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ORIGINAL RESEARCH ARTICLE

Energy efficiency and environmental impacts of road infrastructure construction

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Abstract: Road infrastructure construction is an energy- and emission-intensive activity; however, process-level quantification of fuel use and associated pollutants across material production, transportation, and construction machinery operation remains insufficiently systematic to guide targeted optimization measures. This paper analyzes energy consumption and pollutant emissions during the construction phase of road infrastructure, with particular emphasis on asphalt mixture production (MJ), material transportation, and construction machinery operation. The analysis was conducted using a process-oriented approach and standardized calculation models to estimate fuel consumption and emissions of CO_2, NO_x, and particulate matter. The results indicate that asphalt MJ accounts for approximately 60–70% of total energy consumption, while transportation and construction machinery together contribute about 25–35%. The implementation of energy optimization measures enables a 10–15% reduction in total energy consumption, accompanied by proportional reductions in pollutant emissions. The findings confirm that targeting the most energy-intensive construction processes represents a key step toward improving the sustainability of road construction projects.

Keywords: Energy efficiency; Asphalt mixtures; Emissions; Construction machinery; Road infrastructure

1. Introduction

The construction of road infrastructure is an energy-intensive process involving the use of large quantities of construction materials, the operation of heavy construction machinery, and extensive transportation activities. Unlike the operational phase, which has been extensively analyzed in the literature through vehicle fuel consumption and traffic-related emissions, the construction phase is often addressed only partially, without a systematic quantification of energy consumption and pollutant emissions at the level of individual technological processes.

Previous research in the field of road construction has primarily focused on life-cycle assessments or on specific segments of infrastructure projects, such as asphalt mixture production (MJ) or material transportation. Under these approaches, the energy and environmental impacts of construction machinery and site organization are frequently evaluated at an aggregated level, which limits the identification of processes that contribute most to total energy consumption and pollutant emissions. A similar research focus can be observed in earlier studies published in *Politeknik Dergisi*, where the importance of analyzing energy consumption and emissions associated with materials and construction processes in the context of sustainable engineering design has been emphasized.[1]

Despite the availability of standardized calculation models for estimating fuel consumption and emissions from construction machinery, quantitative studies that clearly distinguish, at the process level, the contributions of material production, transportation, and machinery operation during the construction phase of road infrastructure remain limited. In particular, only a limited number of studies integrate these components within a unified analytical framework while explicitly linking them to practical energy optimization measures. Recent research indicates that substantial energy savings in road construction can be achieved by combining process-level analyses with improved equipment efficiency and optimized material production technologies. Studies published in the past 2 years suggest that focusing on the construction phase, rather than relying solely on full life-cycle indicators, enables more actionable optimization strategies for contractors and project managers.[2,3] In this context, the present study contributes a transparent, process-oriented framework that facilitates the identification of energy-intensive construction activities and supports targeted efficiency improvements.

To address this research gap, the present study focuses on the quantitative assessment of energy consumption and emissions of CO_2, NO_x, and particulate matter (PM) during the key phases of road infrastructure construction, with particular emphasis on construction machinery and the production and transport of asphalt mixtures. By analyzing the most energy-intensive construction processes, the study evaluates the potential to reduce the overall environmental footprint through optimization of technological and organizational solutions during the construction phase.

2. Materials and methods

The study was conducted using a process-oriented analytical approach aimed at quantifying energy consumption and pollutant emissions during the construction phase of road infrastructure. The analysis was limited exclusively to the construction phase; the design, operation, and maintenance phases were not considered. This limitation allows for a focused assessment of the most energy-intensive processes that are directly under the control of contractors.

The analysis is based on a typical road section serving as a representative scenario of road construction activities in practice. The typical road cross-section analyzed in this study represents a standard two-lane, two-way asphalt road characteristic of Southeast European conditions. A 1.0 km long road section with a carriageway width of 7.0 m was defined as the functional unit for the energy and emission assessment. The pavement structure includes a 4 cm asphalt concrete wearing course, a 6 cm asphalt binder course, and a 20 cm unbound granular base layer on a prepared subgrade, corresponding to standard practice for roads with medium traffic loads. The analyzed section represents a generalized construction scenario rather than a specific project, enabling result normalization and comparability with similar studies in accordance with commonly applied European life cycle assessment conventions.[4-6]

The system boundaries include the following processes:

- Asphalt MJ,
- Material transportation to the construction site,
- Operation of construction machinery during construction works.

Processes related to the manufacturing of construction equipment, administrative activities, and project management were excluded from the analysis, as their contribution to total energy consumption and pollutant emissions during the construction phase is considered secondary.

