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Faculty of Energy Technology
Hočevarjev trg 1, 8270 Krško, Slovenia
Koroška cesta 62a, 3320 Velenje, Slovenia
e-mail: jet@um.si
<https://www.fe.um.si>

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Dear Readers of the Journal of Energy Technology (JET)

JURIJ AVSEC

Editor-in-chief of JET

Energy engineering has always been linked closely to the development of science, technology and society. Today, however, we are facing increasingly complex energy challenges that can no longer be addressed within the boundaries of a single scientific or engineering discipline. The transition towards a low-carbon society, ensuring a reliable energy supply and improving energy efficiency, all require the integration of knowledge and experience from different fields.

The boundaries between mechanical engineering, electrical engineering, thermodynamics, mechanics, chemistry, physics, materials science, environmental science, biology and computer science are therefore becoming increasingly blurred. While different areas of energy engineering were once often considered relatively independently, today, electricity, heat, fuels, energy storage and energy management can hardly be addressed in isolation.

Modern energy technologies demonstrate this development clearly. Hydrogen technologies, for example, bring together electrochemistry, thermodynamics, biology, materials science, process engineering and electrical power engineering. The development of batteries and other energy storage technologies requires close

cooperation between chemistry, physics, materials science and electrical engineering. Nuclear energy integrates nuclear physics, thermodynamics, mechanics, materials science and safety engineering, while the efficient use of thermal energy requires a thorough understanding of heat transfer, thermodynamics, fluid mechanics and control engineering.

Digital technologies are becoming increasingly important across all these fields. Artificial intelligence, digital twins, numerical modelling, advanced control systems and the analysis of large amounts of data, are transforming the way energy systems are designed, operated and managed. Energy engineering is thus becoming a field in which the physical and digital worlds are interconnected increasingly.

Interdisciplinarity, however, means more than simply bringing together experts from different fields to work on the same problem. Its true value emerges when their knowledge, methods and perspectives interact genuinely. It is precisely at the interfaces between disciplines that some of the most interesting research ideas and innovative technological solutions emerge.

This perspective is also important to the mission of the Journal of Energy Technology – JET. Energy engineering is, by its very nature, a broad and integrative field. Through JET, we aim to provide a platform for research that reaches beyond traditional disciplinary boundaries and brings together different scientific and engineering approaches.

The future of energy will not be determined by a single technology or a single scientific discipline. It will be shaped by our ability to integrate different areas of knowledge – from fundamental physical principles and advanced materials to innovative energy technologies and artificial intelligence. It is at these intersections that the solutions will emerge to the energy challenges of the future.

I am therefore particularly pleased that the present issue brings together research and professional achievements from a variety of fields within energy engineering. By presenting different perspectives and approaches, these contributions offer the attentive reader a broader and more comprehensive view of current developments in the energy sector. I wish all our readers an interesting and inspiring reading of this issue of JET.

Spoštovani bralci revije Journal of Energy Technology (JET)

Energetika je bila vedno tesno povezana z razvojem znanosti, tehnologije in družbe. Danes pa se srečujemo z energetskimi izzivi, ki postajajo vse bolj kompleksni in jih ni več mogoče reševati znotraj meja ene same znanstvene ali inženirske discipline. Prehod v nizkoogljično družbo, zagotavljanje zanesljive oskrbe z energijo ter povečevanje energetske učinkovitosti zahtevajo povezovanje znanj in izkušenj z različnih področij.

Meje med strojništvom, elektrotehniko, termodinamiko, mehaniko, kemijo, fiziko, znanostjo o materialih, okoljevarstvom, biologijo in računalništvom zato postajajo vse manj izrazite. Če smo nekoč posamezne dele energetike pogosto obravnavali razmeroma ločeno, danes električne energije, toplote, goriv, shranjevanja energije in njihovega upravljanja skoraj ne moremo več obravnavati neodvisno.

To nazorno kažejo sodobne energetske tehnologije. Vodik na primer povezuje elektrokemijo, termodinamiko, biologijo, materiale, procesno tehniko in elektroenergetiko. Razvoj baterij in drugih hranilnikov zahteva sodelovanje kemije, fizike, materialov in elektrotehnike. Jedrska energetika tako povezuje jedrsko fiziko, termodinamiko, mehaniko, materiale in varnostne vede, medtem ko učinkovita raba toplote zahteva dobro poznavanje prenosa toplote, termodinamike, fluidne mehanike in regulacije.

Tem področjem se danes vse intenzivneje pridružujejo digitalne tehnologije. Umetna inteligenca, digitalni dvojčki, numerično modeliranje, napredna regulacija in analiza velikih količin podatkov spreminjajo način načrtovanja in upravljanja energetskih sistemov. Energetika tako postaja področje, kjer se fizični in digitalni svet vse tesneje povezujeta.

