ENERGY MANAGEMENT AND ENVIRONMENTAL SUSTAINABILITY IN EARTHWORKS

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Abstract
The modern construction sector faces the challenge of high energy consumption and emissions of harmful gases, with earthworks occupying a particularly important place due to the intensive use of heavy machinery. This paper analyzes strategies for increasing energy efficiency through process optimization, proper machine management and the application of new technologies. Special emphasis is placed on hybrid and electric machines, telematics systems and software solutions that enable real-time monitoring and planning of work. Experimental studies have shown that changing operating parameters, such as engine speed and depth of engagement, can lead to significant fuel savings, reduced emissions and increased productivity. The results confirm that energy management in earthworks does not only contribute to cost reduction, but is a key step towards sustainable construction and reduction of negative environmental impact.

Keywords: *earthworks, energy efficiency, sustainable construction, emissions of harmful gases, construction machinery.*

JEL classification: **Q01, Q40**

1. INTRODUCTION

Energy efficiency in the construction sector is one of the key issues in modern engineering today. The reasons for this lie in increasingly stringent environmental requirements, rising energy prices and global efforts to reduce the negative impact on the environment. Construction consumes between 30 and 40% of total energy globally, and a significant part is accounted for by earthworks, which are among the most energy-intensive segments of construction due to the intensive use of heavy machinery. A particular challenge is the fact that these works are an unavoidable initial phase of most infrastructure and construction projects, and that the ways in which they are carried out largely determine the subsequent energy efficiency of the entire project.

Earthworks include various procedures such as excavation, filling, leveling, compaction, drainage and slope stabilization. Their implementation requires the use of powerful machines with diesel engines, whose fuel consumption directly affects the cost of construction, but also the emission of CO2 and other harmful gases. On a global level, the burning of fossil fuels in the construction industry is one of the main sources of CO_2 emissions, which further emphasizes the importance of energy responsible management in this sector.

Energy management in earthworks implies an integrated approach on several levels: planning and organization of the workplace, proper selection and optimal use of machines, as well as technical improvements of the equipment itself. A particularly important role is played by modern technologies, such as telematics systems for monitoring consumption in real time,

software solutions for optimizing planning, and hybrid and electric machines that significantly reduce the consumption of fossil fuels and emissions. In addition to technical solutions, equally important factors are operator training and proper equipment maintenance, which can contribute to fuel savings of up to 20%.

In this paper, the focus is placed on the analysis of energy aspects of earthworks and the possibilities of their optimization. Special emphasis is placed on examining the relationship between the operating parameters of machines and their productivity, fuel consumption and emissions. Experimental research conducted in real conditions of a construction site aims to confirm the importance of proper energy management and show that even small changes in the performance of work tasks can lead to measurable savings and productivity improvements.

Based on these facts, the aim of this paper is to show the possibilities of improving energy efficiency in earthworks through the optimization of organization and application of modern technologies, with the ultimate goal of reducing costs, increasing productivity and minimizing the negative impact on the environment.

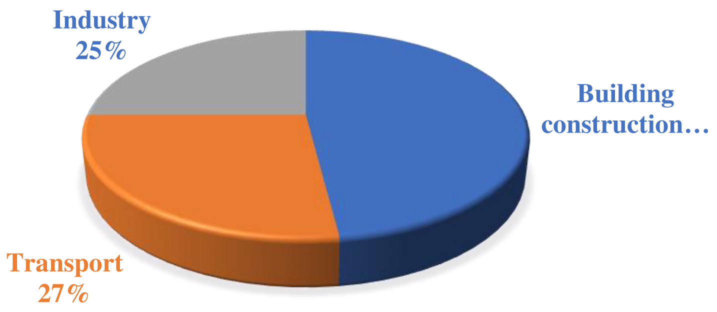
2. ENERGY EFFICIENCY AND ENVIRONMENTAL ASPECTS OF ENERGY SOURCES IN CONSTRUCTION

The increase in the consumption of non-renewable energy sources and the increase in environmental pollution condition the need for more rational use of energy in all industries. Construction, accounting for 30–40% of total energy consumption and about 12% of global water use, has a particular responsibility in the energy transition process [1].

