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A coupled Monte Carlo–Pareto approach for sustainable asphalt mix optimization: Life cycle insights into green hydrogen and reclaimed materials

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ABSTRACT

The decarbonization of transport infrastructure is pivotal for achieving climate neutrality and advancing Circular Economy (CE) goals. Conventional asphalt production, heavily reliant on energy-intensive methods and virgin materials, contributes significantly to greenhouse gas emissions. Integrating alternative materials and low-emission energy sources could offer a viable pathway to minimizing environmental impacts while preserving pavement performance and optimizing Life Cycle Costs (LCC). This study developed a multi-objective optimization model that combines Monte Carlo simulation with Pareto front analysis to identify optimal asphalt mixtures by jointly evaluating LCC, Global Warming Potential (GWP), and product quality. The model incorporated various parameters including mix design, Reclaimed Asphalt Pavement (RAP) content, bitumen, fuel types, heating energy, transport distance, and other influencing factors. The results reveal substantial variability in environmental and economic performance, with GWP ranging from 9.17 to 97.72 kg CO_2-eq per ton and LCC between 2.75 and 13.67 €/ton, primarily driven by the type and amount of fuel consumed, with green hydrogen playing a particularly notable role despite its higher cost. Pareto-optimal solutions achieved average reductions of 35.7% in GWP and 11.7% in LCC, respectively. Analysis of Pareto-optimal solutions demonstrates that achieving low GWP does not inherently require high costs or reduced quality, nor does cost minimization necessarily lead to increased emissions or compromised performance. Overall, this research establishes a practical framework for simultaneously balancing economic, environmental, and technical criteria in asphalt production, thereby enabling more informed and sustainable decision-making in real-world applications.

1. Introduction

Sustainable development and climate action have emerged as central pillars of global policy agendas (Hasan et al., 2020; Traverso et al., 2024). With the accelerating climate crisis and the global commitment of many nations to achieve net-zero Greenhouse Gas (GHG) emissions by 2050, the urgency to reduce emissions from carbon-intensive industries has become more critical than ever (Shokri et al., 2025).

Transport infrastructure is a fundamental pillar of modern societies, underpinning economic development and social connectivity, yet it remains a significant source of environmental pressure (Tokede et al., 2020; Balaguera et al., 2018). Although vehicle operation constitutes the dominant share of transportation-related environmental impacts, the construction of infrastructure and the production of pavement materials (particularly asphalt) also contribute substantially due to their high energy intensity and dependence on virgin resources (Ferrotti et al., 2024b; Nithinchary et al., 2024aa; Milad et al., 2022b; Ma et al., 2019b).

Asphalt is the predominant paving material globally, accounting for approximately 83.5% of all paved road surfaces and therefore represents a critical leverage point for improving the environmental performance of the transport sector (Williams et al., 2022). Despite its widespread application, asphalt production is inherently energy-intensive and relies heavily on natural resources, resulting in considerable environmental burdens across multiple impact categories (Thives and Ghisi, 2017; Han et al., 2019; Rafiq et al., 2021).

Global asphalt production amounts to roughly 1.6 billion metric tons, consuming approximately 14.4 million cubic meters of fuel and 12,800 GWh of electricity. This level of production contributes an estimated 46 million tons of CO_2 emissions, equivalent to nearly 0.15% of the total global carbon dioxide output, highlighting the significant environmental footprint of asphalt manufacturing (Wang et al., 2018).

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Nomenclature

List of abbreviations

AWE	Alkaline Water Electrolysis
CE	Circular Economy
GHG	Greenhouse Gas
GWP	Global Warming Potential
HMA	Hot Mix Asphalt
IDT	Indirect Tensile Test
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LHV	Lower Heating Values
PEM	Proton Exchange Membrane
RAP	Reclaimed Asphalt Pavement
WMA	Warm Mix Asphalt

Over recent decades, asphalt pavements have become the dominant solution for road construction worldwide (Zhu et al., 2020). However, throughout their service life, these pavements undergo progressive deterioration processes (including aging, cracking, and surface distress) which generate substantial quantities of Reclaimed Asphalt Pavement (RAP) (Li et al., 2021).

Growing concerns regarding resource sustainability, escalating asphalt binder prices, and the depletion of high-quality aggregate reserves have significantly intensified interest in RAP recycling. Consequently, the reuse of RAP has emerged as a central focus of contemporary research, motivated by the dual objectives of reducing environmental impacts and improving economic efficiency within asphalt pavement systems (Li et al., 2022; Xiao et al., 2018; Zhang et al., 2021; Zhao et al., 2021).

From a Life Cycle Assessment (LCA) perspective, designing sustainable pavements requires a clear understanding of the key environmental hotspots that drive the overall impact of asphalt systems. Among the various stages of the pavement life cycle, the production phase (A1–A3) consistently accounts for the largest share of Global Warming Potential (GWP) (Gruber and Hofko, 2023). Specifically, LCA studies indicate that the extraction of raw materials and the energy-intensive heating operations during asphalt production are the primary environmental hotspots, exerting a decisive influence on total emissions and resource consumption (Li et al., 2023).

Given these two dominant hotspots, meaningful decarbonization requires targeted interventions that (1) reduce the impacts associated with virgin materials and (2) lower the energy and emissions of the heating process. This dual strategy has shaped much of the recent scientific focus on sustainable asphalt technologies.

To address the substantial upstream burdens associated with virgin binder and aggregate production, recycled constituents, especially RAP, have become one of the most effective pathways for environmental improvement. RAP significantly decreases demand for virgin aggregates and bitumen, thereby reducing resource extraction, energy consumption, and GWP (Yang et al., 2015; Hana and Thakur, 2015; Tarsi et al., 2020). Numerous LCAs show that increasing binder replacement through RAP consistently lowers energy demand, GWP, and total cost (Yang et al., 2023).

Studies report that RAP can reduce virgin material use and production while lowering CO_2 emissions relative to conventional Hot-Mix Asphalt (HMA) or Portland cement concrete pavements. From a long-term perspective, agency evaluations under projected climate scenarios indicate that mixtures incorporating 40–70% RAP reduce life-cycle costs by 18–25% without degrading structural performance when rejuvenators or softer binders are used (Qiao et al., 2019). Even fully recycled mixtures are technically feasible: the production of 100% recycled HMA has demonstrated 35% reductions in CO_2eq and at least 50% cost savings, provided the RAP is appropriately processed and rejuvenated (Zaumanis et al., 2014).

Complementary recycled modifiers such as crumb rubber can also enhance performance and reduce environmental burdens, although they introduce challenges related to binder compatibility and phase stability (Cao et al., 2026). High-RAP mixtures remain the most effective strategy for mitigating raw-material impacts.

A key approach to mitigating the second major (and arguably more critical) hotspot namely fuel-intensive heating during asphalt production, is the replacement of carbon-intensive fuels with cleaner alternatives. Studies demonstrate that adopting lower-carbon fuels in asphalt plants can substantially reduce environmental impacts, particularly when combined with high levels of recycled materials (Abdalla et al., 2022; Shokri et al., 2024; Firozjaei et al., 2025). Among emerging options, green hydrogen represents a promising long-term pathway. Recent data show that modern renewables accounted for about 13.4 % of global final energy consumption in 2022, highlighting a meaningful (albeit still limited) penetration of clean energy into the global mix (Yolcan, 2023; Hassan et al., 2024). Green hydrogen, generated through renewable-powered electrolysis, emits no greenhouse gases and is widely recognized as a critical enabler of deep industrial decarbonization (Shiva Kumar and Lim, 2022; Awad et al., 2024; Mohammadi and Mehrpooya, 2018). Although current adoption is limited by high production costs and infrastructure constraints, hydrogen-fuelled asphalt plants offer a viable route toward near-zero-emission heating in the long term.

Complementing these fuel-switching strategies, another major pathway for reducing heating-related emissions is decreasing production temperatures.Warm-mix Asphalt (WMA) technologies provide a proven and widely implemented solution for lowering thermal energy demand while maintaining mechanical performance. LCA studies consistently confirm that WMA mixtures are more environmentally favorable than conventional HMA, provided long-term durability is preserved (Ferrotti et al., 2024a). Reducing production temperatures through chemical additives can lower thermal energy requirements by approximately 15% and substantially decrease particulate matter, NO_x, and VOC emissions at the plant (Nithinchary et al., 2024ab). WMA achieves temperature reductions of ~20–50 °C, decreases energy consumption by 20–75%, lowers greenhouse gas and $PM_{2.5}$ emissions, and improves workability and compaction (Ma et al., 2019a).

Lower mixing temperatures also enhance compatibility with high RAP incorporation, reducing performance risks when appropriate additives or rejuvenators are used (Milad et al., 2022a). Integrated systems that combine high RAP contents with WMA and cold in-place recycling yield up to 12% reductions in CO_2eq, 15% savings in primary energy demand, and 15% lower water consumption over the pavement life cycle compared with traditional HMA mixtures (Mishra and Sadhu, 2023). Additional LCAs report 13–35% reductions in GWP, fossil resource depletion, and cumulative energy demand for RAP–WMA mixtures, with full life-cycle analyses of 1-km pavement sections indicating 10–15% reductions across multiple environmental categories (Vidal et al., 2013aa; Giani et al., 2015).

Although production-stage heating is the main focus of this study, thermal considerations extend across the pavement life cycle. Emerging research explores in-service thermal regulation techniques (such as thermochromic coatings) which reduce pavement temperatures and mitigate urban heat island effects (Chen et al., 2025). These innovations illustrate the broader significance of integrated thermal management in sustainable pavement systems.

Beyond the primary asphalt production hotspots, the life-cycle environmental impacts are strongly influenced by the inherent complexity of the production process and the interaction of multiple variables (such as mix design composition, transportation distances, fuel types, aggregate thermal properties, mixing temperature) which exhibit substantial real-world variability, introduce significant uncertainties, and highlight the need for careful uncertainty evaluation and the use of robust stochastic approaches in LCA (Liu et al., 2023).

Despite the widespread use of LCA in pavement engineering, conventional deterministic approaches have been repeatedly criticized for their inability to adequately capture input parameter uncertainty and variability, which can lead to significantly biased or overconfident results (Huang et al., 2021a; Santero et al., 2011; Azarijafari et al., 2016). These methods typically rely on fixed, single-point input values and fail to propagate uncertainties through the analysis, masking the true range of possible environmental and economic outcomes and limiting the robustness of decision-making (Gregory et al., 2016). Furthermore, deterministic frameworks rarely support simultaneous multi-objective optimization under stochastic conditions, making it difficult to explicitly identify trade-offs among conflicting sustainability criteria such as Life-Cycle Cost (LCC), GWP, and functional performance (Quality).

To overcome these shortcomings, this study develops an integrated framework for sustainable asphalt mixture design and evaluation. The framework combines carbon footprint analysis within a life-cycle perspective, Monte Carlo simulation, and Pareto-based multi-objective optimization to jointly optimize LCC, GWP, and functional performance (Quality).

This framework accounts for both structural and parametric uncertainties by simulating a wide range of possible values for all input parameters. These include variations in mix design, RAP content, types and proportions of fuel (e.g., green hydrogen, coal, natural gas, lignite, oil), transportation distances, thermal properties of aggregates, and use of additives such as lime. In addition, the costs associated with all processes and materials, including material procurement, fuel consumption, transportation, and energy use, are treated as stochastic variables rather than fixed inputs. In total, more than one million (with further iterations producing negligible changes in the outputs) unique asphalt mix combinations were generated and evaluated in terms of technical performance, environmental impact, and economic cost.

Beyond developing the optimization algorithm, this study identifies and analyzes the key drivers that influence sustainability performance. It reveals the complex interactions among environmental burden, economic feasibility, and mechanical quality. The final outcome is a set of Pareto-optimal asphalt mix designs that can serve as decision-support tools for future infrastructure planning. These results provide not only a practical pathway for enhancing sustainability in asphalt production but also a foundation for developing evidence-based policies that support low-carbon construction.

