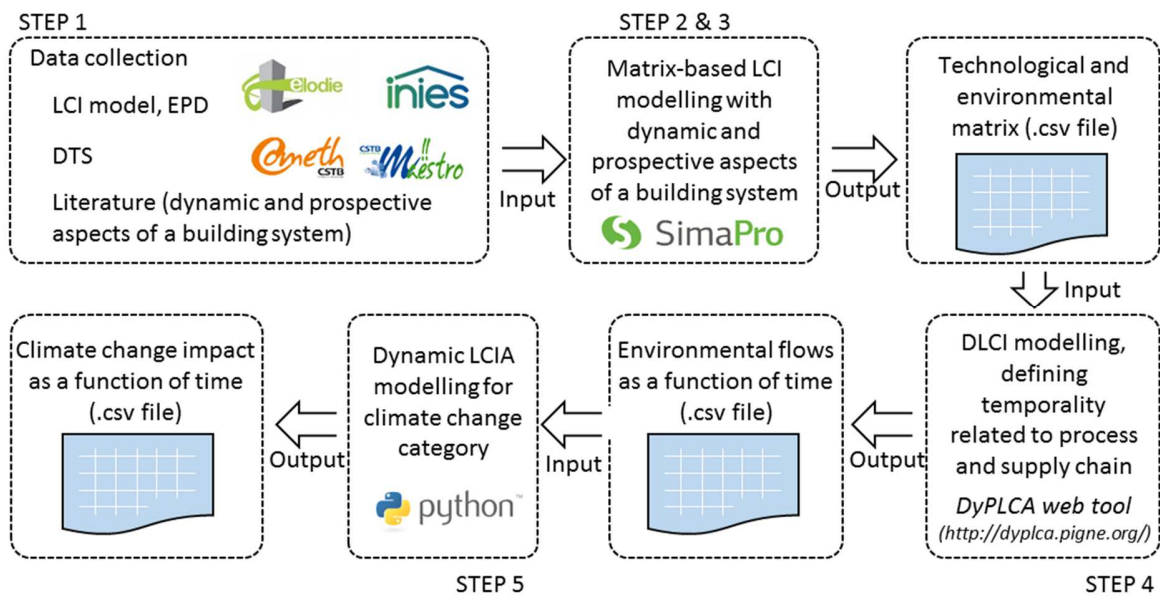
172

173 **2. Materials and methods**

174 **2.1. DLCA Methodology for buildings**

175 In the DLCA methodology applied to buildings [5], the main temporal parameters of a building are expected to be
176 used to derive the temporalized LCI for the foreground and background processes. Figure 1 shows a schematic of
177 the main steps, tools and intermediary results of the methodology, briefly described in the following.

178



179

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181

Figure 1: General framework of the DLCA methodology applied to a building case study.

182

183 *STEP 1 (Data calculation and collection)*. The collection of building data for LCI, and of the dynamic aspects and
 184 prospective scenarios, is performed based on Environmental Product Declaration (EPD) documents, literature
 185 reviews and expert opinions. This step includes a Dynamic Thermal Simulation (DTS), providing the annual
 186 energy consumption during the building occupancy, via the COMETH software [36] on the MAESTRO simulation
 187 platform.

188 *STEP 2 (Static model of the life cycle system)*. The results obtained in Step 1 are completed with the ecoinvent
 189 datasets. The energy and material balances are calculated at the process level over the entire life cycle of the
 190 building. This step provides the links between foreground and background processes as parts of the total life cycle
 191 inventory.

192 *STEP 3 (Temporality of the building life cycle system)*. The processes and sub-systems with specific temporal
 193 evolutions are identified. The temporal characteristics of the building rely broadly on three categories: 1) the
 194 intrinsic building parameters, 2) the inhabitant behaviour and 3) the background system (or context) of the building.
 195 Specific modelling with an LCA software, e.g. SimaPro, is performed for different scenarios, by connecting
 196 processes which occur at different times like e.g. the replacements of products.

197 The outputs of the first three steps are the technology and environmental intervention matrices.

198 *STEP 4 (Dynamic model of the life cycle system)*. The data retrieved from the previous steps are downloaded to
 199 the DyPLCA tool. The dynamic model implemented with the DyPLCA tool allows the characterization of the

200 processes and flows through several parameters [28]; details are presented in the Supplementary Information (SI)
201 (Table SI4). These parameters are user defined and/or available in a dedicated database. The result of this step is
202 the temporalized LCI, i.e. the elementary flows distributed in time (as discrete values at a given time step over the
203 timespan of the analysis).

204 *STEP 5 (Dynamic LCIA calculation)*. The temporal LCI is the input of the models of the dynamic impact indicators
205 (e.g., [32]) or can be used, after data integration over time, with characterization factors from conventional LCIA
206 methods.

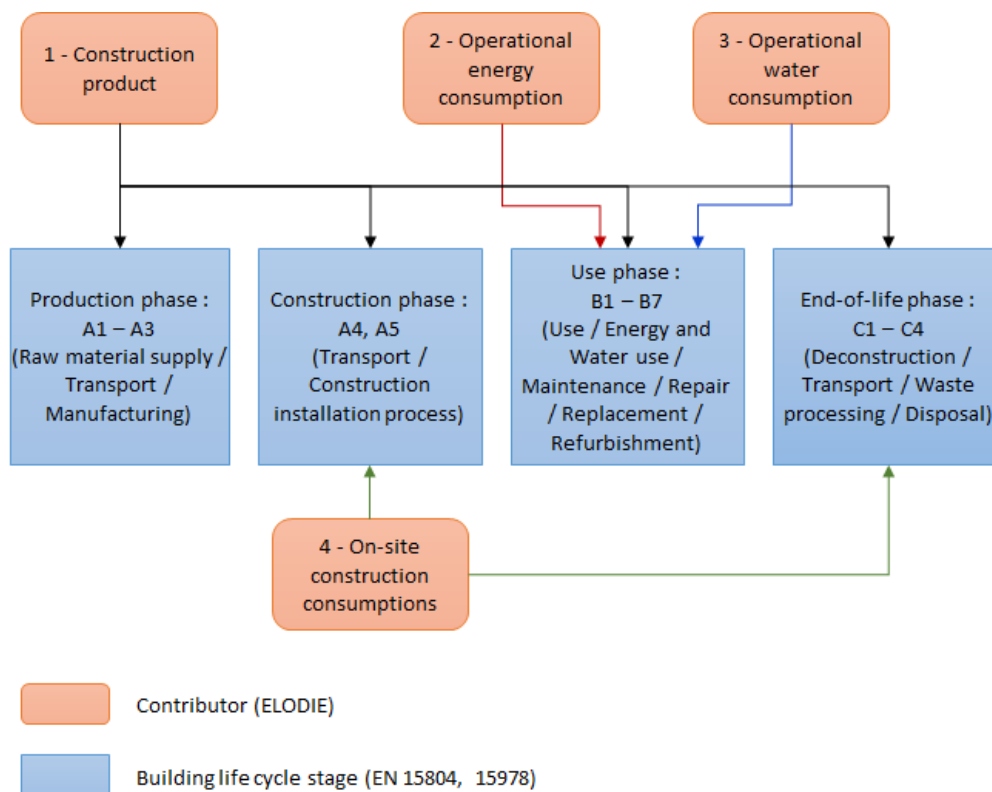
207 In the following sections, a case study is presented according to the four steps of the LCA methodology: i) goal
208 and scope definition, ii) constitution of the LCI, iii) LCIA and iv) interpretation of results.

209

210 **2.2. Goal and scope definition**

211 The building selected as case study is composed of three attached single wooden houses located in the Paris region
212 of France. The structure technology used is wooden post and beam. This building is part of the Observatory project
213 and is an experimental platform for an environmental assessment preparing a new French energy and
214 environmental regulation, E+C- [37]. The reference building service life was considered to be 50 years (2015–
215 2065). Each house has two stories, and the total net floor area of the three houses is 414 m² (details in SI-2). The
216 functional unit is one building as described above. The system boundary includes all processes from primary
217 material production to the end of life (cradle to grave), according to the EN15978 standard [38] (details in SI-1),
218 and the material and energy balances are established within the boundaries defined for each stage (Figure 2).

219



220

221

222 Figure 2: Coupling the life cycle stages (defined by the EN15978 standard) and the contributor approach.

223

224 The start date of the house occupancy (or the origin of the lifetime of the building) is considered to be year zero;
 225 which corresponds to 2015. The timespan of the inventory covers the period from 150 years before the origin year
 226 to year 50, as the end of lifetime, and 1 year after, to include all the past activities (raw material extraction, trees
 227 growth for wood harvesting) and end-of-life activities. Thus the system boundaries and the temporal boundary
 228 include the trees used for the wood pieces composing the building, coming from sustainable forest (included in
 229 the technosphere); no reforestation is considered inside the system's boundaries since the resulting wood does not
 230 belong to the building's life cycle.

231 In this study, the climate change impact was calculated and analysed. The literature [39,40] acknowledges that the
 232 end point damages of climate perturbation are sensitive to at least three parameters: i) impacts related directly to
 233 elevated temperature (e.g. heat waves, coral bleaching and sea level rise), (ii) impacts related to the rate of warming
 234 (e.g. high rates of change give insufficient time for species adaptation and lead to species extinctions) and iii)
 235 impacts related to cumulative warming (e.g. sea-level rise) because certain long-lived gases continue to cumulate
 236 their effects even several hundreds to thousands of years after emission. The analysis of the system performance

237 following dynamic indicators, namely global mean temperature change (GMTC) and cumulated radiative forcing
 238 (CRF), is completely adapted and copes with the above points (I, ii, iii).

239

240 **2.3. Life Cycle Inventory**

241

242 2.3.1. STEP 1: Data calculation and collection

243 To generate a reliable LCI model of the case study, a variety of tools, software, databases and methods were used,
 244 as shown in Table 1.

245

246 Table 1: Data sources used in the case study.

Data source	Type of data	Information retrieved
Observatory project data	General description of the building Dynamic energy simulation model COMETH	Calculations of specific material and energy consumptions of the building life cycle. Energy consumption as a function of time and total energy consumption during the use stage of the building.
EPD	Name, quantity and lifetime of construction products and materials and quantities of intermediary flows	Provides the reference flows used for conventional LCI modelling with SimaPro. Other information (e.g. lifetime of products) is used in the DLCI modelling.
ecoinvent v3.2	Inventory flows (unit processes and APOS system modelling)	Completes the inventory for background processes.

247

248 The MAESTRO platform for DTS was used for the configuration of the building behaviour, and the developed
 249 model was then used as an input of COMETH to simulate the energy consumption. The simulation was performed
 250 with a time step of one hour, as in other reported studies e.g. [8-15], then the cumulated consumption over one
 251 year was considered for the LCI. The energy demand was completely satisfied via electricity. The total energy
 252 consumption for the five types of energy equipment, i.e. the heating and cooling systems, domestic hot water,
 253 ventilation system and lighting, was estimated at $36.9 \text{ kWh.m}^{-2}.\text{year}^{-1}$ for the first year of building use. In addition,
 254 the annual consumption of domestic appliances for this building was set to $20 \text{ kWh.m}^{-2}.\text{year}^{-1}$ according to an

255 expert opinion [41]. The collected data in the EPDs (from INIES database) represent existing buildings recently
256 constructed, in form of technology information and calculated impact indicators. EPDs do not contain detailed
257 inventory, however technological inventory information can be exploited like lists of raw materials used and their
258 quantities. The available information includes the names of the building components and their quantities and
259 lifetimes, which can be used in both static and dynamic LCA modelling. A total of 48 EPDs were exploited for
260 the case study (list added in SI, Table SI3).