The concept of green building encompasses all phases of the life cycle of a building, from site selection, design, construction and use, to maintenance and removal. The basic principles of green building include the efficient use of resources, the protection of the health of users, the increase in employee productivity and the reduction of harmful gas emissions.

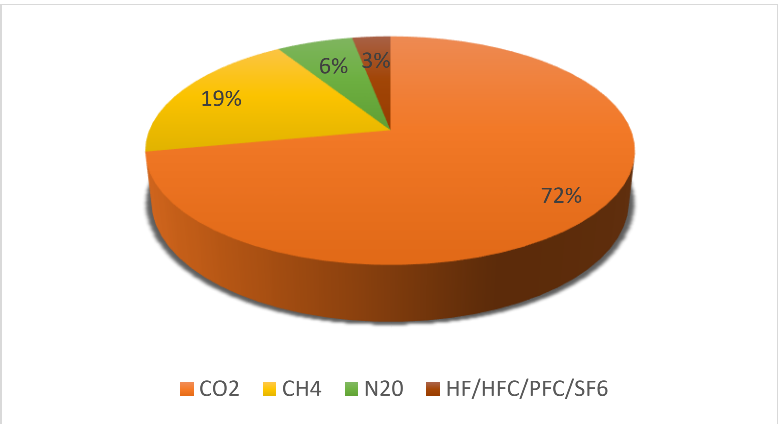
According to the Intergovernmental Panel on Climate Change (IPCC), the construction industry is the largest emitter of greenhouse gases, with the potential to emit 15.6 billion tonnes of CO_2 by 2030, which is about 30% of global emissions. However, by using existing technologies and renewable sources, it is possible to reduce emissions and achieve energy savings of up to one third. However, researchers warn of the so-called rebound effect (Khazzoom-Brookes postulate), where increasing energy efficiency can lead to an increase in overall consumption if energy prices remain stable [3].

The Republic of Serbia still has an unfavorable energy structure, predominantly based on non-renewable resources [5]. The needs of the construction industry include oil and derivatives for machinery, electricity for equipment and lighting, and natural gas for the production of building materials. Domestic reserves cover a small part of the needs, so dependence on imports remains pronounced [6]. This situation points to the necessity of strategic planning and implementation of energy efficiency measures in accordance with national and European decarbonization goals [6].



Picture 1: Percentage of global carbon dioxide production

Burning fossil fuels produces about 98% of the total amount of carbon dioxide, which is the most significant greenhouse gas. Its concentration in the atmosphere has been steadily increasing and has exceeded 396 ppm, further fueling global warming. In 2013, CO_2 concentrations were as much as 40% higher than in the mid-19th century, with an average increase of 2 ppmV/year in the last decade. This trend is accompanied by an increase in the concentration of other greenhouse gases: methane (CH_4), nitrogen oxide (N_2O) and hydrofluorocarbons (HF/HFC/PFC/SF_6). After the Industrial Revolution, CO_2 emissions rose to 32 Gt in 2012.



Picture 2: Percentage of greenhouse gases [7]