2.1. Fuel consumption calculation method

Energy consumption during the construction phase was estimated based on the fuel consumption of construction machinery and energy-intensive material production processes. Total fuel consumption of construction machinery was determined using a standardized calculation model based on rated engine power, load factors, and effective operating time, in accordance with recommendations from relevant technical literature.[7,8] The basic fuel consumption calculation model is expressed by Equation (1):[8]

$$Q = P_n \times k_o \times t \times c_f \quad (1)$$

Where: Q is fuel consumption (L); P_n is rated engine power of the machine (kW); k_o is the engine load factor (0.3–0.8 depending on the type of operation); t is effective operating time (h); and c_f is the specific fuel consumption coefficient (L/kWh), typically ranging from 0.18 to 0.24 L/kWh for diesel engines. Typical values of the load factor and specific fuel consumption coefficient were adopted according to the recommendations reported in the literature.[9,10]

Energy consumption associated with asphalt mixture production was estimated using average values of specific energy demand for heating mineral aggregates and bitumen. Energy consumption related to material transportation was determined based on transport distance, vehicle payload capacity, and fuel consumption per kilometer traveled. All values were normalized with respect to the defined functional unit. Emissions of CO_2, NO_x, and PM were estimated directly from fuel consumption using standard emission factors for diesel fuel obtained from internationally recognized databases. Total emissions for individual processes were determined using the following expression:[8]

$$E_i = Q \cdot EF_i \quad (2)$$

Where E_i is the emission of pollutant *i*; *Q* is total fuel consumption; and EF_i is the corresponding emission factor for pollutant *i*. This approach ensures a consistent linkage between the energy and environmental assessments, with results expressed as total emissions per functional unit.

2.2. Analysis of energy optimization measures

Energy savings were analyzed by comparing a reference construction scenario with optimized scenarios that include modernization of construction machinery, optimization of machine operating regimes, reduction of transport distances, and improvement of technological procedures in asphalt MJ. The effects of these measures were evaluated based on differences in total energy consumption and pollutant emissions, with results expressed relative to the defined functional unit.

Achieved energy savings were determined as the difference between energy consumed in the reference and optimized technological processes, according to the following expression:

$$E_n = E_b - E_o \quad (3)$$

where E_u is achieved energy savings; E_b is energy consumed in the reference process; and E_o is energy consumed in the optimized process. The relative efficiency of energy savings was expressed as:

$$\eta = \frac{E_u}{E_b} \times 100\% \quad (4)$$

For thermally intensive processes, such as asphalt MJ, the energy required for heating mineral materials was estimated based on a fundamental thermodynamic relationship:

$$E_b = m \cdot c \cdot (T_p - T_0) \quad (5)$$

where m is the mass of the material; *c* is the specific heat capacity of the aggregate; T_p is the production temperature; and T_0 is the initial material temperature. The application of warm mix asphalt (WMA) technologies can reduce production temperatures by approximately 20–40°C, which, according to available studies, results in energy savings of about 15–35% in heating processes.

Although the calculation models applied in this study are based on standardized deterministic equations, they allow the formulation of simplified predictive relationships between key technological parameters and energy consumption and emissions.[11,12] For thermally intensive processes such as asphalt MJ, a reduction in production temperature (ΔT) directly reduces the required heating energy. Assuming constant material mass and specific heat capacity, the relative reduction in energy demand ($\Delta E/E$) can be approximated as a linear function of temperature reduction, consistent with thermodynamic energy-balance approaches used in asphalt production analysis:[11,13]

$$\Delta E/E \approx \Delta T/(T_p - T_0) \quad (6)$$

where $\Delta E/E$ denotes the relative energy reduction; ΔT is the temperature reduction; and T_p and T_0 are the production and initial material temperatures, respectively. Since CO_2 emissions are directly proportional to fuel consumption and energy use, the relative reduction in CO_2 emissions can be expressed as:

$$\Delta CO_2/CO_2 \approx \Delta E/E \quad (7)$$

This simplified relationship enables a quantitative assessment of the combined effects of technological measures such as WMA, reduced aggregate moisture, and improved burner efficiency on project-specific energy consumption and emissions, while maintaining a transparent process-oriented framework.[12,13]

3. Energy consumption and pollution sources in road construction

The sources of energy consumption and pollutant emissions during road infrastructure construction can be classified into three main categories: construction material production, material transportation, and the operation of construction machinery. Their relative contributions to the overall energy balance depend on the applied construction technology, site organization, and logistical conditions, as illustrated in Figure 1. Available studies indicate that these processes represent the dominant sources of energy use and environmental impact during the construction phase of road infrastructure.[13]

A review of the literature indicates that construction material production, particularly asphalt MJ, accounts for the largest share of total energy consumption

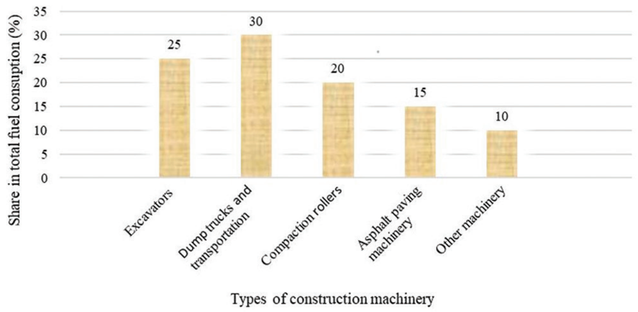

Figure 1. Contribution of construction processes to total energy consumption. Authors' illustration based on data reported in Hong *et al.*,[14] European Commission, Joint Research Centre,[20] Wu *et al.*[21]

during asphalt pavement construction, contributing approximately 60–70%.[13] Material transportation and construction machinery operation together account for about 25–35% of total energy consumption, while the remaining share corresponds to minor indirect processes. This distribution clearly indicates that the greatest potential for reducing energy consumption and pollutant emissions lies in optimizing these dominant processes.

