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# 1 A Life Cycle Scenario Analysis of different pavement technologies for Urban Roads

2

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10

## 11 Abstract

12 In the past, lowest price was the award criterion, given that structural capacity and safety were assured.

13 In the last years, environmental, energy, and long-term impacts have been introduced (climate change, resource  
14 depletion, energy consumption, generated solid waste, discharged water, and emissions).

15 Unfortunately, the introduction of new pavement technologies and materials (i.e., waste plastics) affects  
16 maintenance and rehabilitation processes and call for accurate and timeliness studies and criteria.

17 Consequently, this paper presents an energy and environmental assessment of an Italian urban road and considers  
18 different material-related scenarios that fully comply with emerging technologies.

19 A life-cycle approach is applied to assess energy and environmental impacts of a typical Italian urban road,  
20 according to the ISO 14040 series. In more detail, the authors assess the energy and environmental profile of  
21 different scenarios of bituminous mixtures. The aim of scenario analysis is to identify the less impacting scenario  
22 from an energy and environmental point of view. For each analysed scenario, the contribution of each life-cycle  
23 step to the total impacts and the energy and environmental hotspots are identified in order to define suitable options  
24 for improvement.

25 The results of the analysis show that step of material production, including raw material extraction and resource  
26 supply, is relevant to almost all the assessed impact categories (average contribution higher than 50%). This is  
27 mainly due to the production of bitumen, which is a petroleum-based product. Moreover, the scenario analysis  
28 highlights that the pavement scenarios that are characterized by the use of recycled materials involve lower energy  
29 and environmental impacts, due to the saving of virgin raw materials and avoided impacts for disposal.

30

31 **Keywords**

32 Energy, Environmental Impacts, Hot Mix Asphalt (HMA), Warm Mix Asphalt (WMA), Life Cycle Assessment,  
33 Reclaimed Asphalt Pavement (RAP).

34

35 **1. Introduction**

36 The rapid increase in energy demand and environmental impacts over the past few years requires the development  
37 of low-carbon and low-energy consumption at a global level. The reduction of energy requirement and the  
38 mitigation of environmental impacts have become key targets of EU policies for climate and energy, to be matched  
39 by means of strategies aimed at tackling climate change (European Commission, 2018, 2011; European Council,  
40 2014). In this context, after electricity and heat generation sector, which accounts for 42%, transport accounts for  
41 about 23% of global Greenhouse Gas (GHG) emissions in 2013 and for 30% of the total energy consumption (IEA,  
42 2015). Road construction GHG emissions represent 5-10% of total GHG emissions in the transport sector, but they  
43 are growing rapidly, especially in developing countries due to major ongoing road programs to support economic  
44 development (The World Bank, 2011)<sup>1</sup>. One of the major challenges of pavement engineering is to meet the ever-  
45 increasing demand of economic and natural resources related to construction and maintenance by means of  
46 environmentally sustainable technologies (Santero et al., 2011a). Considering that the amount of paved roads tends  
47 to grow over the years, special attention has to be given to decrease energy consumption and GHG emissions in  
48 sight of environmental sustainability (Araújo et al., 2014; Birgisdóttir et al., 2006).

49 Several paving technologies have been developed to reduce and mitigate the environmental impacts associated  
50 with the use of traditional Hot Mix Asphalt (HMA), such as Warm Mix Asphalt (WMA) (Mohammad et al. 2015),  
51 and HMA or WMA containing recycled materials. Among the most popular recycled materials are crumb rubber  
52 from end-of-life tires, reclaimed asphalt pavement (RAP) (Aurangzeb et al. 2014; Lee et al. 2010), and industrial  
53 wastes and by products (Carpenter & Gardner 2009), (Mladenovič et al. 2015).

54 In such a context, to adopt the life-cycle perspective to assess the energy and environmental impacts is becoming  
55 ever more important for new technologies on pavement construction.