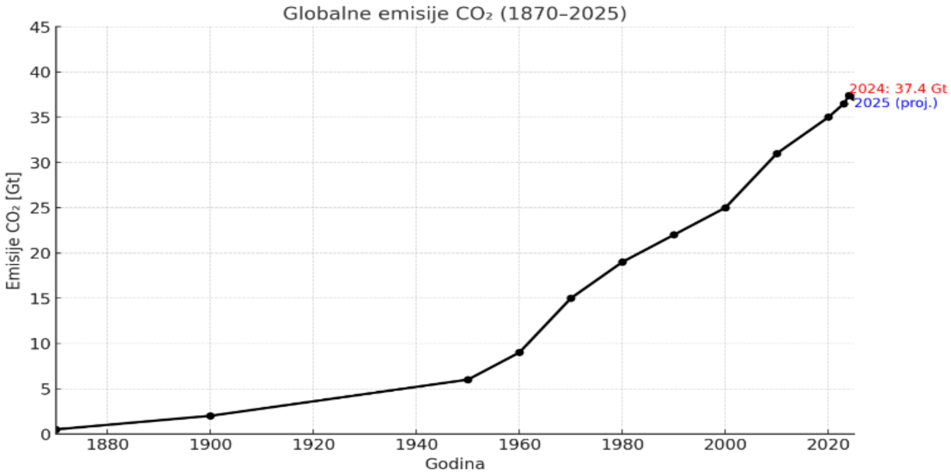


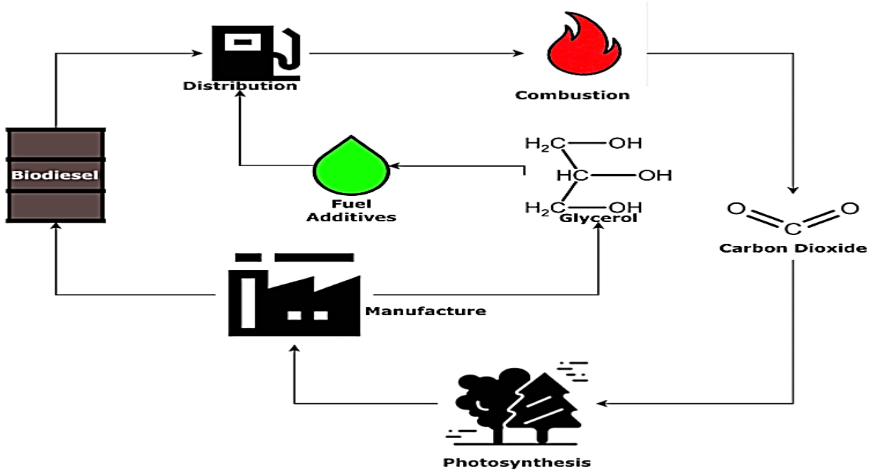
Diagram 1: Increasing CO2 emissions from the combustion of fossil fuels

Table 1: Coefficient of carbon dioxide emissions of different fuels [8]

Fuel	***Show kgCO2/GJ***
Coal (all kinds)	95,99
Lignite	98,27
Heavy fuel	75,09
Diesel	74,14
Kerosene	73,19
Gas	76,11
Natural gas	52,91
Unusable oil	74,00

These data confirm that switching from coal to gas or biofuels can significantly reduce emissions. A particularly important alternative energy source is biodiesel**,** obtained by transforming biomass into liquid fuels. Its application makes it possible to reduce dependence on oil and its derivatives, while emissions of sulfur compounds remain minimal. Although its cost is higher than fossil diesel, using waste edible oil as a feedstock is more economically viable. The life cycle of biodiesel includes the cultivation of raw materials, their pre-treatment, biochemical transformation and end use in internal combustion engines, thus confirming it as a renewable and practically applicable energy source.

In addition to biodiesel, the construction sector is increasingly using natural gas as a transition fuel, while the use of electrical machinery and renewable energy (solar and wind farms, geothermal energy) is expected in the future. The use of these energy sources has the potential to significantly contribute to reducing emissions and costs in the life cycle of buildings.



Picture 3: Life cycle of biodiesel production and use [9]

The life cycle of biodiesel includes the cultivation of raw materials, their pre-treatment, biochemical transformation and end-use in internal combustion engines. This confirms that biodiesel is a renewable, environmentally friendly and practically applicable energy source.

The construction industry makes extensive use of non-renewable energy sources, predominantly oil, its derivatives and natural gas. Their combustion emits a variety of harmful gases. When biofuels are burned, carbon dioxide emissions are generally neutral, as plants absorb an amount of CO2 approximately equal to that released during combustion. Also, sulfur emissions are minimal, which significantly reduces the risk of acid rain. Depending on the chemical composition of the fuel, there are different levels of CO2 emissions. The mass of CO2 emitted per unit of energy released is the CO2 emission coefficient:

$$KCO_2 = 3{,}67\frac{g_c}{H}$$

where: 3.67→ stoichiometric coefficient,

GC → the mass fraction of the fuel carbon in the fuel.

H→ the heat output of the fuel [MJ/kg].

Diagram 2: Evolution of the oil price per barrel (159 l) from 2002 to 2022

Reducing air pollution when using non-renewable energy sources can be implemented through a number of environmental protection measures:

- **catalytic processes** – combustion of unburned fuel residues until complete decomposition,
- **absorption** – removal of harmful gases using solutions or solid absorbents,

- **adsorption** – the binding of gases to solid materials such as activated carbon or silica gel,
- **increasing green areas** – one hectare of forest annually binds about 15t of CO_2 and releases approximately 14.2t of oxygen [7].