The finding that asphalt MJ accounts for approximately 60–70% of total energy consumption is consistent with previous studies, although the exact share depends on regional conditions, construction technologies, and system boundaries. Muench *et al.*[13] reported that material production contributes about 65–75% of total energy consumption in asphalt pavement construction under cradle-to-gate conditions in North America. Similarly, Wang *et al.*[12] identified a share of approximately 68% in Chinese road construction projects dominated by conventional hot-mix technologies and long transport distances, while Hong *et al.*[14] reported values ranging from 60% to 72%, depending on plant efficiency, aggregate moisture content, and site organization.

In the present study, the lower bound of the 60–70% range corresponds to scenarios with optimized logistics and reduced production temperatures (e.g., WMA), whereas the upper bound reflects conventional hot-mix asphalt production with higher aggregate moisture and longer transport distances. This confirms that asphalt MJ remains the dominant energy consumer across different regions and technologies, while its exact contribution is project-specific.

The operation of construction machinery represents a distinct source of CO_2, NO_x, and PM emissions due to diesel fuel combustion during working cycles and idle periods. Although its contribution to total energy consumption may be lower compared to material production, the significance of construction machinery is pronounced in the emission structure, particularly under conditions of suboptimal work organization and the use of outdated equipment.[13]

In modern road infrastructure construction, the production and transportation of construction materials represent energy-intensive segments of the process, with a significant impact on total energy consumption and pollutant emissions. These effects are particularly pronounced in flexible pavement structures, where asphalt mixtures are predominantly used, and their production requires high temperatures and continuous consumption of fossil fuels.[15]

Asphalt mixtures primarily consist of aggregates and bitumen. Aggregates account for the largest mass fraction, while bitumen, as an energy-intensive component, can have a substantial influence on the overall energy balance. According to available studies, asphalt MJ can account for more than 40% of total energy consumption during the road construction phase.[16] Consequently, modifications in mixture composition, reduction of bitumen content, and the use of recycled materials have been identified as important pathways for energy optimization.[17]

The transportation of construction materials, particularly aggregates and asphalt mixtures, constitutes an additional source of fuel consumption and CO_2 emissions. Energy demand depends on transport distance, vehicle type, payload capacity, and logistics organization. Optimizing transport distances and implementing more efficient logistical solutions offer significant potential for reducing the overall energy burden of road construction projects.[12]

Measures such as the application of WMA, increased use of reclaimed asphalt pavement, and rational pavement layer design can further reduce energy consumption and emissions while maintaining the required mechanical performance of the pavement structure.[18]

To estimate energy consumption during asphalt MJ, this study applies a simplified energy balance approach, in which total energy consumption is expressed as:

$$E_p = \sum_{i=1}^{n} m_i \times e_i \tag{8}$$

Where E_p is total energy consumed for asphalt MJ; m_i is the mass of mixture component (kg); and e_i is the specific energy consumption for production of component i (MJ/kg). This approach enables assessment of how changes in asphalt mixture composition influence total energy consumption, particularly through reduced bitumen content or the application of alternative binders and recycled materials.[9]

Energy consumption during the transportation phase was estimated as:

$$E_t = Q \times d \times c_t \quad (9)$$

Where E_t is the energy consumed for material transportation (MJ); Q is the quantity of transported material (t); d is the transport distance (km); and c_t is the specific energy consumption of the transport vehicle (MJ/t·km). This relationship enables quantification of the impact of logistical solutions on the overall energy balance and highlights the importance of reducing transport distances, optimizing transport routes, and using more efficient and modern transport vehicles.[12]

4. Construction machinery

The energy and environmental impact of construction machinery depends on the type of equipment, technical characteristics, operating regimes, and site organization, making this segment particularly suitable for analysis and optimization.[3,13]

In this study, energy consumption and pollutant emissions were evaluated for representative groups of construction machinery commonly used in road construction, including excavators, graders, rollers, asphalt pavers, and transport vehicles. The assessment was based on average fuel consumption under real operating conditions, considering rated engine power, load factors, and effective operating time, in accordance with the methodological framework.

For context, the literature indicates that the typical distribution of energy consumption in asphalt pavement construction, within cradle-to-gate system boundaries, is approximately 74% for material production, 14% for transportation, 7% for construction machinery operation, and about 5% for other indirect processes.[13]

The 74% value represents a literature-based benchmark for cradle-to-gate system boundaries under conventional hot-mix asphalt production conditions.[13] In contrast, the 60–70% range reported in this study reflects project-specific, process-based results that account for optimized logistics and improved construction practices, and it is, therefore, used consistently throughout the paper as the primary outcome.

The construction machinery fleet presented in Table 1 spans a wide production period (1986–2021), reflecting the heterogeneous composition typical of road construction projects and enabling an indicative assessment of the influence of equipment age and emission standards on fuel consumption and emissions.

Older machinery corresponding to pre-Euro or early Euro standards generally exhibits higher specific fuel consumption due to lower engine efficiency and limited emission control, whereas newer Euro V or Stage V equipment achieves lower fuel consumption through improved engine design and combustion efficiency. As shown in Table 1, modern machines (2018–2021) achieve fuel savings of approximately 20–40% compared to older units of similar power, confirming fleet modernization as an effective measure for reducing energy consumption and pollutant emissions during construction.