261 2.3.2. STEP 2: Static model of the life cycle of the system

262 The life cycle of the system was modelled on SimaPro 8.3 using ecoinvent 3.2. The ecoinvent dataset was used
263 mainly for the background processes and those processes for which the building-specific information could not be
264 obtained in Step 1. The list of ecoinvent processes used is given in SI, Table SI15.

265 The geographical information of FR (France) for inventories was privileged when data were available, whereas
266 RER (Rest of Europe Region excluding Switzerland data) or RoW (Rest Of the World excluding Switzerland data)
267 or GLO (global data) were used as an alternative solution for other inventories. In addition, the ‘default allocation
268 method’ for the process modelling of the ecoinvent datasets was chosen.

269 The transport distance of the construction products from factories to the construction site was taken from the EPDs,
270 as average distances supplied by products’ fabricants. When the transport distance was not available for a
271 construction product, it was systematically set to 100 km [42]. The energy consumption for the building demolition
272 and the transport of wastes from the building site to the disposal/treatment site were accounted for. Different waste
273 treatment processes, i.e. landfill, incineration and recycling, were considered for different types of waste materials
274 on the basis of the EPDs.

275 The direct emissions from the construction materials (e.g. the volatile compounds in the indoor air and the
276 substances leached by rain water from the exterior walls and roof) in the use stage of the building were not
277 accounted for due to the lack of data (except for CO₂ uptake by cement based products, as explained below).

278 For the sake of simplicity in the LCI modelling with SimaPro and DyPLCA, some construction products were
279 excluded from the model, particularly when (i) the global warming score of a product was very low (the cut off
280 threshold was 1% of the total global warming score), (ii) inventory data were completely lacking or (iii) the mass
281 was not significant compared to the total mass of the house (the cut off threshold was 1% of the total mass of the
282 building). This last criterion was applied only if criterion (i) was satisfied. As an example, plinths in PVC or wood
283 are excluded from the modelling due to its low level influence on the climate change impact. Packaging materials
284 for all products were also excluded because they represent only a small contribution to climate change and a small
285 fraction of the total mass [42]. The simplification adopted through the criteria (i) to (iii) is acceptable since the
286 GWP100 calculated preliminarily allows selecting all GHG with high emission amount or/and GHG with high
287 radiative efficiency. However the simplification can induce errors if the product is responsible for GHG capture

288 (not accounted by GWP100 indicator). All insulation materials were included even though their mass contribution
289 was very low. With this simplified model, the representativeness of GWP100 was of 97% from the value obtained
290 with the complete EPD-ELODIE data.

291 Concerning the biogenic carbon, conventional LCA does not include biogenic CO₂ emissions and uptake in the
292 LCI and LCIA calculations. Conversely, with DLCA, all forms of carbon flow were considered: CO₂ and CH₄
293 emissions via biomass transformation (e.g. incineration and degradation) and CO₂ uptake via plants (e.g. trees
294 providing wood for the life cycle system of the building). Both types of flows are called biogenic in the present
295 study. In addition, CO₂ uptake into the cement products was also considered when the information was available
296 from EPDs. Carbonation of concrete takes place also in the end of life stage, depending on the disposal process.
297 In the present study, carbonation after building demolition was not considered as EPDs do not provide this
298 information. Therefore, the benefit of such process could be the subject of a dedicated DLCA study.

299 For practical reasons, the convention is to classify the input flows into the life cycle system of the building via the
300 'contributor':

301 1- The 'construction products' contributor takes into account all components of the building throughout its life
302 cycle.

303 2- The 'operational energy consumption' contributor covers all energy consumption during the use of the building.
304 The embodied energy, which is the energy necessary for equipment and construction material production, is
305 accounted for in the construction products contributor.

306 3- The 'operational water consumption' contributor covers all the uses of water during the use of the building. The
307 water consumption during material and product manufacturing or on the construction site is allocated to the
308 construction products or 'on-site construction consumption' contributors.

309 4- The on-site construction consumption contributor accounts for the consumption of energy, water and other
310 materials, the production of wastewater and the evacuation and treatment of soil during construction.

311 Figure 2 illustrates the links between the life cycle stages of a building and the contributors.

312

313 2.3.3. STEP 3: Temporality of the life cycle system of a building

314 Some construction products having lifetimes of less than 50 years need to be replaced. For example, it is assumed
315 that a PVC (polyvinylchloride) window frame will need to be replaced at 30 years (100% landfilling) and disposed
316 of at 50 years (92.1% landfilling and 7.9% recycling) and that insulation materials need to be replaced at 30 years
317 [43]. Table 2 summarizes the temporality of each sub-stage of the life cycle; additional details are available in
318 Table SII0.

319

320 Table 2: Description of the temporality of the main activities involved in the building life cycle.

Module EN15978	Occurrence time, years	Process/activity	Description/indication
A1–A3	$t < -1$	Product fabrication	Product fabrication processing related to the construction activity
A1–A3	$t = [0, 50]$	Product fabrication	Product fabrication processing related to the maintenance and replacement activities, just before the replacement/maintenance time t
A4–A5	$t = [-1, 0]$	Construction	The construction period is 1 year, energy and water consumption are considered
B1	$t = [0, 50]$	Building use	The reference time 0 is the start time of building use
B2	$t \in [0, 50]$	Maintenance	Wall painting at a given time t , $0 < t < 50$
B4	$t \in [0, 50]$	Replacement	Replacement of windows, doors, HVAC systems; each product is replaced at a given time t , $0 < t < 50$
B6	$t = [0, 50]$	Energy use	The end-user's energy consumption takes place over the lifetime of the building
B7	$t = [0, 50]$	Water use	The end-user's water consumption takes place over the lifetime of the building
C1–C4	$t \in [0, 50]$	Waste treatment	Replaced products are treated with end-of-life scenarios
	$t = [50, 51]$	Waste treatment	The building is treated with end-of-life scenarios

321

322 The time variable characteristics of the building were grouped into the following categories: 1) degradation of
 323 material and energy system functions, 2) technological progress related to the building materials, 3) evolution of
 324 the family typology and 4) future mixes of electricity production. Several scenarios were then proposed for
 325 simulations by varying these parameters.

326 *i) Degradation of materials and energy system functions.* Insulation materials used for walls, floors and ceilings
 327 are known for their sensitivity to climatic conditions, particularly humidity. Their thermal performance levels
 328 therefore degrade over time during the use stage of a building. Three types of insulation materials (mineral wool,
 329 glass wool and polyurethane) were used in the studied building and differentiated by their usage types, e.g. exterior
 330 wall or upper floor. The temporal profile of the heat transfer coefficient was estimated for each insulation type
 331 [44,45]. This estimation was implemented with a yearly time step during the service lifespan to calculate the annual
 332 demand for heating and for domestic hot water (DHW). Building heat loads are also altered by variations in the
 333 performance of the energy equipment at the end-user level. The degradation of the energy efficiency was
 334 considered for: heating via the electric convector and DHW via the heat pump system. The pessimistic scenarios

335 of degradation from a previous study [46] were applied assuming that the global energy efficiency of the electric
336 convector and the coefficient of performance (COP) of the heat pump degrade yearly by 1% and 3%, respectively.

337 *ii) Technological progress related to the building materials.* Given the long lifetimes of buildings, technological
338 progress may occur during the use phase (e.g. maintenance, replacement and renovation) and in the background
339 system related to processes for product fabrication, waste treatment and recycling. The integration of such future
340 and potential improvements in DLCA is challenging due to the sparse data and the knowledge gap. Reducing
341 waste and increasing recycling rates of the building materials are stipulated in the 'Energy transition law for green
342 growth in France [47].' For example, in the case of flat glass products, a dataset was created for window products
343 considering an increase in cullet from 30% to 50% and accounting for an energy consumption gain of 2.5% per
344 10% increase in cullet. The evolution from current waste management practises (specified in existent EPDs) to a
345 future scenario was considered for construction products based on concrete, steel and wood.

346 In addition, an electricity consumption reduction of 10% every decade was considered for most energy consuming
347 processes for construction product fabrication (according to an expert opinion). An energy flow analysis was first
348 conducted through the network of processes in order to identify important energy consumers for which a 10%
349 energy reduction was possible. Then, for the relevant processes (the main contributors) the electricity consumption
350 was modified through time.

351 Even though prospective aspects may concern a huge part of building-related technologies, in this case study, the
352 prospective aspects were limited to those described above.

353 *iii) Change in family size.* Changing the inhabitant number leads to a change in the indoor heat gain due to human
354 bodies and hot water needs, which needs to be integrated into the electricity consumption calculations. The family
355 composition and its evolution were estimated using national statistics in France (INSEE [48], <https://www.insee.fr>)
356 and using a calculation method recommended by French thermal regulation 2012 [49] (details in SI-6).

357 *iv) Future electricity mix.* Current LCA practice uses an annual average mix of electricity production for the entire
358 life cycle of the studied system. Conversely, DLCA allows time variations of the energy production to be
359 considered. The present study includes future scenarios of the French electricity mix with the goals of GHG
360 reduction and the progressive replacement of nuclear electricity by electricity from renewable resources [50]. The
361 current mix scenario, retrieved from historical data, contains 72% nuclear electricity. Two future production mix
362 scenarios were considered: one with a high nuclear share of 50% in 2050 and another with a low nuclear share of
363 approximately 5% in 2050, the remainder being satisfied by renewable resources and natural gas. These two
364 scenarios are called 'Mix-50% Nuclear' and 'Mix-90% RE&Gaz', respectively. For the case study, the use phase
365 of the building was segmented into three distinct periods of 2015–2034, 2035–2049 and 2050–2065 to which the
366 current 2010 mix, the 2035 mix and the 2050 mix, respectively, were applied for the two mentioned scenarios
367 (details in SI-6, Figure SI-3). LCI models of the future mix were developed using the existing ecoinvent 3.2 data.

368 The future mix was modelled by varying the mix composition without changing the current technologies, which
 369 represents a limiting assumption. In addition, due to the modelling complexity, the application of the future mixes
 370 was limited to end-use energy consumption, while processes in the background system (e.g. product fabrication,
 371 transport and infrastructure) were still based on the current mix. In the simulations, the prospective mix of
 372 electricity production was considered along with yearly energy consumption values.

373 *v) Scenario modelling*

374 The building case study was modelled with the current inventory as a baseline scenario. To understand the
 375 influence of the variable characteristics on the LCA results, the life cycle system of the building was also modelled
 376 via distinct scenarios by targeting only one variable parameter per scenario, except for S6/sub-scenario 8 (Table
 377 3). The chosen parameter was varied between two (lower and upper) limits such that each corresponded to a sub-
 378 scenario: ‘best’ for the supposed beneficial value and ‘worst’ for the supposed most impactful value (details in SI-
 379 6, Table SI10). The scenarios definition with lower and upper limits for key parameters can also be considered as
 380 a sensitivity analysis with respect to the chosen parameter.

381

382 Table 3: List of scenarios considered for the case study.

Scenario	Baseline	Worst case	Best case
S1 Electricity mix for operational energy consumption	French annual average mix using ecoinvent data for 2015–2065	French annual average mix using ecoinvent data for 2015–2034 ‘Mix-50% Nuclear’ for 2035–2050 and 2050–2065	French annual average mix using ecoinvent data for 2015–2034 ‘Mix-90% RE&Gaz’ for 2035–2050 and 2050–2065
S2 Energy efficiency at product manufacturing	No temporal variation of energy consumption using raw ecoinvent data	No worst scenario (no increase of energy consumption)	10% reduction of energy consumption per decade for the concrete, steel, aluminium and wood product manufacturing processes
S3 End of life for concrete, steel and wood products	EPD processes (landfill, incineration and recycling)	Landfill for all products	Increase in recycling rate with respect to EPDs
S4 HVAC end of life	EPD processes (landfill and recycling)	Landfill for all products	Increase in recycling rate with respect to EPDs
S5 Technological innovations of insulation materials	Replacement (year 30) of insulation materials by the same type as initially used	Replacement (year 30) of all insulation materials by extruded polystyrene	a) Replacement (year 30) of all insulation materials by a bio-based material b) Replacement (year 30) of all insulation materials by one composed of recycled material

S6 Household energy consumption	1. No temporal variation of the energy consumption using raw ecoinvent data	2. Heat Pump, COP, 3% per year drop	3. Heat Pump, COP, 1% per year drop
		4. Airtightness, 1% per year drop	
		5. Insulation, thermal conductivity, nonlinear degradation	6. Insulation, thermal conductivity, 1% per /year drop
		7. Inhabitant change: 5 pers. per house => 2 pers. per house in 2035	
		8. Combination of 2, 4, 5 and 7	

383

384 The temporal assumptions (what was considered, simplified or neglected) of the case study model and for the
385 defined scenarios are gathered in the Supplementary information document, Table SI11.