Interdisciplinarnost pa ne pomeni zgolj tega, da pri istem problemu sodelujejo strokovnjaki različnih področij. Njena prava vrednost se pokaže takrat, ko se njihova znanja, metode in pogledi dejansko prepletajo. Prav na stičiščih disciplin pogosto nastajajo najzanimivejše raziskovalne ideje in nove tehnološke rešitve.

Takšen pogled je pomemben tudi za poslanstvo revije *Journal of Energy Technology – JET*. Energetika je po svoji naravi široko in povezovalno področje, zato želimo v reviji ustvarjati prostor za raziskave, ki presegajo tradicionalne meje posameznih disciplin ter povezujejo različne znanstvene in inženirske pristope.

Prihodnosti energetike namreč ne bo določala ena sama tehnologija ali ena sama znanstvena disciplina. Oblikovala jo bo sposobnost povezovanja različnih znanj – od temeljnih fizikalnih zakonitosti in novih materialov do naprednih energetskih tehnologij in umetne inteligence. Prav na teh stičiščih bodo nastajale rešitve za energetske izzive prihodnosti.

Veseli me, da so v sedanjí številki predstavljene raziskovalni in strokovni dosežki iz različnih področij energetike, ki dajejo pozornemu bralcu celovitejši pogled na razvoj energetike. Vsem želim zanimivo branje revije JET.

Original
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OPTIMIZATION-BASED TECHNO-ECONOMIC ASSESSMENT OF ONSHORE WIND TURBINES UNDER UNCERTAINTY IN SLOVENIA

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DAVID TIAN HREN, ZORKA NOVAK PINTARIČ,
ANDREJA NEMET

University of Maribor, Faculty of Chemistry and Chemical Engineering, Maribor,
Slovenia
david.hren@um.si, zorka.novak@um.si, andreja.nemet@um.si

CORRESPONDING AUTHOR
david.hren@um.si

Abstract Renewable energy systems require site-appropriate technology selection to ensure both high energy production and economic viability. This study developed a general optimization-based techno-economic framework for assessing onshore wind turbine configurations, and applied it to nine representative locations in Slovenia, optimizing hub height, rotor diameter, and rated power using annual energy production, net present value (NPV), levelized cost of energy (LCOE), and a weighted combined objective. The selected configurations were evaluated through deterministic sensitivity analysis and Monte Carlo simulation, to assess the uncertainty in the wind resource, technical, and economic parameters. Maximizing energy production alone produced oversized and economically inefficient configurations, whereas optimization based on the economic objectives (NPV and LCOE) yielded smaller turbines, and the combined-objective formulation provided a more balanced trade-off. Wind resource quality, electricity price, capital expenditure, and discount rate were the principal determinants of profitability, while favorable deterministic outcomes did not always remain economically robust under uncertainty.

Keywords
renewable energy,
onshore wind energy,
wind turbine
optimization,
techno-economic
assessment,
uncertainty analysis

1 Introduction

Renewable energy technologies have evolved from niche alternatives to central components of modern power systems, driven by concerns about energy security, fuel price volatility, and long-term environmental sustainability (Anderson, 2020). Renewable sources such as solar, wind, hydro, biomass, and geothermal energy offer long-term sustainability, because they are replenished naturally and have relatively low environmental impact during operation. However, integrating these sources into existing energy systems involves not only technical challenges, but also economic viability, spatial constraints, and societal acceptance (Biluš et al., 2025). Among these technologies, wind power has emerged as one of the most mature and economically competitive options, supported by rapid technological development and large-scale deployment (Anderson, 2020). By 2050, wind power is projected to supply over 30 % of global electricity, with the potential to reduce CO₂ emissions by up to 14,871 million tons annually, equivalent to China's total emissions in 2021 (Long et al., 2023). Unlike traditional energy systems, wind turbines depend directly on the available resource, resulting in inherently variable and non-dispatchable power output. Most contemporary designs are horizontal-axis turbines with three blades, optimized for efficiency and reliability (Manwell et al., 2009). Their design and operation involve complex interactions between aerodynamic forces, structural loading, control systems, and electrical integration (Anderson, 2020).