Accordingly, the objective of this study is to evaluate whether the proposed integrated, stochastic, Pareto-based optimization framework can effectively identify asphalt mixture designs that simultaneously reduce environmental impacts, control life-cycle costs, and maintain acceptable functional performance under uncertainty. The underlying hypothesis is that explicitly accounting for uncertainty and multi-objective trade-offs enables more robust and sustainable asphalt design decisions compared to conventional deterministic approaches.

2. Materials and methods

This study aims to optimize the composition of HMA mixtures by integrating Monte Carlo simulation, LCA, and a multi-objective optimization method based on the Pareto front approach. The percentages of bitumen, sand, and gravel, along with the proportions of RAP and the transportation distances for all materials, were considered within specified ranges. These variations directly influence production costs, the quality of the final asphalt product, and its environmental footprint. To capture these uncertainties, Monte Carlo simulation was employed as a powerful tool to represent stochastic variability and estimate a broad spectrum of possible outcomes.

In the context of sustainable asphalt production under uncertainty, a Pareto-based analytical framework provides a robust basis for decision-making by enabling the evaluation of optimal material combinations and energy supply strategies, including low-carbon alternatives such as green hydrogen. In Pareto multi-objective optimization, a set of non-dominated solutions (the Pareto front) is generated, where no single criterion can be improved without deteriorating at least one other. This approach allows decision-makers to explore trade-offs among economic, environmental, and technical indicators and to identify balanced solutions that best fit practical requirements.

2.1. Code implementation

To generate diverse yet realistic asphalt mix designs, a custom Python program was developed using several scientific libraries. The variability ranges of the input parameters were not arbitrarily defined but derived from practical references. In particular, the maximum allowable share of RAP was determined based on European specifications and national guidelines (Wang et al., 2025; Dal Ben and Jenkins, 2014; Jain and Chandrappa, 2023; Yang et al., 2021; Yousefi et al., 2021). Other parameters, including bitumen content, aggregate proportions, heating energy, and temperature requirements, were specified according to typical mix designs commonly reported in construction projects and industry practice (MS-2; Schönauer et al., 2024; Sollazzo et al., 2020). Unit prices of materials, fuels, transportation and additives were taken from recent market data (Santolini et al., 2024; Wolf et al., 2024; El-Emam and Özcan, 2019). By constraining the parameter space to these reference-based ranges, the program ensured that all simulated scenarios remain technically feasible and practically implementable.

Each simulation run produces a unique asphalt composition along with its corresponding GWP, cost, and performance quality score. By repeating this process, a comprehensive dataset of mix designs was generated. Subsequently, the Pareto front technique was applied to extract the most optimal combinations, balancing all three indicators without favoring one at the expense of the others. The complete Python implementation supporting this analysis is provided in the **Data availability** section.

2.2. Global Warming Potential and life cycle cost

In this study, a LCA was conducted to evaluate the environmental impacts associated with the production of HMA, specifically the AC16BC mix type. The functional unit was established as one metric ton of asphalt, serving as the basis for all calculations and comparative analyses across different mixture scenarios.

The system boundary was defined as cradle-to-gate, encompassing stages A1 to A3 according to the EN 15804 standard. Fig. 1 schematically illustrates the system boundary. A cut-off approach was applied to allocate carbon credit related to the use of RAP.

GWP was selected as the primary environmental impact indicator because it measures the impact on climate change. The GWP of each material and process in asphalt production was obtained from the GaBi® 10 database and calculated using the CML 2001 method (Gabi Databases & Modeling Principles, 2022).

A stochastic model, implemented in Python, was utilized to randomly generate asphalt mix designs, select fuel types, transportation distances, and other relevant parameters. Each parameter was assigned a permissible range, and values were randomly sampled within these bounds. For each generated combination, GWP, LCC, and Quality were calculated accordingly. Table 1 summarizes the ranges of input parameters used for both the LCA and LCC analyses. The LCC of each asphalt mixture was estimated based on updated cost data, incorporating expenses associated with raw materials, fuel consumption, transportation, and related processes. All cost information was sourced from up-to-date databases and, where applicable, recent peer-reviewed studies (Santolini et al., 2024; Wolf et al., 2024; El-Emam and Özcan, 2019).

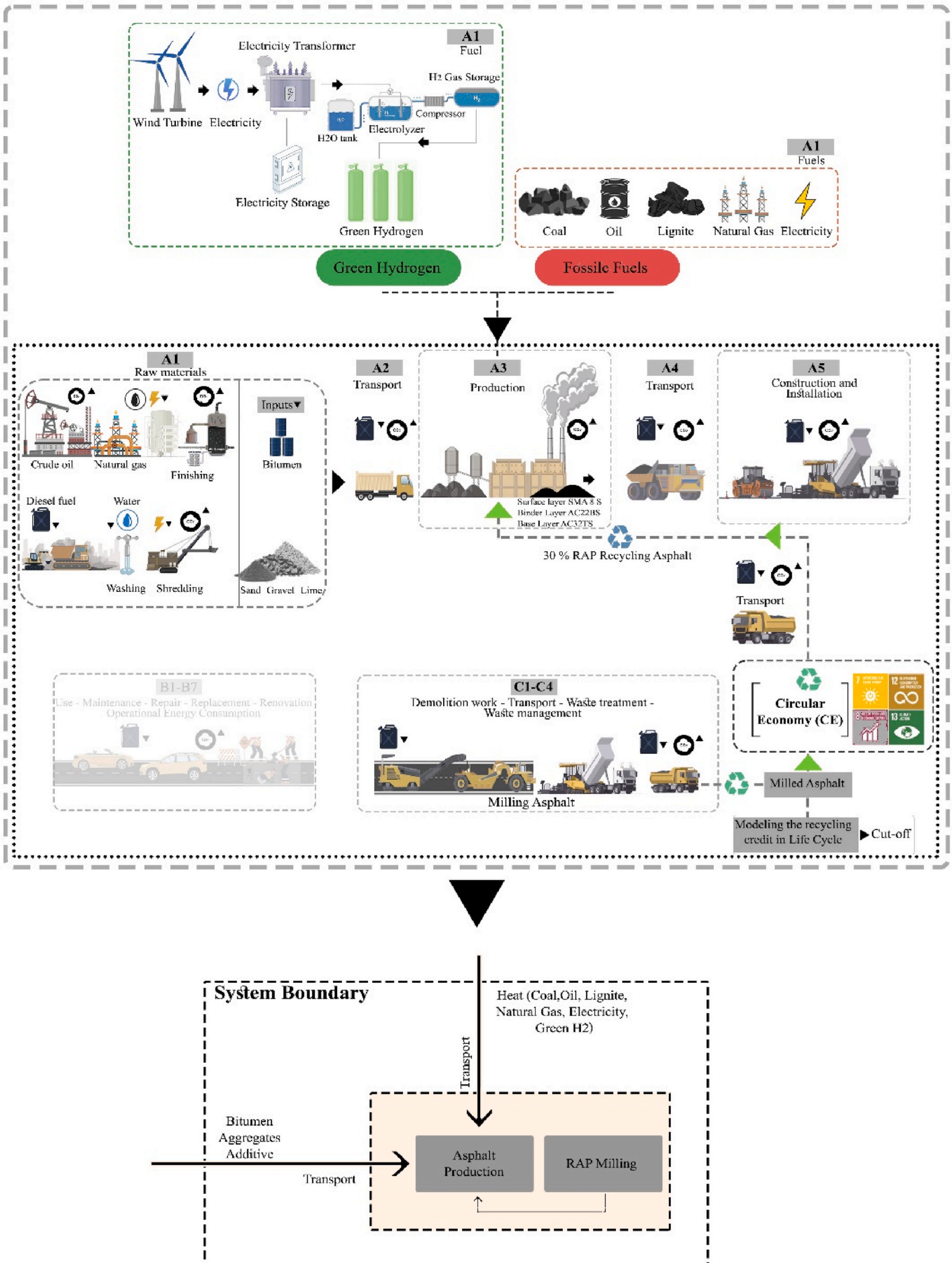

Fig. 1. System boundary of the life cycle assessment case study.

2.3. Heating energy demand

To quantify the thermal energy demand associated with asphalt production, five conventional fuel sources were considered: coal, lignite, natural gas, oil, and green hydrogen. In each simulation, the heating fuel was randomly selected either as a single type or a blend of multiple fuels, with the relative share of each fuel randomly determined. Fuel consumption was computed based on the Lower Heating Value (LHV) range of each fuel type.

For every asphalt mixture generated through the Monte Carlo simulation, the total heating energy requirement was estimated by considering the mass and specific heat capacity of each constituent,

Table 1
Key information used in LCA and LCC modeling.

Material	Consumption per ton HMA (MS-2; Schönauer et al., 2024; Sollazzo et al., 2020)	Cost	CO_2 Emission Factor (GaBi® 10 database)	GaBi Source/ Note
Bitumen	11 – 60 (kg)	0.404 – 0.498 (€/kg)	0.340 (kg CO_2/kg)	DE: Bitumen at refinery Sphera
RAP	0 – 500 (kg)	0.00043 – 0.00176€/tkm	0.0827 (kg CO_2/kg)	(Wang et al., 2025; Dal Ben and Jenkins, 2014; Jain and Chandrappa, 2023; Yang et al., 2021; Yousefi et al., 2021)
Lime	2.5 – 3.5 (kg)	0.120 (€/kg)	0.00466 (kg CO_2/kg)	EU-27: Quicklime EuLa
Sand	Remaining to 1000 kg	0.011 – 0.025 (€/kg)	0.00204 (kg CO_2/kg)	DE: Sand 0/2 Sphera
Gravel				DE: Gravel (Grain size 2/32) Sphera
Electricity	~5.2 (kWh)	0.38-0.42 €/kWh	0.5 (kg CO_2/kWh)	DE: Electricity grid mix Sphera
Transportation	50 – 200 km	0.00043 – 0.00176 €/tkm	0.0827 tkm	GLO: Truck, Euro 5, 28 - 32t gross weight/ 22t payload capacity Sphera
Green Hydrogen	See Section **2.3** for calculation details	3 – 8 (€/kg)	0.020 (kg CO_2/kg)	Created by the authors (Spath and Mann, 2004).
Lignite		0.107-0.15 (€/kg)	0.207 (kg CO_2/kg)	DE: Thermal energy from lignite Sphera
Oil		0.4304-0.6456 (€/kg)	0.097 (kg CO_2/kg)	DE: Thermal energy from heavy fuel oil (HFO) Sphera
Natural Gas		0.42-0.573 (€/kg)	0.0817 (kg CO_2/kg)	DE: Thermal energy from natural gas Sphera
Coal		0.00778-0.1167 (€/kg)	0.206 (kg CO_2/kg)	DE: Thermal energy from hard coal Sphera

including bitumen, aggregates, RAP, and lime, along with their initial and target temperatures. The final mixing temperature was randomly sampled within the range of 170 °C and 180 °C, and the initial material temperature was sampled between 5 °C and 17 °C. The required thermal energy (Q) was calculated using the standard heat transfer equation (Eq. (1)):

$$Q = m.\ c.\ (Ttarget - Tinitial) \quad (1)$$

Where Q is the required energy (MJ), m is the mass of each material (kg), c is the specific heat capacity (MJ/kg°C), $Ttarget$ is the target temperature (°C) and $Tinitial$ is the initial temperature (°C).