386

387 2.3.4. STEP 4: Dynamic model of the life cycle system

388 The DyPLCA tool contains a generic (but modifiable) database of temporal parameters associated to all activities
389 in ecoinvent 3.2. The dynamic LCI was computed from –150 to 51 years: a past time horizon of 150 years was
390 considered to account for tree growth for the different tree species included in the background inventory and the
391 calculation then covered the lifetime of the building (50 years) and one supplementary year for dismantling and
392 waste management. The specifically created processes (e.g. foreground processes) for the case study require the
393 user to define the temporal parameters using the DyPLCA web application (see also SI-4).

394

395 **2.4. Life Cycle Impact Assessment - STEP 5: Dynamic LCIA calculation**

396 The present study focuses on the climate change impact evaluated via three dynamic indicators, instantaneous
397 radiative forcing (RF, $W.m^{-2}$), cumulative radiative forcing (CRF, $W.year.m^{-2}$) and global mean temperature
398 change (GMTC, K), based on IPCC models and data [33]. The models underlying these dynamic indicators
399 consider natural phenomena and all GHGs with their specific dynamics, as reported by IPCC (the decay equations
400 for every GHG and methane oxidation). By coupling time-dependent emissions with these models, one obtains
401 the indicator values as a function of time. All GHGs present in ecoinvent 3.2 were considered, and the dynamic
402 indicators were calculated over a timespan of –150 to 500 years. The computation model provided by Shimako *et*
403 *al.* [30] was used to this end. The conventional approach of the global warming potential GWP100 (kg CO₂ eq.,
404 with a time horizon of 100 years) was also used for comparison. In conventional LCA, the emission and capture
405 of a given CO₂ quantity offset each other because the underlying model of GWP considers that all GHG emissions
406 (and captures) occur simultaneously. Moreover, CO₂ uptake and biogenic emissions are not taken into account.

407

408 **3. Results**

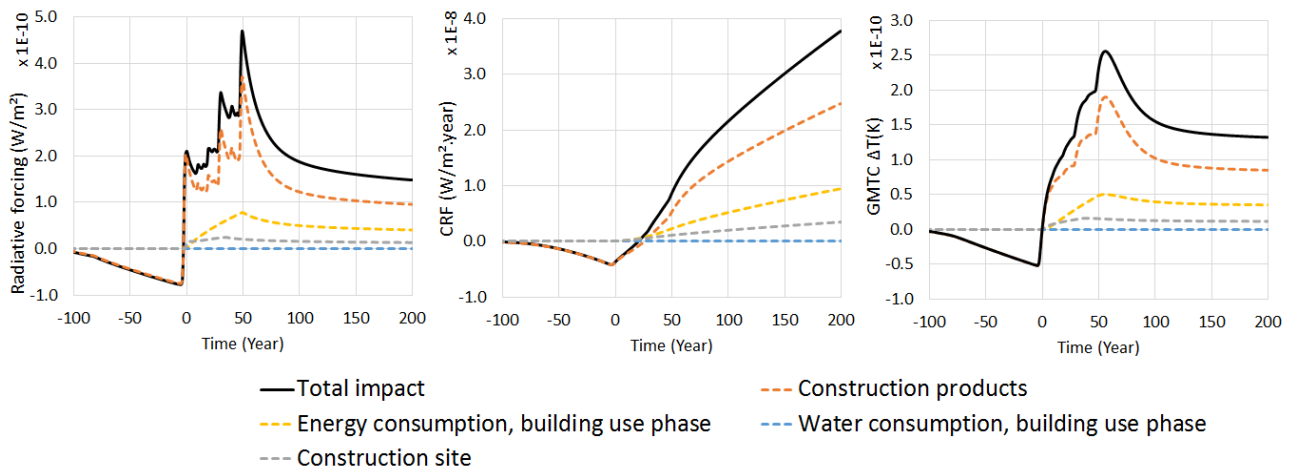
409 The results obtained with conventional LCA and DLCA are difficult to compare given the major differences in
410 the nature of their indicators. GWP100 was used to represent the static LCA, while for the dynamic indicators,
411 graphical representations as a function of time and values at 100 years (as an analogy to GWP100) and 55 years
412 (the end time of the building system) were analysed. Attention was paid to the temporal profiles of the climate
413 indicators such as their amplitude, time scale and impact rate (variation in time).

414 **3.1. Baseline scenario**

415 Figures 3 and 4 show the results obtained for the entire building and for the four contributors. Construction
416 products and operational energy are the main contributors to all the impact indicators. Prior to time zero, the net
417 impact is due to the fabrication of the construction products and, in the present case study, this has a beneficial
418 effect (all the indicators have negative values) due to the growth of trees (wooden raw materials from sustainable
419 forestry). Temperature peaks appear several years after the emission of GHGs due to the thermal inertia of the
420 planet. This time lag depends on the nature of the gas. The overall increase in the temperature peaks near year 55,
421 i.e. several years after the final emission at the end of the building life cycle. This is why year 55 was chosen as a
422 time horizon for the impact analysis.

423 Comparison with conventional global warming indicator shows that the ranking of a contributor is the same
424 whatever the indicator, with little variation in the proportion of the contributor.

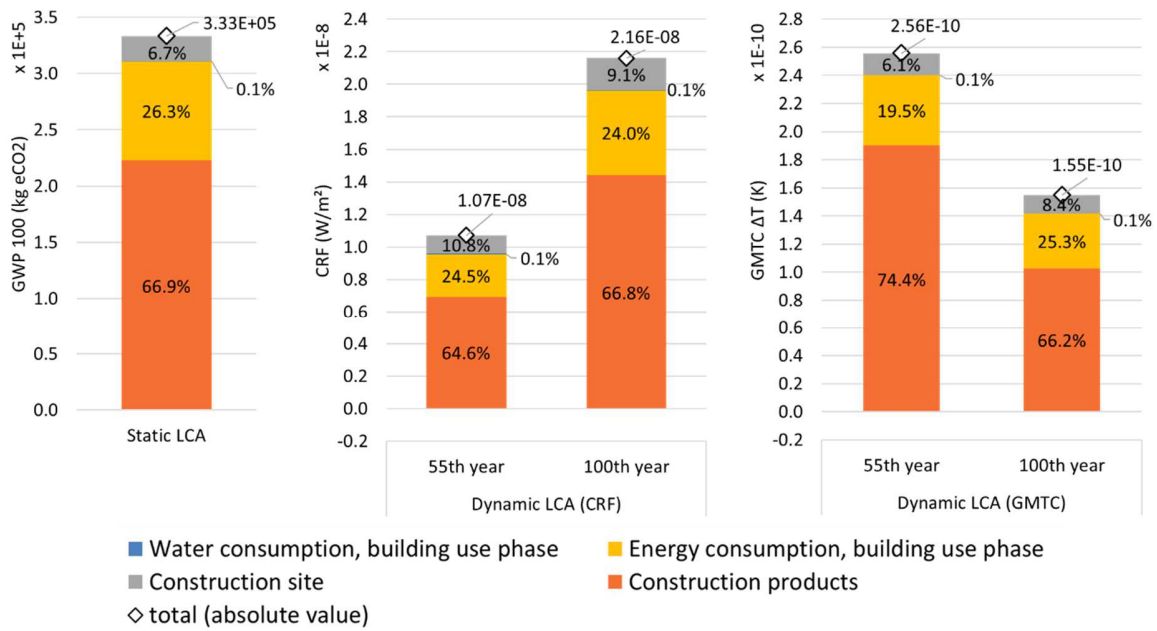
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427 Figure 3: Climate change dynamic impact (including biogenic CO₂) for the entire building and for the four
428 contributors (the functional unit is the building).

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431 Figure 4: Comparison of the climate change results obtained with static LCA and DLCA: the entire building (the
 432 functional unit) and its four contributors.

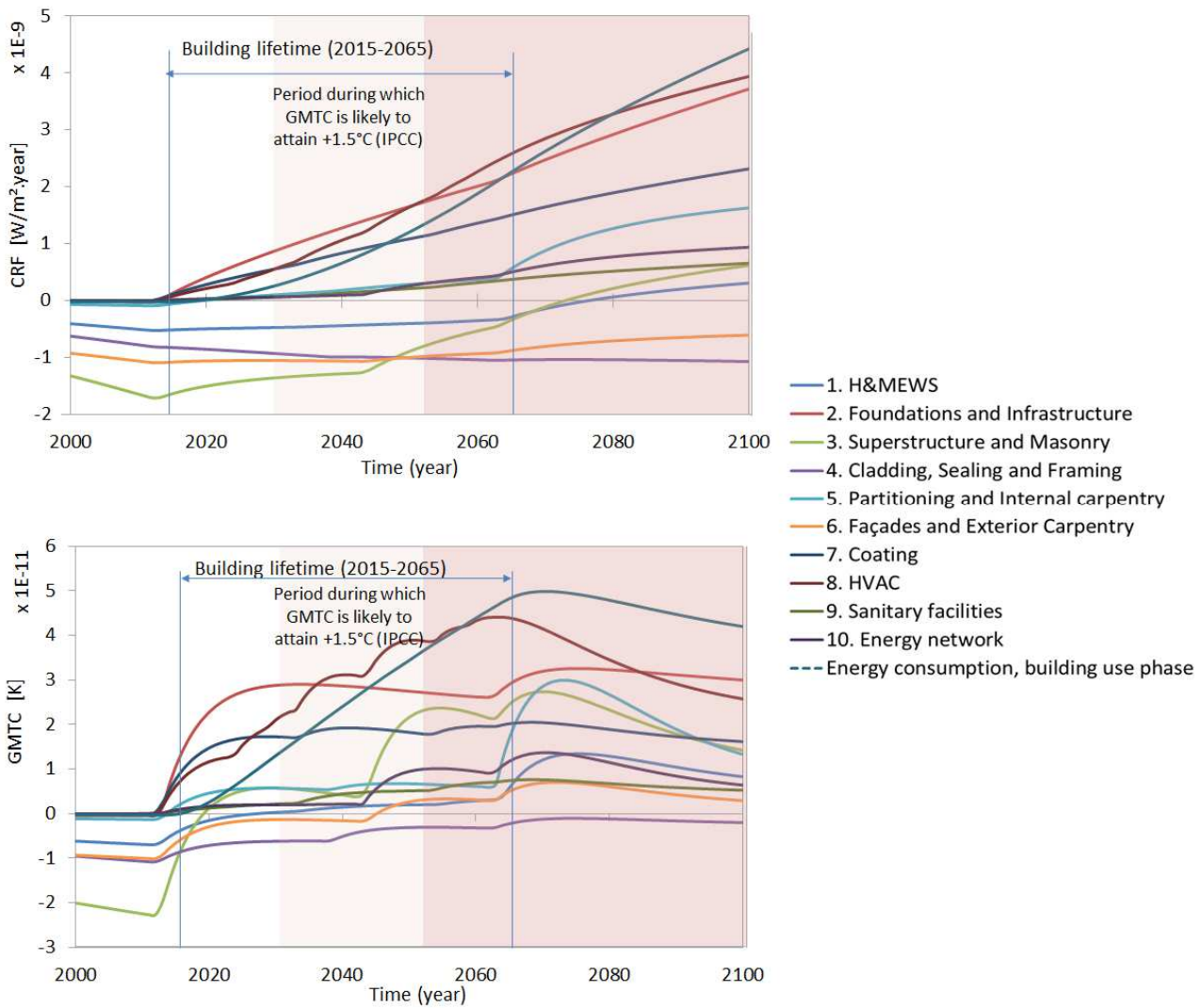
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434 Concerning the impacts related to energy consumption, even if the building was designed with high thermal
 435 performance, the constant GHG emissions due to daily household activities over 50 years make the impact longer
 436 lived, resulting in a continuously increasing CRF and a relatively high temperature peak at the end of life of the
 437 building.

