

PRELIMINARY REPORT

The Economic Feasibility of Solar-Photovoltaic Noise Barriers in Road Infrastructure: A Case Study of Serbia

Duško Bodroža^{1*} | Ondrej Jaško² | Željko Marković³

¹ Institute of Economic Sciences, Belgrade, Serbia,

² University of Belgrade, Faculty of Organizational Sciences, Belgrade, Serbia

³ University of Belgrade, School of Electrical Engineering, Belgrade, Serbia

ABSTRACT

Implementing photovoltaic noise barrier (PVNB) systems may help facilitate significant energy, economic and environmental benefits, including reducing CO₂ emissions and increasing electricity production from renewable sources. Effectively implementing such systems requires conducting pilot projects, developing internal standards and design and construction norms, creating financial support models and putting incentives in place to encourage wider implementation. Through a case study focusing on their application in the Republic of Serbia (RS), this study seeks to analyse the economic feasibility and environmental benefits of PVNB systems as well as their economic potential and sustainability in road infrastructure. The study's methodology employs cost-benefit analysis (CBA), net present value (NPV), internal rate of return (IRR) and payback period (PBP). Two technical solutions (Variant A and Variant B), oriented in eight possible positions in cardinal directions, are considered. The results point to the extended technical solution (Variant B), which achieves better economic indicators by including additional solar panels placed at optimal angles (especially facing south, south-east and south-west).

Keywords: *Photovoltaic noise barrier, Infrastructure, Economic feasibility, Renewable energy integration, Serbia*

JEL Classification: P28, Q42, O18, O44

INTRODUCTION

Following global and national strategic commitments, the necessity to increase renewable energy sources, improve energy efficiency and use resources responsibly has increasingly become an imperative. There is a need for independent studies to explore the potential of green energy in novel but immediately applicable uses, particularly in states with potential for implementing green initiatives through infrastructure development.

Integration of environmentally friendly solutions into infrastructure projects poses a key challenge, particularly in highway and expressway construction. Although these infrastructure systems facilitate the faster and more efficient transportation of both goods and individuals, they also negatively impact the environment, causing both air and noise pollution (Pascale et al., 2021). The latter is a growing problem not only in urban areas but also along major roads, railroads, and in the proximity of industrial zones. Although conventional noise barriers play an important role

* Corresponding author, e-mail: dusko.bodroza@ien.bg.ac.rs

in mitigating the effects of noise pollution on health and quality of life (Eren et al., 2024), they are mono-functional and do not actively contribute to sustainable development goals (Gajović et al., 2023; Mehrabi, R., 2023).

Out of the necessity for multifunctional solutions, the combination of environmental protection and clean-energy production was developed. Photovoltaic noise barriers (PVNB) are an example of multifunctionality, as they combine noise reduction with the ability to generate renewable energy (De Schepper et al. 2012). Erected along highways and railroads, these barriers not only serve as noise barriers, but also as solar panel structures. The use of photovoltaic solar panels in the construction of noise barriers dates back to 1989, with was first put into practice in Switzerland (Nordmann & Goetzberger, 1994). Apart from offering a significant reduction in noise levels, PVNBs are able to produce green energy, thereby helping to reduce both fossil-fuel dependence and carbon dioxide emissions (De Schepper et al. 2012; Hasmden et al, 2022). Although PVNB systems' technical aspects and potential have been thoroughly studied (Goetzberger and Hoffmann, 2005; Faturrochman et al., 2018), the economics of their application remain insufficiently addressed, especially their sustainability and profitability in infrastructure projects. Based on hitherto conducted research, the key indicators of net present value (NPV), payback time on initial investment and energy payback time (EPBT) indicate favourable results under an EPBT of 5.4 years (Gu et al., 2012).

Faturrochman et al. (2018) focused their research on the integration of bifacial photovoltaic modules into PVNB systems, in which a full-size noise barrier was built. In the analysis, electricity production was continuously monitored and compared with advanced numerical model simulations, with the results showing a high degree of accuracy of the model. Moreover, an additional analysis demonstrated that orientation, tilt, and panel configuration have a strong influence on the system's energy yield. In practice, a range of diverse design solutions can be employed when integrating photovoltaic (PV) modules into noise barriers. The most common approaches include mounting modules vertically along the entire barrier's surface, arranging the panels in a zigzag formation to optimize light penetration, and using bifacial modules to enable bi-surface energy harvesting while acting as the load-bearing structure of the barrier itself (Goetzberger et al., 1999; Wadhawan & Pearce, 2017). The effectiveness of such systems largely depends on several factors, including the panels' key location and direction, the site's intensity and duration of solar radiation, and the geometry of the barrier itself (Kanellis et al., 2017). The area of the barrier, the tilt angle of the panels and their direction substantially impact energy yield; hence, careful planning and design are required for all sites in relation to the uniqueness of their locality (Soares and Wang, 2023). Indeed, one analysis of a PVNB system project implemented along a metro-rail line in China (possessing a total generation capacity of 8 kWp from a total length of 360M) found the design of the system to have been optimized according to local conditions based on an economic and environmental assessment conducted (Gu et al., 2012).

Accordingly, one such illustrative example of the implementation of PVNB systems on existing traffic infrastructure may be the Republic of Serbia (RS). As a signatory to the Paris Agreement, the RS has shown its dedication to combating climate change, promoting sustainable development and applying circular economic principles (Jovanović et al., 2023; Đurićin et al., 2016). Bearing this background in mind, this study aims to investigate the technical feasibility, economic viability and environmental benefits of using photovoltaic solar panels as an integrated element of noise protection on RS highways. The implementation of PVNBs in the RS would not only improve the environment by reducing noise levels and carbon dioxide emissions, but would also create additional economic value by transforming these low-productive passive structures into an active sustainable energy resource. The evaluation was carried out using a methodology incorporating a cost-benefit analysis (CBA), applying key financial net present value (NPV) indicators, the internal rate of return (IRR) and payback period (PBP).