The construction industry makes extensive use of non-renewable energy sources, predominantly oil, its derivatives and natural gas. Their combustion emits significant amounts of CO_2, with earthmoving machinery being one of the largest sources of fuel consumption and emissions.

Therefore, switching to biodiesel, natural gas or the use of hybrid and electric machines can have a direct impact on

reducing pollution and costs in this area. That is why the analysis of energy and environmental aspects of energy sources in construction is of particular importance for the optimization of earthworks.

3. EARTHWORKS OPTIMIZATION

The energy impact of earthworks depends on several parameters: the type of soil, the type and number of machines, the mode of operation, as well as the organization of the construction site. Heavy and more powerful machines have more powerful engines that consume significantly more fuel, but allow for more work in less time. On the other hand, lighter machines consume less fuel but are less efficient with large amounts of material. An increase in the number of machines does not necessarily mean greater efficiency, as each heavy machine consumes an average of 10 to 40 liters of diesel per hour of operation, depending on the load and operating regime [12].

Energy management in the process of earthworks can be achieved on three levels:

- Optimization of the construction site – proper planning and arrangement of machines, reduction of unnecessary movement and waiting.
- Optimization of machine use – selection of the appropriate type of machine for a specific task and organization of work that reduces idling and overloads.
- Optimization of the machine itself – technical adjustments and innovations that reduce losses and increase energy efficiency.

Regular maintenance and coordination of work contribute to a reduction in the number of operating hours of machinery and fuel consumption, while the type of soil (hard or loose) significantly affects productivity and energy consumption [12].

Table 2: Potential fuel savings for loaders

Optimization	Potential savings
Optimization of the construction site	up to 30%
Optimization of the use of the machine	-40% to +40%
Optimization of the machine itself: - Reduction of losses - Optimization of mutual cooperation - Separation of the system	up to 50%

Table 2 shows that optimizing the interoperability of the system brings the greatest potential for savings (up to 50%).

The development of construction machinery has enabled the application of new technologies that contribute to the reduction of energy consumption and emissions:

- Telematics systems monitor the parameters of machine operation in real time (speed, fuel consumption, idle time, location), which makes it possible to optimize operation and reduce fuel consumption by 10–15% [7].
- Software solutions (BIM and project management systems) are used to simulate and plan work processes,

thus increasing the efficiency of construction site organization.

- Hybrid and electric machines are becoming more and more common. Hybrids combine a diesel engine with an electric drive and provide fuel savings of up to 30% without compromising productivity. Electric machines do not emit CO_2 and are suitable for working in urban areas and enclosed spaces.