438 The contribution of the construction products was detailed by product family, as shown in Figures 5 and 6.
 439 According to ref [37] the families regroup products with similar functions or utilisation in the same sub-structure
 440 of the building, for example HVAC family contains the heat pump, electric convector and the ventilation system.
 441 The Foundations and Infrastructure (F&I), HVAC and Coating families are the three biggest contributors to the
 442 climate change impact over the long term. This is due to their important GHG emissions and the persistence of the
 443 emitted CO₂ in the atmosphere, which have a very long-term effect. The temperature peak due to the HVAC family
 444 is the highest. The temperature increase due to the F&I family persists for a long period and is 33% higher than
 445 that of HVAC. Partitioning and Internal Carpentry (P&IC) contributes a significant temperature increase at the
 446 end-of-life phase; however, this temperature contribution declines rapidly, which is a consequence of the methane
 447 emission.

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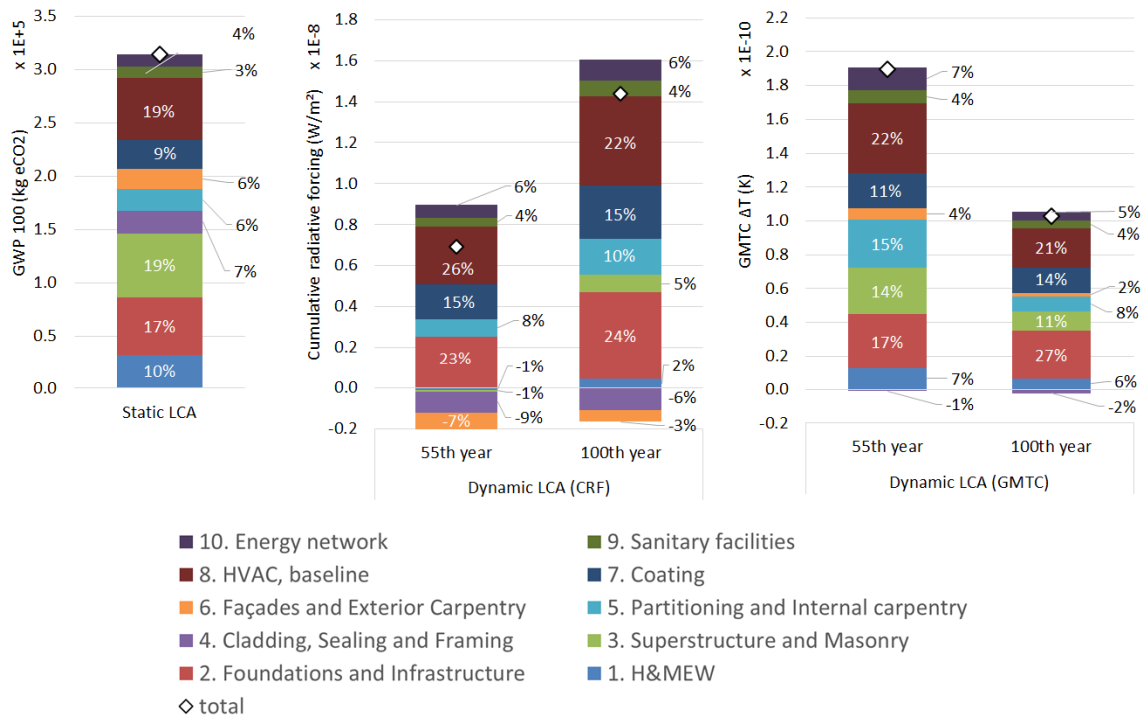


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Figure 5: CRF and GMTC for 10 product families and for the operational energy (the functional unit is the building).



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454 Figure 6: Comparison of the impacts of the construction product families according to the different indicators
 455 (the functional unit is the building).

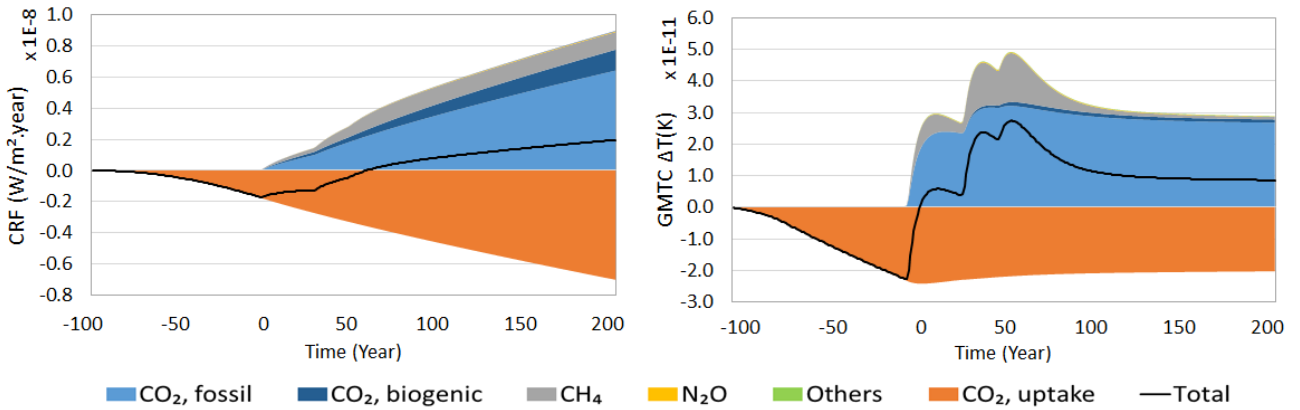
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457 Figure 6 demonstrates that the rankings of the 10 families can vary according to the indicator and the chosen time
 458 horizon, with F&I and HVAC always being the families with the greatest impact. Some contributors, such as
 459 Façade and Exterior Carpentry (F&EC), involving biogenic carbon in their inventories, have a negative (minus)
 460 contribution to CRF and small contributions to GMTC; this contribution diminishes with time. This behaviour is
 461 due to biogenic carbon capture by trees. Some other families also include a significant amount of wood products
 462 (e.g. Superstructure and Masonry (S&M)); however, the effect of biogenic carbon capture is partially offset by
 463 GHG emitters, such as cement production.

464 An analysis by GHG was performed for each product family, and several relevant results are presented in the
 465 following.

466 An interesting case is that of the S&M family, composed of wooden floors, floating screed and mortar in concrete,
 467 insulation material and walls in timber frames. Its relative contribution varies according to the indicator and the
 468 time horizon (Figure 6), and its GMTC and CRF curves have three peaks (Figure 5). These curves are decomposed
 469 in Figure 7 according to the GHG contribution.

470



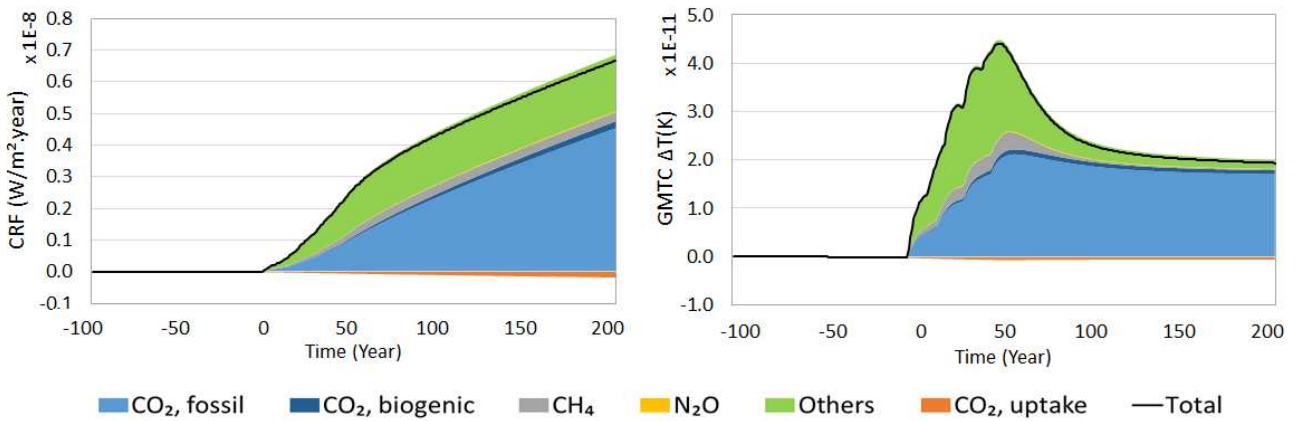
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473 Figure 7: Contribution analysis of principal GHGs to CRF ($\text{W}\cdot\text{m}^{-2}$) and GMTC (K) for the S&M family (the
474 functional unit is the building).

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479 Figure 8: Contribution analysis of the principal GHGs to CRF ($\text{W}\cdot\text{m}^{-2}$) and GMTC (K) for the HVAC family
480 (the functional unit is the building).

481

482 The S&M family uses a large amount of wood-based materials, and the effect of CO₂ capture can reduce the total
483 temperature increase by approximately 1/3 in the long term. The three temperature peaks are observed due to the
484 replacement and end of life of some materials, i.e. a combination of landfilling and incineration (from EPDs),
485 generating primarily CH₄ and biogenic CO₂ (from wood) emissions. This example also emphasizes the influence
486 of CH₄ on the steep temperature peaks. This end-of-life behaviour was observed for all product families.

487 Another example, the HVAC family (Figure 8), contains refrigerants known for their climate change effects. At
488 the temperature peak, HFC-134a (ethane, 1,1,1,2-tetrafluoro-) alone is responsible for 36% of the peak (just after
489 fossil CO₂ with 46%) due to its extremely high radiative efficiency (10,000 times higher than that of CO₂). In the
490 long term, GMTC only depends on the CO₂ concentration (because CO₂ is 30 times more persistent than HFC-
491 134a). The CRF indicator is by far dominated by fossil CO₂ due to its higher persistence in the atmosphere. The
492 specific parameters of main GHG and the relative contribution of the main GHG to the total GMTC is presented
493 in SI5 (Tables SI5 and SI6 - gases with contribution lower than 1% were not reported).

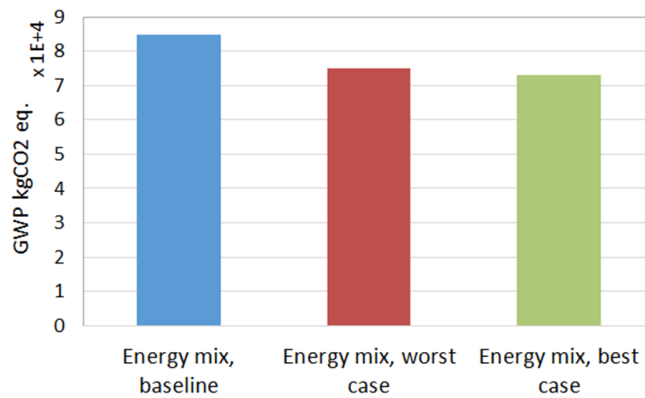
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495 **3.2. Alternative scenarios**

496 For simplicity and clarity, the simulations were performed only for the sub-systems concerned by a parameter
497 modification and not for the entire building. Here, the most interesting results are presented per impact indicator
498 for LCA and DLCA, showing important differences or similarities between the two LCA methods.