56 The scientific literature in the field of road pavement LCA is growing and even more studies show that Life Cycle  
57 Assessment represents a useful methodology to support the selection of the preferred paving techniques, including

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<sup>1</sup>Greenhouse Gas Emissions Mitigation in Road Construction and Rehabilitation. A Toolkit for Developing Countries. The World Bank, 2011. <http://documents.worldbank.org/curated/en/660861468234281955/Transport-Greenhouse-gas-emissions-mitigation-in-road-construction-and-rehabilitation-A-toolkit-for-developing-countries>

58 all the phases in which structures and facilities are built, operation, maintenance, renovation, the disassembly, and  
59 the waste management (Gulotta et al., 2018; Mistretta et al., 2013).

60 Santero et al. (Santero et al., 2011a, 2011b) provided a summary of the application of LCA to pavements. This  
61 reflects the increased attention to the use of the life-cycle approach in assessing the environmental burdens of  
62 pavements. They presented recommendations and necessary actions to fill the identified research gaps with respect  
63 to construction, use, and end-of-life phases of pavement's life cycle.

64 Park et al. (Park et al., 2003) reported that the most energy-intensive step in a road life-cycle is the production of  
65 construction materials, and stated that the construction and demolition steps account for higher energy  
66 consumption than maintenance.

67 Some studies focused only on the energy consumption and greenhouse gas emissions, not assessing other impact  
68 categories. Among these, Thenoux et al. (Thenoux et al., 2007) reported that recycling with foamed bitumen  
69 involves a reduction of energy consumption up to 40%. Wang et al. (Wang et al., 2018) focused on the energy and  
70 GHG emission assessment associated with material production, construction, and pavement use. They included  
71 the effects of pavement rolling resistance on vehicle operation, highlighting that: i) for high traffic volumes rolling  
72 resistance is more important than construction; ii) for low traffic volume highways, construction quality and  
73 material selection play a particularly important role.

74 Blankendaal et al (Blankendaal et al., 2014) focused on the carbon footprint of roads, and found that material  
75 production accounts for 52.3% of the total carbon footprint in newly constructed roads, followed by the  
76 maintenance stage (24.3%), with a carbon footprint contribution of 1000-2500 kgCO<sub>2eq</sub> per km of road. They also  
77 discussed how renovation, maintenance, construction, and materials affect the overall carbon footprint for cement  
78 concrete and asphalt concrete pavements.

79 Most of LCA studies show that the use step involves the highest contribution to the life-cycle environmental  
80 impacts (Vidal et al., 2013; Yu and Lu, 2012). Moreover, such studies show that, including the use step in a LCA  
81 study, the relative shares of road material production, construction, maintenance and end-of-life to the life-cycle  
82 energy and environmental impacts are not significant, if compared to the contribution from the use step.

83 It can be highlighted that it is difficult to compare different literature studies carried out on LCA of road pavements,  
84 since these take into account different methodological assumptions, and different system boundaries and functional  
85 units. Moreover, the environmental performance of asphalt pavements is very sensitive to transportation distances,  
86 hence the comparisons that can be done are very site-specific (Cross et al., 2011). Further, different electricity

87 mixes, production practices, employed materials, local maintenance practices, and other region-specific elements  
88 involve different outcomes which are affected by the location under study.  
89 Such inconsistencies make pavement LCA results difficult to compare and limit their usefulness in a decision-  
90 making process.  
91 In order to comprehensively quantify environmental impacts and to guide toward sustainability goals, functional  
92 units should be standardized, and data quality and reliability should be improved. This could allow future LCA  
93 studies to carry out comparable assessments, in order to create synergies among literature assessments and  
94 outcomes.  
95 The existing literature establishes a framework useful to estimate environmental impacts, but fails to deliver global  
96 conclusions regarding material choices, maintenance strategies, and other best-practice policies for achieving  
97 sustainability goals(Beccali et al., 2007).  
98 In the attempt to overcome the limitations above, this paper presents a LCA study to assess the energy and  
99 environmental performances of a typical Italian urban road, according to the international standards of series ISO  
100 14040-14044 (International Organization for Standardization, 2006a, 2006b). The life-cycle energy and the  
101 environmental impacts, arisen from the production, transportation, laying operations, maintenance and end of life  
102 of road pavement, are assessed in order to identify the main hotspots along the whole life-cycle. This paper takes  
103 into account primary energy, measured at the natural resource level, including losses from the processes of  
104 extraction of the resources, their transformation and distribution, thereby expressing the environmental load  
105 induced by a road pavement in its life-cycle.  
106 Moreover, different road paving technologies are considered and compared in order to identify potential  
107 environmental improvements to the examined system from a life cycle perspective.  
108 Based on the above goals, this study intends to provide the following opportunities and insights: 1) need for  
109 primary energy savings and environmental impact minimization in the road pavement life-cycle; 2) need for  
110 reducing landfills, increasing the reuse of RAP; 3) opportunity of recycling plastics, substituting the corresponding  
111 quantities of bitumen modifiers.  
112 The contributions of the paper to the previously described state-of-the-art are: 1) to increase the limited number of  
113 road pavement LCA studies, most of which take into account only the energy demand and greenhouse gas  
114 emissions, not assessing other impact categories; 2) to support research to improve environmental performance  
115 and help all the involved stakeholders towards sustainable solutions (e.g., recycled materials and emerging  
116 technologies); 3) to enable policy makers to compare different scenarios at the design stage and/or introduce