CASE STUDY ASSESSMENT

Case studies on PVNBs, while present in the literature, are still insufficient (Wadhawan & Pearce, 2017; Muñoz-Cerón et al., 2018; De Schepper et al. 2012; Hasmaden et al, 2022); therefore, a study on their implementation in the RS is expedient. As already noted, hybrid PVNB systems represent a multifunctional solution that, in addition to their primary function of reducing noise levels, also produce electricity from renewable sources. As such, this study discusses a proposed technical solution that may serve as a model for the first implementation of such hybrid systems in the RS, based on the following:

- The recommended integration of photovoltaic modules into noise-barrier construction is either vertical or a combination of both vertical and surface-mounted installation, which optimizes the use of the available surface area while enhancing both energy and acoustic performance.
- The statistical, acoustic and energy analysis of the system must be carried out according to site-specific parameters, which is vital when retrofitting existing noise barriers in order to guarantee structural stability and maintenance of acoustic efficiency.
- Electricity-production optimization determines the photovoltaic modules' installation (i.e., either its side facing traffic or its opposite, as well as on its apex). The geographical location and direction of the noise barrier are key factors affecting the system's energy efficiency
- When photovoltaic modules are placed facing traffic, it is necessary to use anti-reflective coating modules, whose reflections of solar energy may negatively impact road safety. Using advanced technologies, such as anti-reflective coatings, textured surfaces, software simulations and suitable design strategies, can eliminate or significantly reduce such risks.
- The minimum permissible height to install photovoltaic modules on the barrier is 1 meter above the ground. Falling below this height considerably increases the risk of mechanical damage delivered from traffic-induced impacting particles (e.g., pebbles), as well as dust accumulation, leading to diminished power production.

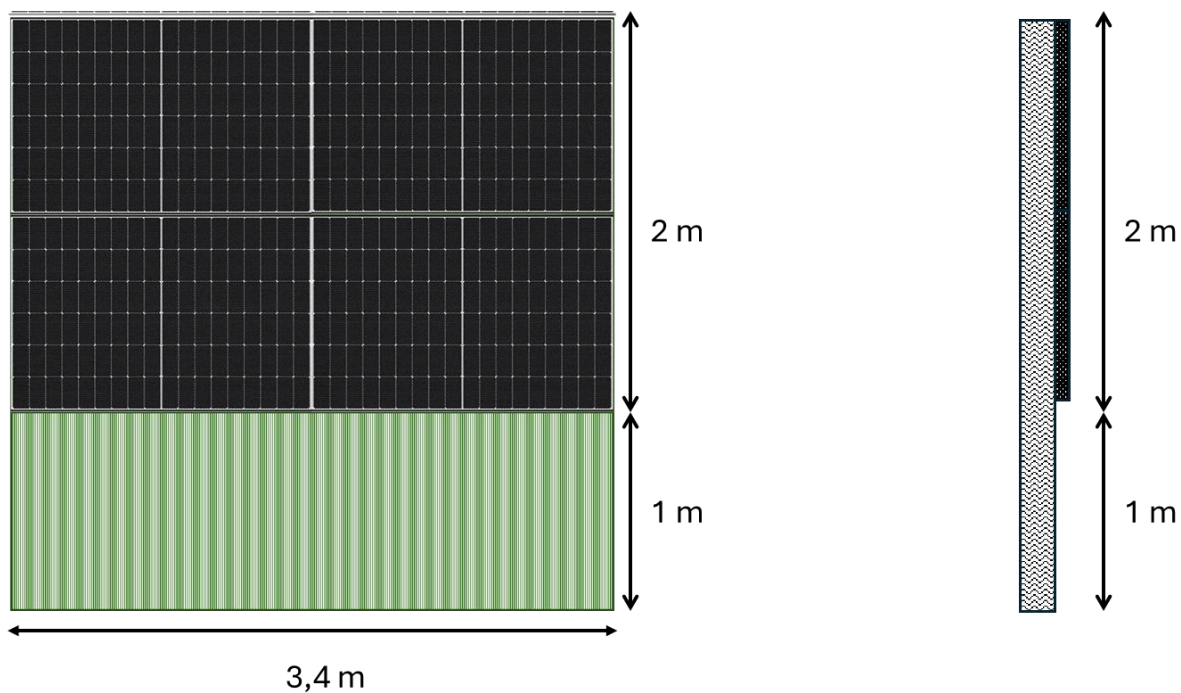
The parameters of the noise barriers and photovoltaic modules considered are as follows:

1. The individual noise barrier varies between 2 and 4 meters in length, while its height is determined according to the sound insulation requirements (generally between 2 and 4 meters).
2. The photovoltaic modules' standard dimensions are approximately 1.7 meters in length and 1 meter in width.

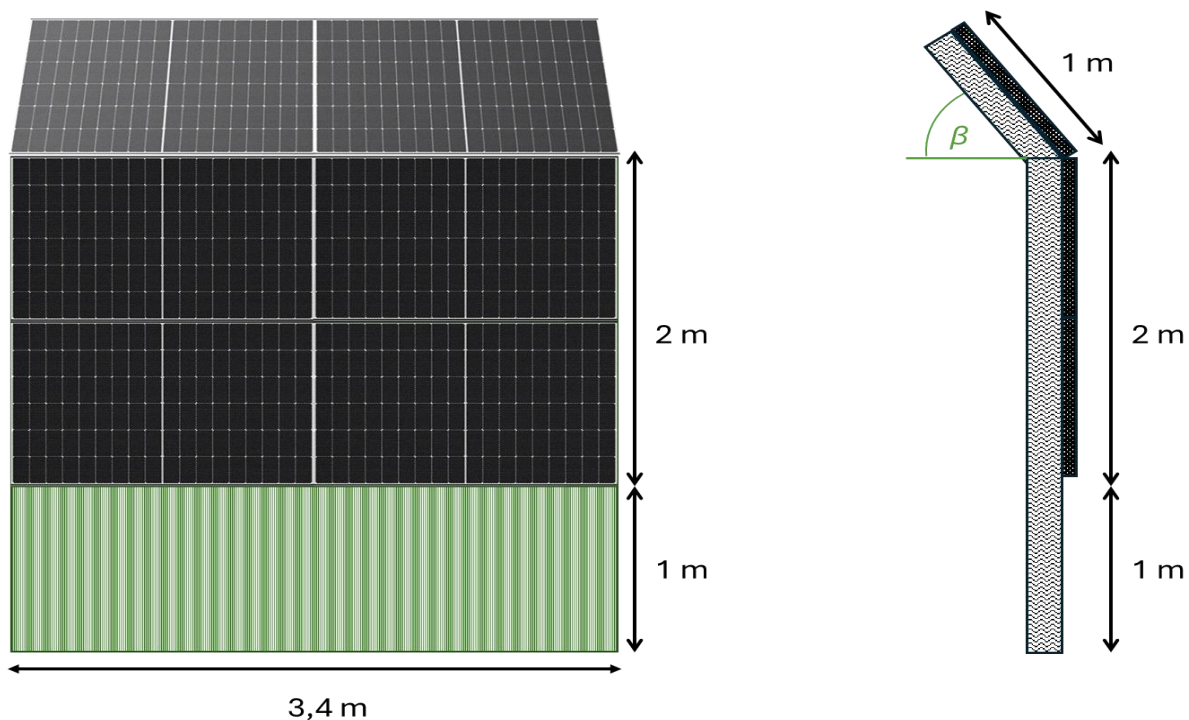
Bearing these dimensions in mind, this study analyses two representative technical solutions for integrating photovoltaic modules with noise barriers:

