

# Evaluation of sustainable use of RAP from LCA perspective: a literature review

Claudia Nodari<sup>1</sup>, Giovanni Dotelli<sup>2</sup>

<sup>1</sup> Politecnico di Milano, DICA – Transport Infrastructures and Geosciences Section

<sup>2</sup> Politecnico di Milano, DCMC

Email: [claudia.nodari@polimi.it](mailto:claudia.nodari@polimi.it)

## Abstract

*Transport infrastructures have an important social and economic role, but also a large environmental impact. As infrastructure requires large amounts of material, infrastructure sustainability has focused on materials and technologies including all phases from design to rehabilitation. In that direction there are a lot of Life Cycle Assessment (LCA) studies conducted on mixtures with different Reclaimed Asphalt Pavement (RAP) content. Using RAP into new mixtures provides advantages from both environmental and economic point of view. The aim of this work is to review previous LCA studies related to an environmentally sustainable use of RAP in mixtures.*

## 1. Introduction

### 1.1 Sustainability

The concept of sustainability rose in 1970s, but the most famous definition was established in 1987 by Brundtland Commission: “Sustainable development is development which meets the needs of the present without compromising the ability of future generations to meet their own needs” (Babashamsi et al., 2016; Acai and Amadi-Echendu, 2018). Firstly, this definition involves two considerations regarding temporal and spatial dependence: a long term perspective leads to an increase in uncertainty as we move forward, so the sustainability should be perceived as a continuous process; moreover, sustainability is locally specific (Acai and Amadi-Echendu, 2018). It is possible to summarize sustainability using this slogan: “Reduce, reuse and recycle”; this behaviour can be achieved through the cooperation and collaboration of different actors that aim at a single common sustainable vision (Acai and Amadi-Echendu, 2018).

### 1.2 Transport infrastructures sustainability

Transport infrastructures are key elements in any nation’s well-being with an important social and economic role, but they have also a large environmental impact (Celauro et al., 2015; Yang et al., 2015; Inyim et al., 2016; Acai and Amadi-Echendu, 2018). Therefore, it is necessary to focus design infrastructures on their social, economic and environmental components, especially for roads design (Aurangzeb et al., 2014; Acai and Amadi-Echendu, 2018). Limited funds availability and construction and raw materials increasing costs (Giani et al., 2015) have moved the transport system, according to the increasing environmental constrictions, towards a greener vision (Celauro et al., 2015; Giani et al., 2015; Guerrieri et al., 2015; Santos et al., 2018). Since pavements act a prominent role in the sustainability of urban systems, evaluation of pavement environmental impacts is basic in order to improve transport system sustainability (Inyim et al., 2016). A sustainable pavement has high-quality standards, long-lasting goals and good environmental-economic-social properties (Aurangzeb et al., 2014).

Quantitative and qualitative approaches, reported in Table 1, are the ways for infrastructures environmental sustainability assessment (Acai and Amadi-Echendu, 2018). Life Cycle Assessment (LCA) is known to be the most effective tool for assessing transport infrastructures and systems impacts on the environment (Santero et al., 2011; Guerrieri et al., 2015; Anthonissen et al., 2016). According to high number of pavement characteristics

(type, thickness, properties of materials) and other goal and scope depending parameters (climate, design, local construction practices, etc.), it is impossible to establish a single functional unit valid for all pavement LCAs studies (Santero et al., 2011; Giani et al., 2015).

Table 1: Pavement sustainability assessment tools.

Pavement Sustainability Assessment Tools		
Quantitative methods	Qualitative methods (Rating System)	
<ul style="list-style-type: none"> <li>● Life Cycle Assessment</li> <li>● Life Cycle Cost Assessment</li> <li>● Performance Assessment</li> </ul>	<ul style="list-style-type: none"> <li>● GreenLITES</li> <li>● BE<sup>2</sup>-ST- in-Highway</li> <li>● INVEST</li> </ul>	<ul style="list-style-type: none"> <li>● GreenRoads</li> <li>● GreenPave</li> <li>● ENVISION</li> </ul>