The specific heat capacities used in this study were 2000 J/kg°C for bitumen, 900 J/kg°C for both RAP and aggregates, and 850 J/kg°C for lime (Kim and Lee, 2025; Jamshidi et al., 2017; Martínez et al., 2019). For RAP, the required thermal energy was divided into two components, assuming that 95% of RAP behaves as aggregate and 5% as bitumen, with the heat demand calculated separately for each fraction. The LHV range of the fuels varied across different fuel types: lignite ranged from 10 to 18 MJ/kg, coal from 17.4 to 23.9 MJ/kg, oil from 42 to 45 MJ/kg, natural gas from 42 to 55 MJ/kg, and green hydrogen from 120 to 140 MJ/kg.

2.4. Quality definition

The impact of RAP on asphalt performance is inherently dual. Properly designed high-RAP mixtures, combined with suitable rejuvenators such as bio-rejuvenators, warm-mix surfactants, or soft bitumen, can effectively restore aged binder properties, enhance fatigue life, and maintain high-temperature performance and ageing resistance, even at RAP contents up to 70% (Jacobs et al., 2021). These approaches also deliver substantial environmental and economic benefits, including reduced virgin material demand and lower CO_2 emissions (Kaseer et al., 2019; Mattinzioli et al., 2020; Huang et al., 2021b).

Conversely, excessive RAP content, inadequate blending, or high moisture levels in RAP stockpiles can negatively affect mechanical performance. Issues include non-uniform binder properties, reduced rutting resistance, cracking, low-temperature cracking, and decreased fatigue life, especially in mixtures with high fine-RAP content (Ma et al., 2015; Lo Presti et al., 2016; Chen and Wang, 2018). Comparative binder studies indicate that while well-selected rejuvenators can restore fatigue life and ageing resistance, incomplete mixing often leads to performance variations across the mixture (Yu et al., 2024; Chen et al., 2021).

Therefore, while RAP offers significant sustainability advantages, its effects on asphalt performance are context-dependent, highlighting the need for careful RAP management, fractionation, rejuvenation, and advanced binder blending methodologies to ensure reliable and durable asphalt mixtures (Ai et al., 2023).

The definition of the asphalt quality function in this study is based on comprehensive studies conducted by Loprencipe et al. (2025). Their study revealed that incorporating RAP into asphalt mixtures produces a dual effect on performance, simultaneously improving some properties while compromising others (Loprencipe et al., 2025). The aged binder in RAP enhances rutting resistance, dynamic modulus, and high-temperature stability due to its increased stiffness and polymer-rich composition. At the same time, it can reduce mixture ductility, fatigue cracking resistance, and tensile strength, particularly at higher RAP replacement levels. As a result, the quality of RAP-modified asphalt increases relative to conventional virgin mixtures up to an optimal threshold, after which it declines as fatigue-related limitations begin to dominate.

To quantitatively capture this non-monotonic behavior, a composite quality index (QI) was defined based on the systematic findings of Loprencipe et al. as shown in Equation (2) (Loprencipe et al., 2025). The unconstrained quadratic function was derived through second-order regression of normalized performance indicators (rutting, fatigue, and moisture damage resistance) from high-quality studies employing the Indirect Tensile Test (IDT) as reviewed in Loprencipe et al. (2025). This function reaches its mathematical maximum of approximately 1.254 at $R \approx 0.28$ (i.e., ~28% RAP), representing the optimum balance between stiffness-related gains and ductility-related losses in the absence of rejuvenators.

For practical interpretation and optimization purposes, the quality index (QI) was normalized such that the peak performance corresponds to Quality = 1.0, while the virgin mixture (R = 0) yields Quality ≈ 0.80 as shown in Equation (3). This normalization reflects the empirical observation that well-designed mixtures with $R \approx 0.28$ consistently outperform virgin mixtures in overall structural contribution and resistance to permanent deformation, even without rejuvenation. The final form of the quality index is therefore:

$$QI = 1.0 + 1.8R - 3.2R^2 \quad \text{(Eq.2)}$$

$$QUALITY(Q) = \max\left(0.65, \frac{QI}{QI_{\max}}\right) \quad \text{(Eq.3)}$$

This lower limit of 0.65 directly reflects the worst-case scenario documented in the literature for 100% RAP mixtures produced without any rejuvenating or modifying agents (Loprencipe et al., 2025). Fig. 2 illustrates the behavior of the quality function across different RAP contents. Following current European practices, where the maximum allowable RAP content in surface and binder courses is limited, the model was therefore constrained to $R \leq 0.50$ in all optimization scenarios, in line with practical asphalt construction practices in Germany (Verkehrsflächenbefestigungen von, 2007; Mantalovas et al., 2023; Nielsen et al., 2003).

In each Monte Carlo simulation, the RAP content was first randomly selected within the predefined range. Then, the quantities of other constituents including bitumen, sand, gravel, RAP bitumen and additive were proportionally adjusted to maintain material balance. The total weight of each asphalt mixture was kept exactly at one metric ton, a condition implemented within the Python computational model.

3. Results

Statistical analysis of simulated combinations of material compositions and fuel types in asphalt production revealed significant variations in GWP, LCC, and quality indicators, as provided in Fig. 3. As illustrated in Fig. 3 the substantial disparity between the minimum and maximum values highlights the critical influence of fuel types and material compositions on both environmental and economic performance metrics.

The LCC values ranged from 2.75 to 13.67 €/ton, with a mean of 5.37 €/ton. This wide range (spanning nearly a fivefold difference) reflects the presence of scenarios with substantially higher costs, likely due to expensive raw materials or energy sources. The GWP values varied from 9.17 to 97.72 kg CO_2/ton, with a mean of.

41.61 kg CO_2/ton, indicating that variations in material and fuel combinations significantly affect the results. These broad distributions emphasize the influence of material-fuel interactions on both environmental and economic outcomes.

From a statistical perspective, the LCC distribution demonstrated positive skewness and high kurtosis, suggesting the presence of outliers and a non-normal distribution skewed toward higher cost values. The GWP distribution was relatively more symmetric but exhibited a wide interquartile range, highlighting significant variability.

The observed narrow distribution of the Quality is a direct consequence of the quadratic formulation of the quality model and the constrained RAP domain (0–50%). Since the quality function reaches its maximum at approximately 28% RAP and decreases only mildly toward both ends of the interval, the normalized quality values remain high across most scenarios. Even at the upper limit (50% RAP), the quality index remains above 0.85, leading to a strongly concentrated distribution near the optimum.

These findings underscore the necessity of applying multi-objective optimization techniques in asphalt mix design. Without such methods, random selection of input parameters could result in mixes with high costs or adverse environmental effects. To illustrate the diversity of outcomes, representative values from the dataset are provided in Table 2.

Six representative asphalt mixtures, selected from the simulated combinations, are presented in Table 2. These scenarios were intentionally chosen to illustrate the trade-offs and optimization potential of the system. For each performance metric (GWP, LCC, and Quality), two *near-extreme* cases were selected, representing values close to the observed minimum and maximum, rather than the absolute extremes, in order to provide realistic and practically relevant comparisons.

In the LG scenario, which exhibits a GWP close to the lower bound of the simulated range (9.5 kg CO_2/ton), the production cost (6.16 €/ton) is lower than that of the HG scenario, which represents a near-maximum GWP case (95.8 kg CO_2/ton) with a corresponding cost of 6.69 €/ton. This result indicates that carbon reduction does not necessarily lead to higher costs. The low-emission scenario utilizes green hydrogen and a high RAP content (490 kg), whereas the high-emission scenario relies heavily on lignite and contains only 217 kg of RAP, explaining the substantial difference in environmental impact.

In the LL scenario, which exhibits a LCC close to the lower bound of the simulated range (2.89 €/ton), the GWP (34.2 kg CO_2/ton) is lower than that of the HL scenario, which represents a near-maximum LCC case (13.6 €/ton) with a corresponding GWP of 34.4 kg CO_2/ton. This comparison demonstrates that higher costs do not necessarily translate into lower GWP. Although the low-cost scenario relies on inexpensive and carbon-intensive coal as the heating fuel, its reduced bitumen

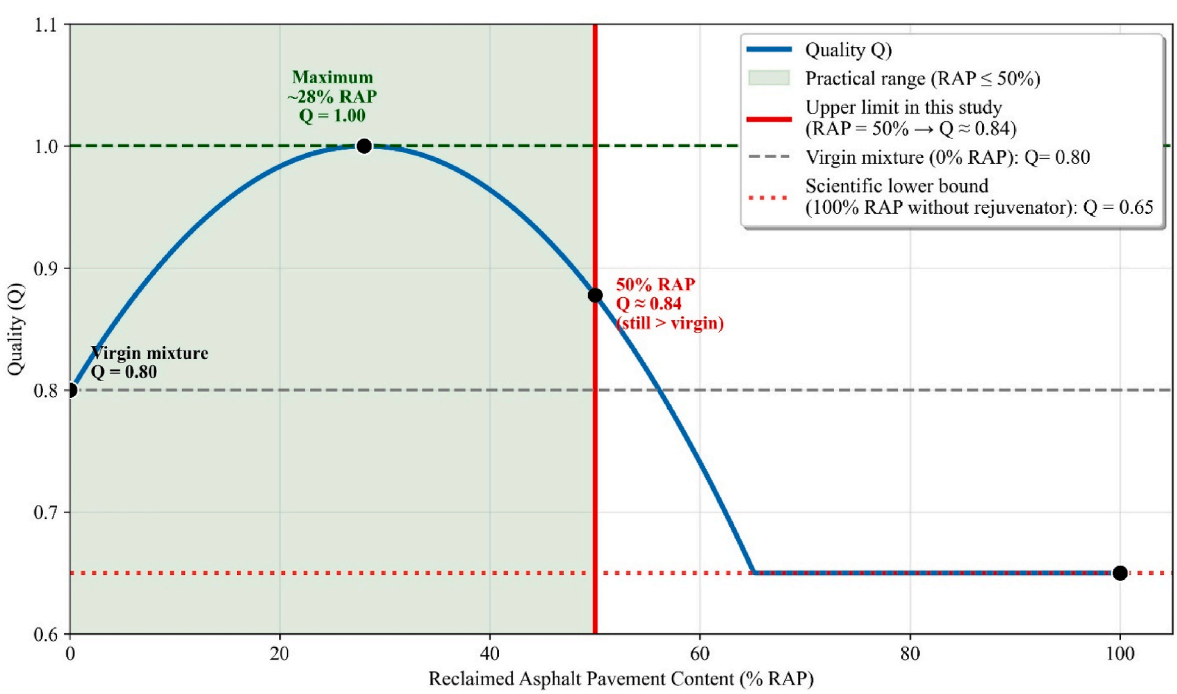

Fig. 2. Quality as a function of RAP percentage in the asphalt mixture.

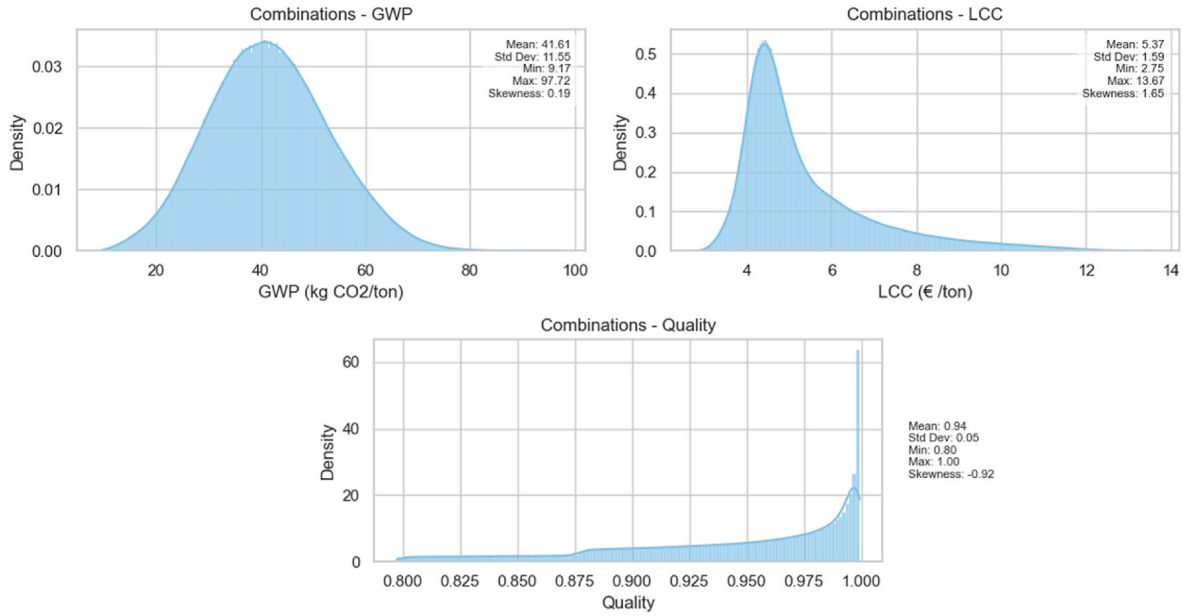

Fig. 3. Distributions of GWP, LCC, and Quality across the asphalt mixture design space.