- Immediate solution (Variant A): a basic installation of four 2-meter-wide photovoltaic modules integrated directly into the body of a 3.4-meter-wide, 3-meter-high noise barrier made of sound-absorbing material.
- Extended solution (Variant B): Builds on Variant A by adding an additional row of two photovoltaic modules arranged at an angle β to the horizontal. The typical value of the angle β is 30° , representing a compromise between acoustic calculations and optimal panel orientation for the RS's geographical locations. For specific applications, this angle may be further optimized to increase electricity production; however, it remains necessary to verify that any optimization complies with both acoustic calculations and noise protection requirements.

Both solutions are represented in the following pictures:



Picture 1: Immediate Solution (Variant A) (No Additional Upgrades, Angled Solar Panels)
Source: Authors



Picture 2. Extended Solution (Variant B) (Incorporating Apex Solar-slanted Panels at Angle β)
Source: Authors

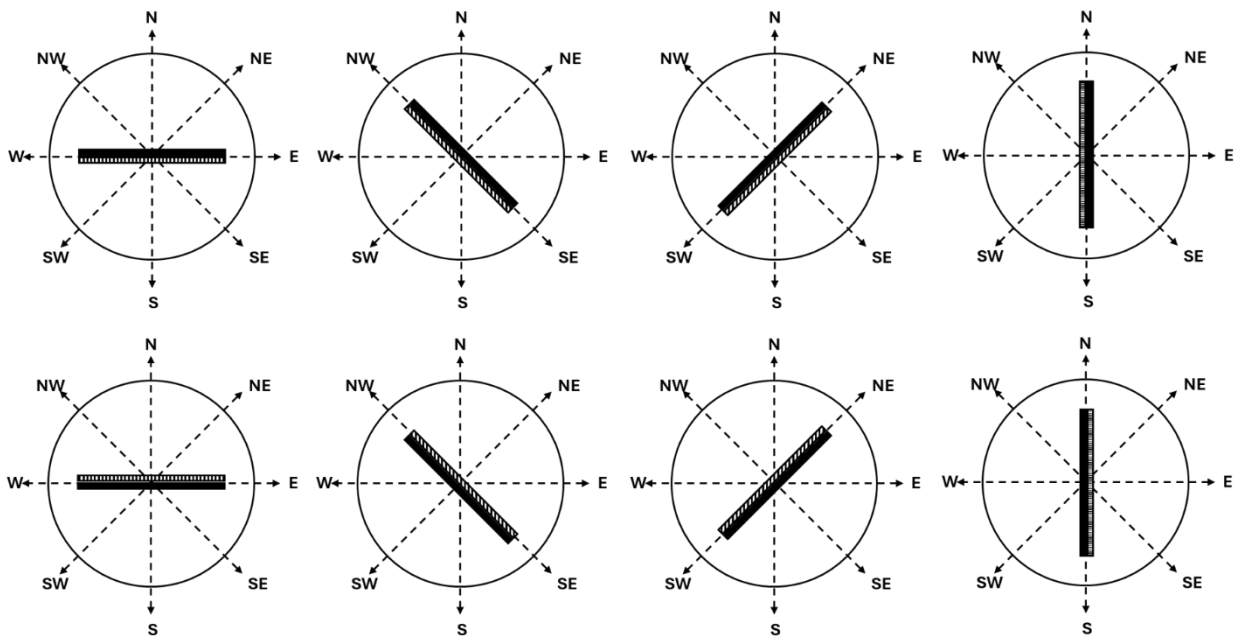
At the time of writing, modern photovoltaic solar modules are manufactured across a wide performance spectrum, with diverse outputs and levels of manufacturing quality (Belsky et al.,

2022). Under the selected module dimensions, the nominal output of commercially available panels reaches values of up to 670 W per module. However, the most prevalent modules stem from production lines characterized by an excellent ratio between technical and economic performance and price, with individual output ranging between 420 and 440 W. Therefore, a module rated at 440 W was assumed for the purposes of this analysis. Regarding power degradation over time, standard values based on leading manufacturers' technical specifications were used: 2% after the first year of use and 0.5% per annum thereafter.

Based on the assumed nominal output of the individual modules, the total installed outputs of the photovoltaic system of the two technical variants are as follows:

- Immediate Solution (Variant A): four 440 W power modules result in a total installed output of 1,760 W.
- Extended solution (Variant B): six 440 W power modules correspond to a total installed output of 2,640 W.

In relation to the system's geographical position, both technical solutions, as potential solar-integrated structures, were analysed across all eight standard cardinal directions of the sound-insulating structure. By combining two variant solutions, a total of sixteen characteristic cases were considered.



Picture 3. The eight possible cardinal directions of the solar photovoltaic panels (north, northeast, northwest, east, south, southwest, southeast and west)

Source: Authors

METHODOLOGY

Economic and financial analyses are essential to examine the viability and profitability of investing in the installation of PVMB noise barriers. The main difference between such analyses is reflected in the manner in which the project is monitored and evaluated. The financial analysis assesses the investor's perspective of the project's profitability, taking into account the direct sales revenue from the electricity generated. Further, financial indicators determine whether the project generates a sufficient return on the invested funds. Economic analysis, conversely, scrutinizes the project's wider impact, including its social and environmental benefits. In addition

to direct revenues, economic analysis also takes into account the savings achieved through reducing CO₂ emissions, which contributes to long-term sustainability and improved environmental quality (World Bank. 2023; Zdravković et al., 2024). To determine the economic and financial viability of the project, standard evaluation methods were used: cost-benefit analysis (CBA), net present value (NPV), internal rate of return (IRR) and payback period (PBP).