As infrastructure requires large amounts of material, infrastructure sustainability has focused on materials (recycled, co-product, waste materials) and technologies (mixing and compaction temperature lowering, different maintenance strategies) including all phases from design to rehabilitation (Yang et al., 2015; Acai and Amadi-Echendu, 2018; Pantini et al., 2018; Santos et al., 2018). For these reasons recycled or secondary materials have attracted attention; their usage cuts down the use of virgin materials and limits the environmental burden (Giani et al., 2015; Guerrieri et al., 2015). In that direction, for example, there are a lot of studies conducted on mixtures with different Reclaimed Asphalt Pavement (RAP) content (Pantini et al., 2018). RAP is different from other construction and demolition wastes (CDW) because of its economic value, compared with the increasing cost of virgin bitumen and the limited availability of good quality aggregates (Pantini et al., 2018). Moreover, bitumen, even if present in reduced quantities, can contribute highly to the total energy consumption; therefore, a partial substitution of virgin binder with RAP binder leads to environmental savings (Yang et al., 2015). Using RAP into new mixtures provides advantages from both environmental and economic point of view (Giani et al., 2015; Yang et al., 2015; Pantini et al., 2018). In addition to RAP, there are other examples of materials that can be use in partial or full replacement of virgin ones: Recycled Concrete Aggregate (RCA), Recycled Asphalt Shingles (RAS), Air-Cooled Blast Furnace Slag (ACBFS), Steel Furnace Slag (SFS), Foundry Sand, etc. (Yang et al., 2015; Santos et al., 2018).

## 2. Literature review

The aim of this work is to review previous LCA studies, conducted according to ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b), related to an environmentally sustainable use of RAP in mixtures with:

- different production temperatures -HMA, WMA, CMA<sup>11</sup>- (Giani et al., 2015; Pantini et al., 2018; Santos et al., 2018);
- different RAP content (Aurangzeb et al., 2014; Celauro et al., 2015; Santos et al., 2018);
- other waste materials -RAS- (Yang et al., 2015).

Nowadays using RAP in bituminous mixtures is quite common habits, but there are limitations on the quantity of RAP that is allowed to be included in mixtures by many institutions. The aim of this review is offering food for thought for institutions in order to update standards. That means increasing the maximum allowed quantity of RAP in bituminous mixtures, starting from successful mechanical results and considering also environmental benefits.

<sup>11</sup> HMA: Hot Mix Asphalt; WMA: Warm Mix Asphalt; CMA: Cold Mix Asphalt.

This literature review considers studies published in the five-year period (2014-2019), selected according to the keywords *LCA / Pavement / RAP*. The final selected six papers are resumed in Table 2, with indication of the analysed mixtures, the functional unit, the system boundary and the characterization method used in the LCIA (Life Cycle Impact Assessment).

## 2.1 **Goal and scope**

The selected papers have different goals and scopes. Some of them (Aurangzeb et al., 2014; Celauro et al., 2015; Giani et al., 2015; Pantini et al., 2018; Santos et al., 2018) are comparative studies, that offer discussion on mixtures with/without RAP content and with different production technologies. Yang et al. (Yang et al., 2015) propose impacts deriving from mixtures with various RAP and RAS contents, without comparison. Moreover, two works (Aurangzeb et al., 2014; Yang et al., 2015) make considerations regarding pavement performance and environmental impact assessment. Finally, three analyses (Yang et al., 2015; Pantini et al., 2018; Santos et al., 2018) provide results to be used by transportation agencies and pavement practitioners as an objective guidance to evaluate benefits from more sustainable strategies.

## 2.2 **System boundary**

This section describes all the phases included in the system boundary.

- Raw Materials Extraction: it includes processes required to extract raw materials and to transform them into pavement input materials. Transport of raw materials from the extraction to the process site is incorporated too. In one study (Celauro et al., 2015) this phase is linked with the Mixture Production one.
- Mixture Production: it includes processes required to produce mixture.
- Road Construction: it includes all the execution for road infrastructure construction, included final product transport to the construction site. Just in one work (Celauro et al., 2015), this transportation is incorporated in Mixture Production phase. Construction machinery fuel is included too.
- Maintenance: it includes damaged material demolition, production of new material, laying process and equipment fuel. One of the studies (Santos et al., 2018) linked this phase with the Road Construction one.
- Use: it deals with the pavement influence on vehicle operation and the interaction between pavement, environment and humans.
- End of Life: it deals with the pavement fate once the project analysis period is reached. For this phase the *cut off approach* is adopted: the recycling burden associated with a product is ascribed to any other product which uses this recycling burden; this method is the most commonly used in pavement LCA because of future uncertainties related to pavements (Aurangzeb et al., 2014).
- WZ traffic management phase: it consists of the additional environmental impacts produced by the on-road vehicles when a traffic flow variation occurs due to maintenance.
- RAP Transportation: asphalt waste transportation from road worksites to the recycling plants.
- RAP Treatment: asphalt waste treatment, which includes crushing and screening, is carried out on the received RAP before adding it into the production process.