117 remediation actions that could suitably modify the overall environmental performances of road infrastructures; 4)  
118 to improve LCA research in order to lead industry and government agencies to successful paths towards  
119 sustainability goals.

120

## 121 **2. Methods: Life Cycle Assessment**

### 122 **2.1 Goal and scope definition**

123 LCA is a useful tool for assessing primary energy demand and environmental burdens related to the full life-cycle  
124 of products (Cellura et al., 2017; Mistretta et al., 2019). In this paper, the authors apply an attributional LCA  
125 approach, according to the international standards of series ISO 14040 (International Organization for  
126 Standardization, 2006a, 2006b). The goals of the study are:

- 127 • to assess the energy and environmental impacts (eco-profile) of the asphalt pavement of a typical South Italy  
128 urban road, following a life cycle approach;
- 129 • to identify the hotspots of impacts along the supply chain;
- 130 • to identify potential environmental improvement by analysing different types of bituminous mixtures from a  
131 life cycle perspective. In detail, different scenarios, based on different construction techniques of road pavement, are  
132 defined, and a scenario analysis is carried out in order to identify the less impacting one from the energy and  
133 environmental point of view. The contribution of each life-cycle step to the global energy demand and to  
134 environmental impacts is assessed. Further the energy and environmental hotspots are identified in order to define  
135 suitable options of improvement.

136 Selection of the type of road to be studied is carried out considering that in Italy there are 172,356 km of sub-urban  
137 roads, while 6,668 km of motorway (Celauro et al., 2015).

138

#### 139 **2.1.1. Functional unit and system boundaries**

140 The selected functional unit (FU), which represents the reference unit through which a system performance is  
141 quantified in a LCA study, is 1 m<sup>2</sup> of road, as prescribed by the Environmental Product Declaration (EPD) Product  
142 Category Rules (The International EPD® System, 2013).

143 The study includes all the processes and activities that encompass material production, laying operations, maintenance  
144 works during pavement lifetime, and end of life, according to a cradle to grave approach.

145 In detail, the system boundaries include the following steps (Figure 1):

- 146 - Material production, which includes raw material and energy supply (extraction of raw material for all main  
147 parts and components and impacts due to the production of electricity and fuels to use in the subsequent  
148 steps), and manufacturing stage, which involves handling and processing operations occurring in asphalt  
149 plants (which depend on the assumed scenario).
- 150 - Laying operations, which include all the processes for the construction of the road.
- 151 - Maintenance, which consists of milling and reconstruction of the upper layer of the pavement, in order to  
152 ensure functionality, in terms of bearing capacity, surface regularity and friction over the lifespan of the  
153 road infrastructure. They include the demolition and discard of damaged material, the production of new  
154 material, transport to the site, laying processes, always considering the appropriate equipment and related  
155 emission/fuel consumption.
- 156 - Transport, including the transport of raw materials from the extraction to the asphalt plant, as well as the  
157 transport of the produced materials to the construction site.
- 158 - End of life, which includes the definition of the final destination of the materials, in terms of re-allocation  
159 as recycling material or disposal as waste.