Cost-Benefit Analysis

Based on the quantification of all costs and benefits associated with the project, cost-benefit analysis (CBA) is a methodological framework used to assess an investment project's profitability and determine its net economic benefit. The analysis expresses benefits and costs in monetary terms, taking into account the time value of money.

The ratio of costs and benefits is calculated using the formula as follows:

$$CBA = \frac{\sum_{t=0}^n \frac{K_t}{(1+r)^t}}{\sum_{t=0}^n \frac{T_t}{(1+r)^t}} \quad (1)$$

where:

K_t – benefits in period t

T_t – costs in period t

r – the discount rate

t – year (or period of time)

n – the number of years

Net Present Value

By discounting all future net cash flows to the present, the net present value (NPV) method is used to estimate the project's total economic value. The following formula calculates the NPV:

$$NPV = \sum_{t=1}^n \frac{C_t}{(1+r)^t} - C_0 \quad (2)$$

where:

C_t – the net cash flow in period t

r – the discount rate

n – the number of years

C₀ – initial investment (CAPEX)

Internal Rate of Return

The internal rate of return (IRR) represents the discount rate at which the net present value equals zero, i.e., the point at which the project's revenues fully cover the investment costs. The IRR is determined by interpolation by the following equation:

$$0 = \sum_{t=1}^n \frac{C_t}{(1+IRR)^t} - C_0 \quad (3)$$

where:

C_t – the net cash inflow or outflow in year t

C_0 - initial investment (CAPEX)

n - the number of years,

t – the specific year or period of time for which the cash flow is measured

Payback Period

The payback period (PBP) measures the time required to recover the initial investment through cumulative net cash flows, as determined as follows:

- Net cash flows are summed by years until the cumulative flows reach the initial investment's original amount.
- The first year in which the cumulative cash flows exceed the investment is referred to as PBP.

The formula for the payback period (PBP) is based on the analysis of the cumulative cash flows over the given period. Mathematically, it is expressed as follows:

$$\text{PBP} = n + \frac{C_{\text{cum}}}{C_{n+1}} \quad (4)$$

where:

n – the last full (calendar) year prior to the cumulative net cash flow (C_{cum}) equal to the initial investment

C_{cum} – the absolute value of the remaining amount of the investment to be covered at the end of year n

C_{n+1} – the net cash flow of the following year ($n+1$)

CASE STUDY DATA

Selection of Loss Values

As with all energy-conversion processes, converting solar energy into electricity is inevitably associated with certain energy losses. The total losses in commercial photovoltaic systems found in Europe are typically between 10 % and 20 % (Shakeel and Mokheimer, 2022; Ryan et al., 2016). To reduce these, careful system design, regular maintenance and the use of high-quality components are necessary. Therein, the most commonly used percentage of 14% is used as a reference value for total losses for the purposes of this study.

Determining Average Annual Radiation

The average annual value of global horizontal radiation per square meter assumed for the purposes of this analysis was determined based on the RS's solar potential map (World Bank Group and Solargis, 2024), using the following formula:

$$E_{\text{ma}} = 1600 \frac{\text{kWh}}{\text{m}^2} \quad (5)$$

Calculating Annual Electricity Production

Containing the hourly values of solar radiation produced from 2005 to 2023, annual electricity production was calculated using the PVGIS software and the PVGIS - SARAH3 database (European Commission, 2024). The following input data were used for all case characteristics:

Table 1. Input Data for PVGIS Applied to all Case Characteristics

Entry Parameter	Selected Value
Module technology	Monocrystalline-silicon modules
Installed power	Representing the PV panel's power specified by the manufacturer under standard test conditions (STC), it assumes a solar radiation intensity of 1000 W/m ² across the panel's plane at a module 25 °C. Peak power is specified in kilowatts (kWp).
Losses	Total losses of 14% were assumed, corresponding to a positive effect coefficient of 0.86.
Mounting position	As the solar modules are integrated into the structure of the noise barrier itself, the "building-integrated" option was selected for the calculation.
Tilt and azimuth of the PV module	Specific values for the tilt and azimuth of the PV module define each characteristic case, as determined in accordance with the analysed position and panel orientation, on a case-by-case basis.

Source: Authors

Based on these calculations, annual electricity production values were determined for both system variants in relation to their spatial orientation.

Table 2. Annual Electricity Production (in kWh) for both Variants

E (kWh)	N	NE	NW	E	W	S	SE	EW
Immediate Solution (Variant A)	356.4	602.6	592.4	1,015.8	1,034.2	1,432.0	1,326.1	1,359.4
Extended Solution (Variant B)	976.2	1,293.4	1,288.5	1,869.5	1,897.6	2,483.6	2,318.6	2,359.6

Source: Authors

Assuming all photovoltaic panels in both variants are optimally positioned in terms of their incline and azimuth, the annual electricity production for Variant A would yield 2,110.8 kWh, whereas it would be 3,166.2 kWh for Variant B. Taking into account the explicated values above, the table below displays the relative ratios of the annual electricity production for both variants in relation to the spatial orientation of the panels. The ratios shown represent the proportion of production achieved in relation to the maximum possible annual production for the solution.

Table 3. Relative ratios of annual electricity production for both variants, determined by the panel spatial orientation and expressed relative to their maximum possible production

E (kWh)	N	NE	NW	E	W	S	SE	EW
Immediate Solution (Variant A)	0.17	0.29	0.28	0.48	0.49	0.68	0.63	0.64
Extended Solution (Variant B)	0.31	0.41	0.41	0.59	0.6	0.78	0.73	0.75

Source: Authors

Assessment of Wholesale Electricity Price Trends

Based on the application of the compound annual growth rate and starting from the reference wholesale electricity price for 2025, the assessment of wholesale electricity prices in the RS's market covers the period from 2025 to 2045. In creating a long-term forecast, the results and conclusions of three pertinent studies analysing the electricity market in the SEE region were used. The first, "SEE Electricity Market Perspectives until 2030: Assessing the Impact of Regional

Connections to Italy - Final Report” (Southeast Europe Cooperation Initiative, 2017), examines the impact of regional energy connections on the electricity market in Southeast Europe. The second, “SEERMAP: Southeast Europe Electricity Roadmap Country Report: Serbia” (REKK, TU Wien, OG Research, & EKC, 2017), provides a detailed analysis of development projections for the RS’s power sector in line with regional and European trends. The third, “Assessment of the Impact of High Levels of Decarbonization and Clean Energy on the Electricity Market and Network Operation in Southeast Europe” (EKC & EIHP, 2021), deals with the consequences of high levels of decarbonization and the use of clean energy sources in the electricity market and the Southeast European electricity grid.