The results show that the highest share of total fuel consumption is associated with machinery operating

Table 1. Characteristics and estimated fuel consumption of construction machinery used in road construction

S. No.	Appendix D reference No.	Machine type	Manufacturer	Year of production	Rated engine power (hp)	Fuel type	Average fuel consumption (L/h)
1	G15 0.00	Motor grader	HBM NOBAS	2004	160	Diesel	18.65
2	L50 0.00	Combined excavator	JCB	2018	100	Diesel	9.73
3	H30 0.02	Backhoe loader	JCB	2006	173	Diesel	20.19
4	R50 0.00	Vibratory roller	14. OKTOBAR	1986	135	Diesel	17.07
5	T55 0.10	Truck	MAN	2005	425	Diesel	28.94
6	T55 0.10	Truck	VOLVO	2006	400	Diesel	27.24
7	T55 0.10	Truck	M. BENZ	2006	530	Diesel	36.09
8	T40 0.10	Truck	FAP	2008	230	Diesel	29.09
9	T40 0.10	Truck	FAP	2008	170	Diesel	21.50
Σ					2,323		208.50

Note: Data adapted from United States Army Corps of Engineers.[8]

continuously under high load, such as asphalt pavers and heavy transport vehicles. Conversely, machinery with frequent operating changes and idle periods, including graders and rollers, exhibits a disproportionately higher impact on NO_x and PM emissions relative to its energy consumption.

Emissions of CO_2, NO_x, and PM from construction machinery are directly linked to fuel consumption and engine characteristics, with equipment age and compliance with emission standards playing an important role. Accordingly, fleet modernization and optimization of operating regimes are effective measures for reducing the environmental footprint during the construction phase.[11,19] Previous European assessment frameworks indicate that material production, transportation, and construction machinery represent the dominant sources of energy consumption during the construction phase of road infrastructure.[20]

The emission structure shown in Figure 2 indicates that CO_2 is the dominant emission component, while NO_x and PM represent smaller but environmentally relevant shares, consistent with real-world testing of construction machinery.

The percentage shares of CO_2, NO_x, and PM in Table 2 are normalized values based on absolute hourly emission rates calculated from fuel consumption and standard emission factors for diesel construction machinery, following the EMEP/EEA Air Pollutant Emission Inventory Guidebook methodology.[21] This normalization allows comparison of emission structures among machine types, independent of operating time.

The analyzed construction machinery represents typical ranges of engine power and emission standards in modern road construction, with CO_2 identified as the dominant emission component, while NO_x and PM vary depending on machine type and operating regime.[15]

The estimated CO_2 emissions shown in Figure 2 are directly related to the fuel consumption of individual machines, with higher-powered equipment exhibiting the highest hourly CO_2 emissions.

An additional analysis was performed by comparing the existing machinery fleet with an optimized scenario involving partial replacement of older equipment with more energy-efficient models. Fuel consumption under this scenario was estimated using the United States Army Corps of Engineers (USACE) methodology, and the results illustrate the potential for energy savings.

This study examines the main types of construction machinery used in road construction, their relative contributions to total energy consumption, and technical

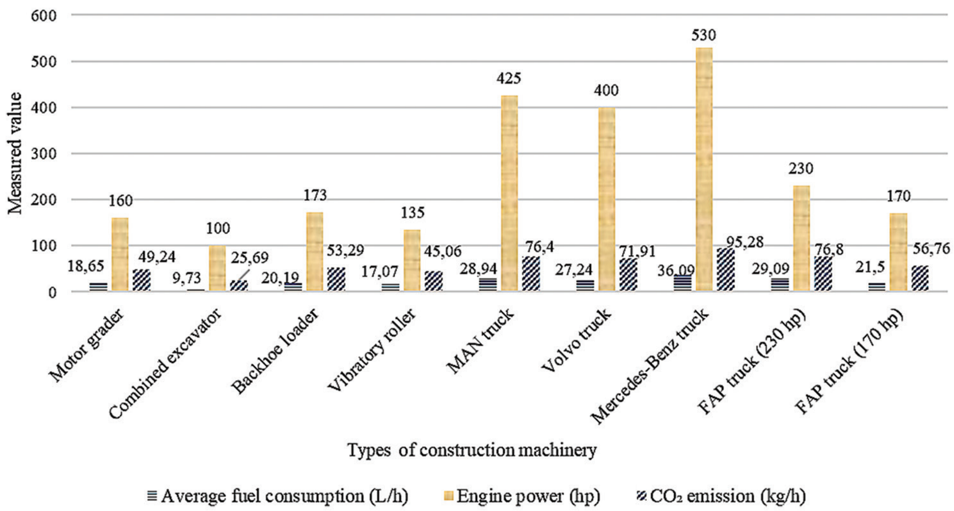

Figure 2. Energy and emission characteristics of construction equipment

Table 2. Emission structure and basic technical characteristics of construction machinery

Machine	Rated engine power (kW)	Engine type	Emission standard	CO_2 (%)	NO_x (%)	Particulate matter (%)
Excavator	110–190	Diesel four-stroke engine	Euro III–V	88	10	2
Loader	120–210	Diesel four-stroke engine	Euro III–V	85	13	2
Roller	90–160	Diesel four-stroke engine	Euro III–V	90	8	2

Note: Data adapted from Wu *et al.*[21]