Table 2
Selected asphalt mixtures illustrating trade-offs in LCC, GWP, and quality.

ID	Scenario	LCC (€/ton)	GWP ($kgCO_2$/ton)	Quality	Bitumen (kg)	RAP (kg)	Lime (kg)	Sand (kg)	Gravel (kg)	Fuel Type	Total Fuel (kg)	Target Temp (°C)
HG	**High GWP Combination**	**6.69**	**95.8**	**0.98**	**57.14**	**217**	**2.98**	**115**	**608**	**Lignite**	**16.46**	**175.2**
LG	**Low GWP Combination**	**6.16**	**9.5**	**0.88**	**12.97**	**490**	**2.67**	**72**	**422**	**Green Hydrogen**	**1.17**	**175.7**
HL	**High LCC Combination**	**13.6**	**34.4**	**0.99**	**55.36**	**325**	**3.04**	**98**	**519**	**Green Hydrogen**	**1.37**	**172.8**
LL	**Low LCC Combination**	**2.89**	**34.2**	**0.82**	**19.85**	**19**	**3.0**	**158**	**801**	**Coal**	**5.58**	**170**
LQ	**Low Quality Combination**	**5.05**	**49.8**	**0.79**	**57.25**	**0.0**	**3.15**	**148**	**804**	**Green H2+Coal + Natural Gas + Oil**	**3.25**	**174.8**
HQ	**High Quality Combination**	**4.61**	**44.1**	**0.99**	**29.10**	**281**	**3.39**	**99**	**588**	**Green H2+Oil + Lignite + Natural Gas**	**5.42**	**171.7**

content ultimately results in a lower overall GWP.

In the LQ scenario, which exhibits a quality close to the lower bound of the simulated range (0.79), the GWP (49.8 kg CO_2/ton) and cost (5.05 €/ton) is higher than that of the HQ scenario, which represents a near-maximum quality case (0.99) with a corresponding GWP of 44.1 kg CO_2/ton and cost of 4.61 €/ton. This outcome indicates that a reduction in performance quality does not inherently lead to lower costs or environmental impacts. In fact, the higher-quality scenario benefits from an optimized combination of increased RAP content, reduced virgin bitumen use, and lower heating demand, collectively contributing to improved GWP and cost performance.

These findings underscore that fuel type, target heating temperature and RAP management strategies exert a profound (and often dominant) influence on overall performance indicators, frequently outweighing the effect of material proportions alone. Consequently, conclusions derived solely from material composition, without incorporating fuel strategy and process parameters, are likely to be incomplete and potentially misleading. Therefore, to identify truly optimal asphalt mixtures with respect to cost, carbon footprint, and performance, the application of multi-objective optimization techniques is not merely recommended but essential. Only through such an integrated approach can balanced mixtures be achieved that satisfy the competing demands of economic viability, environmental sustainability, and mechanical durability.

3.1. Multi-objective optimization and pareto front

Fig. 4 Illustrates the results of the multi-objective optimization, focusing on three key performance: LCC, GWP, and asphalt quality. The left panel shows the overall structure of the solution space: a large cloud of blue points representing the wide range of possible combinations. The Pareto points (in red) lie roughly along the outer boundary of this cloud, forming the frontier beyond which improving one objective necessarily leads to a deterioration in at least one of the others.

In the right panel, presenting the Pareto front, distinct clusters are clearly visible. The Pareto front effectively highlights optimal asphalt mixtures that occupy the lower ranges of both cost and GWP. The yellow points (indicating higher Quality) form a distinct cluster and are primarily located in regions with relatively low to mid-range LCC values. This pattern demonstrates that achieving high Quality does not inherently require higher costs, and that there exist mixtures capable of delivering superior Quality at reasonable expense.

The solutions exhibiting the lowest GWP values (the darker points along the vertical axis) are not found within the high-Quality cluster; instead, they are scattered across regions where Quality is generally moderate or lower. This distribution supports the interpretation that minimizing GWP is driven more by choices related to fuel and energy sources than by adjustments in mixture quality or RAP-based

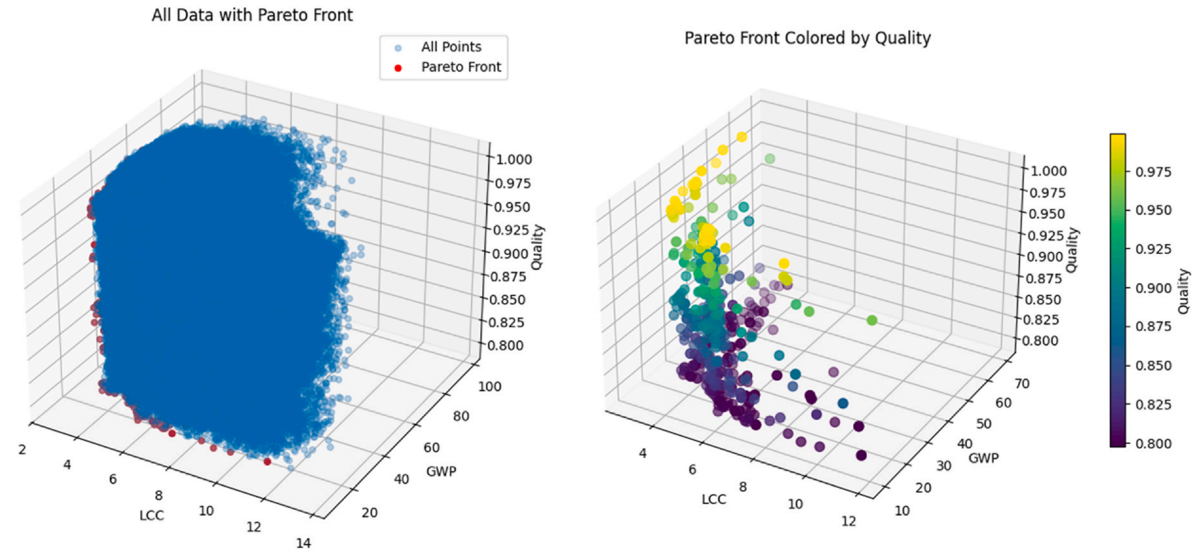

Fig. 4. Visualization of all asphalt mixtures and the corresponding Pareto front based on GWP, LCC, and Quality.

formulation.

A more in-depth quantitative analysis of these trade-offs is provided in Fig. 5 which presents histograms of GWP, LCC, and the Quality, comparing the full dataset with the corresponding Pareto-optimal solutions.

The distribution of GWP in the full Monte Carlo population approximates a normal distribution, centered around 41 kg CO_2/ton, indicating that, in the absence of optimization, most asphalt formulations result in average environmental performance. In contrast, the GWP distribution of Pareto-optimal solutions is distinctly shifted toward lower values and exhibits a multimodal pattern. These multiple peaks likely correspond to alternative decarbonization strategies, such as the use of high RAP content in combination with low-emission fuels like green hydrogen. The presence of multiple local optima suggests that there is no single optimal pathway to minimizing GWP; instead, various viable strategies can achieve substantial emission reductions without compromising cost or quality excessively.

Regarding the LCC indicator, the unoptimized population exhibits a wide distribution ranging from 2.8 to 13.6 €/ton, reflecting considerable economic variability across asphalt mix configurations. The Pareto front, trending toward lower values, demonstrates the potential for optimizing asphalt formulations while simultaneously reducing costs. A similar bimodal pattern in the LCC histogram further suggests that, as with GWP, there is no unique optimal pathway for minimizing LCC.

The Quality histogram reflects the structural constraints imposed by the quality function, which depends solely on the RAP content. Neither the full population nor the Pareto set includes mixtures with Quality below 0.8 due to the practical RAP limit of 50%. Moreover, because high RAP contents introduce aged binder that increases heating demand (and thus raises GWP) the optimization process tends to discard mixtures with very high RAP percentages. This leads to a concentration of Pareto-optimal solutions cluster within a narrow quality range (≈0.8–0.82), producing a visibly left-skewed distribution.

3.1.1. *Fuel patterns in Pareto results*

Given the prominent influence of fuel type on environmental and

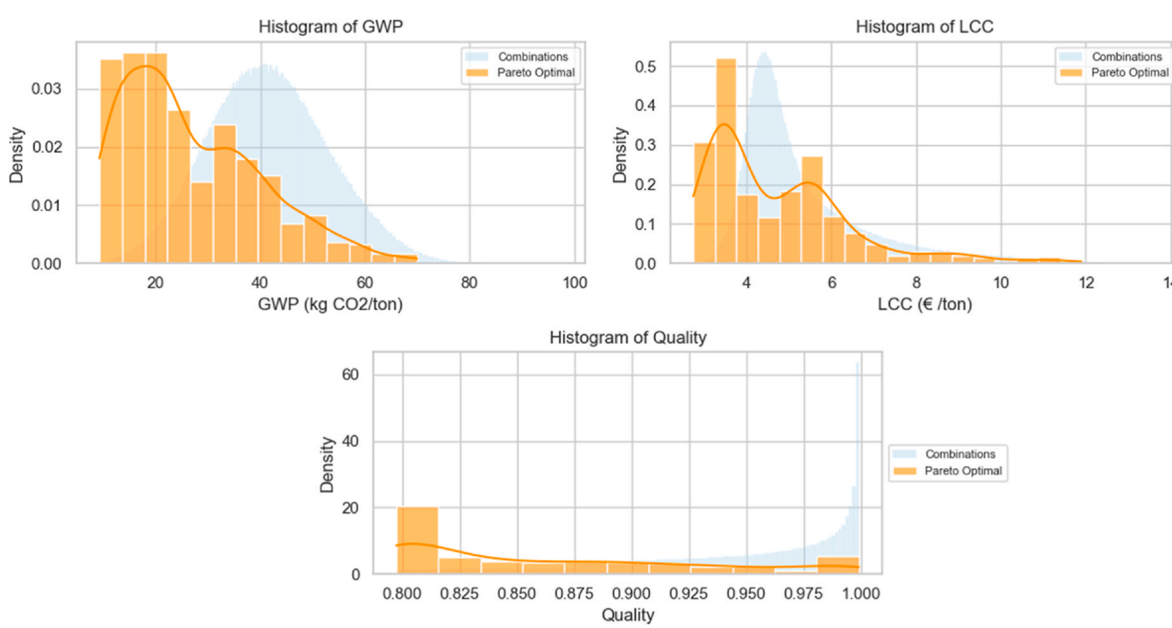

Fig. 5. Comparative distributions of GWP, LCC, and Quality in the full solution space and the Pareto-optimal set.

economic outcomes, a detailed analysis was conducted on the fuels selected in Pareto-optimal combinations. The results indicate a consistent preference for specific fuels across a wide range of optimized scenarios, emphasizing their strategic role in balancing emissions, cost, and quality.