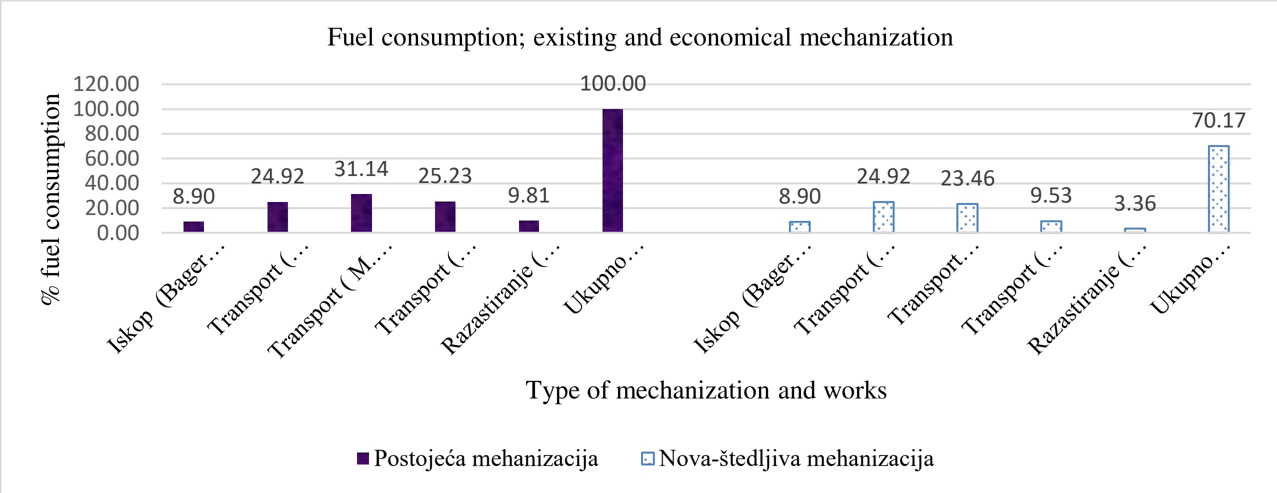


Diagram 3: Display of fuel consumption with existing and new-economical earthmoving machines according to the USACE standard

In addition to technical innovation, the human factor plays a crucial role in energy efficiency.
Regular maintenance of machines (filters, lubrication, replacement of worn parts) can reduce fuel consumption by 10–20%.
Operator training is one of the most cost-effective ways to increase efficiency, since the correct use of the operating mode and the avoidance of idling significantly affects consumption. The differences between operators on the same tasks and the same machine can be as high as 40% [10].
Advanced operator support systems, including the development of autonomous driving, further increase efficiency and reduce emissions.
Fuel Efficiency (FE) is defined as the relationship between productivity and fuel consumption.

$$FE\ [t/L] = \frac{\text{productivity}\ [t/h]}{FC\ [L/h]}$$

where:
FC – fuel consumption (L).
We can convert fuel consumption in liters to kg.

$$m_{fuel}\ (kg) = FC \cdot \rho$$

where is:
ρ- Fuel density (kg/l; typically ~0,832 kg/l for diesel).
Fuel efficiency can be increased either by increasing productivity at the same consumption, or by reducing consumption while maintaining productivity.
Experiments with hydraulic excavators have shown that combinations of different engine speeds and cutting depths can increase productivity by up to 30%, reduce greenhouse gas emissions by 24%, and move 62% more material per week for every liter of fuel consumed.

$$CO_{2emission} = E_{CO_2} * \left(3600 * n_{th} * \frac{E_{con}}{P} * LHV\right)$$

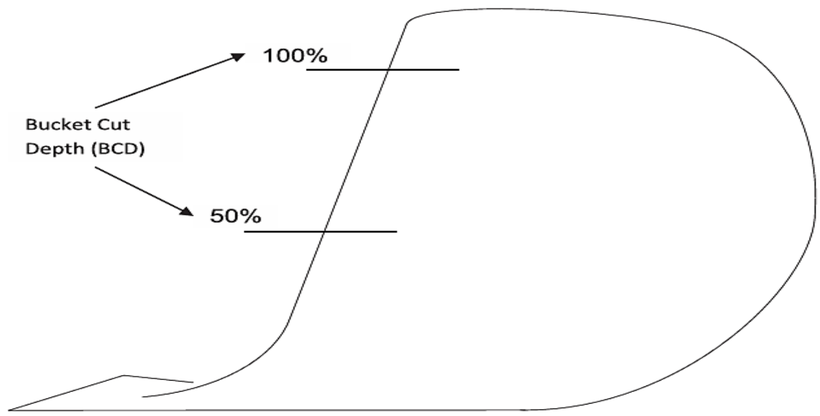
E_{CO_2}- CO2 emission factor for diesel combustion (kg CO_2/kg fuel), (approx. 3.16 kg CO_2 / kg diesel or ~2.64 kg CO_2 / l diesel).

NTH - Thermal Efficiency of the Machine
Econ – energy consumed during a given operation (kWh)

P – density of diesel fuel (kg/m3)
LHV (Lower heating value of diesel fuel) – lower heat value of diesel fuel (kJ/kg)
Operator training, which improves the choice of engine speed and bucket gripping depth, is a cost-effective way to reduce fuel consumption and emissions, while extending the life of the machines.
The CO2 emissions formula can be simplified and calculated solely on the basis of fuel consumption:

$$CO_2\left(\frac{kg}{h}\right) \approx 2{,}63 * FC\left(\frac{l}{h}\right) * t(h)$$

- Cycle time is a key indicator of productivity.
- The Bucket Cut Depth – BCD parameter introduces a more accurate measurement of the impact of the depth of the grip.