499 *SI. Electricity mix.* Figure 9 presents the conventional LCA results for GWP100 (following EN15804). The worst-
500 and best-case scenarios show 11.5% and 13.8% reductions, respectively. Even though the electricity mix
501 composition radically evolved due to the replacement of most of the nuclear power by other renewable energy
502 sources, the impact did not change dramatically. The same energy consumption model (operational energy) leads
503 to the dynamic indicator results presented in Figure 10. There is no clear difference between the worst- and best-
504 case scenarios, and, contrary to the conventional LCA results, DLCA ranks the three scenarios differently. At 100
505 years, both the worst- and best-case scenarios have a 7% higher CRF than the baseline and a 10% higher GMTC.
506 The small difference between the baseline and the other scenarios is explained by the fact that nuclear power
507 already produces energy with a very low carbon footprint (according to the current inventory dataset in ecoinvent
508 for the French electricity mix) and replacing it by renewable systems does not significantly modify this
509 performance. When analysing the benefit of future production mixes, the ranking is inverted for conventional
510 LCA and DLCA. This result is explained by the way biogenic CO₂ is considered in the two methods. In both the
511 best- and worst-case scenarios, the contribution of bio-based resources to the French mix tends to increase over
512 time (Figure SI3). Therefore, CO₂ uptake by biomass and its release when generating energy modifies the
513 atmospheric CO₂ balance during the concerned period (the use phase of the building). The dynamics of biogenic
514 CO₂ is correctly considered in DLCA, while it is missing in conventional LCA, which results in an incorrect
515 ranking.

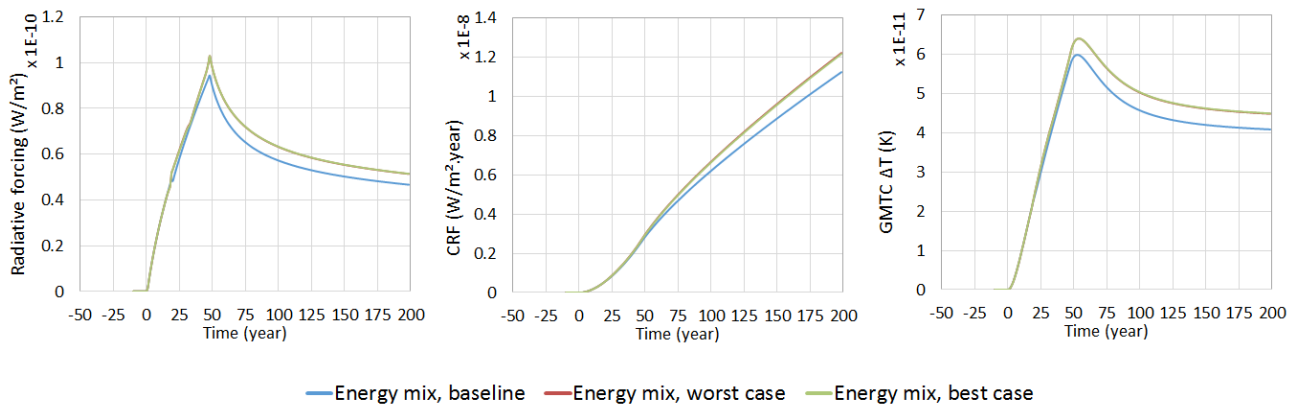
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518 Figure 9: LCA results for the electricity mix scenarios: GWP100 (the functional unit is the amount of electricity
519 consumption in the use stage of the building).

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522 Figure 10: DLCA results for the electricity mix scenarios: the dynamic indicators for climate change impacts
523 (the functional unit is the amount of electricity consumption in the use stage of the building).

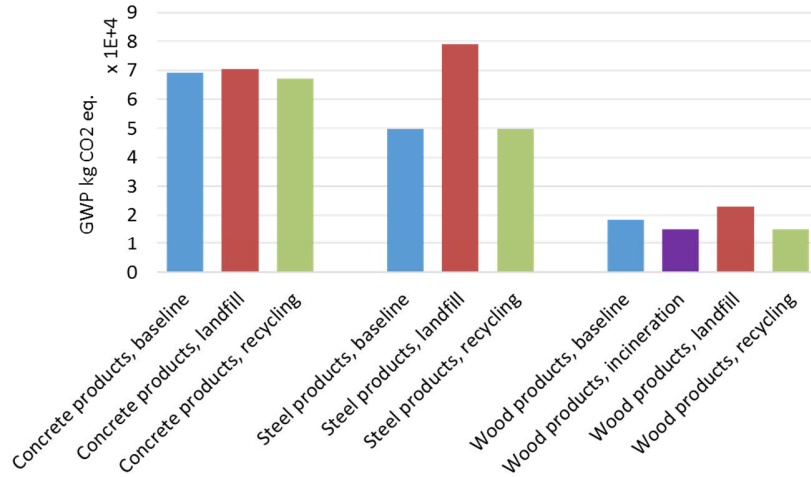
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525 *S2. Energy efficiency at product manufacturing.* An energy consumption reduction of 10% per decade for the most
526 energy-intensive processes had only a small effect on the four indicators: a 4% reduction for GWP with respect to
527 the baseline scenario and 3% and 4% reductions for CRF and GMTC, respectively, at year 100 (SI-7, Figures SI4,
528 SI5).

529 *S3. End of life for concrete, steel and wood products.* For each type of material, the system boundaries encompass
530 all life cycle stages (from A1 to C4, see Figure 2) and all products containing that material, including variations in
531 the waste treatment processes (landfill, incineration or recycling, Table 3) at the end of life of the products. The
532 reference flow of each material was calculated with respect to the functional unit of the entire case study, i.e. the
533 three single attached houses for 50 years. The construction products concerned in this scenario are listed in SI-6
534 with their respective end-of-life processes. Following the GWP100 indicator in Figure 11, landfilling is the most
535 impactful process, while recycling does not provide a large benefit with respect to the baseline. Wood products

536 have a smaller impact than all the other materials, even with incineration as the end-of-life process. Accordingly,
 537 100% incineration appears to be one of the less impactful scenarios, equivalent to 100% recycling.

538



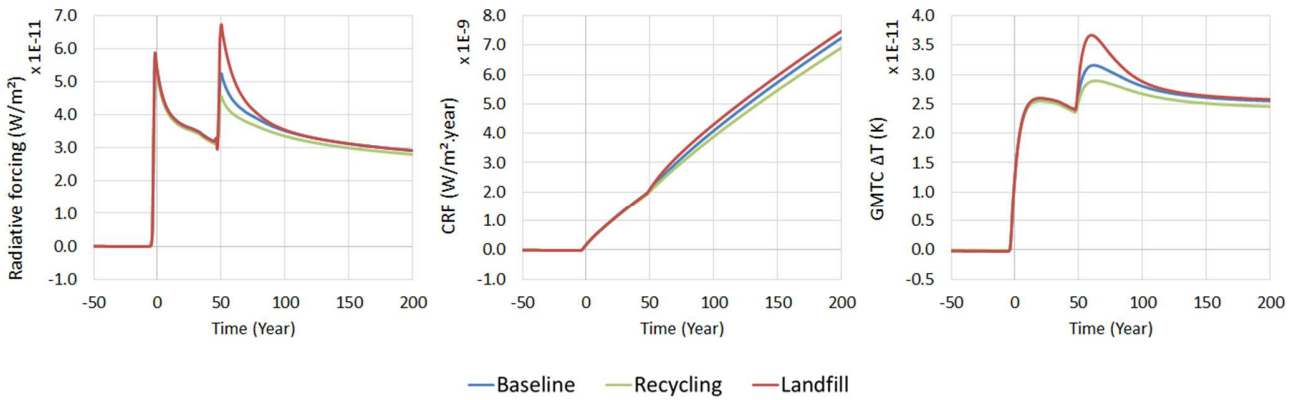
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540 Figure 11: GWP100 results for concrete, steel and wood products with different end-of-life technologies (the
 541 functional unit is the amount of products produced, used and eliminated for one building).

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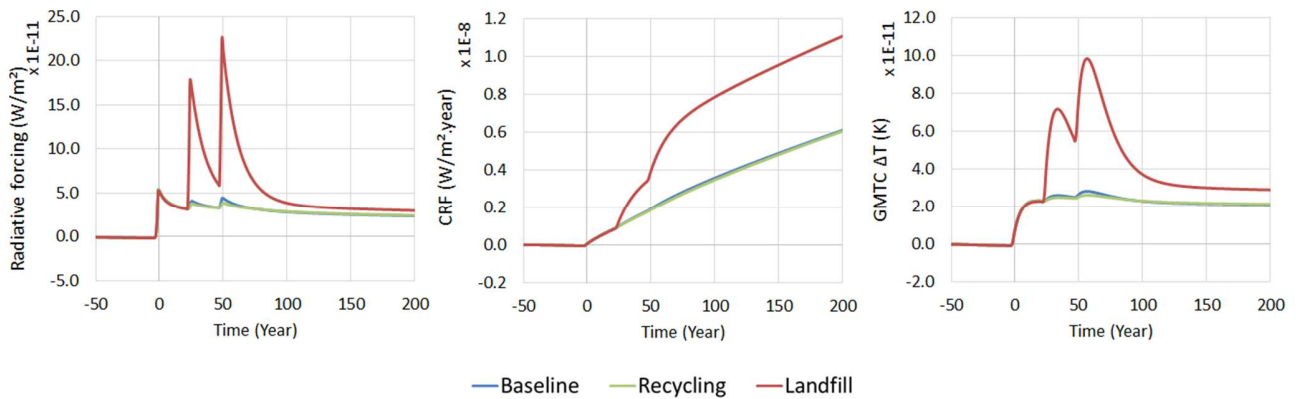
Concrete products



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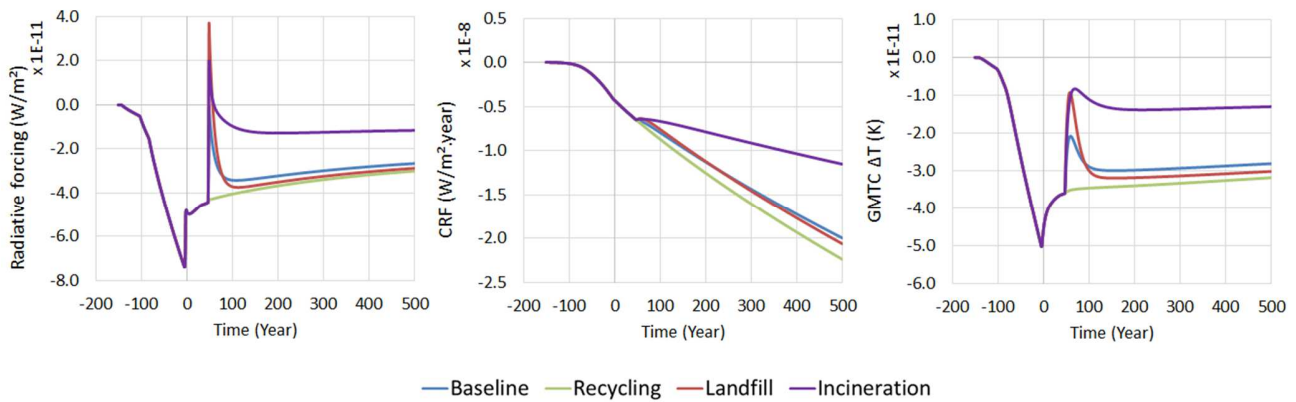
Steel products



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Wood products



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Figure 12: Dynamic climate change indicators for concrete (top), steel (middle) and wood (bottom) products with different end-of-life technologies (the functional unit is the amount of products produced, used and eliminated for one building).