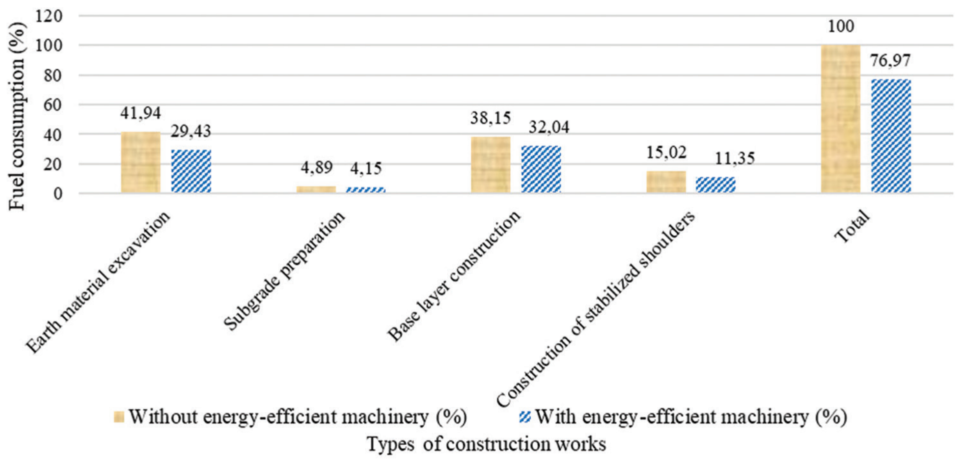

Figure 3. Fuel consumption with and without energy-efficient machinery

Table 3. Effect of construction machinery optimization on fuel consumption

S. No.	Machine type	Manufacturer	Model	Year of manufacture	Engine power (hp)	Fuel type	Average fuel consumption (L/h)
1	Motor grader	HBM NOBAS	BG 160 TA 6×6	2004	160	Diesel	18.65
2	Excavator	Liebherr	A910 Compact Litronic	2021	116	Diesel	5.54
3	Backhoe loader	Liebherr	L538 Speeder	2021	167	Diesel	6.92
4	Vibratory roller	SAKAI	SV521D (10t)	2021	112	Diesel	10.00
5	Truck	MAN	TGA 26.430 6×4 BB	2005	425	Euro diesel	28.94
6	Truck	VOLVO	FM 400	2006	400	Euro diesel	27.24
7	Truck	M. BENZ	ACTROS 2654 LK 6×4	2006	530	Diesel	36.09
8	Truck	Shifeng	Fengchi2000	/	105	Diesel	11.00
Σ					2,120		155.38

Notes: Data adapted from United States Army Corps of Engineers.[8] "/" indicates data not available.

Table 4. Effect of optimization measures on fuel consumption

Machinery status	Relative fuel consumption (%)
Without optimization	100
With optimization applied	85

and organizational measures for reducing fuel use and pollutant emissions. Emphasis is placed on proper equipment sizing, operator training, and the application of modern monitoring systems for real-time machinery performance tracking.[21,22]

Construction machinery exhibits varying operational roles and energy demands, with transport vehicles accounting for the largest share of total fuel consumption, followed by earthmoving and compaction equipment. The distribution of fuel consumption by machinery type is shown in Figure 3.[14] The characteristics of the construction machinery used in this study are presented in Table 3.

Table 4 summarizes the calculated fuel consumption and energy-related parameters for the construction machinery considered in this study.

Optimization of construction machinery operation is one of the most effective approaches for reducing fuel consumption and pollutant emissions during road infrastructure construction. Key measures include the use of modern machinery with improved energy performance, regular and planned maintenance, and improved site organization. Proper maintenance directly reduces specific fuel consumption and emissions of CO_2, NO_x, and PM. Operator training is also critical, as improved operating practices and reduced idle time can achieve fuel savings of up to 10–15%.[23]

In contemporary engineering practice, real-time monitoring systems are increasingly used to enable continuous tracking of fuel consumption and identification of inefficient operating regimes. Studies indicate that the implementation of such systems can reduce fuel consumption by up to 15% in large infrastructure projects.[23]

The optimized scenario is defined through targeted replacement of selected construction machines with the highest energy demand in the reference fleet by functionally equivalent modern models within the same machinery categories. Specifically, excavators, wheel loaders, and rollers were identified as priority candidates for replacement due to their high operating hours and specific fuel consumption. In the optimized scenario, these machines were replaced by newer models of comparable rated power and functional capacity, ensuring technological equivalence while improving engine efficiency and emission standards.

To preserve comparability of construction logistics and operational conditions, transport vehicles were intentionally retained unchanged in both scenarios. Consequently, the reference and optimized scenarios include the same types of construction machinery, and differences in energy consumption and emissions arise primarily from improved engine performance, fuel efficiency, and emission compliance of the modernized equipment. Fuel consumption and emission estimates for both scenarios were calculated using the same USACE-based methodology and identical operational assumptions, ensuring that the observed differences can be attributed exclusively to fleet modernization effects rather than changes in construction scope or process definition.[8]

To quantify fuel consumption in this study, the USACE methodology was applied, as it is widely used in engineering practice due to its simplicity and reliability.[4] Fuel consumption expressed per hour of machine operation is based on rated engine power, load factor, and operating conditions, and is defined in accordance with the methodology proposed by the United States Army Corps of Engineers.[*]

$$FC = HP \times FF \times t \tag{10}$$

where FC is fuel consumption (L); HP is the rated engine power (hp); FF is the fuel consumption factor (L/hp·h); and t is the effective operating time (h).

