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THE IMPACT OF LOAD-SENSING REGULATION ON THE ENERGY, ECONOMIC AND ENVIRONMENTAL EFFICIENCY OF AXIAL-PISTON PUMPS

Research paper

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Abstract: Modern technologies require a high level of system efficiency. In the case of hydraulic systems, this efficiency is generally considered in terms of energy, economic, and environmental performance. In the research part of the paper, the authors conducted a comparative analysis of two different designs of the same type of hydraulic pump, namely an axial piston pump: a conventional pump with a fixed displacement and a modern pump equipped with load-sensing regulation. Based on the research presented in the paper, a clear comparison was obtained showing the extent to which the application of load-sensing regulation contributes to improving system efficiency after the implementation of hydraulically regulated pumps.
Key words: hydraulic, axial-piston pump, LS regulation, efficiency.

INTRODUCTION

Fluid power is an established engineering discipline that uses pressurized fluids to transmit and control mechanical energy and perform mechanical actuation. Hydraulic systems are widely used in agriculture, construction, transportation, manufacturing, aerospace, marine, and other industrial applications. Hydraulic systems, most commonly hydraulic presses, operate under quite demanding conditions, involving variations in operating parameters such as pressure, flow rate, and temperature, as well as in the fundamental physical properties of the fluid (Novaković et al., 2026).

Axial-piston pumps are commonly applied in systems where variable pressure and flow rates are required under different operating conditions (Vacca, 2018). Their operating efficiency depends not only on the characteristics of the pump itself, but also on the way the pump output is adjusted to the actual requirements of the hydraulic system. Conventional fixed-displacement pumps provide a relatively constant flow while the pump is operating, regardless of the actual flow demand of the system (Kärnell & Ericson, 2023). When the required flow is lower than the pump output, part of the supplied hydraulic energy is lost through throttling and pressure losses (Mahato & Ghoshal, 2021). These losses increase energy consumption and can also affect the operating cost and environmental performance of the system. The use of variable-displacement axial-piston pumps with load-sensing regulation allows the pump displacement to be adjusted according to the required flow, while the pump pressure is maintained in accordance with the load demand (Axin et al., 2014; Kralev et al., 2026; Li et al., 2022).

Load-sensing regulation therefore provides a different operating principle compared with conventional fixed-displacement pump systems (Lisowski et al., 2021). The difference can be observed through changes in energy consumption, hydraulic losses, operating costs, and other parameters related to the use of the system. An analysis of these parameters can provide a more detailed comparison of conventional and load-sensing axial-piston pump configurations and can be used to assess their energy, economic, and environmental efficiency.

The energy efficiency of a hydraulic system is determined by the interaction between the pump, control valves, actuators, and the operating conditions of the system. In conventional hydraulic circuits, the difference between the flow supplied by the pump and the flow required by the actuator is often dissipated through throttling. Similar losses can occur when the pump

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operates at a pressure level higher than that required by the load. In load-sensing systems, the pump displacement is adjusted according to the flow demand, while the pressure is controlled based on the highest load pressure in the system. This reduces the amount of flow and pressure that needs to be dissipated compared with conventional constant-flow arrangements (Siebert et al., 2017). Load-sensing systems still contain pressure losses associated with valves, pressure compensators, flow restrictions, and the pressure margin required for stable operation. These losses can become more pronounced when several actuators operate simultaneously at different load pressures.
Energy consumption is also directly related to the economic and environmental performance of hydraulic equipment. For systems driven by an internal combustion engine, hydraulic power losses increase the required input power and can consequently increase fuel consumption and associated carbon dioxide emissions. An analysis of a mobile hydraulic system using an axial-piston pump showed that pump losses were associated with both fuel consumption and CO2 emissions, with the magnitude of these effects changing with operating pressure and rotational speed (Kapsiz, 2022). From an economic perspective, lower energy consumption can reduce operating costs during the service life of the equipment, particularly in applications with long operating cycles and high hydraulic power requirements. The relationship between operating energy use, life-cycle cost, and environmental impact has also been considered in life-cycle assessments of pumping systems, where the use phase can represent a substantial part of the total energy and environmental burden (Nault & Papa, 2015).