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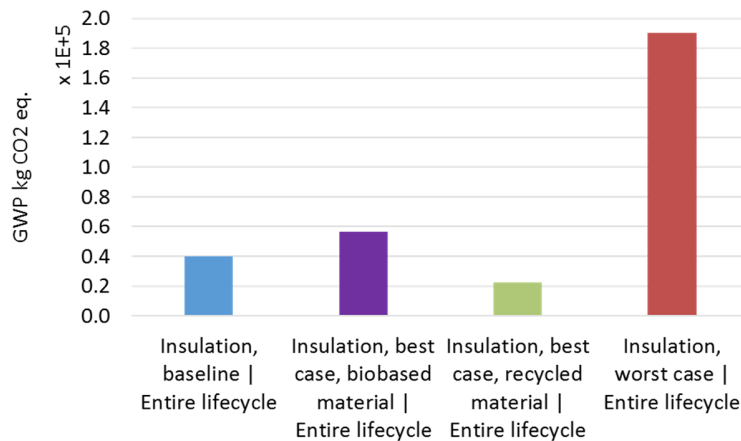
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Figure 12 represents the dynamic profiles of the climate change indicators. For concrete and steel materials, two and three events appear, respectively, on both the RF and GMTC curves for each of the three scenarios. The first peak (near time zero) corresponds to the construction product manufacturing and is therefore identical for all scenarios, while the others correspond to end-of-life activities (near year 50, and one intermediary peak for steel products). The worst scenario is 100% landfilling, while 100% recycling results in a small benefit. This feature is akin to conclusions from conventional LCA. Concerning wood products, two events are observed: the first corresponds to trees cut (and is the same for all four scenarios) and the second corresponds to the end of life of the building. The less impacting scenario is recycling, followed by landfilling and the baseline scenario, while the worst is incineration. This ranking is different from those obtained with GWP100 indicator. The dynamic indicators have globally negative values demonstrating the beneficial effect of CO₂ capture by tree growth far in the past. The GMTC indicators of the incineration and landfilling scenarios present very similar peak values at the end of life but very different subsequent evolutions. This behaviour is explained by the nature of the emitted GHGs.

565 The 100% incineration scenario nearly exclusively emits CO₂, while the landfilling scenario emits a mixture of
 566 CH₄ and CO₂. Because CH₄ is a short-lived gas, GMTC declines much more rapidly for landfilling and, in the long
 567 term, only the effect of CO₂ persists. Therefore, the behaviour of the baseline GMTC is explained by its mix of
 568 end-of-life processes: recycling, landfilling and incineration.

569 *S4. Technology of end-of-life scenarios for the HVAC system.* Here also, very little difference was observed
 570 between the scenarios, with landfilling being the worst scenario according to the four climate change indicators.
 571 The particularity of this system (SI-7, Figures SI6 and SI7) is that the end-of-life processes occur at multiple
 572 moments during the lifetime of the building because replacements of various components take place with distinct
 573 schedules (e.g. the electric convector is replaced three times, the heat pump is replaced four times and the
 574 ventilation system is replaced two times).

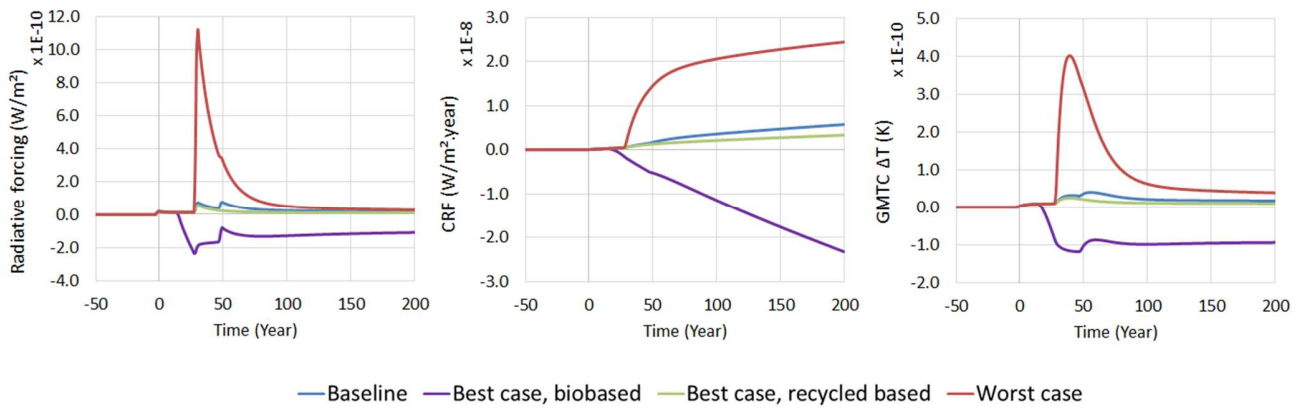
575 *S5. Technological innovations of insulation materials.* The conventional insulation materials of mineral wool,
 576 glass wool and polyurethane were all replaced at year 30 in the best-case scenario (Table 3) by two innovative
 577 materials (a bio-based one and one composed of recycled materials). GWP100 (Figure 13) placed the recycled
 578 material in the first position, followed by the baseline, the bio-based material and, far behind, extruded polystyrene
 579 (the worst case).



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582 Figure 13: GWP100 results for the insulation material scenarios (the functional unit is the amount of insulation
 583 material necessary for one building).

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Figure 14: Dynamic climate change indicators for the insulation material scenarios (the functional unit is the amount of insulation material necessary for one building).

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4. Discussion

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Situation in the climate context. The last IPCC report [2] mentioned the building and construction sectors as key actors for reducing GHG emissions. The first critical climate targets are placed between 2030 and 2052, with the

610 objective being to not surpass a temperature increase of 1.5°C. Moreover, net GHG emissions should be zero by
611 2050. The long lifetimes of buildings need to be placed on a time scale with respect to such climate targets. This
612 is what Figure 5 shows for the case study. The critical period is situated in the middle of the building lifetime for
613 a building constructed in 2015 and currently inhabited. The building should reach zero net emissions towards its
614 end of life, meaning that no temperature peaks should appear at this time horizon. Otherwise, as the figure shows,
615 the temperature peaks will increase with time until 2065 for all contributors and, after that, GMTC will never fall
616 to its initial value (see also Figure 3). This case study provides evidence of the importance of performing *ex-ante*
617 dynamic evaluations of future, new typologies of buildings and placing the system in the actual temporal context
618 of climate evolution and climate strategies.

619 *Influence of GHG nature and timing on climate indicators.* The parameters determining the climate footprint of a
620 system are the nature and quantity of the GHGs emitted/captured and the emission profile through time. Due to
621 the variability in the lifetimes of gases (examples in SI) and their radiative efficiencies, the intensities of their risks
622 related to climate perturbation are also variable depending on the gas, that is, i) short-lived gases with high radiative
623 efficiency (e.g. CH₄ and HFC-134a, Figures 7 and 8) generate high and steep temperature peaks (more harmful
624 for living species), while ii) long-lived gases, especially CO₂, have persistent impacts for long periods far after the
625 end time of the emission with high cumulative effects.

626 In addition, the temporal profile of the emissions (pulse or continuous and the emission duration) determines the
627 intensity of the effect and whether the effect spreads on a long time scale. The same emission is more harmful
628 when it occurs late in time than early because it adds a supplementary temperature increase at an already higher
629 temperature (the temperature is continuously increasing) [40]. In addition, the same quantity of GHG emission has
630 a smaller impact when the emission is spread over a long time interval than if the emission is released
631 instantaneously: a sudden large emission will generate a high temperature peak, as in the case of HFC-134a. As a
632 general trend, a continuous emission over a period results in continuously increasing dynamic indicators, with a
633 peak corresponding to the end of the emission period, as in the case of household energy consumption.

634 As Figures 3 and 5 show, the CRF indicator always increases due to the persistence of GHG in atmosphere beyond
635 the lifetime of the system; it stores the history of the emissions and never declines (except if a capture process
636 offsets the emissions). The GMTC indicator is critical (peaks) during the lifetime of the system prolonged with
637 several years. Concerning the timing, the highest GMTC appears at the end of life of the building in this case study,
638 demonstrating that the highest threat is in the near future. These features clearly demonstrate that a fixed, universal
639 time horizon for the impact analysis is not justified. Instead, impact observations all along the lifetime of the
640 system and several decades beyond ensure a better knowledge of the behaviour of a system and the identification
641 of hot spots.

642 *The importance of considering GHG capture and biogenic carbon.* The analysis of different families of
643 construction products sheds light on the importance of considering GHG capture within the boundaries of the life

644 cycle of a system. For the GHG emissions, the capture efficiency in terms of the climate response depends on the
645 nature and amount of the GHG and on the timing and profile of the capture process. In the present case study, only
646 CO₂ was captured by trees and in a much lesser extent by concrete carbonation. The effect of CO₂ uptake is visible
647 in Figures 5, 7, 12 and 14 and can be observed in the offset of the GHG emissions, quantified by the CRF and
648 GMTC indicators. However, the offset effect depends on the time profiles and the timings of the emission and
649 capture processes and is smaller when the two processes are temporally remote. This observation is in agreement
650 with the literature in the field (e.g., [9], [12], [13]). It is therefore possible to (partially) neutralize the effect of
651 GHG emissions (as shown by the S&M family) via a sufficient CO₂ capture with an appropriate timing within the
652 boundaries of the same system (e.g. the life cycle system of the studied house).

653 *Relevant information that DLCA can provide - comparison with conventional LCA.* DLCA provides important
654 information concerning the amplitude and rate of change of climate parameters, which conventional LCA cannot
655 provide. Figures 4 and 6 demonstrate that it is actually irrelevant to compare results obtained with GWP and
656 dynamic indicators, especially when capture processes are present, because i) the ranking and proportion of the
657 contributors can change following the time horizon for a given dynamic indicator and ii) the ranking and proportion
658 of the contributors can differ between the three represented indicators. For example, in the case of scenario 3,
659 when comparing the three material groups (steel, concrete and wood), the dynamic indicators clearly discriminate
660 wood products from the two other groups. While conventional LCA calculates a significant GWP impact, the
661 dynamic indicators show that the carbon capture effect can offset and even overtake the effect of GHG emissions.
662 The dynamic indicators are very well adapted to account for the effect of biogenic CO₂ and, consequently, can be
663 used to define strategies for the neutralization of the effects of other GHGs. The fact that the contribution results
664 in Figure 4 are similar between the climate indicators is a particular situation and cannot be generalized: the
665 inventory is much aggregated on five contributors, with a small global contribution of biogenic CO₂ and a
666 dominance of fossil CO₂ (long life GHG), and with a global emission increasing with the time over the lifetime
667 (Figure 3 shows increasing RF for the main four contributors).

668 Another example is the effect of the electricity mix, as shown in Figures 9 and 10. The transition from a nuclear-
669 dominated production to a renewable-based mix is accompanied by a slight GWP100 reduction and a slight
670 increase in CRF and GMTC. This unexpected behaviour (one would have assumed that a renewable energy system
671 would produce a smaller impact than the current situation) is explained by the fact that biogenic CO₂
672 emissions/capture are not considered in GWP100. All electricity generation technologies constituting the different
673 electricity mix scenarios were taken from ecoinvent without any modification. The main biomass used in these
674 processes is wood from sustainable forests, such as oak, spruce and beech, with long growth times (100–150 years).
675 The long growth duration (translating to a low capture rate of CO₂) is followed by the sudden emission of the
676 embodied carbon via incineration. The result is a small but positive temperature peak, i.e. in GMTC. This temporal
677 behaviour explains this surprising result and, at the same time, suggests that short rotation biomass be used for

678 energy production instead of long-lived trees. Finally, this result should also be placed in the multicriteria context
679 by considering a panel of impact indicators, climate change impact being one of them; for instance nuclear energy
680 production is accompanied by important impacts ensued from ionising radiations.