5. Energy and environmental aspects of asphalt mixtures

The analysis of the energy and environmental aspects of asphalt mixtures in this study encompasses the production phase at the asphalt plant and the transportation phase to the construction site. The functional unit is defined as 1 t of produced asphalt mixture. The pavement operation and maintenance phases were not considered.

Asphalt mixtures primarily consist of aggregates and bitumen. Aggregates account for the largest mass fraction, whereas bitumen has a decisive influence on the overall energy balance. The production process involves aggregate drying and heating, bitumen heating, and subsequent mixing, all of which require continuous consumption of thermal and electrical energy. According to available studies, the production of asphalt mixtures can account for more than 40% of the total energy consumption during the road construction phase.[14]

The total energy consumption of asphalt MJ is evaluated using the energy balance defined in Equation (7), which relates cumulative energy demand to the mass and specific energy consumption of mixture components.[11]

Based on the production temperatures in Table 5, asphalt mixture types show notable differences in energy demand. Compared to hot mix asphalt, bitumen-treated aggregates require lower production temperatures, resulting in energy savings of approximately 10–20% during aggregate heating and corresponding reductions in fuel consumption and CO_2 emissions at the asphalt plant.[11]

Most of the energy consumed in asphalt MJ is

Table 5. Properties of different asphalt types

Mixture type	Production temperature	Bitumen content (%)	Air voids (%)	Application
Hot mix asphalt	140–180°C	5–7	2–6	Major roadways
Bitumen-treated aggregate	120–160°C	3–5	3–10	Base layers
Cold mix asphalt	< 50°C	–	–	Light traffic, winter maintenance

Notes: Data adapted from Hong.[14] "–" indicates data not available.

Table 6. Bitumen and asphalt mixture temperatures

Types of bitumen	Bitumen tank temperature (°C)		Mix discharge temperature (°C)		Placement temperature (°C)	
	Optimal	Maximum	Optimal	Maximum	Optimal	Minimum
BIT 200	130	140	140±10	160	130±10	110
BIT 130	135	150	145±10	165	135±10	115
BIT 90	140	160	150±10	170	140±10	120
BIT 60	150	165	160±10	175	150±10	130
BIT 45	160	175	170±10	180	160±10	135
BIT 25	170	185	180±10	190	170±10	140
BIT 15	180	195	190±10	200	180±10	150

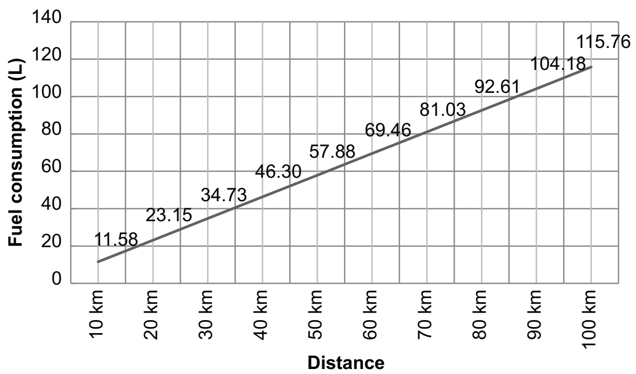

Figure 4. Fuel consumption for asphalt mixture transport at different distances

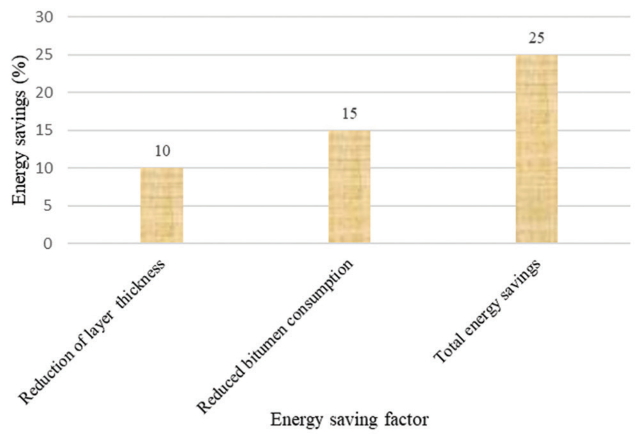

Figure 5. Relative energy savings before and after asphalt layer optimization

associated with aggregate heating, making moisture reduction a key factor for energy efficiency. Covered aggregate storage reduces drying energy demand, while the use of lower-viscosity bitumen enables lower processing temperatures and further decreases total energy consumption.

The influence of transport distance on fuel consumption during asphalt mixture delivery is illustrated in Figure 4.

The potential for reducing energy consumption and emissions in asphalt pavement construction includes the application of WMA, increased use of reclaimed asphalt pavement, and optimization of transport logistics. Since aggregate heating represents the most energy-intensive stage of asphalt MJ, reducing aggregate moisture and selecting lower-viscosity bitumen are crucial for lowering total energy demand.[15] A comparative overview of the overall energy indicators and potential savings, taking into account the type of bitumen in the asphalt mixture, is presented in Table 6.