Table 2: List of selected paper with some main features.

\* System boundary (S.B.): RME: Raw Materials Extraction; MP: Mixture Production; RC: Road Construction; M: Maintenance; U: Use; EoL: End of Life; WZ: Work Zone traffic management phase; RTrn: RAP transportation; RTrt: RAP treatment.

Reference	Mixtures	Functional Unit	S.B.*	Characterization Method
Aurangzeb et al., 2014	Binder-layer mixtures with: <ul style="list-style-type: none"> <li>• 30% RAP</li> <li>• 40% RAP</li> <li>• 50% RAP</li> </ul>	<ul style="list-style-type: none"> <li>• Analysis period: 45 years</li> <li>• Length: 1,6 km</li> <li>• Surface course: 51 mm</li> <li>• Binder course: 254 mm</li> <li>• Shoulder: 1,8 m wide and 305 mm thick</li> </ul>	<ul style="list-style-type: none"> <li>• RME</li> <li>• MP</li> <li>• RC</li> <li>• M</li> <li>• EoL</li> </ul>	Characterization factors from: <ul style="list-style-type: none"> <li>• USEPA (2008)</li> <li>• GREET (2012)</li> <li>• IPCC</li> </ul>
Celauro et al., 2015	Total of 15 scenarios from the combination of different transversal sections (embankment and cut ones) and different amount of: <ul style="list-style-type: none"> <li>• Virgin materials (V)</li> <li>• RAP: 15, 40, 100% (R)</li> <li>• Stabilization with lime in situ (L)</li> </ul>	<ul style="list-style-type: none"> <li>• Typical Italian two-lane rural road</li> <li>• Two-lane single carriageway with a lane width of 3,5 m and paved shoulders of 1,25 m each</li> <li>• Length: 1 km</li> </ul>	<ul style="list-style-type: none"> <li>• RME</li> <li>• MP</li> <li>• RC</li> <li>• M</li> </ul>	Included in LCA tool "PaLATE"
Yang et al., 2015	Total of 11 mixtures with different amount of: <ul style="list-style-type: none"> <li>• RAP (8 - 50%)</li> <li>• RAS (4 - 8%)</li> </ul>	<ul style="list-style-type: none"> <li>• Four-lane-miles</li> <li>• Length: 1,6 km</li> <li>• Asphalt overlay: 102 mm</li> <li>• Expected life: 15 years</li> </ul>	<ul style="list-style-type: none"> <li>• RME</li> <li>• U</li> </ul>	<ul style="list-style-type: none"> <li>• TRACI 2.1 (Bare, 2012)</li> <li>• CED</li> </ul>
Giani et al., 2015	Three variants of road packages defined in collaboration with a road pavements manufacturer: <ul style="list-style-type: none"> <li>• RP1: virgin materials and HMA</li> <li>• RP2: RAP and HMA</li> <li>• RP3: RAP and WMA</li> </ul>	<ul style="list-style-type: none"> <li>• Suburban road</li> <li>• Two independent roadway each with 2 lanes in each direction separated by a traffic island</li> <li>• Length: 1 km</li> <li>• Pavement width: 15 m</li> <li>• Pavement total depth: 25 cm</li> <li>• Lifetime: 15 years in a first analysis, then extended to 30 years.</li> </ul>	<ul style="list-style-type: none"> <li>• RME</li> <li>• MP</li> <li>• RC</li> <li>• M</li> <li>• U</li> <li>• EoL</li> </ul>	<ul style="list-style-type: none"> <li>• Greenhouse Gas Protocol (characterization factors from IPCC, 2007)</li> <li>• ReCiPe 2008 (Goedkoop et al., 2009)</li> <li>• CED (Frischknecht et al., 2007a)</li> <li>• Selected LCI results, additional (Frischknecht et al., 2007a)</li> </ul>
Pantini et al., 2018	Comparison between different recycling technologies: <ul style="list-style-type: none"> <li>• HMA with 20% RAP</li> <li>• CMA with 80% RAP</li> </ul>	1 tonne of non-hazardous asphalt waste (EWC 170302) to use as a component of new asphalt mixtures.	<ul style="list-style-type: none"> <li>• MP</li> <li>• RTrn</li> <li>• RTrt</li> </ul>	<ul style="list-style-type: none"> <li>• ILCD 2011 (EC-JRC, 2011)</li> <li>• CED (Frischknecht et al., 2007b)</li> </ul>
Santos et al., 2018	Total of 6 mixtures with different production technologies and materials: <ul style="list-style-type: none"> <li>• HMA, 0% RAP</li> <li>• WMA - CECABASE®, 0% RAP</li> <li>• WMA - foamed, 0% RAP</li> <li>• HMA, 50% RAP</li> <li>• WMA - CECABASE®, 50% RAP</li> <li>• WMA - foamed, 50% RAP</li> </ul>	<ul style="list-style-type: none"> <li>• Typical French highway section</li> <li>• Length: 1 km</li> <li>• Two independent roadways, each with two lanes with an individual width of 3,5 m</li> <li>• Project analysis period (PAP): 30 years</li> <li>• Two-way average annual daily traffic (AADT): 6500 vehicles/day (33% heavy duty vehicles)</li> </ul>	<ul style="list-style-type: none"> <li>• RME</li> <li>• MP</li> <li>• RC</li> <li>• M</li> <li>• U</li> <li>• WZ</li> <li>• EoL</li> </ul>	<ul style="list-style-type: none"> <li>• CML 2001 (Guinee et al., 2002)</li> <li>• ReCiPe (Goedkoop et al., 2013)</li> <li>• CED (Frischknecht et al., 2007c)</li> </ul>