681 *Choosing mitigation options within the temporal context.* The dynamic metrics emphasize the importance of
682 differentiating mitigation actions according to the type of gas and the emission timing. Based on the case study,
683 main mitigation objectives could be proposed for the different contributors (Table SI14). A global objective is the
684 reduction of energy consumption, especially during the use stage of a building. Indeed, the results obtained for
685 sub-scenario S6 - 8, with a combination of various parameters (energy efficiency of equipment and insulation,
686 occupant behaviour) attest to an energy consumption increase of 37% over 50 years. In addition, reducing energy
687 consumption is not enough but should be combined with the integration of more renewable sources in the power
688 generation mix as early as possible. Moreover, the necessary massive reduction in the carbon emissions requires
689 the use of non-carbon renewable resources (decarbonized energy) or sub-systems with CO₂ capture for impact
690 neutralization in order to reverse the trends observed in Figure 10. The case study indicates that, by combining the
691 life cycle system of a building with a sub-system of a sustainable forest, it is possible to obtain a net effect near
692 zero for CRF and/or GMTC.

693 For certain product families, for example, H&MEWS and F&EC, the emissions were primarily generated at the
694 end of life of the product. In this case, the concerned industrial sectors should concentrate on eliminating the
695 punctuated emissions from waste treatment, for example, by promoting recycling. Conversely, other families such
696 as Energy Network or F&I present more important impacts during the fabrication/construction processes. In this
697 case, a revision of the technologies and materials used should improve the environmental performance of these
698 contributors. Other families, e.g. HVAC, contribute GHG emissions throughout the entire product life cycle and
699 determine important increases in temperature and cumulative radiative forcing. Processes and materials involved
700 in component manufacturing should be replaced by less impactful ones (replace for example HFC-134a with other
701 substances with lower radiative efficiency), and end-of-life strategies should promote recycling.

702 The obtained DLCA results are case specific, dependent on the specificities of the GHG emission and capture
703 (timing, temporal profile, amount and GHG nature) and cannot be extrapolated to other building typologies; the
704 graphs presented in Figure 5 represent, in fact, the footprint of the specific modelled building. The wood species
705 used for the construction materials inecoinvent are beech, oak, birch, pine, spruce and eucalyptus. If other wood
706 species are used for a given construction product, the result of coupled emission and capture will be different,
707 depending on the CO₂ flows and the time gap between capture and emission, and a shorter tree growth time would
708 be beneficial. Finally, a concrete-based building cannot contribute to GHG offsets via significant gas capture
709 because the life cycle system of such a building does not include a significant amount of wood. In this case,
710 mitigation actions are restrained to and dependent on technological evolution, especially for the end-of-life stage.

711 *Increasing temporal representativeness within a complex dynamic model.* Such a modelling approach implies
712 managing (very) different dynamics (temporal variations) at the level of LCI and LCIA, and numerical resolution
713 parameters for the time variable. For example, the energy consumption in the use stage of buildings can be
714 calculated with different time resolutions. An hourly resolution has commonly been used and linked to the grid
715 composition, as mentioned in the Introduction section, to evaluate the GWP100 value of the energy consumption.
716 In previous studies (e.g., [12], [22]), it has been observed that climate indicators are sensitive to emissions
717 described with a time resolution of several months to one year, and this time-granulometry is sufficiently narrow
718 given the temporal characteristics of the environmental phenomena (e.g. gas mixing and interactions with the
719 ocean and biosphere and thermal transfers) involved in climate perturbation. In the present case study, the energy
720 consumption was simulated with hourly resolution (using the COMETH software) and was then used in LCI with
721 a yearly value (the hourly data were summed up over a year to obtain the yearly consumption). This simplification
722 was adopted for the following reasons: i) the daily modification of the French electricity mix has not significant
723 repercussion on the GHG emission variation because the mix is based on nuclear power (or renewable sources in
724 the future) as detailed in section 2.3.3 and SI – Fig. SI3; ii) very short time variations of the GHG emissions are
725 not captured in the climate dynamic indicators, as explained here above; iii) the complexity resulted from a hourly
726 variable electricity mix would lead to an unacceptable higher computation time for LCI.

727 The dynamic LCI was calculated with a time step of 1 day (numerical resolution of simulations) in the DyPLCA
728 tool in order to capture the processes with short duration and their related intermediary and elementary flows.
729 Consequently, the results were obtained as discrete values of elementary flows for each day, during the whole life
730 cycle time. The time step influences the simulation duration and is a limiting factor in current versions of the used
731 tool, especially when many scenarios of technological change are considered together on the same timeline.

732 The technology representativeness with respect to time is already a requirement for system modelling in LCA and
733 still remains a condition for temporal representativeness in DLCA. Placing the timeline of the studied system's
734 life cycle on the calendar helps at: i) choosing the relevant technologies and their performances for a given period
735 (e.g. in this case study the temporal evolution of the performance of energy equipment); ii) an easier evaluation of
736 missing information for future scenarios (e.g. from when on our knowledge about the recycling technologies
737 becomes uncertain); iii) including external factors dependent on the time, as economic and social evolution,
738 climate conditions, etc. (family evolution for instance in this work).

739 Given the fact the LCI was based (in the present work) on ecoinvent, EPD information and additional simulations,
740 the global LCI model gathers different uncertainty sources to which the temporal characteristics of the processes
741 and supply chains are added. All these complex parameters deserve further investigation together with an
742 uncertainty evaluation; however, such aspects are beyond this study, which focused on the feasibility and
743 usefulness of a DLCA using a real case application.

744

745 **5. Conclusions**

746 The methodology of DLCA for buildings was applied to a case study with already existent or recently developed
747 tools: the EPD database for the building sector, a new developed database for temporal parameters in the building
748 sector, the SimaPro software and the ecoinvent database, and a recent DyPLCA tool for dynamic LCI calculations
749 coupled with models for dynamic indicators for climate change impact evaluations. The specific temporal
750 characteristics were collected on site, simulated (e.g. operational energy consumption) or obtained from sectorial
751 databases. The simulation results were obtained as climate change indicators as a function of time, without a
752 predefined time horizon (radiative forcing, cumulated radiative forcing and global mean temperature change).

753 The literature reports many temporal LCA approaches in the building domain. However, to the best of our
754 knowledge, this is the first application of a complete DLCA using operational software and temporal databases
755 (DyPLCA) at the level of LCI and LCIA, addressing all components and contributors over the entire life cycle of
756 a building (at both the foreground and background levels) and using dynamic impact indicators.

757 In this analysis, details of the dynamic climate change impacts of 10 construction product families and various
758 operational energy scenarios were individually analysed. The results show that each component has its own climate
759 footprint determined by the nature of the GHG, the emission timing and the intensity. Analyses of the results
760 highlighted the effects of the studied systems or sub-systems and indicated which mitigation actions are necessary.

761 Such analyses should always be placed in the climate context, with regard to the fixed objectives of limiting the
762 global temperature increase within critical time windows. It is in this way that the evaluation can be understood
763 and provides effective support to decision making. In the present case study, the lifetime of the building
764 encompassed the critical period of 2030–2050, which is considered to be a turning point for limiting the
765 temperature increase to 1.5°C, with an objective of zero net emissions beyond 2050.

766 Finally, a comparison between conventional LCA and DLCA results is not straightforward due to the different
767 physical meanings of the indicators (with different measurement units) and the concept of time horizon in the
768 GWP definition. A comparison was attempted after choosing the most relevant points in time: 100 years for
769 GWP100 and the end of lifetime where the last temperature peak of the system occurs. The main outcome of the
770 comparison was that the results can differ greatly, especially when GHG capture is present in the LCI, that is, i)
771 the ranking and proportion of the contributors can change according to the time horizon for a given dynamic
772 indicator and ii) the ranking and proportion of the contributors can be different between the considered indicators,
773 demonstrating the need for a more detailed assessment (at least two dynamic indicators) in the context of the
774 imminent climate target.

775

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783 **References**

- 784 [1] IEA, UNEP, 2018 Global Status Report: towards a zero-emission, efficient and resilient buildings and
785 construction sector, Int. Energy Agency U. N. Environ. Program. (2018).
- 786 [2] IPCC, Global warming of 1.5°C, 2018. <http://www.ipcc.ch/report/sr15/> (accessed March 5, 2019).
- 787 [3] ISO, ISO 14040 - Environmental Management - Life Cycle Assessment - Principles and Framework.
788 International Standard., (2006a).
- 789 [4] ISO, ISO 14044 - Environmental Management - Life Cycle Assessment - Principles and Framework.
790 International Standard., (2006b).
- 791 [5] C. Breton, P. Blanchet, B. Amor, R. Beauregard, W.-S. Chang, Assessing the Climate Change Impacts of
792 Biogenic Carbon in Buildings: A Critical Review of Two Main Dynamic Approaches, Sustainability. 10
793 (2018) 2020. doi:10.3390/su10062020.
- 794 [6] K. Negishi, L. Tiruta-Barna, N. Schiopu, A. Lebert, J. Chevalier, An operational methodology for applying
795 dynamic Life Cycle Assessment to buildings, Build. Environ. 144 (2018) 611–621.
796 doi:10.1016/j.buildenv.2018.09.005.
- 797 [7] C.K. Anand, B. Amor, Recent developments, future challenges and new research directions in LCA of
798 buildings: A critical review, Renew. Sustain. Energy Rev. 67 (2017) 408–416.
799 doi:10.1016/j.rser.2016.09.058.
- 800 [8] S. Frijia, S. Guhathakurta, E. Williams, Functional Unit, Technological Dynamics, and Scaling Properties
801 for the Life Cycle Energy of Residences, Environ. Sci. Technol. 46 (2012) 1782–1788.
802 doi:10.1021/es202202q.
- 803 [9] W.O. Collinge, A.E. Landis, A.K. Jones, L.A. Schaefer, M.M. Bilec, Dynamic life cycle assessment:
804 framework and application to an institutional building, Int. J. Life Cycle Assess. 18 (2013) 538–552.
805 doi:10.1007/s11367-012-0528-2.
- 806 [10] C. Roux, P. Schalbart, B. Peuportier, Accounting for temporal variation of electricity production and
807 consumption in the LCA of an energy-efficient house, J. Clean. Prod. 113 (2016) 532–540.
808 doi:10.1016/j.jclepro.2015.11.052.
- 809 [11] C. Roux, P. Schalbart, E. Assoumou, B. Peuportier, Integrating climate change and energy mix scenarios in
810 LCA of buildings and districts, Appl. Energy. 184 (2016) 619–629. doi:10.1016/j.apenergy.2016.10.043.
- 811 [12] C. Roux, P. Schalbart, B. Peuportier, Development of an electricity system model allowing dynamic and
812 marginal approaches in LCA—tested in the French context of space heating in buildings, Int. J. Life Cycle
813 Assess. 22 (2017) 1177–1190. doi:10.1007/s11367-016-1229-z.
- 814 [13] D. Vuarnoz, S. Cozza, T. Jusselme, G. Magnin, T. Schafer, P. Couty, E.-L. Niederhauser, Integrating hourly
815 life-cycle energy and carbon emissions of energy supply in buildings, Sustain. Cities Soc. 43 (2018) 305–
816 316. doi:10.1016/j.scs.2018.08.026.