Additional optimization potential can be achieved through the selection of aggregates with improved mechanical properties, particularly in the wearing course, where silicate rocks (e.g., basalt, diabase, and andesite) enable adequate performance with more efficient mixture composition and pavement design.[15,17] Due to improved resistance to rutting and deformation, such aggregates allow for composition optimization and potential layer-thickness reduction without compromising mechanical performance.[16,17]

The literature indicates that a large share of energy in asphalt pavement structures is associated with aggregate drying and mixing processes, as well as bitumen production, further emphasizing the importance of optimizing mixture composition and technological parameters.[12]

6. Results and discussion

The results of the analysis indicate that applying energy optimization measures during the construction of asphalt pavement layers can lead to a significant reduction in energy consumption and pollutant emissions. The most pronounced effects were achieved through combined optimization of asphalt mixture composition, rational design of layer thickness, and improvements in production and paving technologies.

A comparative analysis of pavement variants incorporating limestone and silicate aggregates shows that the use of silicate aggregates in the wearing course enables the achievement of the required mechanical performance with a more efficient asphalt mixture composition. Due to their higher resistance to wear and deformation, silicate aggregates allow a reduction in the designed thickness of the wearing course without adversely affecting the load-bearing capacity and durability of the pavement structure. The relative energy savings achieved before and after asphalt layer optimization are illustrated in Figure 5.

The analysis results indicate that replacing limestone aggregates with silicate aggregates enables:

- A reduction in the designed wearing course thickness by approximately 10%,
- A reduction in bitumen demand of up to 15%, and
- Overall energy savings of about 20–25% during asphalt MJ and transportation.

Additional energy savings are achieved through the application of remixing technology, which regenerates approximately 70% of existing asphalt layers with the addition of about 30% new bitumen, significantly reducing energy consumption and pollutant emissions during the reconstruction phase.

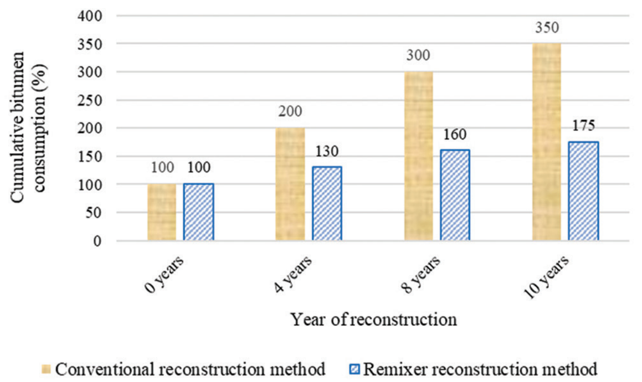

Figure 6. Relative bitumen consumption for wearing course reconstruction

The achieved energy savings are directly related to the reduced quantity of materials requiring heating and transportation, as well as lower production temperatures in asphalt mixture manufacturing. The relative bitumen consumption for wearing course reconstruction is illustrated in Figure 6.

Consequently, fuel consumption at asphalt plants and in transport vehicles is reduced, leading to lower emissions of CO_2, NO_x, and PM.

The cumulative effects of individual energy optimization measures are shown in Figure 7, with the largest contribution achieved through asphalt mixture optimization and reduced bitumen consumption.

As shown in Figure 8, the combined effect of multiple energy optimization measures can be approximated using a simplified multiplicative approach, in which the total relative energy reduction is expressed as the cumulative contribution of individual measures. Assuming independent effects of temperature reduction, logistics optimization, and machinery efficiency improvement, the total energy saving can be estimated as:[12]

$$\Delta E_{total} \approx 1 - \prod(1 - \Delta E_i) \quad (11)$$

where ΔE_{total} is the total relative energy reduction, ΔE_i represents the relative reduction associated with the i-th optimization measure, and ∏ denotes the product of individual reduction terms. Such aggregation approaches are commonly used in preliminary energy and emission assessments to evaluate combined intervention scenarios at the