160 The manufacturing of production equipment, buildings and other capital goods were not taken into account, because  
161 they are not included in the technical system (The International EPD® System, 2013).

162 With regard to the use phase, the relevance of which is well known in road LCAs, as clearly highlighted in the sector  
163 literature, in this study it is omitted, due to the lack of reliable and consistent data for the innovative materials considered  
164 in the investigation.

165 The average lifetime of road pavements, which includes all processes showed before, is difficult to determine and road  
166 infrastructure is maintained frequently to ensure an adequate level of service. In this study, lifetime is assumed to be  
167 20 years. For the sake of simplicity, with regard to the maintenance step, milling and reconstruction of the top layer of  
168 the pavement (friction course) is assumed as half of the lifespan (10 years), as required by PCR (The International  
169 EPD® System, 2013).

170 With regard to the end-of-life, the main activities related to this phase are demolition (milling) and transportation of  
171 materials, to be considered in terms of emissions and fuel use. Leaching should be accounted for, during this phase,  
172 depending on the use of the material after demolition.

173 **(FIGURE 1 HERE)**

174 **2.1.2. Models: Impact assessment methods and indicators**

175 The life cycle impacts are calculated using SimaPro software<sup>2</sup>. The characterisation models used are the Cumulative  
176 Energy Demand method for the Global Energy Requirement estimation (Wernet et al., 2016), and the Environmental  
177 Product Declaration (EPD) characterisation factors for the environmental impacts assessment (EPD, 2016).

178 In detail, the assessed energy and environmental categories are:

- 179 - Global Energy Requirement (MJ<sub>primary</sub>);
- 180 - Global Warming Potential (GWP, kg CO<sub>2eq</sub>);
- 181 - Acidification Potential (AP, kg SO<sub>2eq</sub>);
- 182 - Eutrophication Potential (NP, kg PO<sub>4eq</sub><sup>3-</sup>);
- 183 - Photochemical Oxidation Potential (POCP, kgC<sub>2</sub>H<sub>4eq</sub>).

184 No allocation procedures are performed. All the energy and environmental loads are attributed to the FU (Ardente and  
185 Cellura, 2012).

186

187 **2.1.3. Definition of case study and of scenarios**

188 The case study under analysis refers to a two-lane, single carriageway road (length 1 km and width 9.5 m), with a  
189 pavement thickness of 320 mm. The pavement structure, which lays on the subgrade, is composed of:

- 190 - Friction course (mix asphalt, 50 mm).
- 191 - Binder course (mix asphalt, 70 mm).
- 192 - Unbound base course (granular layer, 200 mm).

193 Subgrades, embankments, drainages and road marking are not included in the analysis: these aspects are also excluded  
194 in previous pavement LCA studies reported in literature (Santero et al., 2011a).

195 In detail, five different optimized scenarios of bituminous mixtures are defined and compared to a baseline case,  
196 named as Reference Scenario, involving the use of standard paving materials. Thus, a scenario analysis, integrated  
197 with the LCA methodology is carried out, to assess the variations induced in the energy and environmental impacts  
198 by the use of recycled materials (Reclaimed Asphalt Pavement, waste plastics, and crumb rubber), and by the  
199 asphalt plant characteristics and technology (Hot Mix Asphalt and Warm Mix Asphalt), in order to identify the  
200 best alternative in terms of energy and environmental performance.

201 Hot Mix Asphalts (HMA) are composed of aggregates and asphalt binder and are produced at about 170°C. Warm  
202 Mix Asphalts (WMA) include also additives that allow using temperatures 30-50 degrees lower than traditional HMA.

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<sup>2</sup> <https://simapro.com/>

203 The low production temperatures of WMA build on the reduction in binder viscosity. WMA technologies exhibit  
204 environmental benefits related with the reduction of the energy consumption, while technical benefits include better  
205 compaction, and the ability to haul paving mix for longer distances (extending the paving season), with the expectation  
206 that the mixes have strength, durability, and performance characteristics better than HMAs.

207 In the Reference Scenario, the friction course is a traditional porous asphalt concrete, which includes HMA, composed  
208 of modified bitumen (5% by mix weight) with Styrene-Butadiene-Styrene (SBS) Polymer (SBS), quicklime (QL),  
209 cellulose fibres (FB), mineral filler (FIL), and mineral aggregates, with in-place residual air voids of 18%.