The analyses of these studies demonstrate that wholesale electricity price development has largely been determined by both natural gas prices and the price of carbon dioxide (CO₂) emission allowance. As expectations regarding the future development of these factors are consistent with the assumptions and projections of the analysed studies, it is assumed that wholesale electricity prices will develop in line with the cited complex growth rates over the long term. Taking into account all available data and their assumptions, a low-case scenario is also presumed, as taken from the study “Assessment of the Impact of High Levels of Decarbonization and Clean Energy on the Electricity Market and Network Operation in Southeast Europe” (EKC & EIHP, 2021), which predicts a compound annual growth rate (CAGR) of 3.53%.

Long-Term Assessment of CO₂ Price Trends

In addition to projecting the development of wholesale electricity prices for the purposes of the economic analysis, this study also carried out a long-term assessment of carbon dioxide (CO₂) emission prices, i.e., the prices of emission allowances under the EU ETS (European Union Emissions Trading System - EUA). The assessment is based on the conclusions published in the European Commission's “Economic Appraisal Vademecum 2021–2027” (European Commission, 2021), which provides guidance for economic analysis and projections of key parameters for the European Union's decarbonisation and climate policies.

CAPEX and OPEX Costs Assessment

The assessment of capital (CAPEX) and operating (OPEX) costs is based on the data and findings obtained from several international sources, including the results from the study “Renewable Power Generation Costs in 2022” (IRENA, 2023), the report “The Levelized Cost of Electricity: Renewable Energy Technologies” (Kost et al., 2021), the publication “Lazard's Levelized Cost of Energy Analysis - Version 17.0” (Lazard, 2024) and the public document “Annual Technology Baseline: Commercial PV” (NREL, 2024).

The cost calculation is based on systems comparable in their function and technical characteristics to commercial photovoltaic power plants installed on building roofs. The key difference, however, lies in panel installation (i.e., in the construction solutions for their mounting). For rooftop installations, the substructure requires a larger number of elements and more complex installation work, resulting in slightly higher investment costs than for solutions in which the photovoltaic modules are attached directly to the noise barrier structure.

According to the literature, construction costs for typical rooftop systems account for roughly 10 to 15 % of the total investment value of the project (Lugo-Laguna et al., 2021; International Energy Agency, 2021). Against this background, total capital costs are estimated by reducing the assumed reference CAPEX values by 12.5 % per unit of installed capacity.

In the literature, the capital costs of photovoltaic systems are usually expressed as an average value per unit of installed PV system capacity, typically in USD or EUR per kilowatt (EUR/kW) (Sens et al., 2022). The aforementioned studies analyse the investment costs for commercial PV projects with technical characteristics similar to those considered in this study. Based on the

analysis of the available data, the value of the capital costs was assumed to be EUR 1,385.00/kW of the installed photovoltaic system capacity.

As such, total CAPEX values were defined for two typical cases:

- Immediate Solution (Variant A) under an installed output of $R_{inst} = 1,760 \text{ W}$ - total investment costs estimated to be EUR 2,438.00.
- Extended solution (Variant B) under an installed output of $R_{inst} = 2,640 \text{ W}$ - total investment costs estimated to be EUR 3,656.00.

Operation and maintenance costs (OPEX) are usually expressed as the average annual cost per unit of the power output of the installed PV generator (measured in direct current - DC) and in USD or EUR/kW per year (Muñoz-Cerón et al., 2018). According to the data provided in the studies noted above, a recent observable trend towards decreasing OPEX costs has occurred due to technological improvements and increasing automation of maintenance processes. Taking into account the particularities of the placement and distribution of photovoltaic panels along roads, which complicate access and increase demands on operational logistics, it is assumed that the annual operating and maintenance costs amount to EUR 17/kW of the total installed capacity. This estimate includes all system costs for regular and extraordinary maintenance, including specific logistics costs resulting from the installation location.

Based on these assumptions, the following annual values for operating and maintenance costs were determined:

- Immediate Solution (Variant A) under an installed output of $R_{inst} = 1,760 \text{ W}$ - the annual operating and maintenance costs are estimated to be EUR 29.9
- Extended Solution (variant B) under an installed output of $R_{inst} = 2,640 \text{ W}$ - the annual operating and maintenance costs are estimated to be EUR 44.9.

Evaluation Period

The construction of a photovoltaic power plant requires a high initial investment while the benefits generated by the project only appear over a longer period of time. Therefore, one of the most important parameters in investment evaluation is the selection of an appropriate time horizon, as it bears a significant impact on the results of the financial analysis.

The reference period recommended by the Ministry of Finance of the RS for analysing investment projects is between 15 and 25 years, which accords with the European Commission's guidelines for the energy sector (European Union, 2014). As such, a time horizon of 20 years was assumed for the purposes of the financial and economic analysis.

Dynamics and Uncertainty of Cost-Benefit Assessment

As a matter of course, the operation of photovoltaic solar power plants is subject to degradation effects that affect system efficiency, leading to increased operating costs (e.g., equipment amortization and technical failures). These undesirable events cause additional maintenance costs, the extent of which depends on the type and severity of the failures, as well as the complexity of the interventions required to restore the functionality of the system.

In the economic analysis, it is most crucial to evaluate the expected benefits (i.e., the avoided costs) in the power plant's operating modes by accounting for potential errors and deviations in the calculations. Two basic assumptions, based on experience with similar projects, are defined to incorporate the effects of uncertainties and risks associated with the operation of the model power plant. The first is the occurrence of plant failures, which is accounted for by projecting increased operating and maintenance costs. The second is the benefit reduction from the power-generation degradation. According to the manufacturer, total production is expected to be

reduced by 2% in the first year of operation, followed by an average annual degradation rate of 0.55% in subsequent years.

Discount Rate

Reflecting the capital costs, alternative investment opportunity costs, and project-specific risks, the discount rate is one of the most important parameters in financial analysis, as it is used to discount future cash flows to their current value. For the purposes of this analysis, the nominal social discount rate was 7%, as recommended by the Ministry of Finance of the RS. To obtain a real discount rate, the nominal value was corrected using the Fisher formula (Doan Van, 2020), taking into account anticipated inflation (IMF, 2024).