### 2.3 *Data sources*

Data sources are different among the six studies. Three of them (Aurangzeb et al., 2014; Giani et al., 2015; Santos et al., 2018) use primary data collected from plant and job-site; Pantini et al. (Pantini et al., 2018) instead collects these data from several sources (MUD declarations, Provinces' documents, asphalt manufacturing plants and some road companies). Ecoinvent database is used in four analyses (Yang et al., 2015; Giani et al., 2015; Pantini et al., 2018; Santos et al., 2018) with adaptations whenever possible to the local context (local databases and surveys); two studies (Giani et al., 2015; Santos et al., 2018) use also data from scientific literature. Giani et al. (Giani et al., 2015) adopts construction equipment fuel consumptions from manuals of construction machinery. Just an investigation (Pantini et al., 2018) carries out a sensitivity analyses to test influence of transport distances and of the amount of virgin materials saved with the addition of RAP on LCA results: the analyses were performed changing one per time two investigated parameters. This generated different type of scenery.

### 2.4 *Impact categories*

All the studies consider *Climate Change* (CO<sub>2eq</sub>) and *Energy Consumption* as impact categories. Four investigations (Celauro et al., 2015; Giani et al., 2015; Pantini et al., 2018; Santos et al., 2018) consider a wide selection of impact categories: all of them include *Water Consumption* and just a study (Giani et al., 2015) discusses *Land Use*. Another investigation (Pantini et al., 2018) develops an indicator *ad hoc* to take into account the consumption or saving of natural mineral resources: *kg of sand and gravel consumed or saved by the system*.

### 2.5 *Results*

Table 3 shows the results of both impact categories *Climate Change* and *Energy Consumption* for all the analysed studies.

Table 3: Climate Change and Energy Consumption results, referred to the F.U.