210 The binder course is a dense-graded asphalt concrete (still a type of HMA) that includes neat bitumen (5% by mix  
211 weight), mineral filler, and mineral aggregates with in-place residual air voids of 6%.

212 The unbound base course includes a given gradation of mineral aggregates, compacted at a given moisture content.

213 Starting from the Reference Scenario, the authors define five supplementary scenarios of paving technologies, as  
214 described in the following paragraphs.

215 Scenario 1 includes no modified bitumen, while waste plastics (WP), and crumb rubber (CR) from end-of-life tires are  
216 used. It is assumed that the selected WP derive from municipal solid wastes, as well as CR from waste tyres are used  
217 into the friction course, thus addressing at the same time issues that concern land use reduction for disposal, non-  
218 renewable resource saving, and climate change mitigation.

219 Scenario 2 is devoted to the addition of reclaimed asphalt pavement (RAP) in the bituminous mixtures of friction and  
220 binder courses. Reclaimed Asphalt Pavement (RAP) is the term given to removed or reprocessed pavement for  
221 maintenance or rehabilitation. It contains asphalt and aggregates and can be recycled in the production of the  
222 bituminous mixtures. The addition of RAP is addressed to save virgin materials and to avoid undesired impacts to  
223 landfills. The main phases involved for RAP-added mixtures are the following (Bonicelli et al., 2017; Praticò et al.,  
224 2013):

- 225 - RAP in-place milling and transport to the crushing plant (or directly to the asphalt plant);
- 226 - RAP pre-processing or pre-treatment (crushing plant, sieving, transport, stockpiling);
- 227 - RAP processing at the asphalt plant (heating in the drum; mixing in the mixer).

228 The remaining processes of RAP-based mixtures are the same as *per* common mixtures (see Reference Scenario). The  
229 higher the RAP percentage, the lower the virgin aggregates and the virgin bitumen percentages are.

230 In Scenario 2, 30% of RAP used in the friction and binder layers of the Reference Scenario. Further a rejuvenating  
231 agent is added in order to fulfil bituminous viscosity requirements and increase mix expected life (Praticò et al, 2011).

232 In Scenario 3 the bituminous layers are supposed the same of the previous scenario, but, in this case, even the unbound  
233 base is mixed with RAP (30%). This has positive consequences in terms of landfill volumes and virgin material  
234 consumption.

235 In Scenario 4, a porous and warm mix asphalt (PAWMA) is considered as friction course. It includes mineral  
236 aggregates, filler, and modified bitumen, as for Reference Scenario. Organic additive in a standard dosage (0.5% based  
237 on bitumen weight) is added in the pursuit of reducing the viscosity of the asphalt binder at a given temperature. Also  
238 the binder course is manufactured using the WMA technology. It includes the same components reported above for  
239 the PAWMA, where the gradation of mineral filler and aggregates is different and a different asphalt binder percentage  
240 is given.

241 In Scenario 5, the friction course is a PAWMA as for Scenario 4, but in this case it contains 30% of RAP (Praticò,  
242 2004). Similarly, the binder course is composed of WMA with 30% of RAP.

243 Furthermore, the unbound base layer is mixed with 30% of RAP.

244 Table 1 shows the main characteristics of the proposed scenarios, while in Table 2 materials used in the road  
245 pavement are presented for each of the above defined scenarios.

246 (TABLE 1 HERE)

247 (TABLE 2 HERE)

248

## 249 **2.2 Data quality and Life Cycle Inventory**

250 Life Cycle Inventory (LCI) is performed to quantify the energy and environmental significant inputs and outputs of  
251 the examined system, by means of mass and energy balances of the selected FU for each scenario. In this section, the  
252 authors describe the data collection and the assumption made to model the life cycle phases within the selected system  
253 boundaries and to perform the scenario analysis.

254 Data for LCI, related to material production and construction processes in the road pavement field, are sometimes  
255 incomplete, thus LCA experts have to refer to estimate methods (Farina et al., 2017; Santagata and Zanetti et al., 2012).