- 817 [14] A.A.W. Karl, E. Maslesa, M. Birkved, Environmental performance assessment of the use stage of buildings
818 using dynamic high-resolution energy consumption and data on grid composition, *Build. Environ.* 147
819 (2019) 97–107. doi:10.1016/j.buildenv.2018.09.042.
- 820 [15] W.O. Collinge, H.J. Rickenbacker, A.E. Landis, C.L. Thiel, M.M. Bilec, Dynamic Life Cycle Assessments
821 of a Conventional Green Building and a Net Zero Energy Building: Exploration of Static, Dynamic,
822 Attributional, and Consequential Electricity Grid Models, *Environ. Sci. Technol.* 52 (2018) 11429–11438.
823 doi:10.1021/acs.est.7b06535.
- 824 [16] Y. Zhang, Taking the Time Characteristic into Account of Life Cycle Assessment: Method and Application
825 for Buildings, *Sustainability.* 9 (2017) 922. doi:10.3390/su9060922.
- 826 [17] X. Zhang, F. Wang, Analysis of embodied carbon in the building life cycle considering the temporal
827 perspectives of emissions: A case study in China, *Energy Build.* 155 (2017) 404–413.
828 doi:10.1016/j.enbuild.2017.09.049.
- 829 [18] B. Gimeno-Frontera, M.D. Mainar-Toledo, A. Sáez de Guinoa, D. Zambrana-Vasquez, I. Zabalza-Bribián,
830 Sustainability of non-residential buildings and relevance of main environmental impact contributors'
831 variability. A case study of food retail stores buildings, *Renew. Sustain. Energy Rev.* 94 (2018) 669–681.
832 doi:10.1016/j.rser.2018.06.027.
- 833 [19] M. Fouquet, A. Levasseur, M. Margni, A. Lebert, S. Lasvaux, B. Souyri, C. Buhé, M. Woloszyn,
834 Methodological challenges and developments in LCA of low energy buildings: Application to biogenic
835 carbon and global warming assessment, *Build. Environ.* 90 (2015) 51–59.
836 doi:10.1016/j.buildenv.2015.03.022.
- 837 [20] S. Su, X. Li, Y. Zhu, B. Lin, Dynamic LCA Framework for Environmental Impact Assessment of Buildings,
838 *Energy Build.* (2017). doi:10.1016/j.enbuild.2017.05.042.
- 839 [21] G. Cardellini, C.L. Mutel, E. Vial, B. Muys, Temporalis, a generic method and tool for dynamic Life Cycle
840 Assessment, *Sci. Total Environ.* 645 (2018) 585–595. doi:10.1016/j.scitotenv.2018.07.044.
- 841 [22] A. Levasseur, P. Lesage, M. Margni, L. Deschênes, R. Samson, Considering Time in LCA: Dynamic LCA
842 and Its Application to Global Warming Impact Assessments, *Environ. Sci. Technol.* 44 (2010) 3169–3174.
843 doi:10.1021/es9030003.
- 844 [23] F. Cherubini, G.P. Peters, T. Berntsen, A.H. Strømman, E. Hertwich, CO₂ emissions from biomass
845 combustion for bioenergy: atmospheric decay and contribution to global warming: Global warming potential
846 of CO₂ from bioenergy, *GCB Bioenergy.* 3 (2011) 413–426. doi:10.1111/j.1757-1707.2011.01102.x.
- 847 [24] N. Ericsson, C. Porsö, S. Ahlgren, Å. Nordberg, C. Sundberg, P.-A. Hansson, Time-dependent climate
848 impact of a bioenergy system - methodology development and application to Swedish conditions, *GCB
849 Bioenergy.* 5 (2013) 580–590. doi:10.1111/gcbb.12031.
- 850 [25] D. Beloin-Saint-Pierre, R. Heijungs, I. Blanc, The ESPA (Enhanced Structural Path Analysis) method: a
851 solution to an implementation challenge for dynamic life cycle assessment studies, *Int. J. Life Cycle Assess.*
852 19 (2014) 861–871. doi:10.1007/s11367-014-0710-9.
- 853 [26] D. Beloin-Saint-Pierre, A. Levasseur, M. Margni, I. Blanc, Implementing a Dynamic Life Cycle Assessment
854 Methodology with a Case Study on Domestic Hot Water Production, *J. Ind. Ecol.* (2016).
855 doi:10.1111/jieec.12499.
- 856 [27] A. Pinsonnault, P. Lesage, A. Levasseur, R. Samson, Temporal differentiation of background systems in
857 LCA: relevance of adding temporal information in LCI databases, *Int. J. Life Cycle Assess.* 19 (2014) 1843–
858 1853. doi:10.1007/s11367-014-0783-5.
- 859 [28] L. Tiruta-Barna, Y. Pigné, T. Navarrete Gutiérrez, E. Benetto, Framework and computational tool for the
860 consideration of time dependency in Life Cycle Inventory: proof of concept, *J. Clean. Prod.* 116 (2016) 198–
861 206. doi:10.1016/j.jclepro.2015.12.049.

- 862 [29] Y. Pigné, L. Tiruta-Barna, T. Navarrete-Gutiérrez, T. Gibon, T. Schaubroeck, E. Popovici, A.H. Shimako,
863 E. Benetto, A tool to compute fully time-differentiated life cycle environmental impacts of production-
864 consumption systems, *Submitt. Int. J. Life Cycle Assess.* (2019).
- 865 [30] A.H. Shimako, L. Tiruta-Barna, Y. Pigné, E. Benetto, T. Navarrete Gutiérrez, P. Guiraud, A. Ahmadi,
866 Environmental assessment of bioenergy production from microalgae based systems, *J. Clean. Prod.* 139
867 (2016) 51–60. doi:10.1016/j.jclepro.2016.08.003.
- 868 [31] A.H. Shimako, L. Tiruta-Barna, A. Ahmadi, Operational integration of time dependent toxicity impact
869 category in dynamic LCA, *Sci. Total Environ.* 599–600 (2017) 806–819.
870 doi:10.1016/j.scitotenv.2017.04.211.
- 871 [32] A.H. Shimako, L. Tiruta-Barna, A.B. Bisinella de Faria, A. Ahmadi, M. Spérandio, Sensitivity analysis of
872 temporal parameters in a dynamic LCA framework, *Sci. Total Environ.* 624 (2018) 1250–1262.
873 doi:10.1016/j.scitotenv.2017.12.220.
- 874 [33] IPCC, ed., *Climate Change 2013 - The Physical Science Basis: Working Group I Contribution to the Fifth*
875 *Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press,
876 Cambridge, 2013. doi:10.1017/CBO9781107415324.
- 877 [34] M.Z. Hauschild, M. Huijbregts, O. Jolliet, M. Macleod, M. Margni, D. van de Meent, R.K. Rosenbaum, T.E.
878 McKone, Building a Model Based on Scientific Consensus for Life Cycle Impact Assessment of Chemicals:
879 The Search for Harmony and Parsimony, *Environ. Sci. Technol.* 42 (2008) 7032–7037.
880 doi:10.1021/es703145t.
- 881 [35] R.K. Rosenbaum, T.M. Bachmann, L.S. Gold, M.A.J. Huijbregts, O. Jolliet, R. Juraske, A. Koehler, H.F.
882 Larsen, M. MacLeod, M. Margni, T.E. McKone, J. Payet, M. Schuhmacher, D. van de Meent, M.Z.
883 Hauschild, USEtox—the UNEP-SETAC toxicity model: recommended characterisation factors for human
884 toxicity and freshwater ecotoxicity in life cycle impact assessment, *Int. J. Life Cycle Assess.* 13 (2008) 532–
885 546. doi:10.1007/s11367-008-0038-4.
- 886 [36] B. Haas, P. Corrales, Solution pour l’intéropérabilité avec COMETH, IBPSA. (2014).
- 887 [37] FME and MTES, French Ministry of the Environment, Ministère de la Transition Ecologique et Solidaire,
888 2016. <http://www.batiment-energiecarbone.fr/> (accessed January 12, 2018)
- 889 [38] CEN, EN 15978 - Assessment of environmental performance of buildings., *Eur. Comm. Stand.* (2012).
- 890 [39] K. Tanaka, G.P. Peters, J.S. Fuglestedt, Policy Update: Multicomponent climate policy: why do emission
891 metrics matter?, *Carbon Manag.* 1 (2010) 191–197. doi:10.4155/cmt.10.28.
- 892 [40] M.U.F. Kirschbaum, Climate-change impact potentials as an alternative to global warming potentials,
893 *Environ. Res. Lett.* 9 (2014) 034014. doi:10.1088/1748-9326/9/3/034014.
- 894 [41] O. Sidler, *Connaissance et maîtrise des usages spécifiques de l’électricité dans le secteur résidentiel*, (2009)
895 93. <https://www.enertech.fr/pdf/47/Maitrise%20demande%20electricite%20residentiel.pdf> (accessed
896 March 10, 2018)
- 897 [42] S. Lasvaux, *Étude d’un modèle simplifié pour l’analyse de cycle de vie des bâtiments*, PhD thesis, Mines
898 ParisTech, 2012.
- 899 [43] JRC European Commission, *Level(s): a common EU framework of core sustainability indicators for office*
900 *and residential buildings : parts 1 and 2, introduction to level(s) and how it works (Beta v1.0).*, (2017).
901 [https://publications.europa.eu/en/publication-detail/-/publication/f3c2fc97-f102-11e7-9749-](https://publications.europa.eu/en/publication-detail/-/publication/f3c2fc97-f102-11e7-9749-01aa75ed71a1/language-en/format-PDF)
902 [01aa75ed71a1/language-en/format-PDF](https://publications.europa.eu/en/publication-detail/-/publication/f3c2fc97-f102-11e7-9749-01aa75ed71a1/language-en/format-PDF) (accessed January 12, 2018).
- 903 [44] F. Stazi, F. Tittarelli, G. Politi, C. Di Perna, P. Munafò, Assessment of the actual hygrothermal performance
904 of glass mineral wool insulation applied 25 years ago in masonry cavity walls, *Energy Build.* 68 (2014) 292–
905 304. doi:10.1016/j.enbuild.2013.09.032.

- 906 [45] H.-J. Choi, J.-S. Kang, J.-H. Huh, A Study on Variation of Thermal Characteristics of Insulation Materials
907 for Buildings According to Actual Long-Term Annual Aging Variation, *Int. J. Thermophys.* 39 (2018).
908 doi:10.1007/s10765-017-2318-3.
- 909 [46] R. Hendron, I. Paper, NREL is operated by Midwest Research Institute - Battelle Contract No. DE-AC36-
910 99-GO10337 NOTICE, 2006.
- 911 [47] MTES, La loi de transition énergétique pour la croissance verte en actions, 2016. [https://www.ecologique-](https://www.ecologique-solidaire.gouv.fr/loi-transition-energetique-croissance-verte)
912 [solidaire.gouv.fr/loi-transition-energetique-croissance-verte](https://www.ecologique-solidaire.gouv.fr/loi-transition-energetique-croissance-verte) (accessed January 10, 2019)
- 913 [48] INSEE, Des ménages toujours plus nombreux, toujours plus petits - Insee Première - 1663, (2017).
914 <https://www.insee.fr/fr/statistiques/3047266> (accessed July 15, 2018).
- 915 [49] CSTB, Méthode de calcul Th-BCE 2012, 2011. [http://construction.senova.fr/telechargements/Annexe-](http://construction.senova.fr/telechargements/Annexe-arrete-methode-de-calcul-TH-B-C-E-2012-CSTB.pdf)
916 [arrete-methode-de-calcul-TH-B-C-E-2012-CSTB.pdf](http://construction.senova.fr/telechargements/Annexe-arrete-methode-de-calcul-TH-B-C-E-2012-CSTB.pdf) (accessed July 15, 2018)
- 917 [50] ADEME, Actualisation du scénario énergie-climat ADEME 2035-2050, 2017.
918 <https://www.ademe.fr/actualisation-scenario-energie-climat-ademe-2035-2050> (accessed July 15, 2018).
- 919
- 920