Macroeconomic Factors: Forecasting the Average Inflation Rate

The strong inflationary pressures present since 2021 began to ease at the end of 2023. According to projections by the National Bank of Serbia, a gradual slowdown in interannual inflation is projected, which will approach the central value of the target corridor of $3\% \pm 1.5\%$ by the end of 2026. In the medium term, inflation should remain within the target corridor due to RS's restrictive monetary policy, stabilization of short and medium-term inflation expectations, a decline in import inflation, and a decline in crude oil prices in line with shifts in the futures market. In addition, expected wage growth, aligned with productivity growth, might contribute to a further decline in core inflation, which would ensure its long-term convergence with headline inflation. Considering all these factors, Table 4 presents a summary of all pertinent input data used in the financial and economic analysis of the project under consideration.

Table 4. A Summary of all input data, macroeconomic and other parameters

Parameter	Value	Source / Note
Total losses	14%, Coefficient of useful effect: 0.86	Authors' calculation; Shakeel and Mokheimer, 2022; Ryan et al., 2016
Mean annual global horizontal radiation	1,600 kWh/m ²	World Bank Group and Solargis, 2024
Installed power: Immediate Solution (Variant A)	1,760 W (1.76 kW)	Authors' calculation
Installed power: Extended Solution (Variant B)	2,640 W (2.64 kW)	Authors' calculation
Annual electrical production - Variant A (maximum)	2,110.8 kWh	Authors' calculation
CAPEX (Immediate Solution A)	Pinst = 1.760 W, 2.438,0 EUR	Authors' calculation
CAPEX (Extended Solution B)	Pinst = 2,640 W, 3,656 EUR	Authors' calculation
OPEX Annual (Immediate Solution A)	Pinst = 1,760 W, 29.90 EUR	Authors' calculation
OPEX Annual (Extended Solution B)	Pinst = 2,640 W, 44.90 EUR	Authors' calculation
Project evaluation period	20 years	The Ministry of Finance - RS, European Union, 2014
Discount rate	7.0%	Authors' calculation
Wholesale price el. energy - CAGR projection (2025–2045)	3.53%	EKC & EIHP, 2021

Parameter	Value	Source / Note
Emission price of CO ₂ permits	European Commission Document, 2021	Economic Appraisal Vademecum 2021-2027
Inflation rate	3.0%	Authors' calculation, NBS, IMF
Excise duty on electricity	7.50%	Ministry of Finance, RS
Corporate income tax	15%	Ministry of Finance, RS
Value Added Tax (VAT)	20%	Ministry of Finance, RS

Source: Authors

RESULTS

Based on the case characteristics examined and selected, both financial and economic analyses were carried out for all eight defined directions of panel placement. A comparative financial analysis of both the immediate and extended solutions (Variants A and B) clearly indicates that Variant B is more viable and acceptable. Although both have their own limitations, the results for Variant B yield significantly better financial ratios in all key aspects: Net Present Value (NPV), Internal Rate of Return (IRR) and Payback Period (PBP). With Variant A, most alignments yield negative results for all indicators analysed. Not only is the net present value (NPV) below zero, indicating clear losses, but the internal rate of return (IRR) also remains negative or minimally positive for the majority of directions. Therefore, investments in A would not achieve a satisfactory return. The payback period (PBP) is also largely undefined, except for the directions of South, Southeast and Southwest, which, exceeding 15 years, are relatively long. Furthermore, Variant B delivers significantly better results, with three directions being distinctive: south, southwest and southeast. These alignments achieve a positive net present value (NPV) and a higher internal rate of return (IRR), solidifying their financial viability. In addition, the payback period is acceptable at 13 and 14 years, making these the most promising options.

Table 5. A comparative financial analysis of Variants A and B

Direction	Immediate Solution (Variant A)				Extended Solution (Variant B)			
	CBA	NPV (EUR)	IRR	PBP	CBA	NPV (EUR)	IRR	PBP
North	0.28	-2,168.83	-11.34%	n/a	0.52	-2,415.00	-4.90%	n/a
Northeast	0.48	-1,702.09	-5.69%	n/a	0.69	-1,813.42	-2.03%	n/a
Northwest	0.47	-1,721.36	-5.86%	n/a	0.69	-1,822.72	-2.07%	n/a
East	0.81	-918.51	-0.33%	n/a	1	-721.12	1.89%	17.1
West	0.83	-883.65	-0.14%	n/a	1.01	-667.73	2.05%	16.86
South	1.14	-129.25	3.46%	15,05	1.32	443.42	5.18%	13.14
Southeast	1.06	-330.09	2.58%	16,16	1.24	130.57	4.36%	14.02
Southwest	1.09	-266.93	2.86%	15,79	1.26	208.24	4.56%	13.79

Source: Authors' calculation

A comparative financial analysis of Variants A and B strongly indicates that Variant B performs significantly better across all key indicators: Cost-Benefit Ratio (CBA), Net Present Value (NPV), Internal Rate of Return (IRR) and Payback Period (PBP). Variant B offers higher returns and a shorter payback period for the investment. While certain directions, such as south, southwest and southeast, provide solid results for Variant A, the extended Variant B significantly improves their profitability. The best directions for both variants are facing south, southwest and southeast. However, Variant B achieves both higher net profits and internal rates of return with shorter payback periods on investments. Facing south is the most profitable option, offering the highest

returns and fastest recovery of the invested capital. Further, the most attractive investment options would be for placement to the south-west and south-east, as these also achieve excellent results.

Table 6. A comparative economic analysis of Variants A and B

Direction	Immediate Solution (Variant A)				Extended Solution (Variant B)			
	CBA	NPV (EUR)	IRR	PBP	CBA	NPV (EUR)	IRR	PBP
North	0.94	-616.01	1.45%	17.91	1.72	1,838.06	8.11%	11.17
Northeast	1.59	923.2	7.18%	11.88	2.27	3,821.92	11.77%	8.88
Northwest	1.56	859.67	6.98%	12.04	2.26	3,791.28	11.72%	8.91
East	2.68	3,507.30	14.15%	7.74	3.29	7,424.10	17.44%	6.5
West	2.73	3,622.24	14.42%	7.63	3.33	7,600.19	17.70%	6.41
South	3.77	6,110.11	19.92%	5.75	4.36	11,264.52	22.79%	5.06
Southeast	3.49	5,447.78	18.52%	6.16	4.07	10,232.82	21.40%	5.37
Southwest	3.58	5,656.07	18.96%	6.03	4.15	10,488.95	21.75%	5.29

Source: Authors' calculation

As indicated in the comparative economic analysis, the majority of solutions (for both Variants A and B) meet the cost-efficiency criteria where wider social and environmental benefits are taken into account. In particular, all southern-oriented configurations (i.e., south, south-east and south-west) provide satisfactory, potentially profitable results. Furthermore, both the financial and economic analyses indicate that the best results are achieved with the southern direction of Variant B.