256 In the presented case study, LCI data used to model the foreground system ((European Commission -- Joint Research  
257 Centre -- Institute for Environment and Sustainability, 2010) are arisen from literature, and/or collected through  
258 interviews with local contractors and experts involved in road works.

259 With regard to material production, primary data are collected through interviews with experts involved in road works.

260 Virgin aggregates are mainly sand and gravel and are assumed to be selected from crushed and sieved fractions from

261 quarries. The related transport distances are calculated assuming that they are extracted from Calabrian and Sicilian  
262 quarries.

263 Secondary data are taken from (Wernet et al., 2016) and from (Blomberg et al., 2011), which provide from-cradle-  
264 to-gate LCIs of bituminous materials, representative of the European scenario..

265 Primary data on the eco-profile of crumb rubber (Scenario 1) are not available, thus information are derived from the  
266 literature (Farina et al., 2017). Fuel consumption due to transport of end-of-life tires is calculated assuming the  
267 following distances:

- 268 - 75 km from the collection point of the end-of-life tires to the processing plant to produce CR.
- 269 - 100 km from the CR processing plant to the HMA plant. Further, the benefits derived from the avoided disposal  
270 of end-of-life tires are taken into account.

271 No assessment of CR co-products recycling (steel and textile) has been performed. Data on RAP are extracted from an  
272 available study on its use in road pavements (Giani et al., 2015).

273 Primary data concerning electricity consumption of equipment used in quarries and asphalt plants are collected from  
274 contractors in Calabria Region, which provided figures based on yearly averages. In the case of vehicles and  
275 machineries involved in construction and maintenance operations, calculations are based on average hourly fuel  
276 consumption data and on reference values of productivity and working hours, available in the literature (Huang et al.,  
277 2009). Data on machinery performance, diesel consumption, natural gas consumption, and electricity consumption are  
278 obtained from the literature (Zapata and Gambatese, 2005).

279 The eco-profiles of energy sources, raw materials, transports, and waste treatments are included in the analysis based  
280 on international environmental databases (Wernet et al., 2016). In particular, the eco-profile of electricity is referred to  
281 the Italian electricity mix. The eco-profiles of input materials are mainly referred to the European context.

282 For each defined scenario, LCI is performed on the basis of the data listed in Table 3, which shows the amounts per  
283 FU of the different materials used in pavement layers, and of the average haul distances from production/supply sites  
284 to the road construction site.

285

286 **(TABLE 3 HERE)**

287

288 Laying operations are accomplished using different types of equipment. In this phase, the environmental burdens  
289 are due to the combustion-related emissions from equipment.

290 The primary energy demand during the layer construction is calculated considering data shown in Table 4. Diesel  
291 consumption of machinery used in place to compact layers are calculated, taking into account hourly fuel consumption  
292 of construction equipment.

293

294 **(TABLE 4 HERE)**

295

296 With regard to the maintenance step, one replacement of the friction course after ten years from the construction is  
297 assumed. Fuel and water consumptions, due to the reconstruction of the friction course are added to those deriving  
298 from the milling of the old damaged surface layer and from the transportation of the removed material to a landfill  
299 located at 100 km.

300

### 301 **2.3 Life Cycle Impact Assessment (LCIA)**

302 LCIA results are shown in the following section, which highlights different aspects of the energy and environmental  
303 performance associated to the six assessed scenarios of road pavements.

304 Paragraph 2.3.1 provides a description of the life-cycle energy demand in terms of GER, and paragraph 2.3.2 describes  
305 the environmental impacts.

306

#### 307 **2.3.1. Life-cycle energy demand: GER**

308 GER is calculated as the total primary energy demand of the whole life cycle of the road pavement.

309 Table 5 shows the results of GER for each investigated scenario. Outcomes show that, while the Reference Scenario  
310 presents the highest value of GER (2,024.62 MJ<sub>primary</sub>/m<sup>2</sup>), Scenario 5 (PAWMA with 30% of RAP) involves the lowest  
311 GER (1,815.28 MJ<sub>primary</sub>/m<sup>2</sup>), with a reduction of 10% in comparison with Reference Scenario. This result is essentially  
312 due to the lower consumption of energy in WMA production and to the use of RAP in the pavement layers, which  
313 implies a reduction of virgin raw materials requirement. A similar reduction occurs in Scenario 1, due to the use of  
314 materials containing CR and WP.