Reference	Mixtures	Climate Change results [t CO <sub>2eq</sub> ]	Energy Consumption results [MJ]
Aurangzeb et al., 2014	30% RAP	475,48	6.621.473
	40% RAP	462,77	6.447.308
	50% RAP	450,07	6.273.143
Celauro et al., 2015  Only two of the 15 scenarios are reported. They are the two with the greatest content of recycled materials	Scenario 9 (embankment section) Wearing course: V+15%R; Binder course: V+40%R; Base Course: V+40%R; Sub-base: 100%R; Top layer of embankment: L; Body of embankment: L; Embankment foundation: L	934	14.358.082
	Scenario F (cut section) Wearing course: V+15%R; Binder course: V+15%R; Base Course: V+40%R; Sub-base: 100%R; Subgrade: L	1.026	15.781.628
Yang et al., 2015  Values obtained from processing	Mix 1: 0%RAP e 0%RAS	0,0195	354,5
	Mix 2: 29%RAP e 0%RAS	0,0179	329,685
	Mix 3: 8%RAP e 5%RAS	0,0230	425,4
	Mix 4: 30%RAP e 0%RAS	0,0172	315,505
	Mix 5: 40%RAP e 0%RAS	0,0164	297,78
	Mix 6: 30%RAP e 5%RAS	0,0178	326,14
	Mix 7: 50%RAP e 0%RAS	0,0156	290,69
	Mix 8: 30%RAP e 5%RAS	0,0158	294,235
	Mix 9: 42%RAP e 4%RAS	0,0166	301,325
	Mix 10: 10%RAP e 8%RAS	0,0209	389,95
	Mix 11: 42%RAP e 6%RAS	0,0152	283,6
Giani et al., 2015	RP1: virgin materials and HMA	738	40,68
	RP2: RAP and HMA	688	37,80
	RP3: RAP and WMA	650	34,62
Pantini et al., 2018	HMA with 20% RAP CMA with 80% RAP	Values not available	Values not available
Santos et al., 2018  Values obtained from processing	HMA, 0% RAP	1.259	69.520.000
	WMA - CECABASE®, 0% RAP	1.239	69.410.000
	WMA - foamed, 0% RAP	1.227	68.610.000
	HMA, 50% RAP	1.208	63.490.000
	WMA - CECABASE®, 50% RAP	1.182	63.499.000
	WMA - foamed, 50% RAP	1.180	63.380.000

## 2.6 Discussion of the results

In the calculation of results, just an analysis (Giani et al., 2015) adopts the normalization step: each score was compared with the total known effect of the examined category in Europe in 2000.

Moreover, this study (Giani et al., 2015) conducts an uncertainty assessment with Monte Carlo simulation to determine the variability (95% confidence interval) of the LCA results due to uncertainties in LCI. All the six reviewed LCAs make considerations on *Climate Change* and *Energy Consumption* evaluating the same performance for all mixtures -except for CMA of Pantini et al. (Pantini et al., 2018)-. In two investigations (Aurangzeb et al., 2014; Celauro et al., 2015), characterized by mixtures made with different RAP content, direct correlation is found between CO<sub>2eq</sub> emissions/energy consumption reductions and RAP content: in one of them (Aurangzeb et al., 2014) the mix with 50% RAP saves 12% both in terms of energy and CO<sub>2eq</sub>. In one of the six studies (Santos et al., 2018) in addition to different contents of RAP, different production technologies are considered: *WMA - foamed 50% RAP* is the most environmentally friendly mixture. Two researches (Giani et al., 2015; Pantini et al., 2018) compare the environmental impacts of mixtures with RAP at different temperatures: in the first one (Giani et al., 2015) the comparison between HMA and WMA is made, in the second one (Pantini et al., 2018) between HMA and CMA. In the investigation of Giani et al. (Giani et al., 2015) the mixtures produced at lower temperatures -WMA- are the most sustainable, with a 12% and 15% reduction of CO<sub>2eq</sub> and of energy consumption respectively. Pantini et al. (Pantini et al., 2018), on the other hand, obtain that the production of CMA mixtures leads to higher environmental impacts compared to HMA mixtures. This result has two main causes: use of bituminous emulsion and cement inside CMA (stabilizing agents whose productions are definitely very impacting) and replacement coefficient equal to 0,67 (to replace equivalent virgin products). This research (Pantini et al., 2018) nevertheless highlights intrinsic limitations of his own study such as the fact of not including the construction phase, in which CMA impacts are largely minor compared to HMA due to lower temperature. In another investigation (Yang et al., 2015) mixture with the highest content of recycled material (42% RAP and 6% RAS) records the greatest environmental reductions with 22% CO<sub>2eq</sub> and 20% energy savings respectively. Some analyses (Aurangzeb et al., 2014; Celauro et al., 2015; Giani et al., 2015; Santos et al., 2018) note that mixtures with virgin materials are characterized by the higher environmental burden. In fact, all studies highlight the great environmental burden deriving from the production of bitumen. Therefore, decreasing the amount of virgin bitumen to be used in the mixtures leads to significant environmental improvements.