Picture 4: Side view of the construction bucket [14]

BCD is expressed as a percentage (BCD50 = 50% of the procedure, BCD100 = complete penetration). Operating at the BCD50 allows for greater productivity stability and 25% lower fuel consumption than the BCD100 [14].

Filling the bucket increases productivity by up to 80% [14]. Spinelli et al. (2009) show that productivity increases to the optimal piece size and then decreases due to machine overload.

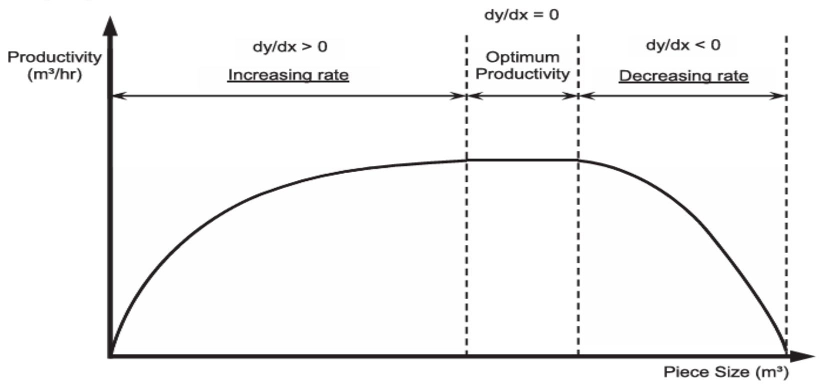


Diagram 4: The Law of Piece Size [14]

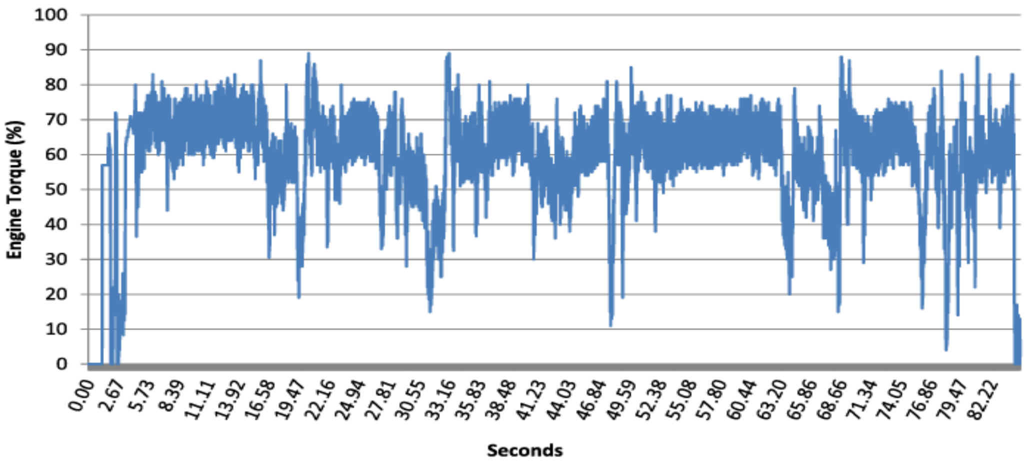


Diagram 5: Torque behavior when digging trenches [14]

Overloading the engine shortens service life and increases emissions.
Optimization of earthworks includes technical innovation, proper organization and the human factor. The greatest potential for savings lies in:

- reduction of idling,
- Use telematics and software solutions.
- The introduction of hybrid and electric machines.
- Continuous training of the operator.

Experiments confirm that relatively small changes in parameters (rpm, depth of stroke) lead to significant fuel savings and increased productivity. This makes earthworks optimization a key element of sustainable construction and reducing the environmental footprint of construction.
By analyzing the different depths of the bucket, it was found that the BCD50 provides greater productivity stability and lower fuel consumption than the BCD100. In particular, at 1600 RPM, up to 23.5% lower fuel consumption per kilogram of material moved was achieved, with the ability to move 30% more material and achieve about 25% fuel savings compared to the BCD100 [14].
Similar research shows that the correct positioning of excavators and trucks, as well as optimal digging technique, significantly reduce emissions and costs. Volvo Construction Equipment Division states that proper machine management can reduce fuel consumption by 5–25%, while Komatsu points out that a 25% reduction in engine power delivers 23% fuel savings with a smaller drop in productivity.