The development and widespread adoption of wind farms as a promising source of electrical energy worldwide require an appropriate balance between aerodynamic efficiency, structural integrity, economic viability, spatial limitations, and environmental restrictions (Tahtah et al., 2023). Numerous factors must be evaluated to achieve a design that provides an appropriate trade-off between performance and cost, while considering various other constraints that make the specific design solution viable from all the relevant perspectives (Bottasso et al., 2012). Structurally, turbine design is governed by the need to provide sufficient support for the rotor–nacelle assembly, while elevating the rotor to heights with stronger and more stable wind resources. The design must account for multiple load types, including aerodynamic thrust from the rotor, wind loads acting on the tower, and gravitational loads from the structure and equipment (Alves Ribeiro et al., 2025). Increasing the size of wind turbines introduces a fundamental trade-off between energy production and structural and economic limitations. While the energy

captured by a turbine increases approximately with the square of its characteristic size due to the larger swept area, structural loads, mass, and associated stresses tend to increase with the cube, or even higher powers of scale. This results in increasingly demanding design conditions, particularly because weight-induced stresses become dominant as turbines grow larger (Sieros et al., 2012).

Performance and economic viability are influenced strongly by a combination of technical and financial parameters, with uncertainty playing a central role in project assessment. The most critical factor is the average wind speed, which has a dominant impact on energy production due to its nonlinear relationship with the power output. Turbine-related parameters such as the power curve and air density also affect performance significantly, while the wake effects play a comparatively smaller role in this context. On the economic side, parameters such as electricity price, installation cost, and discount rate determine profitability largely, with the net present value (NPV) being highly sensitive, because it captures the difference between large cash inflows and outflows (Afanasyeva et al., 2016). Wind turbine optimization therefore requires careful selection of the objective functions, since different choices can lead to fundamentally different and often suboptimal designs. Maximizing the annual energy production (AEP) alone is insufficient, because many geometrically different turbines can achieve nearly identical energy output while having significantly different structural mass, leading to inefficient designs (Ning et al., 2014). A multidisciplinary design optimization framework that incorporates both energetic and economic criteria is needed for an accurate assessment (Ashuri et al., 2016).

In Slovenia, the development of wind energy is shaped by a relatively constrained spatial and environmental context. Although the country has several areas with favorable wind conditions, especially in elevated and topographically exposed regions, Slovenia is not among the most wind-rich European countries due to its sheltered position relative to the Alps (Biluš et al., 2025). The largest wind energy potential is concentrated in selected mountainous, hilly, and karst regions, including parts of the Julian Alps, Karavanke, Kamnik–Savinja Alps, Pohorje, Kočevski Rog, Snežnik–Javorniki–Hrušica, Podgorski Kras, Slavnik, Nanos, Trnovski gozd, and Banjšice (Biluš et al., 2025; Republika Slovenija, Ministrstvo za infrastrukturo, 2015). However, many wind-suitable areas overlap with Natura 2000 sites, protected landscapes, cultural heritage zones, forests, water protection areas, or settlement-

related restrictions, which limits the practical spatial availability for wind turbine deployment substantially. The Slovenian national spatial assessment therefore defines potential wind energy areas not only according to wind resource criteria, but also according to environmental protection, legal restrictions, and distances from settlements, including the exclusion of areas less than 800 m from settlements (Republika Slovenija, Ministrstvo za infrastrukturo, 2015). Consequently, despite the existence of technically promising locations, wind energy deployment in Slovenia remains limited, and requires careful site-specific assessment of the measured wind conditions, environmental acceptability, spatial feasibility, and economic justification (Biluš et al., 2025; Republika Slovenija, Ministrstvo za infrastrukturo, 2015). Accordingly, this study aims to evaluate the technical and economic performance of onshore wind turbine configurations at selected Slovenian locations under uncertainty, and to identify the most favorable locations and turbine configurations.

The paper is organized as follows. Section 2 presents the model formulation and optimization framework, including the definition of turbine design variables and constraints, Weibull-based wind resource characterization, hub height wind speed correction, turbine power estimation, annual energy production calculation, and economic evaluation. Section 3 describes the computational workflow used for the selected Slovenian wind energy areas, including area-specific wind resource parameters, deterministic optimization, sensitivity analysis, and a Monte Carlo uncertainty analysis. Section 4 presents the results of the deterministic optimization, sensitivity analysis, and uncertainty assessment, comparing the selected areas and turbine configurations in terms of energy production, economic performance, financial risk, and robustness under uncertain input parameters. Section 5 discusses the main findings and study limitations, while Section 6 summarizes the conclusions, identifies the most favorable locations and turbine configurations, and outlines directions for future work.

2 Model Formulation and Optimization Framework

This section presents the mathematical model used for the techno-economic assessment of wind turbine configurations. The model combines wind speed distribution modeling, hub height correction, turbine power estimation, annual energy production calculation, and economic evaluation.