MATERIAL AND METHODS

The research was conducted using an empirical and analytical approach based on established equations for the analysis of hydraulic pump performance. The study focused on axial-piston pumps and included a comparative assessment of a conventional fixed-displacement pump and a variable-displacement pump with load-sensing regulation. The analysis was based on relevant input parameters obtained from manufacturer catalogues and technical documentation for axial-piston pumps. The selected parameters included pump displacement, rotational speed, operating pressure, flow rate, volumetric efficiency, and other performance characteristics required for the calculation. The experimental part of the study was performed through numerical calculations based on the selected input data and established mathematical relationships for the determination of hydraulic and energy performance. The relevant equations were used to calculate the theoretical and actual flow rate, hydraulic power, input power, energy losses, and pump efficiency under different operating conditions. The same input conditions were applied to the compared pump configurations in order to provide a consistent basis for the analysis. The load-sensing configuration was evaluated by considering the change in pump displacement and pressure according to the required system flow and load conditions. The calculated results were used to compare the operating characteristics of the fixed-displacement and load-sensing configurations. Particular attention was given to the differences in hydraulic power demand, energy consumption, and power losses under different pressure and flow conditions. The economic and environmental aspects were subsequently assessed using the calculated energy consumption as the basis for estimating the corresponding operating costs and environmental effects. This approach allowed the performance of the two pump configurations to be evaluated under comparable operating conditions using manufacturer-specified data and established calculation procedures.

COMPARISON OF REGULATED AND NON-REGULATED AXIAL-PISTON PUMPS

Axial-piston pumps can be divided according to the method used to control their displacement and output flow. In a non-regulated configuration, the pump operates with a fixed displacement, and the delivered flow is mainly determined by the pump displacement and rotational speed. The hydraulic system must therefore accommodate the difference between the flow supplied by the pump and the flow required by the load. In a regulated configuration, the pump displacement can be changed during operation, allowing the delivered flow to be adjusted

according to the operating requirements. This principle is particularly relevant in hydraulic systems with variable loads, where the required flow and pressure change during operation.
Variable-displacement axial-piston pumps are widely used in hydraulic systems where the pump output has to follow changing load requirements. The displacement is commonly controlled through the swash-plate angle, which changes the piston stroke and consequently the theoretical displacement of the pump. The control mechanism can be based on hydraulic-mechanical regulation or on an electrohydraulic control system. The use of variable displacement allows the pump to reduce its output when the required flow decreases, which can reduce the power consumed during operating conditions with low flow demand. Research on variable-displacement axial-piston pumps has shown that displacement control is closely related to pump pressure, flow rate, and the dynamic behaviour of the control system (Helian et al., 2022).
The operating characteristics of regulated and non-regulated pumps also differ with respect to their response to changes in system demand. A fixed-displacement pump can provide the required flow only when the operating conditions are compatible with its fixed displacement and rotational speed. Additional hydraulic elements are therefore required when the system demand changes significantly. In contrast, a variable-displacement pump can modify its displacement and adapt its output to the required operating point. Studies of axial-piston pump control have shown that the control of displacement has a direct effect on the dynamic response and efficiency of the hydraulic source, while the performance of the control system depends on the operating point and load conditions (Yamada et al., 2024).
The comparison of these parameters provides a basis for evaluating how changes in pump displacement and regulation affect the hydraulic power supplied by the pump and the corresponding energy requirements of the system. In Figure 1a, a pump with a fixed volume is shown, while in Figure 1b, a pump with regulation is shown.



Fig.1a. *Fixed displacement axial-piston pump (Bosch, 2026)*



Fig .1b. *Variable displacement axial-piston pump* (Parker, 2026)

Figure 2 shows the scheme of two-way load-sensing control, i.e. regulation.