The results of the economic-financial analysis clearly demonstrate that investment in the installation of photovoltaic systems is profitable. To achieve maximum economic profitability, the panels should be installed facing south, south-west or south-east, as these are the most cost-effective orientations, offering the most favourable benefit-cost ratio, the highest net present value (NPV), a higher internal rate of return (IRR) and the shortest payback period for the initial investment.

In contrast to Variant A, Variant B proves to be substantively more efficient and cost-effective, as it achieves significantly higher revenues and better economic indicators, including positive NPV values and higher returns. Although the costs of Variant B are slightly higher, they are fully justified by the higher financial return and the shorter time required to repay the funds invested.

CONCLUSIONS AND LIMITATIONS

The analyses conducted to provide economic justification for the installation of PVNB on noise barriers in the RS clearly point to the significant potential of such systems to improve the energy efficiency and sustainability of infrastructure projects. By integrating noise reduction and electricity generation from renewable sources, PVNB systems deliver multiple benefits, both in terms of environmental protection and economic viability.

Both the economic and financial analyses demonstrate that the extended technical solution (Variant B), which includes additional solar modules placed at an optimal angle, achieves substantively better results across the main financial indicators: Net Present Value (NPV), Internal Rate of Return (IRR) and Payback Period of Investment (PBP). The directions of south, south-east and south-west stand out, as they ensure not only maximum electricity production but also the most favourable cost-benefit ratio. Although Variant B requires a higher initial investment compared to Variant A, its economic advantages fully justify the increased expenditure.

Taking into account the forecasts for wholesale electricity prices and CO₂ emission costs, the PVNB systems in the configurations analysed were confirmed to be able to contribute to the long-term sustainability of investment projects, and their implementation bears the potential to provide investors with direct financial benefits. Moreover, by reducing harmful gas emissions and improving environmental quality, the installation of these systems promotes broader social and environmental benefits.

Based on the conclusions drawn, the future development and application of PVNB technologies is fully recommended in the planning and implementation of infrastructure projects in the RS. This includes pilot-project implementation, the development of internal standards and norms for planning and construction, as well as financial-support models and incentives to create the conditions necessary for wider implementation.

Due to the scope and methodology of this study, certain economic factors were included as a matter of course but should be considered in future studies. This study does not account for unforeseen overheads resulting from third-party losses in infrastructure development, which could increase CAPEX as well as extend PBP. While this factor is outside the purview of this study, it should receive attention where relevant to provide a more comprehensive estimate of total cost. Furthermore, the study does not include an impact analysis of how this would affect electrical production within the wider grid, including integration costs and potential contributions to system load, which could have a net positive impact on lowering electrical prices.

ACKNOWLEDGEMENTS

This paper is a result of research financed by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia, under contract number 451-03-33/2026-03.

REFERENCES

- Belsky, A. A., Glukhanich, D. Y., Carrizosa, M. J., & Starshaia, V. V.** (2022). Analysis of specifications of solar photovoltaic panels. *Renewable and Sustainable Energy Reviews*, 159, 112239. <https://doi.org/10.1016/j.rser.2022.112239>
- De Schepper, E., Van Passel, S., Manca, J., & Thewys, T.** (2012). Combining photovoltaics and sound barriers—A feasibility study. *Renewable energy*, 46, 297-303.
- Doan Van, D.** (2020). Money supply and inflation impact on economic growth. *Journal of Financial Economic Policy*, 12(1), 121-136.
- Đuričin, S., Savić, S., Bodroža, D., Cvijanović, G., & Đorđević, S.** (2016). Posledice klimatskih promena na menadžment voda u poljoprivredi: Izazov za povećanje produktivnosti useva u Srbiji. *Ekonomika poljoprivrede*, 63(4), 1333-1346. DOI: [10.5937/ekoPolj1604333D](https://doi.org/10.5937/ekoPolj1604333D)
- EKC & EIHP** (2021). *Assessment of the impacts of high levels of decarbonization and clean energy on the electricity market and network operation in Southeast Europe*. Prepared for the United States Agency for International Development and the United States Energy Association. Cooperative Agreement AID-OAA-A-12-00036.
- Eren, B., Likos, S., & Çelebi, A.** (2024). Effectiveness of noise barriers in sensitive urban areas: a comprehensive study on noise reduction strategies and public health implications. *Environmental Science and Pollution Research*, 31(50), 60093-60107.
- European Commission** (2021). *Economic appraisal vademecum 2021-2027: General principles and sector applications*. Luxembourg: Publications Office of the European Union. <https://doi.org/10.2776/182302>
- European Commission, Joint Research Centre.** (2025). *Photovoltaic geographical information system (PVGIS)*. Retrieved March 19, 2025, from https://joint-research-centre.ec.europa.eu/photovoltaic-geographical-information-system-pvgis_en
- European Union.** (2014). *Commission delegated regulation (EU) No 480/2014 of 3 March 2014*

supplementing Regulation (EU) No 1303/2013 of the European Parliament. Official Journal of the European Union, L 138, 30.4.2014, p. 5–52. <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014R0480&from=EN>