Fig. 6 Illustrates the frequency of individual fuels and fuel combinations among the Pareto-optimal solutions. In both multi-fuel configurations and single-fuel cases, green hydrogen appears as the most frequently selected fuel, followed by natural gas and coal. Oil and lignite also appear in the optimal solutions when used in combination with other fuels; however, as single-fuel options they are selected only rarely (1.3% and 1.6%, respectively).

Notably, green hydrogen, despite its high cost, features prominently in the optimal set. This prevalence suggests that hydrogen plays a key role in low-emission strategies, particularly in solutions that prioritize environmental impact without incurring excessive cost penalties.

Moreover, in single-fuel scenarios, the almost complete exclusion of lignite and oil (both characterized by high GWP) reinforces the decisive influence of fuel type in determining sustainability outcomes. These findings are consistent with earlier results and underscore the transformative potential of green hydrogen in decarbonizing asphalt production, provided economic barriers are addressed. Its selection across multiple optimized scenarios highlights its viability as a core component in future sustainable fuel portfolios.

4. Discussion

The results presented above demonstrate that the ranges of LCC and GWP values obtained in this study are broadly consistent with those reported in the literature. However, the minimum GWP value recorded (9.17 kg CO_2/ton) represents a significant advancement in the field of HMA, as such a low value has not been previously documented in peer-reviewed studies.

The observed variability (ranging from 9.17 to 97.72 kg CO_2/ton for GWP and 2.75 to 13.67 €/ton for LCC) underscores the high sensitivity of the modeling outcomes to input parameters. Importantly, these extreme values were predominantly influenced by fuel type and heating temperature, while other factors such as RAP content, bitumen proportion, and mineral aggregate composition remained largely constant. This highlights the central role of thermal energy inputs in driving both environmental and economic performance in asphalt production.

These findings are in strong agreement with prior LCA that have identified the heating phase as a key environmental hotspot in HMA production (Moretti et al., 2017; Araújo et al., 2014; Yu and Lu, 2012; Tatari et al., 2012; Vidal et al., 2013ab). The Pareto front analysis (Fig. 6) further corroborates this insight, revealing that green hydrogen (the cleanest) are frequently present in optimal solutions. Conversely, the exclusion of lignite and oil from the single-fuel optimal combinations reinforces the importance of strategic fuel selection.

Given the pivotal influence of fuel type on both LCC and GWP outcomes, a dedicated, in-depth analysis of fuel impacts is warranted. Applying advanced statistical techniques to the optimized combinations would facilitate a more granular understanding of fuel-specific effects on model outputs, thereby enhancing both the precision of optimization strategies and the reliability of design recommendations.

4.1. *Effect of mixture design on GWP, LCC, quality*

The Monte Carlo simulation results underscore the pivotal influence of input uncertainty (especially in the type and quantity of fuel consumed) on the variability of key optimization indicators. As demonstrated in the **Results** section, all three metrics exhibited non-normal and skewed distributions, indicating complex, non-linear relationships between inputs and outputs.

This behavior highlights the necessity for deeper investigation into the parameters that most significantly influence these outcomes. To better understand these interdependencies and quantify the degree of influence, a comprehensive correlation and sensitivity analysis was performed. These analyses aim to identify the key drivers behind variations in GWP, LCC, and quality, and to improve the robustness and interpretability of the optimization framework.

4.1.1. *Correlation analysis*

Fig. 7 presents the correlation coefficients between several input parameters and the three criteria: GWP, LCC, and quality, calculated across the entire asphalt mixture design space. Correlations with absolute magnitude below $|r| = 0.01$ were removed and are not reported. For GWP, the dominant predictor is Total Fuel Required ($\rho = 0.78$), confirming that energy consumption for heating and processing is the main source of climate impact in asphalt production. Bitumen ($\rho = 0.462$) and the two coal-derived fuels Coal and Lignite ($\rho = 0.461$ each) also show substantial positive associations with GWP, reflecting the high carbon intensity of binder production and fossil fuels. Smaller but reportable positive correlations were observed for Sand ($\rho = 0.013$) and Green Hydrogen ($\rho = 0.013$); these marginal coefficients are near the reporting threshold and likely reflect indirect model couplings rather than major

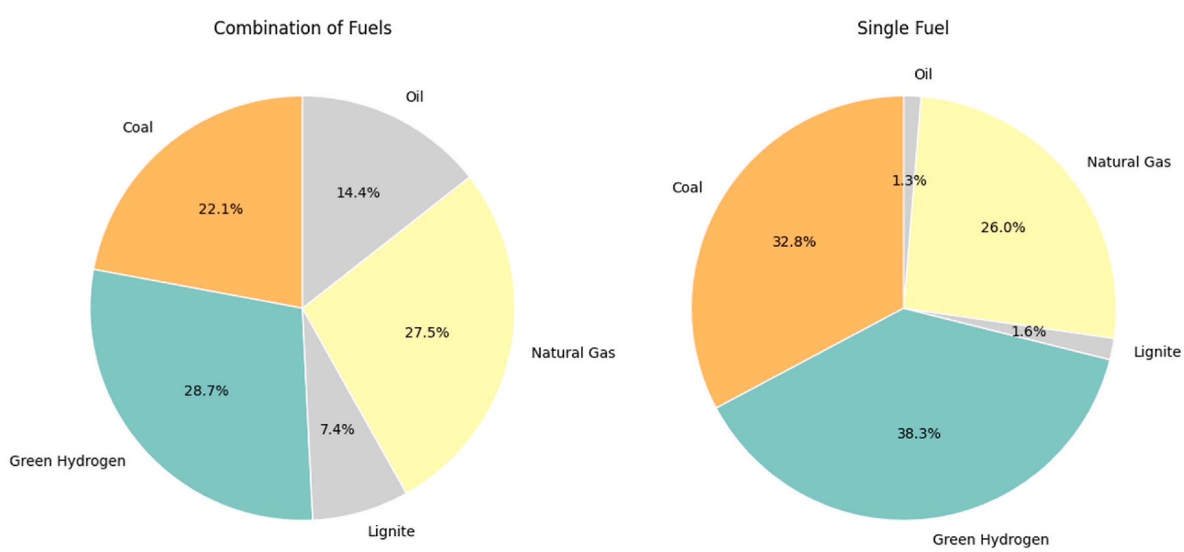

Fig. 6. Frequency of fuel types used for asphalt heating in Pareto-optimal mixtures.

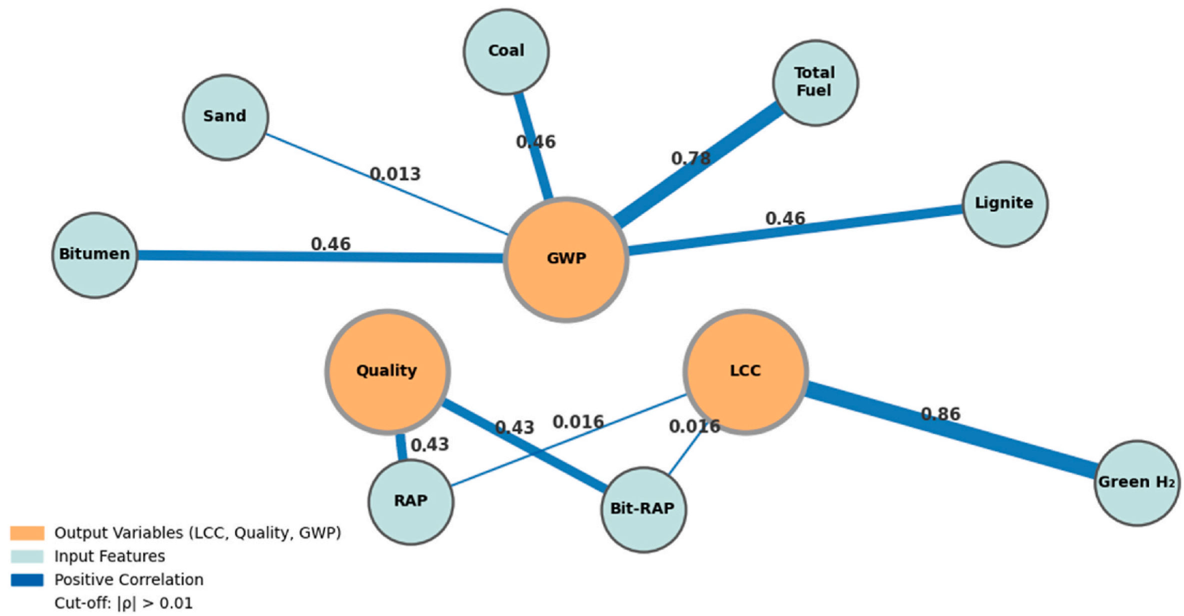

Fig. 7. Correlation analysis between GWP, LCC, and Quality and the input parameters.

direct emissions from those inputs.

The cost indicator (LCC) is overwhelmingly influenced by Green Hydrogen (ρ = 0.858), confirming that the high unit cost of this fuel dominates the economic performance of the system. Two material-related variables, Bit_RAP (ρ = 0.0162) and RAP (ρ = 0.0162), also exceed the reporting threshold. Their positive correlations with LCC can be explained by the fact that higher RAP contents introduce aged binder, which requires additional heating to achieve proper mixing temperatures. This elevated heat demand increases total energy consumption, thereby raising production costs and allowing RAP-related variables to appear (albeit modestly) in the cost correlations. All remaining correlations with LCC fall below the |ρ| = 0.01 cutoff and are therefore not reported.

As expected from the definition of the quality indicator (which is directly governed by the RAP content) the variables RAP and Bit_RAP exhibit the highest correlations with Quality. The presence of Bit_RAP in the results is consistent with its formulation, as it is a direct derivative of the RAP fraction and therefore mirrors its influence on mixture quality. No fuel-related variables exceeded the reporting cutoff for Quality, confirming that the quality metric in this model is effectively independent of fuel choice and energy inputs.

The correlation analysis reveals that fuel type and consumption level are the primary determinants of optimal asphalt mixture performance, whereas the influence of other materials appears secondary or context-dependent. This insight underscores the central role of energy-related decisions in advancing sustainability outcomes within asphalt production.

4.1.2. *Sensitivity analysis*

To complement the statistical findings and deepen the understanding of key drivers influencing environmental and economic outcomes, a sensitivity analysis was conducted using a cut-off threshold of 0.01 to

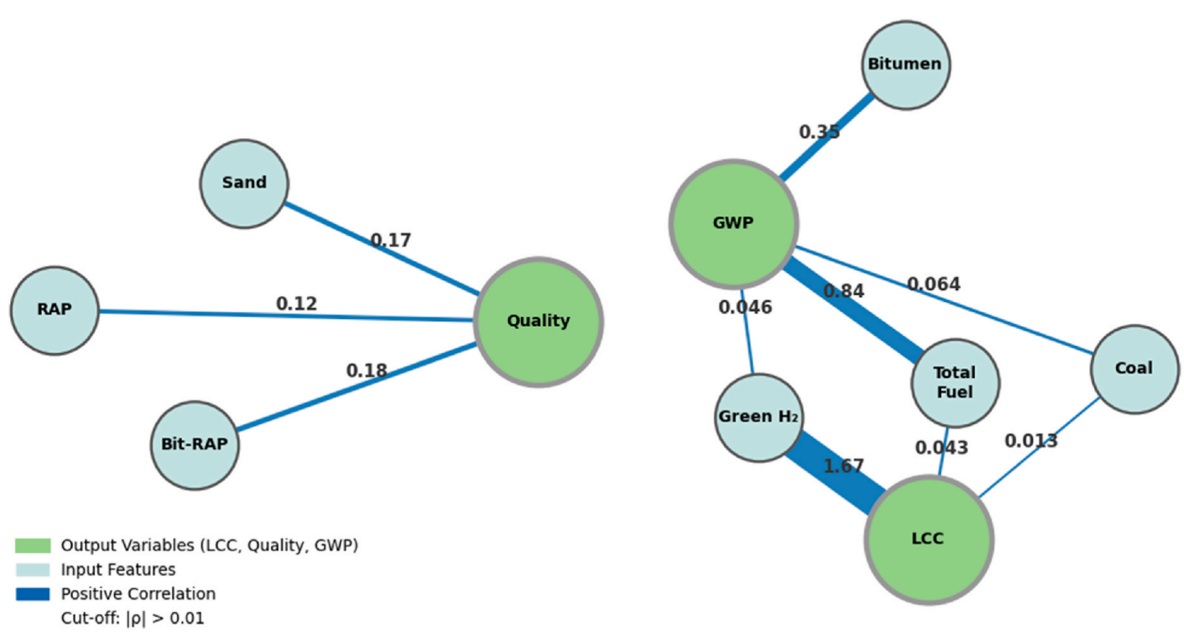

Fig. 8. Sensitivity analysis of GWP, LCC, and Quality to input parameters.

identify the most influential factors. This approach enables the ranking of input variables based on their relative importance in predicting the target metrics. Fig. 8 presents the relative importance scores for each variable in relation to GWP, LCC, and asphalt quality, calculated across the entire asphalt mixture design space.