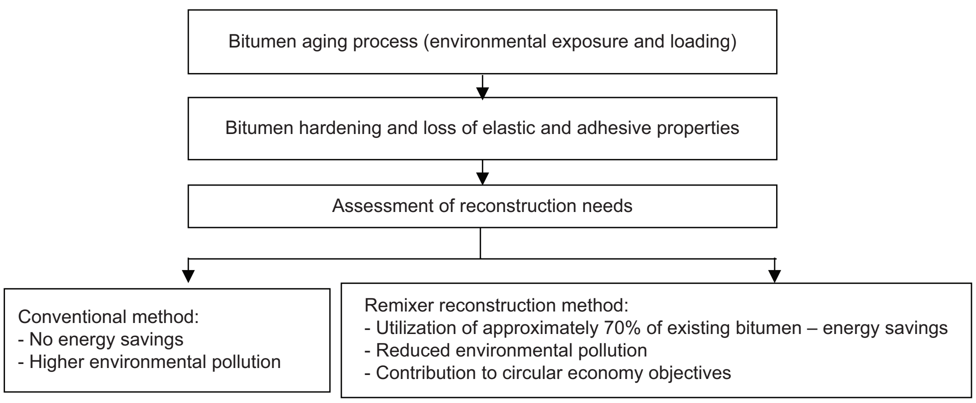

Figure 7. Energy savings analysis for wearing and base layer reconstruction

Energy efficiency and environmental impacts

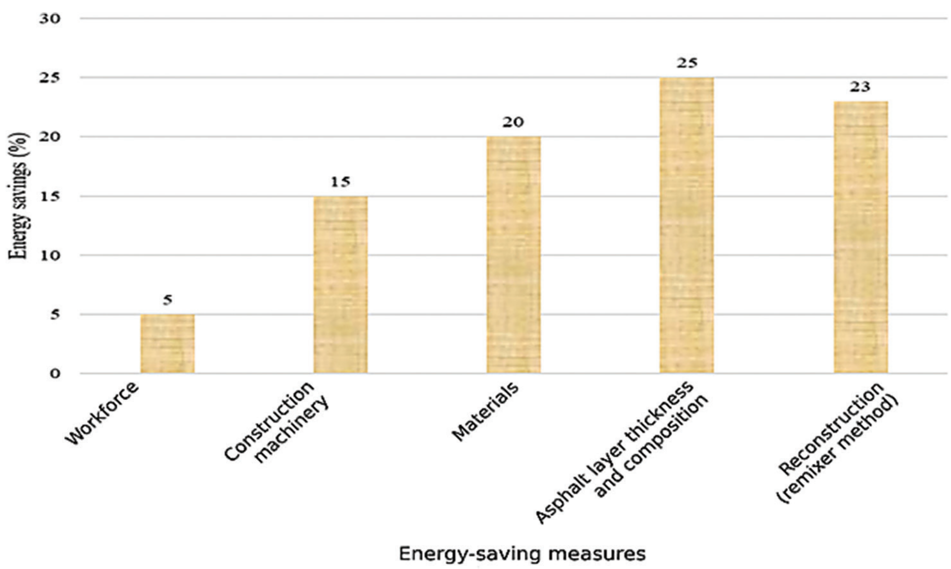

Figure 8. Contribution of intervention categories to energy savings in road construction

project level, while preserving a process-oriented analytical structure.

The results of this study are subject to several limitations. Energy consumption and emissions were estimated using standardized calculation models rather than real-time site measurements, which may introduce uncertainties related to operating conditions and site-specific variability. Emission estimates based on average factors may also not fully capture the effects of machine age, maintenance status, and transient operating regimes. Such limitations are common in process-based assessments of construction energy use and emissions and should be considered when interpreting the results.[14]

7. Conclusion

Road infrastructure construction represents a significant source of energy consumption and pollutant emissions, with asphalt MJ, material transportation, and construction machinery operation identified as the key processes contributing to energy use and environmental impact. The results of the process-oriented analysis indicate that asphalt MJ accounts for approximately 60–70% of total energy consumption during the construction phase, primarily due to the energy-intensive thermal treatment of mineral aggregates, while transportation activities and construction machinery together contribute about 25–35%.

The analysis of construction machinery operation shows that the highest energy contribution and emissions of CO_2 and NO_x originate from equipment operating continuously under high load, particularly heavy transport vehicles and asphalt pavers. In contrast, machinery characterized by significant idle periods exhibits a relatively higher share of NO_x and PM emissions. Modernization of construction machinery and optimization of site organization can reduce fuel consumption of up to 10–15%, accompanied by proportional emission reductions.[23]

The results related to asphalt mixture analysis confirm that the largest share of energy consumption is associated with aggregate drying and heating. Therefore, technologies with reduced production temperatures (WMA), reduction of aggregate moisture content, and the use of lower-viscosity bitumen provide energy savings in the range of 15–35%. In addition, the use of silicate aggregates in the wearing course allows more rational pavement design, including a reduction in layer thickness of approximately 10% and a decrease in bitumen consumption of up to 15%, resulting in total energy savings of 20–25%.

The obtained results confirm that an integrated approach to energy optimization—encompassing construction machinery operation, logistics, and asphalt mixture composition—represents an effective tool for reducing the environmental footprint of road construction projects and provides a solid basis for technical decision-making during the construction phase.

While the present study applies a process-oriented and deterministic calculation framework, recent studies demonstrate that machine learning methods can significantly enhance the modeling and optimization of energy-intensive industrial processes by capturing complex and nonlinear interactions among multiple influencing factors. In particular, data-driven approaches based on neural networks have shown strong potential for predicting energy consumption and emissions under variable operational and environmental conditions, outperforming traditional averaged or rule-based models.[24,25]

In the context of road construction, such machine learning models could be integrated with the process-based framework adopted in this study to enable equipment-specific prediction of fuel consumption, optimization of fleet deployment, and identification of optimal asphalt mixture compositions for project-specific conditions. The process-oriented structure presented in this paper provides a transparent definition of system boundaries, energy flows, and emission sources, which can serve as a baseline for training and validating adaptive predictive models based on real-world construction data.

Integrating deterministic process models with machine learning techniques represents a practical pathway toward developing a digital twin of the construction phase, enabling dynamic monitoring, scenario analysis, and continuous optimization of energy consumption and emissions at the level of individual machines and technological operations. Implementation of such data-driven models requires large-scale, high-resolution operational datasets, which were not available within the scope of the present study; however, acquiring such datasets represents a logical and highly relevant direction for future research.

From a practical perspective, the results of this study can be directly applied by contractors and project managers to identify energy-intensive construction processes and prioritize targeted optimization measures, such as reducing asphalt production temperatures, modernizing key equipment, and improving transport logistics. The process-oriented framework supports informed decision-making during the construction phase without requiring complex data acquisition systems.[12]

Future research should focus on validating the proposed framework using real-world construction site data and extending the analysis toward a full life-cycle assessment that integrates construction, operation, and maintenance impacts.

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Conflict of interest

The authors declare that they have no competing interests.

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Availability of data

The data used in this study are primarily based on theoretical analyses and research and are publicly available through relevant scientific literature and open sources.

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