- Faturrochman, G. J., de Jong, M. M., Santbergen, R., Folkerts, W., Zeman, M., & Smets, A. H. M. (2018).** Maximizing annual yield of bifacial photovoltaic noise barriers. *Solar Energy*, 162, 300–305. <https://doi.org/10.1016/j.solener.2018.01.001>
- Gajović, A., Bjelica, D., Pavlović, D., & Vukmirović, D. (2023).** Educating youth on project sustainability: Project engagement and recognition of the Green Deal. *Applied Ecology and Environmental Research*, 21(4), 2969–2989. https://doi.org/10.15666/aeer/2104_29692989
- Goetzberger, A., & Hoffmann, V. (2005).** *Photovoltaic solar energy generation*. Springer. <https://doi.org/10.1007/b138657>
- Gu, M., Liu, Y., Yang, J., Peng, L., Zhao, C., Yang, Z., Yang, J., Fang, W., Fang, J., & Zhao, Z. (2012).** Estimation of environmental effect of PVNB installed along a metro line in China. *Renewable Energy*, 45, 237–244. <https://doi.org/10.1016/j.renene.2012.02.021>
- Hasmaden, F., Zorer Gedik, G., & Yüğrük Akdağ, N. (2022).** An approach to the design of photovoltaic noise barriers and a case study from Istanbul, Turkey. *Environmental Science and Pollution Research*, 29(22), 33609–33626.
- International Energy Agency. (2021).** *Utility-scale PV investment cost structure by component and by commodity breakdown*. Based on NREL (2020), IRENA (2020), and BNEF (2021c).
- International Monetary Fund. (2024).** *World Economic Outlook, October 2024*. <https://www.imf.org/-/media/files/publications/weo/2024/october/english/text.pdf>
- IRENA. (2023).** *Renewable power generation costs in 2022*. International Renewable Energy Agency, Abu Dhabi.
- Jovanović, M., Bakić, V., Škobalj, P., Cvetinović, D., Erić, A., Živković, N., & Duić, N. (2023).** Scenarios for transitioning the electricity sector of the Republic of Serbia to sustainable climate neutrality by 2050. *Utilities Policy*, 85, 101681.
- Kanellis, M., de Jong, M.M., Slooff, L., Debije, M.G. (2017).** The solar noise barrier project: 1. Effect of incident light orientation on the performance of a large-scale luminescent solar concentrator noise barrier. *Renew. Energy* 103, 647–652.
- Kost, C., Shammugam, S., Fluri, V., Peper, D., Davoodi Memar, A., & Schlegl, T. (2021).** *Levelized cost of electricity: Renewable energy technologies*. Fraunhofer Institute for Solar Energy Systems ISE.
- Lazard. (2024).** *Levelized cost of energy+, levelized cost of storage, and levelized cost of hydrogen* [Report]. Lazard Power, Energy & Infrastructure Group.
- Lugo-Laguna, D., Arcos-Vargas, A., & Nuñez-Hernandez, F. (2021).** A European Assessment of the Solar Energy Cost: Key Factors and Optimal Technology. *Sustainability*, 13(6), 3238. <https://doi.org/10.3390/su13063238>
- Luxor Solar. (2025).** *ECO LINE half-cell modules*. Retrieved March 18, 2025, from <https://www.luxor.solar/en/solar-modules/eco-line/eco-line-half-cell.html>
- Mehrabi, R. (2023).** Systematic literature review of sustainable finance: Implications for entrepreneurial finance through venture capitals (VC). *Economic Analysis: Applied Research in Emerging Markets*, 56(2), 68–83. <https://doi.org/10.28934/ea.23.56.2.pp68-83>
- Muñoz-Cerón, E., Lomas, J. C., Aguilera, J., de la Casa, J. (2018).** Influence of Operation and Maintenance expenditures in the feasibility of photovoltaic projects: The case of a tracking pv plant in Spain. *Energy policy*, 121, 506–518.
- National Bank of Serbia. (2024).** *Inflation Report - November 2024*. https://www.nbs.rs/export/sites/NBS_site/documents-eng/publikacije/ioi/izvestaji/inflation_report_11_2024.pdf
- National Renewable Energy Laboratory (NREL). (2024).** *Annual technology baseline: Commercial PV*. U.S. Department of Energy. https://atb.nrel.gov/electricity/2024/commercial_pv
- Nordmann, T., & Goetzberger, A. (1994).** Motorway sound barriers: Recent results and new

concepts for advancement of technology. *Solar Energy Materials and Solar Cells*, 33(1-4), 451–457. [https://doi.org/10.1016/0927-0248\(94\)90087-6](https://doi.org/10.1016/0927-0248(94)90087-6)

- Pascale, A., Fernandes, P., Guarnaccia, C., & Coelho, M. C.** (2021). A study on vehicle Noise Emission Modelling: Correlation with air pollutant emissions, impact of kinematic variables and critical hotspots. *Science of the Total Environment*, 787, 147647.
- Ryan, L., Dillon, J., La Monaca, S., Byrne, J., & O'Malley, M.** (2016). Assessing the system and investor value of utility-scale solar PV. *Renewable and Sustainable Energy Reviews*, 64, 506–517. <https://doi.org/10.1016/j.rser.2016.06.004>
- Sens, L., Neuling, U., & Kaltschmitt, M.** (2022). Capital expenditure and levelized cost of electricity of photovoltaic plants and wind turbines–Development by 2050. *Renewable Energy*, 185, 525-537.
- Shakeel, M. R., & Mokheimer, E. M. A.** (2022). A techno-economic evaluation of utility scale solar power generation. *Energy*, 261(Part A), 125170. <https://doi.org/10.1016/j.energy.2022.125170>
- Soares, L., & Wang, H.** (2023). Design Study and Potential Implementation of Photovoltaic Noise Barriers for Sustainable Highways. *Transportation Research Record*, 2678(3), 855-864. <https://doi.org/10.1177/03611981231182977>
- Southeast Europe Cooperation Initiative (SECI).** (2017). *SEE electricity market perspectives until 2030: Assessing the impact of regional connections to Italy – Final report*. Prepared for the United States Agency for International Development and the United States Energy Association. Cooperative Agreement AID-OAA-A-12-00036.
- Wadhawan, S.R., Pearce, J.M.** (2017). Power and Energy potential of mass-scale photovoltaic noise barrier deployment: A case study for the U.S. *Renew. Sustain. Energy Rev.* 80, 125–132
- World Bank Group & Solargis.** (2024). *Global solar atlas: Serbia*. International Finance Corporation. <https://globalsolaratlas.info/download/serbia>
- World Bank.** (2023). *Financial and economic analysis: Differences and similarities*. World Bank. <https://documents1.worldbank.org/curated/en/099093024122526452/pdf/P179103-ce55a292-c282-4136-b911-b0b1e66d7ad5.pdf>
- Zdravković, A., Bodroža, D., Kolavčić, M., Jovičić, E., Pavlović, D., & Sekulić, D.** (2024). The economic development effects on freshwater abstraction from the European perspective. *Economic of Agriculture*, 71(1), 155–172. <https://doi.org/10.59267/ekoPolj2401155Z>

Article history:	Received: 10.2.2026.
	Revised: 15.4.2026.
	Accepted: 8.5.2026.