4. EXPERIMENTAL RESEARCH

The aim of the study was to quantify the impact of different operating parameters of earthmoving machinery on fuel consumption and CO_2 emissions. The focus is on hydraulic excavators, as they are one of the most widely used machines in the construction industry.

- Machine: hydraulic excavator (typical engine power 120–150 kW, bucket volume 1 m^3).
- Operating parameters: bucket grip depth (BCD50 and BCD100), engine speed (1600 and 2000 RPM).
- Data: taken from [14], adjusted for own calculations.
- Calculation of CO_2 emissions: the formula used:

$$CO_2\left(\frac{kg}{h}\right) \approx 2{,}63 * FC\left(\frac{l}{h}\right) * t(h)$$

  where:
  FC - fuel consumption.
- Scenarios are formed for combinations:
  - BCD50, 1600 RPM
  - BCD50, 2000 RPM
  - BCD100, 1600 RPM
  - BCD100, 2000 RPM

Table 3: Fuel consumption and CO_2 emissions depending on operating parameters

Script	Fuel consumption (l/h)	CO_2 emissions (kg/h)	Productivity (t/h)	Fuel Efficiency (t/L)
BCD50 – 1600 RPM	18,5	48,6	520	28,1
BCD50 – 2000 RPM	23,0	60,5	600	26,1
BCD100 – 1600 RPM	24,0	63,1	570	23,8
BCD100 – 2000 RPM	29,0	76,3	640	22,0

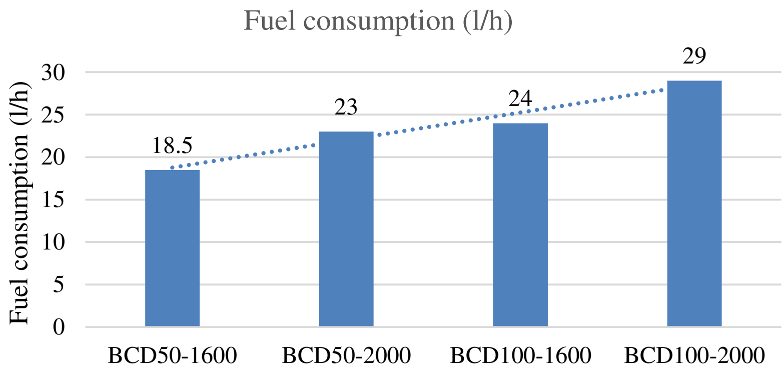


Diagram 6: Display of the dependence of fuel consumption on the depth of engagement and engine speed

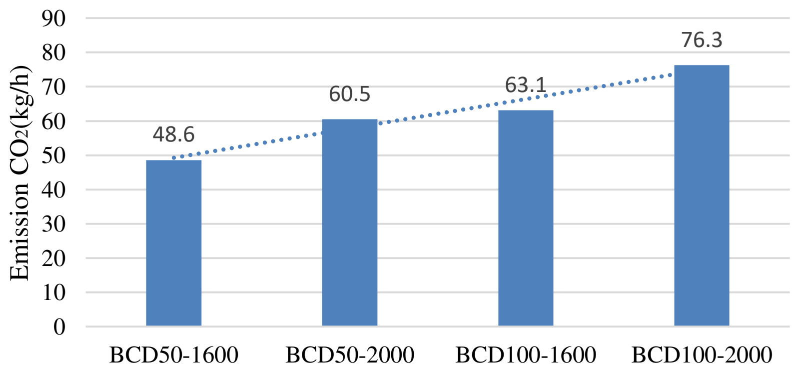


Diagram 7: Display of the dependence of CO2 emissions on the depth of engagement and engine speed