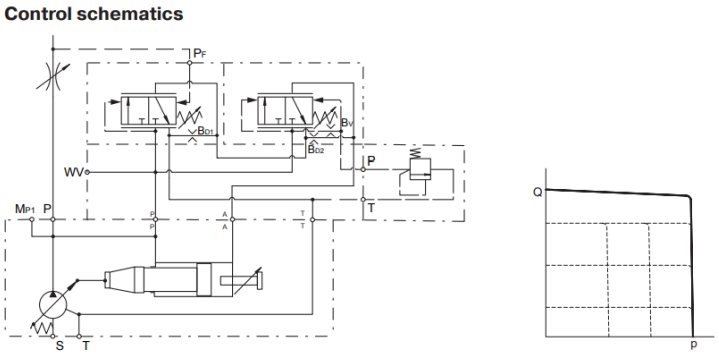


Fig 2. *Two-way load-sensing control*

ANALYTICAL AND EMPIRICAL INVESTIGATION OF AXIAL-PISTON PUMP PERFORMANCE

To assess the practical advantages and limitations of load-sensing regulated axial-piston pumps in comparison with non-regulated fixed-displacement pumps, a comparative analysis was conducted using three pump models with different operating parameters. The analysis included pumps with maximum operating pressures of 150, 250, and 300 bar, and nominal flow rates of 120, 200, and 250 L/min, respectively. For each pump type, two configurations were considered: a load-sensing regulated pump and a fixed-displacement pump. The electric motor used to drive the regulated 150 bar axial-piston pump had a rated power of 22 kW, with an estimated required active power of approximately 20 kW, whereas the corresponding fixed-displacement pump was driven by a 30 kW motor. For pump type B, the regulated configuration was driven by a 55 kW electric motor equipped with a variable frequency drive, while the fixed-displacement configuration used an 80 kW motor. For pump type C, the regulated configuration used a 77 kW electric motor, whereas the fixed-displacement pump was driven by a 120 kW motor. The main objective of the analysis was to quantify the differences between the two pump configurations in terms of energy consumption, electricity costs, carbon dioxide (CO_2) emissions, and cumulative costs over the considered service period. The analysis also included the payback period associated with the additional investment required for regulated pumps, the expected service life under ideal operating conditions, and the maintenance costs and frequency. Several assumptions were defined for the calculations, including the pump duty cycle, the efficiency of electric motors with and without a variable frequency drive, the annual operating hours, the electricity price, and the CO_2 emission factor. The selected assumptions were intended to represent typical industrial operating conditions and provide a consistent basis for the comparative calculations. The applied methodology included the calculation of annual energy consumption under the defined system load conditions, followed by a projection of cumulative costs over a twelve-year period and an estimation of the total CO_2 emissions for both pump configurations. Particular attention was given to the calculation of the simple payback period as a parameter for evaluating the economic implications of the additional investment in load-sensing regulation. The obtained results were presented in tabular and graphical form to enable a direct comparison of the analyzed pump configurations with respect to energy consumption, economic performance, and environmental impact. The calculated parameters were subsequently used to assess the differences between regulated and non-regulated axial-piston pumps under the defined operating conditions.
The power of the non-regulated pump was calculated using Equation (1):

$$P(t) = p \cdot Q(t) \tag{1}$$

For calculating the power of regulated axial-piston pumps, the time fraction of each operating condition was taken into account, as given in Equation (2):

$$P_{ls} = (1 + f_{ls}) p Q_m, Q_m = i \sum d_i \alpha_i Q_{m,max} \tag{2}$$

One of the main parameters used to compare load-sensing regulated axial-piston pumps with non-regulated pumps is electricity consumption during operation. Based on the defined operating cycle, in which the pump operates at full flow for 30% of the time, at 60% of its capacity for 50% of the time, and at 30% of its capacity for 20% of the time, the annual electricity consumption was calculated for each of the analyzed pumps. The operating time during a typical working day was also taken into account. Since the system operates continuously in three shifts, the active operating time was assumed to be approximately 18 hours per day. The annual electricity consumption was calculated using Equation (3):

$$E_{yr} = \frac{P_{el}^{F} \cdot t_{yr}}{1000}, E_{yr}^{ls} = \frac{P_{el}^{ls} \cdot t_{yr}}{1000} \quad (3)$$

The results presented in the table and graph show that load-sensing regulated pumps have lower electricity consumption compared with fixed-displacement pumps. The difference becomes more pronounced for pumps with higher power ratings and higher operating pressures. This indicates that the potential energy savings associated with load-sensing regulation increase as the power requirements of the hydraulic system increase. Table 1 shows the ratio of consumed electrical energy in three types of pumps with fixed and variable displacement.