The analysis strongly underscores the pivotal role of fuel selection and heating processes in governing GWP outcomes within the multi-objective optimization of asphalt mixture. Among all input parameters, Total Fuel Required emerges as the dominant contributor to GWP, with a coefficient of 0.837, followed by Bitumen at 0.354.

Regarding LCC, Green Hydrogen was overwhelmingly influential with a contribution of 1.67, while Total Fuel Required had a minor effect of 0.043. All other inputs, including conventional fuels and physical materials, were below the 0.01 cut-off and thus considered negligible. This indicates that controlling the use of Green Hydrogen is critical for minimizing life-cycle costs.

The sensitivity of asphalt quality was solely determined by the proportions of physical materials, with Bit_RAP, Sand, Gravel, and RAP contributing 0.18, 0.17, 0.15, and 0.12, respectively. All fuels and other materials had negligible influence below the 0.01 cut-off, confirming that fuel selection does not affect quality.

4.2. Feasibility and implementation of green hydrogen

Among the Pareto-optimal solutions, green hydrogen frequently appears as a preferred fuel choice. Its consistent presence is driven by its near-zero GWP, highlighting its strong promise for decarbonizing asphalt production, even though current costs remain high. This underscores the importance of continued technological and economic improvements to fully realize its practical feasibility.

Recent studies demonstrate that the deployment of green hydrogen is increasingly feasible from both technical and economic perspectives. A systematic review of 153 publications and reports from IRENA and IEA shows that the success of green hydrogen projects depends on a combination of techno-economic, site-specific, and socio-political factors, including international financing and strategic (Leuthold et al., 2025).

Comprehensive analyses of green hydrogen production technologies indicate that water electrolysis, particularly Proton Exchange Membrane (PEM) and Alkaline Water Electrolysis (AWE), is the most promising and scalable option. These technologies offer high hydrogen purity, operational flexibility, and compatibility with renewable energy sources, while achieving relatively low levelized costs in optimistic scenarios) (Mansilha et al., 2026).

Techno-economic assessments of production plants further confirm that combining solar, wind, or hydro power with alkaline or PEM electrolyzers and appropriate storage options can provide high efficiency, low life-cycle greenhouse gas emissions, and cost-effective hydrogen production at scale. Such configurations demonstrate that large-scale, environmentally sustainable green hydrogen deployment is achievable and can be strategically planned to balance cost, efficiency, and environmental (Shahzad et al., 2026; Abdelsalam et al., 2024).

5. Conclusion

This study introduced an integrated Monte Carlo–Pareto framework to evaluate asphalt mixture configurations under uncertainty and to jointly optimize LCC, GWP, and technical performance. The results reveal a wide sustainability spectrum across the design space, with GWP ranging from 9.17 to 97.72 kg CO_2/ton and LCC ranging from 2.75 to 13.67 €/ton, underscoring the dominant influence of heating-related parameters.

The average across all simulations yielded LCC of 5.37 €/ton, GWP of 41.61 kg CO_2-eq/ton, and quality of 0.94, while the average of Pareto-optimal solutions achieved LCC of 4.74 €/ton (an 11.7% reduction), GWP of 26.75 kg CO_2-eq/ton (a 35.7% reduction), and quality of 0.86 (an 8.6% decrease). These results highlight the framework's effectiveness in identifying configurations that simultaneously lower both cost and emissions with only a minor compromise in mixture quality.

Correlation analysis identified Total Fuel Required ($\rho = 0.78$), bitumen content ($\rho = 0.462$), and coal/lignite ($\rho \approx 0.461$) as the strongest drivers of GWP, while Green Hydrogen ($\rho = 0.858$) was the principal determinant of LCC. Sensitivity analysis confirmed the same pattern: Total Fuel Required (0.837) and bitumen (0.354) governed environmental impact, whereas the cost metric was overwhelmingly driven by Green Hydrogen (1.67). In contrast, the quality was almost entirely determined by RAP-related variables, validating that mixture quality remains independent of energy inputs.

Importantly, the Pareto front shows that low-GWP, low-cost, and acceptable-quality mixtures can be achieved simultaneously, contradicting the common assumption that carbon reduction inevitably increases cost or compromises performance. Optimal mixtures consistently favored low-emission fuels (especially Green Hydrogen, despite its high unit price) and excluded carbon-intensive fuels such as lignite. RAP proved environmentally and economically favorable when used within optimized bounds, though its influence remained secondary compared to energy-related factors.

Collectively, these findings demonstrate that energy-related decisions (specifically fuel type, fuel blends, and total heating demand) represent the central leverage point for decarbonizing asphalt production, exerting a far stronger influence on GWP and LCC than any material composition variable. The proposed framework therefore provides a robust decision-support architecture for identifying asphalt mixtures that minimize emissions and cost while maintaining satisfactory technical performance. Future research may extend this approach by incorporating policy scenarios, renewable energy integration pathways, and additional sustainability metrics to guide the transition toward large-scale, low-carbon asphalt technologies.

5.1. Limitation and future work

The current analysis is intentionally restricted to a maximum of 50 % RAP without the use of rejuvenating agents which represents the practical upper limit for many conventional European asphalt plants when no additional chemical or technological measures are applied. Increasing the RAP content beyond 50 % (which is already feasible today with commercially available rejuvenators and/or warm-mix technologies) would simultaneously enable lower production temperatures and higher mobilisation of the aged binder. This would shift the entire Pareto front toward considerably lower GWP and LCC while maintaining or even improving mechanical performance. The environmental and economic benefits identified in the present study therefore represent a conservative estimate; real-world implementation of currently available high-RAP technologies would deliver substantially greater reductions than those reported here.

The analysis is limited to cradle-to-gate modules A1–A3. Extending the system boundary to full cradle-to-grave, would further amplify the already favorable environmental profile of high-RAP mixtures.

LCC calculations exclude fixed plant costs, labour, and equipment depreciation because these items are nearly identical across the compared scenarios and do not affect relative optimization outcomes or the shape of the Pareto front. Including them would increase absolute cost values uniformly without altering the identified optimal solutions.

Although the multi-dimensional quality function proposed in this study offers a practical and computationally tractable proxy for the performance of RAP-incorporated asphalt mixtures, it remains a high-level simplification. Future developments can substantially increase its realism and predictive power by integrating physically based, micromechanical indicators. In particular, the bitumen–aggregate interfacial adhesion (widely recognized as the dominant factor controlling moisture damage, cracking resistance, and long-term durability when reclaimed asphalt pavement is used) can be rigorously quantified using the detailed experimental and analytical framework recently proposed by Peng et al. (2024). Simultaneously, advanced 3D morphological descriptors of aggregate particles and surface texture, such as sphericity and normal vector distribution derived from high-precision laser scanning and Vision Transformer segmentation can be incorporated to capture deterioration mechanisms at the pavement surface. Combining these two complementary micro-scale approaches (interfacial adhesion metrics and 3D aggregate morphology indicators) with the current quality function would enable the evolution toward a new generation of multi-scale, physics-informed models for the truly optimal and sustainable design of asphalt mixtures containing high RAP contents (Peng et al., 2024; Li et al., 2025).

CRediT authorship contribution statement

Manouchehr Shokri: Writing – original draft, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Marzia Traverso:** Supervision, Funding acquisition, Data curation. **Rose Nangah Mankaa:** Writing – review & editing, Visualization, Supervision, Data curation.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Not applicable.

Data availability

The complete Python code used in this study is available at the following link:

https://github.com/shokrimanouchehr12-beep/HMA/blob/main/HMA_PARETO.py.

References

Abdalla, A., Faheem, A.F., Walters, E., 2022. Life cycle assessment of eco-friendly asphalt pavement involving multi-recycled materials: a comparative study. J. Clean. Prod. 362. https://doi.org/10.1016/j.jclepro.2022.132471.

Abdelsalam, R.A., Mohamed, M., Farag, H.E.Z., El-Saadany, E.F., 2024. Green hydrogen production plants: a techno-economic review. Energy Convers. Manag. 319. https://doi.org/10.1016/j.enconman.2024.118907. Elsevier Ltd.

Ai, X., Pei, Z., Cao, J., Zhu, X., Hu, W., Gao, L., Feng, D., Yi, J., 2023. Environmental impact assessment of recycled HMA with RAP materials from the rotary decomposition process compared to virgin HMA and conventional recycled HMA. J. Clean. Prod. 389. https://doi.org/10.1016/j.jclepro.2023.136078.

Araújo, J.P.C., Oliveira, J.R.M., Silva, H.M.R.D., 2014. The importance of the use phase on the LCA of environmentally friendly solutions for asphalt road pavements. Transport. Res. Transport Environ. 32, 97–110. https://doi.org/10.1016/j.trd.2014.07.006.

Awad, M., Said, A., Saad, M.H., Farouk, A., Mahmoud, M.M., Alshammari, M.S., Alghaythi, M.L., Abdel Aleem, S.H.E., Abdelaziz, A.Y., Omar, A.I., 2024. A review of water electrolysis for green hydrogen generation considering PV/wind/hybrid/hydropower/geothermal/tidal and wave/biogas energy systems, economic analysis, and its application. Alex. Eng. J. 87, 213–239. https://doi.org/10.1016/j.aej.2023.12.032. Elsevier B.V.

Azarijafari, H., Yahia, A., Ben Amor, M., 2016. Life cycle assessment of pavements: reviewing research challenges and opportunities. J. Clean. Prod. 112, 2187–2197. https://doi.org/10.1016/j.jclepro.2015.09.080. Elsevier Ltd.

Balaguera, A., Carvajal, G.I., Albertí, J., Fullana-i-Palmer, P., 2018. Life cycle assessment of road construction alternative materials: a literature review. Resour. Conserv. Recycl. 132, 37–48. https://doi.org/10.1016/j.resconrec.2018.01.003. Elsevier B.V.

Cao, L., Wan, S., Zhou, T., Jin, C., Dong, Z., Gershome, A.G., Huang, Q., 2026. Quantifying crumb rubber separation in rubberized asphalt using X-ray computed tomography. Fuel 406. https://doi.org/10.1016/j.fuel.2025.136955.

Chen, X., Wang, H., 2018. Life cycle assessment of asphalt pavement recycling for greenhouse gas emission with temporal aspect. J. Clean. Prod. 187, 148–157. https://doi.org/10.1016/j.jclepro.2018.03.207.