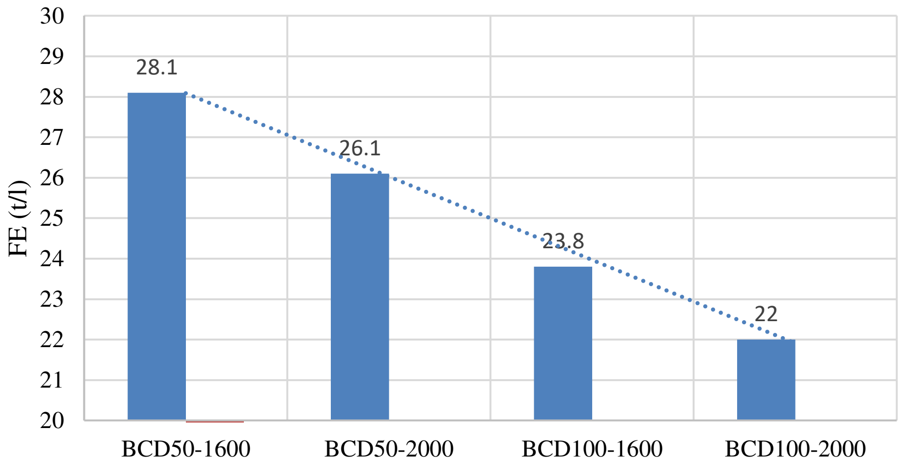


Diagram 8: Display of the dependence of emissions, fuel efficiency (FE) on the depth of engagement and engine speed

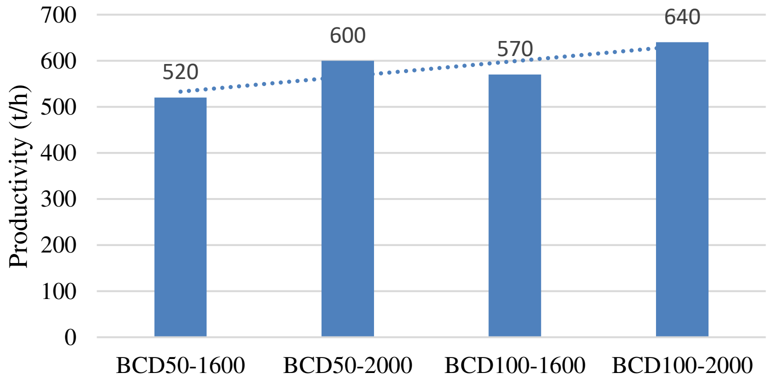


Diagram 9: Display of productivity from depth of engagement and engine speed

- The lowest fuel consumption and CO_2 emissions are obtained at BCD50 – 1600 RPM.
- The highest productivity was achieved at BCD100 – 2000 RPM, but with significantly higher fuel consumption.
- The optimal compromise is achieved at BCD50 – 2000 RPM, where productivity is increased (600 t/h), with a moderate increase in emissions.
- The results are in line with data from Volvo CE and Komatsu, which state that a reduction in revs can result in up to 25% fuel savings, but also slightly lower productivity [14].

Fuel efficiency can be increased by optimizing the operating parameters (BCD, revs).

Switching from a maximum grip (BCD100) to a semi-grip (BCD50) brings savings of 20–25% with a relatively small drop in productivity.

Operator training and the application of telematics are key to choosing the optimal operating mode.

CONCLUSION

Earthworks represent one of the most energy-intensive segments of construction, but at the same time they offer great potential for improving energy efficiency and reducing the negative impact on the environment. Their complexity stems from the use of heavy machinery with powerful engines, which consume large amounts of fuel and emit significant amounts of harmful gases. That is why the application of modern energy management methods and technologies is essential for the development of sustainable construction.

By analyzing all factors – from the type and number of machines, work organization, planning of operations and soil type, to the human factor – it has been shown that a high degree of energy efficiency can be achieved. Experimental studies have confirmed that even the smallest changes in operating parameters, such as engine speed or bucket grip depth, can bring fuel savings of 20–25% with an increase in productivity. Further advances are being achieved through the application of telematics systems, scheduling software solutions, hybrid and electric machines, as well as continuous operator training.

Energy efficiency in earthworks should not only be seen as an economic benefit, but also as a social obligation in the context of global efforts to achieve climate neutrality. Energy management at this level is not only a way to reduce costs, but also a way to a more responsible attitude towards natural resources and the environment. Sustainable construction starts from the first phase, i.e. earthworks, so knowledge, planning and the use of innovative technologies are key elements in the transformation of the construction industry into an energy-efficient and environmentally friendly system. Contractors are encouraged to standardize operator training, introduce telematics systems, and plan to switch to hybrid machines in larger projects.

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