Table 1. *Energy efficiency*

Pumps	Working pressure (bar)	Flow (l/min)	Energy consumption LS (kWh/god)	Energy consumption fixed (kWh/god)	Saving (%)
Pump A	150	120	97,631.6	145,927.5	33.07 %
Pump B	250	200	269,250.9	402,576.5	33.14 %
Pump C	300	250	385,964.9	603,864.7	36,12 %

Figure 3 graphically shows the ratio of consumed energy for pump type A, with regulation and without regulation.

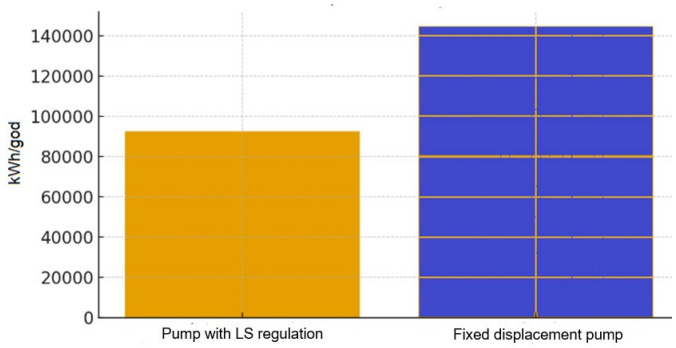


Fig. 3*. Ration of cosumed energy Pump A*

The figure 4 shows the ratio of annual energy consumption for pump B, operating parameters of pressure 250 bar and flow rate 200 l/min.

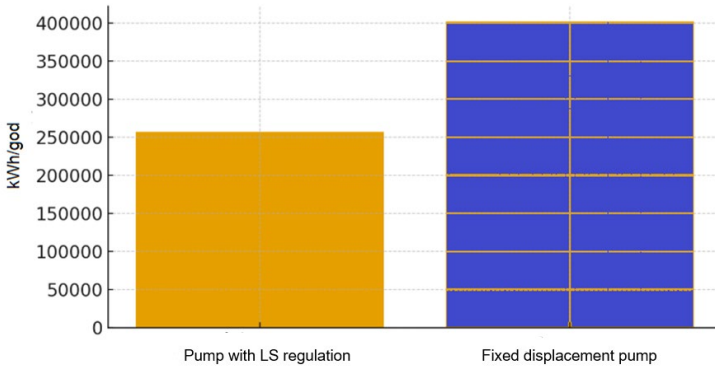


Fig. 4. *Ration of cosumed energy Pump B*

The figure 5 shows the ratio of annual energy consumption for pump type C.

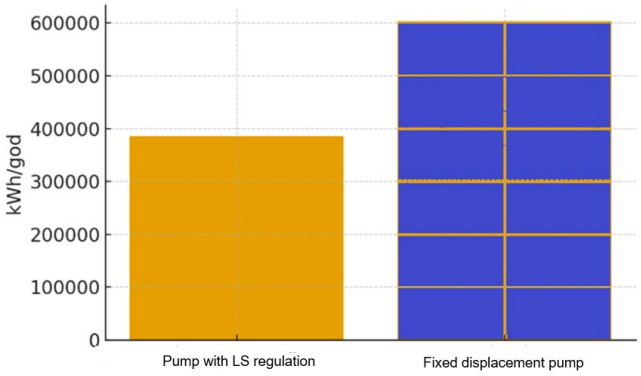


Fig. 5. *Ration of cosumed energy Pump C*

Cumulative cost analysis is a key tool in technical-economic studies of hydraulic systems because it allows making decisions that balance between initial investment, energy consumption and long-term maintenance, where LS regulation significantly contributes to reducing total costs and increasing system efficiency. Cumulative costs are calculated on an annual basis according to Equation (4):

$$Cost_{tol}^{x} = C_{cap}^{x} + \sum C_{op,t}^{x}, X \in \{F, LS\} \tag{4}$$

where is it

$$C_{op,t}^{x} = C_{el} \cdot E_{yr,t}^{x} + M_{i}^{x} \tag{5}$$

The figure 6. shows the cumulative cost analysis for the first group of pumps, i.e. for Pump A.