Chen, Y., Chen, Z., Xiang, Q., Qin, W., Yi, J., 2021. Research on the influence of RAP and aged asphalt on the performance of plant-mixed hot recycled asphalt mixture and blended asphalt. Case Stud. Constr. Mater. 15. https://doi.org/10.1016/j.cscm.2021.e00722.

Chen, Y., Sha, A., Lu, Q., Jiang, W., Cao, Y., Hu, K., Li, C., Du, P., 2025. Solar-to-heat conversion control of pavement through thermochromic coating: integration of thermal management and visual temperature indication. Energy 333. https://doi.org/10.1016/j.energy.2025.137383.

Dal Ben, M., Jenkins, K.J., 2014. Performance of cold recycling materials with foamed bitumen and increasing percentage of reclaimed asphalt pavement. Road Mater. Pavement Des. 15 (2), 348–371. https://doi.org/10.1080/14680629.2013.872051.

Gabi Databases & Modeling Principles, 2022. https://www.scribd.com/document/809221342/MODELING-PRINCIPLES-GaBi-Databases-2022.

El-Emam, R.S., Özcan, H., 2019. Comprehensive review on the techno-economics of sustainable large-scale clean hydrogen production. J. Clean. Prod. 220, 593–609. https://doi.org/10.1016/j.jclepro.2019.01.309. Elsevier Ltd.

Ferrotti, G., Mancinelli, E., Passerini, G., Canestrari, F., 2024a. Comparison of energy and environmental performance between warm and hot mix asphalt concrete production: a case study. Constr. Build. Mater. 418. https://doi.org/10.1016/j.conbuildmat.2024.135453.

Ferrotti, G., Mancinelli, E., Passerini, G., Canestrari, F., 2024b. Comparison of energy and environmental performance between warm and hot mix asphalt concrete production: a case study. Constr. Build. Mater. 418. https://doi.org/10.1016/j.conbuildmat.2024.135453.

Firozjaei, M.K., Abdeyazdan, H., Esmailzadeh, A., Sedighi, A., 2025. Optimizing urban solar photovoltaic potential: a large group spatial decision-making approach for Tehran. Energy Sustain. Dev. 85, 101689. https://doi.org/10.1016/j.esd.2025.101689.

Giani, M.I., Dotelli, G., Brandini, N., Zampori, L., 2015. Comparative life cycle assessment of asphalt pavements using reclaimed asphalt, warm mix technology and cold in-place recycling. Resour. Conserv. Recycl. 104, 224–238. https://doi.org/10.1016/j.resconrec.2015.08.006.

Gregory, J.R., Noshadravan, A., Olivetti, E.A., Kirchain, R.E., 2016. A methodology for robust comparative life cycle assessments incorporating uncertainty. Environ. Sci. Technol. 50 (12), 6397–6405. https://doi.org/10.1021/acs.est.5b04969.

Gruber, M.R., Hofko, B., 2023. Life cycle assessment of greenhouse gas emissions from recycled asphalt pavement production. Sustainability 15 (5). https://doi.org/10.3390/su15054629.

Han, S., Cheng, X., Liu, Y., Zhang, Y., 2019. Laboratory performance of hot mix asphalt with high reclaimed asphalt pavement (RAP) and fine reclaimed asphalt pavement (FRAP) content. Materials 12 (16). https://doi.org/10.3390/ma12162536.

Hana, J., Thakur, J.K., 2015. Sustainable roadway construction using recycled aggregates with geosynthetics. Sustain. Cities Soc. 14 (1), 342–350. https://doi.org/10.1016/j.scs.2013.11.011.

Hasan, U., Whyte, A., Al Jassmi, H., 2020. Life cycle assessment of roadworks in United Arab Emirates: recycled construction waste, reclaimed asphalt pavement, warm-mix asphalt and blast furnace slag use against traditional approach. J. Clean. Prod. 257. https://doi.org/10.1016/j.jclepro.2020.120531.

Hassan, Q., Algburi, S., Sameen, A.Z., Al-Musawi, T.J., Al-Jiboory, A.K., Salman, H.M., Ali, B.M., Jaszczur, M., 2024. A comprehensive review of international renewable energy growth. In: Energy and Built Environment. KeAi Communications Co. https://doi.org/10.1016/j.enbenv.2023.12.002.

Huang, M., Dong, Q., Ni, F., Wang, L., 2021a. LCA and LCCA based multi-objective optimization of pavement maintenance. J. Clean. Prod. 283. https://doi.org/10.1016/j.jclepro.2020.124583.

Huang, W., Guo, Y., Zheng, Y., Ding, Q., Sun, C., Yu, J., Zhu, M., Yu, H., 2021b. Chemical and rheological characteristics of rejuvenated bitumen with typical rejuvenators. Constr. Build. Mater. 273. https://doi.org/10.1016/j.conbuildmat.2020.121525.

Jacobs, G., Margaritis, A., Hernando, D., He, L., Blom, J., Van den bergh, W., 2021. Influence of soft binder and rejuvenator on the mechanical and chemical properties of bituminous binders. J. Clean. Prod. 287. https://doi.org/10.1016/j.jclepro.2020.125596.

Jain, S., Chandrappa, A.K., 2023. A laboratory investigation on benefits of WCO utilisation in asphalt with high recycled asphalt content: emphasis on rejuvenation and aging. Int. J. Pavement Eng. 24 (1), 2172577. https://doi.org/10.1080/10298436.2023.2172577.

Jamshidi, A., Kurumisawa, K., Nawa, T., Mao, J., Li, B., 2017. Characterization of effects of thermal property of aggregate on the carbon footprint of asphalt industries in China. J. Traffic Transport. Eng. 4 (2), 118–130. https://doi.org/10.1016/j.jtte.2017.02.001.

Kaseer, F., Martin, A.E., Arámbula-Mercado, E., 2019. Use of recycling agents in asphalt mixtures with high recycled materials contents in the United States: a literature review. Constr. Build. Mater. 211, 974–987. https://doi.org/10.1016/j.conbuildmat.2019.03.286. Elsevier Ltd.

Kim, S.K., Lee, K.H., 2025. Evaluation of heat transfer properties of asphalt mixtures. KSCE J. Civ. Eng. 29 (7). https://doi.org/10.1016/j.kscej.2024.100138.

Leuthold, A., Terrapon-Pfaff, J., Viebahn, P., 2025. Implementation factors for green hydrogen projects: a systematic literature review. Sustain. Energy Technol. Assessments 82. https://doi.org/10.1016/j.seta.2025.104555. Elsevier Ltd.

Li, M., Liu, L., Xing, C., Liu, L., Wang, H., 2021. Influence of rejuvenator preheating temperature and recycled mixture's curing time on performance of hot recycled mixtures. Constr. Build. Mater. 295. https://doi.org/10.1016/j.conbuildmat.2021.123616.

Li, M., Xing, C., Liu, L., Huang, W., Meng, Y., 2022. Gel permeation chromatography-based method for assessing the properties of binders in reclaimed asphalt pavement mixtures. Constr. Build. Mater. 316. https://doi.org/10.1016/j.conbuildmat.2021.126005.

Li, K., Yan, X., Pu, J., Wang, Y., Chen, Y., Fang, K., Hu, J., Yang, Y., 2023. Quantitative evaluation on the energy saving and emission reduction characteristics of warm mix asphalt mixtures. Constr. Build. Mater. 407. https://doi.org/10.1016/j.conbuildmat.2023.133465.

Li, Y., Liu, C., Weng, Z., Wu, D., Du, Y., 2025. Aggregate-level 3D analysis of asphalt pavement deterioration using laser scanning and vision transformer. Autom. ConStruct. 178. https://doi.org/10.1016/j.autcon.2025.106380.

Liu, Q., Cai, M., Yu, B., Qin, S., Qin, X., Zhang, J., 2023. Life cycle assessment of greenhouse gas emissions with uncertainty analysis: a case study of asphaltic pavement in China. J. Clean. Prod. 411. https://doi.org/10.1016/j.jclepro.2023.137263.

Lo Presti, D., Jiménez Del Barco Carrión, A., Airey, G., Hajj, E., 2016. Towards 100% recycling of reclaimed asphalt in road surface courses: Binder design methodology and case studies. J. Clean. Prod. 131, 43–51. https://doi.org/10.1016/j.jclepro.2016.05.093.

Loprencipe, G., Moretti, L., Saltaren Daniel, M., 2025. Fatigue resistance of RAP-modified asphalt mixes versus conventional mixes using the indirect tensile test: a systematic review. In designs. Multidisciplinary Digital Publishing Institute (MDPI) 9 (Issue 5). https://doi.org/10.3390/designs9050104.

Ma, T., Huang, X., Zhao, Y., Zhang, Y., 2015. Evaluation of the diffusion and distribution of the rejuvenator for hot asphalt recycling. Constr. Build. Mater. 98, 530–536. https://doi.org/10.1016/j.conbuildmat.2015.08.135.

Ma, H., Zhang, Z., Zhao, X., Wu, S., 2019a. A comparative life cycle assessment (LCA) of warm mix asphalt (WMA) and hot mix asphalt (HMA) pavement: a case study in China. Adv. Civ. Eng. 2019. https://doi.org/10.1155/2019/9391857.

Ma, H., Zhang, Z., Zhao, X., Wu, S., 2019b. A comparative life cycle assessment (LCA) of warm mix asphalt (WMA) and hot mix asphalt (HMA) pavement: a case study in China. Adv. Civ. Eng. 2019. https://doi.org/10.1155/2019/9391857.

Mansilha, C., Barbosa-Póvoa, A., Tarelho, L., Fonseca, A., 2026. A comprehensive review of green hydrogen production technologies: current status, challenges, research trends and future directions. Renew. Sustain. Energy Rev. 225. https://doi.org/10.1016/j.rser.2025.116119. Elsevier Ltd.

Mantalovas, K., Dunn, I.P., Acuto, F., Vijayan, V., Inzerillo, L., Di Mino, G., 2023. A top-down approach based on the circularity potential to increase the use of reclaimed asphalt. Infrastructure 8 (5). https://doi.org/10.3390/infrastructures8050083.

Martínez, M., Ferrer, M., van Eldik, R., et al., 2019. Adv. Inorg. Chem. 84. Elsevier. https://www.sciencedirect.com/bookseries/advances-in-inorganic-chemistry/vol/84/suppl/C. (Accessed 26 August 2025).

Mattinzioli, T., Sol-Sánchez, M., Martínez, G., Rubio-Gámez, M., 2020. A critical review of roadway sustainable rating systems. Sustain. Cities Soc. 63. https://doi.org/10.1016/j.scs.2020.102447. Elsevier Ltd.

Milad, A., Babalghaith, A.M., Al-Sabaeei, A.M., Dulaimi, A., Ali, A., Reddy, S.S., Bilema, M., Yusoff, N.I.M., 2022a. A comparative review of hot and warm mix asphalt technologies from environmental and economic perspectives: towards a sustainable asphalt pavement. Int. J. Environ. Res. Publ. Health 19 (Issue 22). https://doi.org/10.3390/ijerph192214863. MDPI.

Milad, A., Babalghaith, A.M., Al-Sabaeei, A.M., Dulaimi, A., Ali, A., Reddy, S.S., Bilema, M., Yusoff, N.I.M., 2022b. A comparative review of hot and warm mix asphalt technologies from environmental and economic perspectives: towards a sustainable asphalt pavement. Int. J. Environ. Res. Publ. Health 19 (Issue 22). https://doi.org/10.3390/ijerph192214863. MDPI.

Mishra, V., Sadhu, A., 2023. Towards the effect of climate change in structural loads of urban infrastructure: a review. Sustain. Cities Soc. 89. https://doi.org/10.1016/j.scs.2022.104352. Elsevier Ltd.