315 Material production step involves the most significant contribution, and accounts for about 70% of GER in each  
316 scenario.

317 With regard to construction step, the scenarios with RAP involve a slight increase (13%) respect to the Scenarios  
318 without RAP, due to higher energy required for the milling process.

319 About the maintenance step, it is foreseen one replacement of the friction course layer during the pavement lifespan in  
320 all the scenarios. It accounts for 18-19% of the total GER, and includes the contribution of the transport from the paving  
321 site to landfill and the waste asphalt management. With regard to transport and end-of-life, GER is around 5-6% in all  
322 scenarios.

323 **(TABLE 5 HERE)**

324 Figure 2 shows the contribution of materials to GER in the production step. The main contribution to GER comes  
325 from virgin bitumen production (about 70% in Reference scenario and Scenario 4, while Scenarios with recycled  
326 materials show lower shares (nearly 60%), followed by filler production, which provides a contribution varying  
327 from 21% (Scenario 3, Reference Scenario) to 27% (Scenarios 2 and 5). Quicklime accounts for 5-6% in the  
328 production GER in all the scenarios, while mineral aggregates contribute for about 3%.

329 **(FIGURE 2 HERE)**

330

331

### 332 **2.3.2. Life-cycle environmental impacts**

333 Life-cycle environmental impacts of the road pavement, referred to the FU, are showed in Table 6 for all the  
334 assessed scenarios. For each impact category the results show slight differences among the assessed scenarios.

335 **(TABLE 6 HERE)**

336 With regard to GWP, Reference Scenario involves the biggest value of GWP (90.6 kgCO<sub>2eq</sub>/m<sup>2</sup>), while Scenarios 1, 4,  
337 and 5 involve the lowest contribution (about 87 kgCO<sub>2eq</sub>/m<sup>2</sup>).

338 With regard to AP, NP, and in POCP the scenarios containing RAP (Scenarios 2, 3, and 5) present slight higher shares.  
339 Figure 3 shows a contribution analysis to identify the life-cycle steps, which involve the most significant share to the  
340 assessed environmental impact indicators.

341 The outcomes highlight that material production phase causes the highest share in almost all the assessed impact  
342 categories, varying from nearly 60% to 70%. The contribution of production step to NP varies from 3% to 24%.

343 With regard to transport, it involves the highest contribution to GWP, accounting for nearly 8% in all the scenarios,  
344 while its share to AP, NP and POCP is not more than 3%

345 Construction step involves a contribution not higher than 1% to each impact category in all the assessed scenarios.

346 With regard to the maintenance step, referred to the replacement of the friction course after 10 year of lifespan, in all  
347 the assessed scenarios it involves a contribution of about 14-15% in GWP, AP, and NP, and a contribution that varies  
348 from 22% to 38% in POCP. With regard to the end-of-life, it contributes for about 60-80% to NP.

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(FIGURE 3 HERE)

### 3. Discussion

In the eco-profiles assessed based on different bituminous mixtures for road pavement, the scenario analysis has been carried out in order to identify the less impacting one from the energy and environmental point of view. The contribution of each life-cycle step of road pavement on the overall impacts has been assessed in order to identify the steps and processes responsible of the highest impacts.

Table 7 shows the percentage variations of the life cycle energy and environmental impacts linked to the scenarios investigated with respect to the Reference Scenario. The analysis shows that all the assessed scenarios show lower GER and GWP, in comparison to the Reference Scenario.

The use of waste plastics and crumb rubber from end-of-life tires in Scenario 1 involves reduction in all the impact categories. In particular, it shows the most significant reduction in POCP (- 68%).

Scenarios with RAP (Scenarios 2, 3, and 5) show the increase of AP and NP.

(TABLE 7 HERE)

Starting from the above LCA results the following considerations can be traced:

- The picture of the whole life cycle describes different results that do not identify clearly the best scenario among all the six cases for all indicators.