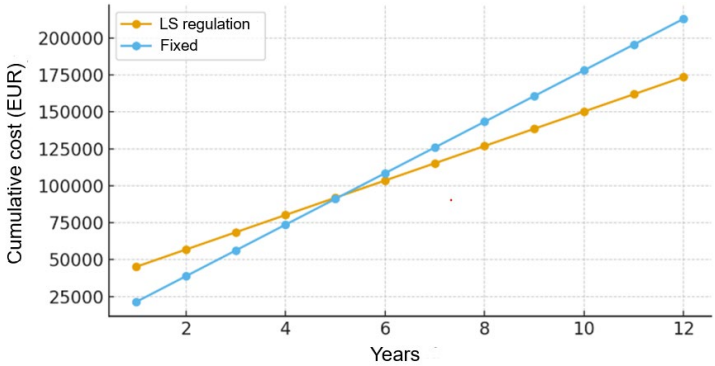


Fig. 6. *Cumulative cost analysis for. for Pump A*

The figure 7. shows the cumulative cost analysis for the Pump B.

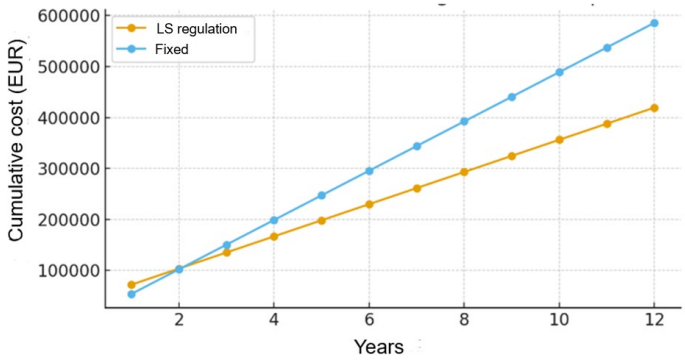


Fig. 7. *Cumulative cost analysis for. for Pump B*

The figure 8. shows the cumulative cost analysis for the Pump C.

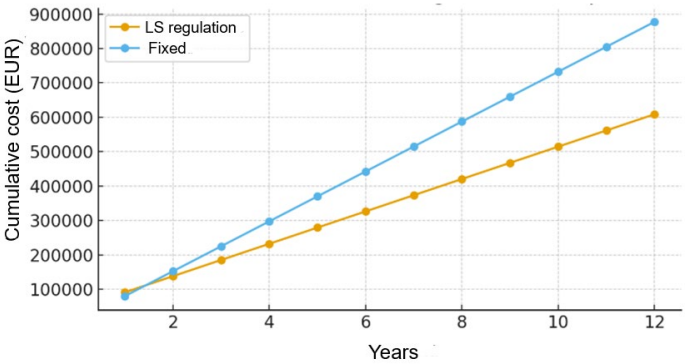


Fig. 8. *Cumulative cost analysis for. for Pump C*

The analysis of cumulative CO_2 emissions during the operational period provides a quantitative insight into the environmental impact of different types of hydraulic pumps, enabling the comparison of traditional pumps with fixed flow and pumps with Load-Sensing (LS) regulation. The presentation of these emissions through a line diagram during 12 years of operation clearly shows that pumps with LS regulation achieve significantly lower cumulative CO_2 emissions, which is a consequence of proportionally reduced electricity consumption. The figure 9 shows the cumulative emission of CO2 gases, for the period of exploitation of the pumps in the range of 12 years, on the example of Pump type A.

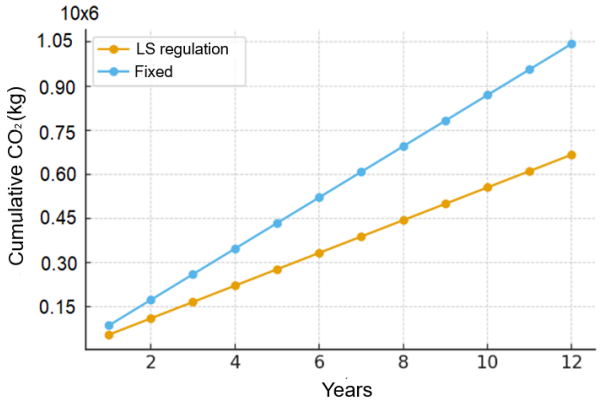


Fig.9. *The cumulative emission of CO2 gases for Pump A*

The figure 10 shows the cumulative emission of CO2 gases, for the period of exploitation of the pumps in the range of 12 years, on the example of Pump type B.