Mohammadi, A., Mehrpooya, M., 2018. A comprehensive review on coupling different types of electrolyzer to renewable energy sources. Energy 158, 632–655. https://doi.org/10.1016/j.energy.2018.06.073.

Moretti, L., Mandrone, V., D'Andrea, A., Caro, S., 2017. Comparative "from cradle to gate" life cycle assessments of Hot Mix Asphalt (HMA) materials. Sustainability 9 (3). https://doi.org/10.3390/su9030400.

MS-2 Design Methods Asphalt Mix seventh ed. (n.d.).

Nielsen, C.B., Rosenberg, J., Raaberg, J., 2003. Denmark Telephone +45 4630 7000 Telefax +45 4630 7105 Title Selection of Pavement Maintenance by Use of Accelerated Load Testing Serie Report 123.

Nithinchary, J., Dhandapani, B.P., Mullapudi, R.S., 2024aa. Application of warm mix technology - design and performance characteristics: review and way forward. Constr. Build. Mater. 414. https://doi.org/10.1016/j.conbuildmat.2024.134915. Elsevier Ltd.

Nithinchary, J., Dhandapani, B.P., Mullapudi, R.S., 2024ab. Application of warm mix technology - design and performance characteristics: review and way forward. Constr. Build. Mater. 414. https://doi.org/10.1016/j.conbuildmat.2024.134915. Elsevier Ltd.

Peng, Y., Zhao, T., Miao, J., Kong, L., Li, Z., Liu, M., Jiang, X., Zhang, Z., Wang, W., 2024. Evaluation framework for bitumen-aggregate interfacial adhesion incorporating pull-off test and fluorescence tracing method. Constr. Build. Mater. 451. https://doi.org/10.1016/j.conbuildmat.2024.138773.

Qiao, Y., Dave, E., Parry, T., Valle, O., Mi, L., Ni, G., Yuan, Z., Zhu, Y., 2019. Life cycle costs analysis of reclaimed asphalt pavement (RAP) under future climate. Sustainability 11 (19). https://doi.org/10.3390/su11195414.

Rafiq, W., Musarat, M.A., Altaf, M., Napiah, M., Sutanto, M.H., Alaloul, W.S., Javed, M. F., Mosavi, A., 2021. Life cycle cost analysis comparison of hot mix asphalt and reclaimed asphalt pavement: a case study. Sustainability 13 (8). https://doi.org/10.3390/su13084411.

Santero, N.J., Masanet, E., Horvath, A., 2011. Life-cycle assessment of pavements. Part I: critical review. Resour. Conserv. Recycl. 55 (Issues 9–10), 801–809. https://doi.org/10.1016/j.resconrec.2011.03.010.

Santolini, E., Tarsi, G., Torreggiani, D., Sangiorgi, C., 2024. Towards more sustainable infrastructures through circular processes: environmental performance assessment of a case study pavement with recycled asphalt in a life cycle perspective. J. Clean. Prod. 448. https://doi.org/10.1016/j.jclepro.2024.141380.

Schönauer, P., Gruber, M.R., Hofko, B., 2024. Case study of a batch asphalt mix plant: energy consumption and emission allocation based on primary data. Case Stud. Constr. Mater. 21. https://doi.org/10.1016/j.cscm.2024.e03669.

Shahzad, S., Alrumayh, O., Almutairi, A., Altamimi, A., 2026. Green hydrogen: a review of technological innovations, economic viability, and global prospects. Renew. Sustain. Energy Rev. 225. https://doi.org/10.1016/j.rser.2025.116162. Elsevier Ltd.

Shiva Kumar, S., Lim, H., 2022. An overview of water electrolysis technologies for green hydrogen production. Energy Rep. 8, 13793–13813. https://doi.org/10.1016/j.egyr.2022.10.127. Elsevier Ltd.

Shokri, M., Mankaa, R.N., Traverso, M., 2024. Toward sustainability – life cycle perspective in green hydrogen and By-Products material in asphalt production: a case study for road pavement. In: Flintsch, G.W., Amarh, E.A., Harvey, J., Al-Qadi, I. L., Ozer, H., Lo Presti, D. (Eds.), Pavement, Roadway, and Bridge Life Cycle Assessment 2024. ISPRB LCA 2024, 51. RILEM Bookseries, Cham. https://doi.org/10.1007/978-3-031-61585-6_30. Springer.

Shokri, M., Mankaa, R.N., Traverso, M., 2025. Geo-environmental analysis and mechanical properties of geosynthetics in railway components industry (Sub and Superstructures). J. Clean. Prod. 501. https://doi.org/10.1016/j.jclepro.2025.145366.

Sollazzo, G., Longo, S., Cellura, M., Celauro, C., 2020. Impact analysis using life cycle assessment of asphalt production from primary data. Sustainability 12 (24), 1–21. https://doi.org/10.3390/su122410171.

Spath, P.L., Mann, M.K., 2004. Life cycle assessment of renewable hydrogen production via Wind/Electrolysis: milestone completion report. http://www.osti.gov/bridge.

Tarsi, G., Tataranni, P., Sangiorgi, C., 2020. The challenges of using reclaimed asphalt pavement for new asphalt mixtures: a review. In materials. MDPI AG 13 (Issue 18). https://doi.org/10.3390/ma13184052.

Tatari, O., Nazzal, M., Kucukvar, M., 2012. Comparative sustainability assessment of warm-mix asphalts: a thermodynamic based hybrid life cycle analysis. Resour. Conserv. Recycl. 58, 18–24. https://doi.org/10.1016/j.resconrec.2011.07.005.

Thives, L.P., Ghisi, E., 2017. Asphalt mixtures emission and energy consumption: a review. Renew. Sustain. Energy Rev. 72, 473–484. https://doi.org/10.1016/j.rser.2017.01.087. Elsevier Ltd.

Tokede, O.O., Whittaker, A., Mankaa, R., Traverso, M., 2020. Life cycle assessment of asphalt variants in infrastructures: the case of lignin in Australian road pavements. Structures 25, 190–199. https://doi.org/10.1016/j.istruc.2020.02.026.

Traverso, M., Mankaa, R., Concetta Pedalá, M., Covais, A., 2024. Social Hotspot analysis of the e-waste sector in Ghana and Nigeria. Waste Manag. 183, 271–277. https://doi.org/10.1016/j.wasman.2024.05.023.

Verkehrsflächenbefestigungen von, 2007. TL Asphalt-StB 07/13. www.fgsv-verlag.de.

Vidal, R., Moliner, E., Martínez, G., Rubio, M.C., 2013aa. Life cycle assessment of hot mix asphalt and zeolite-based warm mix asphalt with reclaimed asphalt pavement. Resour. Conserv. Recycl. 74, 101–114. https://doi.org/10.1016/j.resconrec.2013.02.018.

Vidal, R., Moliner, E., Martínez, G., Rubio, M.C., 2013ab. Life cycle assessment of hot mix asphalt and zeolite-based warm mix asphalt with reclaimed asphalt pavement. Resour. Conserv. Recycl. 74, 101–114. https://doi.org/10.1016/j.resconrec.2013.02.018.

Wang, T., Xiao, F., Zhu, X., Huang, B., Wang, J., Amirkhanian, S., 2018. Energy consumption and environmental impact of rubberized asphalt pavement. J. Clean. Prod. 180, 139–158. https://doi.org/10.1016/j.jclepro.2018.01.086. Elsevier Ltd.

Wang, J., Hong, B., Wang, D., Liu, W., Tan, S., Lin, J., Li, T., 2025. Performance and modification mechanism investigation of polyurethane prepolymer system modified bitumen for 100 % reclaimed asphalt pavement (RAP) application. Constr. Build. Mater. 462. https://doi.org/10.1016/j.conbuildmat.2025.139882.

Williams, B.A., Richard Willis, J., Shacat, J., 2022. Asphalt Pavement Industry Survey on recycled materials and warm-mix asphalt usage 2021 information series 138. 12th annu. Asph. Pavement Ind. Surv. 51. April. https://dx.doi.org/10.31274/etd-180810-854.

Wolf, N., Tanneberger, M.A., Höck, M., 2024. Levelized cost of hydrogen production in Northern Africa and Europe in 2050: a Monte Carlo simulation for Germany, Norway, Spain, Algeria, Morocco, and Egypt. Int. J. Hydrogen Energy 69, 184–194. https://doi.org/10.1016/j.ijhydene.2024.04.319.

Xiao, F., Yao, S., Wang, J., Li, X., Amirkhanian, S., 2018. A literature review on cold recycling technology of asphalt pavement. Constr. Build. Mater. 180, 579–604. https://doi.org/10.1016/j.conbuildmat.2018.06.006. Elsevier Ltd.

Yang, R., Kang, S., Ozer, H., Al-Qadi, I.L., 2015. Environmental and economic analyses of recycled asphalt concrete mixtures based on material production and potential performance. Resour. Conserv. Recycl. 104, 141–151. https://doi.org/10.1016/j.resconrec.2015.08.014.

Yang, C., Zhang, J., Yang, F., Cheng, M., Wang, Y., Amirkhanian, S., Wu, S., Wei, M., Xie, J., 2021. Multi-scale performance evaluation and correlation analysis of blended asphalt and recycled asphalt mixtures incorporating high RAP content. J. Clean. Prod. 317. https://doi.org/10.1016/j.jclepro.2021.128278.

Yang, S.H., Tran, N.H., Suprayoga, G.B., Nguyen, C. Van, Rachman, F., 2023. Developing materials and energy-related indicators and identifying barriers to their adoption in an adjustable urban road sustainable rating system. Sustain. Cities Soc. 98. https://doi.org/10.1016/j.scs.2023.104848.

Yolcan, O.O., 2023. World energy outlook and state of renewable energy: 10-Year evaluation. Innov. Green Dev. 2, 100070. https://doi.org/10.1016/j.igd.2023.100070.

Yousefi, A.A., Sobhi, S., Aliha, M.R.M., Pirmohammad, S., Haghshenas, H.F., 2021. Cracking properties of warm mix asphalts containing reclaimed asphalt pavement and recycling agents under different loading modes. Constr. Build. Mater. 300. https://doi.org/10.1016/j.conbuildmat.2021.124130.

Yu, B., Lu, Q., 2012. Life cycle assessment of pavement: methodology and case study. Transport. Res. Transport Environ. 17 (5), 380–388. https://doi.org/10.1016/j.trd.2012.03.004.

Yu, J., Lin, Z., Zou, G., Yu, H., Leng, Z., Zhang, Y., 2024. Long-term performance of recycled asphalt mixtures containing high RAP and RAS. Journal of Road Engineering 4 (1), 36–53. https://doi.org/10.1016/j.jreng.2024.01.003. KeAi Publishing Communications Ltd.

Zaumanis, M., Mallick, R.B., Frank, R., 2014. 100% recycled hot mix asphalt: a review and analysis. Resour. Conserv. Recycl. 92, 230–245. https://doi.org/10.1016/j.resconrec.2014.07.007. Elsevier B.V.

Zhang, J., Guo, C., Chen, T., Zhang, W., Yao, K., Fan, C., Liang, M., Guo, C., Yao, Z., 2021. Evaluation on the mechanical performance of recycled asphalt mixtures incorporated with high percentage of RAP and self-developed rejuvenators. Constr. Build. Mater. 269. https://doi.org/10.1016/j.conbuildmat.2020.121337.

Zhao, Y., Goulias, D., Peterson, D., 2021. Recycled asphalt pavement materials in transport pavement infrastructure: sustainability analysis & metrics. Sustainability 13 (14). https://doi.org/10.3390/su13148071.

Zhu, J., Ma, T., Fan, J., Fang, Z., Chen, T., Zhou, Y., 2020. Experimental study of high modulus asphalt mixture containing reclaimed asphalt pavement. J. Clean. Prod. 263. https://doi.org/10.1016/j.jclepro.2020.121447.