- The life cycle contribution analysis of each investigated scenario highlights that the production phase is the most significant phase, since it involves the highest contribution in all the examined impact categories, with a contribution of 60-70%. The exception is represented by NP in which the most significant share is given by the end-of-life phase in all the assessed scenario.

- The use of WMA in bituminous mixtures, coupled with the use of recycled materials involves lower GER and environmental impacts. In particular, combining WMA with the use of RAP allows reducing the consumption of virgin bitumen and aggregates, thus involving reduction in primary energy consumption and raw materials, and avoiding impacts for disposal.

The results for the material production step show the need to implement measures to reduce energy demand and environmental impacts. Thus, eco-design of production should be investigated more in detail and eco-design solutions should be checked to improve the eco-profile of the road pavement, but not forgetting that a pillar for the sustainability development is the integration between environmental friendly production systems and technological feasibility..

378 Moreover, the results show that use of recycled and waste materials (RAP, CR, and WP) represents a viable strategy  
379 to promote resource and energy efficiency, thus contributing to UN Sustainable Development Goals of Agenda 2030.  
380 In such a context, the authors intend to continue the presented research in order to identify strategies of primary energy  
381 saving in the material production and transport steps, focusing on the renewable energy source employment.

382

#### 383 **4. Conclusions**

384 The analysis proposed in this paper marks the concept of providing a systemic approach for life-cycle energy and  
385 environmental impact assessment for the sake of all stakeholders, in order to support the development of new models  
386 of low-energy consumption and innovative production models in the road field. Benefits can be better policies with  
387 clear environmental objectives, more sustainable business strategies, and environmentally friendly product design.  
388 Thus, LCA-based metrics can contribute significantly to the Sustainable Development Goals.

389 In particular, the LCA results obtained in this paper show that recycled materials, coupled with Warm Mix Asphalts  
390 can lead to benefits in terms of energy saving and environmental impact minimization. Thus, the use of such materials  
391 in road paving technologies can be attractive for policy makers, since it represents an example of resource efficiency  
392 and sustainable waste management, limiting land use for landfill and the consumption of natural aggregates.

393 From a methodological point of view, the literature review showed the difficulty to compare different studies, due to  
394 different methodological assumption regarding to functional unit and system boundaries. With regard to functional  
395 unit, the authors selected 1 m<sup>2</sup> of road, following the prescription of the Environmental Product Declaration (EPD)  
396 Product Category Rules.

397 One key issue of the analysis is the selection of secondary data for modelling the life-cycle of a number of production  
398 materials, due to the limited availability of process-specific data for such materials. This lack of data is mainly linked  
399 to the fact that there is a very high number of chemical agents that can be used, and no appropriate measurement of the  
400 life-cycle impacts can be possible for all of them. For these products it is necessary to make use of estimates from  
401 literature data and this may cause uncertainties in the study.

402 Even though the results obtained are promising, this paper needs to be considered as preliminary, since calculations  
403 were based on several hypotheses and estimates. For this reason, the application of a sensitivity analysis on the initial  
404 assumptions is quite relevant for the reliability of the results. In this field the authors are still investigating and carrying  
405 out a further research activity. In future studies, the authors will try to overcome these limits by monitoring production,  
406 construction laying, and use phase, thus leading to a more complete and reliable set of Life Cycle Inventory data.

407 Despite the limitations above, outcomes show that the LCA methodology can support the development of studies that  
408 aim at reducing energy and environmental and can provide a systemic approach for energy and environmental  
409 assessment for the sake of all stakeholders, in order to support the development of the eco-design in the road fields,  
410 voted to low-carbon and low-energy production models.

411 The adoption of the LCA approach ensures a systemic accounting of primary energy consumption and other  
412 environmental impacts, like GWP, linked to the road pavement, avoiding the shift from one life cycle phase to another.  
413 Moreover, it allows identifying the main area of intervention and the most effective strategies.

414 Public authorities and other stakeholders involved could benefit from basing the management practices and climate  
415 strategies upon scientific evidence, e.g. in the context of Green Public Procurement Criteria for Road Design,  
416 Construction and Maintenance, green products, and EU Environmental Product Declarations.

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