## **2.7 Alternative mixtures performances**

Even if some investigations (Celauro et al., 2015; Giani et al., 2015; Pantini et al., 2018; Santos et al., 2018) make considerations regarding pavement durability, according to previous paragraph, only two of six selected papers (Aurangzeb et al., 2014; Yang et al., 2015) make practical evaluation regarding pavement performance to assess the effect of performance on environmental impact assessment. Aurangzeb et al. (Aurangzeb et al., 2014) find that as the RAP content increases in the mixture, energy consumption and GHGs decrease. Similar results are found in another study (Yang et al., 2015) in the highest percentage of recycled material mixture (42% RAP and 6% RAS). If the recycled mixtures performance is insufficient, the environmental benefit of using recycled materials will be offset by the need for more frequent maintenance and rehabilitation activities in the first investigation (Aurangzeb et al., 2014) and in an additional fuel consumed by users' vehicles in the second one (Yang et al., 2015). It can be defined *breakeven performance* level, the pavement performance level at which environmental benefit or energy savings from material production phase are balanced by maintenance activities environmental burden in (Aurangzeb et al., 2014) or by extra fuel in (Yang et al., 2015). Further considerations rise in specific case studies: in the first analysis (Aurangzeb et al., 2014), it is assessed that the major margin for underperformance are tolerated by mixtures with a high RAP content, as they are characterized by the greater reduction in GHG emissions and energy consumption,

as shown in Figure 1; in the second investigation (Yang et al., 2015) it is found that this *breakeven point* is highly dependent on the overlay traffic level (major impacts for high traffic volume). Therefore, the *breakeven performance level* highlights the importance of achieving equivalent recycled mixture performance.

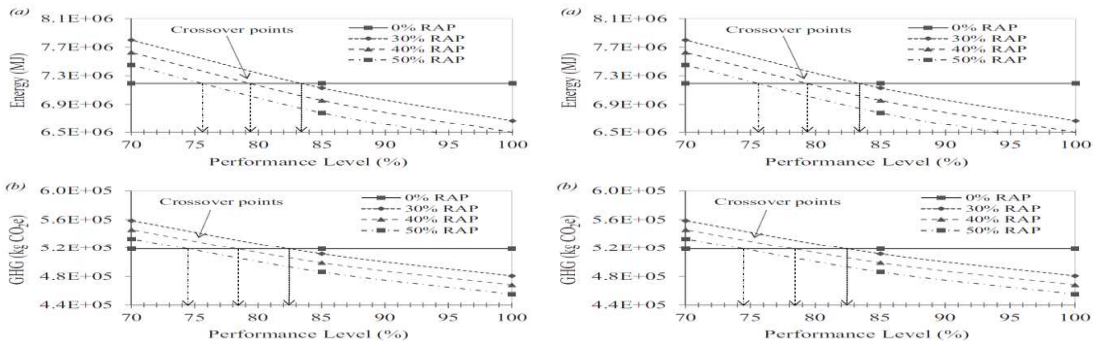


Figure 1: Breakeven performance levels based on (a) energy consumption and (b) GHG emissions in the study of Aurangzeb et al. Source: Aurangzeb et al., 2014.

### 3. Conclusions

This work reviews previous LCA studies related to an environmentally sustainable use of RAP in mixtures with different production temperatures, different RAP content and other waste materials. The aim of this review is offering food for thought for institutions in order to update standards. That means increasing the maximum allowed quantity of RAP in bituminous mixtures, starting from successful mechanical results and considering also environmental benefits. The analysis shows numerous differences in goals and scopes, functional units, system boundary settings, methodological choices; however, all studies evaluate as impact categories *Climate Change* and *Energy Consumption*. Regarding results, from all the studies emerges that RAP use leads to significant environmental benefits with reductions in terms of CO<sub>2eq</sub> emission and energy consumption. Alternative technologies (lower production temperatures or additives use) led in all cases, except one, to more sustainable mixtures. Technical performances represent a relevant aspect of paving materials properties and they must be considered during material selection: recycled mixtures should have the same performances of traditional ones, in order to save environmental benefit obtained during the production phase.

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