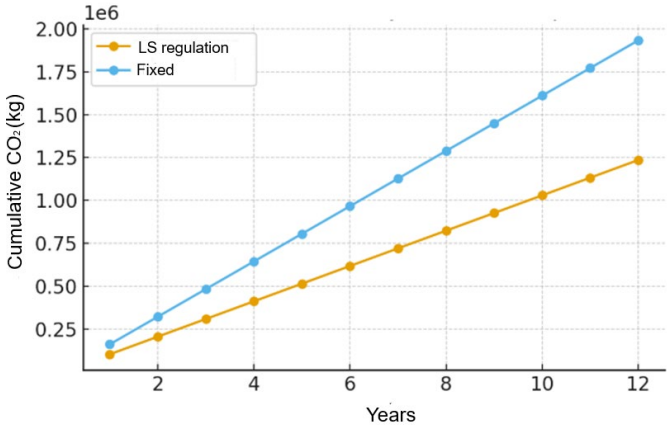


Fig.10. *The cumulative emission of CO2 gases for Pump B*

The figure 11 shows the cumulative emission of CO2 gases, for the period of exploitation of the pumps in the range of 12 years, on the example of Pump type C.

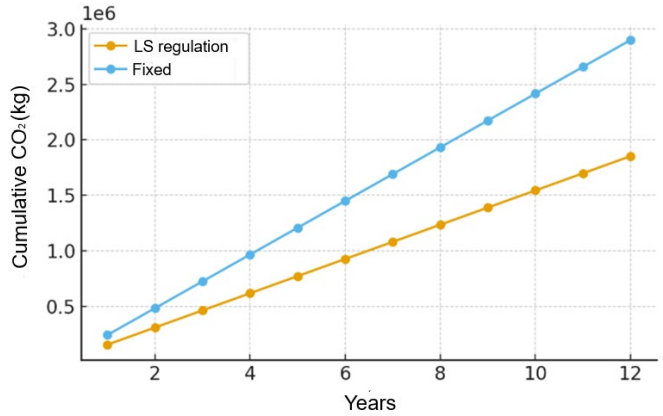


Fig.11. *The cumulative emission of CO2 gases for Pump C*

CONCLUSION

The results of the conducted analysis clearly demonstrate that the selection of pump type has a significant influence on the energy efficiency and overall operating costs of hydraulic systems. Pumps equipped with LS (Load-Sensing) regulation, owing to their ability to adjust the delivered flow rate according to the actual requirements of the consumers, achieve substantial reductions in electricity consumption compared with fixed-flow pumps. This effect becomes particularly pronounced in applications involving higher-capacity pumps and elevated operating pressures, where the difference in energy consumption increases accordingly. These findings support the initial hypothesis that the application of LS pumps enables more efficient utilization of the input power.

From an economic perspective, although LS-regulated pumps generally require higher initial capital investment, the analysis of cumulative costs indicates that the additional investment can be recovered within a relatively short operating period through the achieved energy savings. In the case of larger pump units, the payback period may be reduced to only a few years, further supporting their application in industrial environments characterized by intensive operating regimes and high energy demand. This finding highlights the importance of conducting a comprehensive life-cycle cost (LCC) analysis, as a comparison based solely on initial purchase prices does not provide a sufficiently realistic assessment of the long-term economic viability of the selected pumping solution.

The environmental aspect further supports the application of LS-regulated pumps. The analysis of cumulative CO_2 emissions over a 12-year operating period demonstrates that variable-flow regulation can substantially reduce greenhouse gas emissions. Consequently, in addition to the direct economic benefits associated with lower energy consumption, the

implementation of LS technology may contribute to broader objectives related to decarbonization and sustainable development.

Overall, the results indicate that the application of LS-regulated pumps provides significant technical, economic, and environmental advantages compared with conventional fixed-flow pump systems. Nevertheless, certain limitations should also be considered, particularly the greater complexity of the regulation system, potentially more demanding maintenance procedures, and possibly higher service costs over the long term. Despite these considerations, the overall balance between the identified benefits and limitations supports the wider implementation of LS-regulated pumps in modern hydraulic systems, particularly in applications characterized by variable load requirements and intensive operating conditions.

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