2.1 Design Variables and Constraints

The wind turbine design is defined by three continuous variables: hub height, rotor diameter, and rated power. These variables determine the overall size of the turbine and affect the available wind resource, swept rotor area, maximum electrical output, investment cost, and economic performance directly. The limits of the design variables were selected based on the specifications of the existing commercial onshore wind turbines. Specifications from five major manufacturers were reviewed using their respective product documentation (ENERCON, 2026; GE Vernova, 2026; Nordex Group, 2026; Siemens Gamesa Renewable Energy, 2026; Vestas, 2026). The rated powers of the reviewed turbines range from approximately 2.4–7.2 MW. The reviewed commercial turbines also indicate typical rotor diameters of approximately 75–175 m and hub heights of approximately 75–175 m; these ranges were therefore used as the corresponding bounds for the design variables.

An additional ground clearance constraint was included to ensure physically feasible turbine geometries. The minimum distance between the lowest blade tip position and the ground was set to 20 m, preventing unrealistic combinations of low hub height and large rotor diameter. This constraint was calculated as the difference between hub height and rotor radius, so only configurations satisfying the minimum blade-tip clearance were considered feasible. Thus, the optimization design space was restricted to commercially representative and geometrically feasible onshore wind turbine configurations.

2.2 Wind Speed Characterization Using the Weibull Distribution

Wind resource characterization is necessary to estimate the expected energy production of a wind turbine at a selected location (Solari & Losada, 2016). Because wind speed is a stochastic variable, its frequency distribution must be described before the turbine output can be calculated (Loukatou et al., 2018). In this work, the wind resource is represented by a two-parameter Weibull distribution, which is used commonly for long-term wind speed modeling in renewable energy studies (Afanasyeva et al., 2016; Shi et al., 2021; Wais, 2017). The Weibull probability density function is given in Equation (1):

$$f(v) = \frac{k}{A} \left(\frac{v}{A} \right)^{k-1} \exp \left[- \left(\frac{v}{A} \right)^k \right], \quad v \geq 0 \quad (1)$$

where v is the wind speed, A is the Weibull scale parameter, and k is the Weibull shape parameter. The parameter A describes the characteristic wind speed level at the location, while k determines the form and spread of the distribution (Shi et al., 2021). Because wind resource data are usually available at a reference height, they must be adjusted to the selected turbine hub height. This adjustment is made using the power-law wind shear relation (Afanasyeva et al., 2016), shown in Equation (2),

$$A(h) = A_{\text{ref}} \left(\frac{h}{h_{\text{ref}}} \right)^a \quad (2)$$

where h is the turbine hub height, h_{ref} is the reference height, and a is the wind shear exponent. The value of a depends on the terrain roughness and atmospheric conditions, with lower values typical of open terrain and higher values typical of areas with more obstacles (Rasaq, A. K. et al., 2015). In the case study the reference height is 100 m, so A_{ref} corresponds to A_{100} . The parameter k is assumed to remain constant with the height.

The Weibull distribution is divided into discrete wind speed intervals. For each interval, the probability of occurrence is calculated and converted into annual operating hours. These hours are then combined with the turbine power output at the representative wind speed for each interval. This links the location-specific Weibull parameters with the turbine power model and the subsequent economic evaluation.

2.3 Turbine Power Model and Operational Constraints

After the wind speed distribution is adjusted to the hub height, the turbine power output is calculated for each wind speed interval. The model uses a system-level power formulation based on rotor diameter, rated power, power coefficient, drivetrain efficiency, and operational constraints. The aerodynamic power relation

used to estimate the power extracted from the wind passing through the rotor swept area is based on the standard wind turbine power formulation reported by (Castillo et al., 2023), as shown in Equation (3),

$$P_{\text{aero},i} = \eta C_{p,i} P_{\text{wind},i} = \eta C_{p,i} \frac{1}{2} \rho \pi R^2 v_i^3 \quad (3)$$

where $P_{\text{aero},i}$ is the turbine power obtained after accounting for the power coefficient and drivetrain efficiency in the wind speed interval i , $P_{\text{wind},i}$ is the power available in the wind passing through the rotor swept area, v_i is the representative wind speed of interval i , ρ is the air density, R is the rotor radius, $C_{p,i}$ is the power coefficient, and η is the drivetrain efficiency. In the implemented optimization model, this aerodynamic power term is not taken directly as the final turbine output, but is constrained further by the rated power, cut-in and cut-out wind speeds, maximum blade-tip speed, and rated-torque limitations.

The power coefficient $C_{p,i}$ represents the fraction of available wind power extracted by the turbine and is limited by the Betz limit (Bavanish & Thyagarajan, 2013). In the implemented model, $C_{p,i}$ is expressed as a polynomial function of the tip-speed ratio λ_i (González et al., 2010), as shown in Equation (4).

$$C_{p,i} = 0.0344 - 0.0864\lambda_i + 0.1168\lambda_i^2 - 0.0484\lambda_i^3 + 0.00832\lambda_i^4 - 0.00048\lambda_i^5 \quad (4)$$

The maximum value of this function is $C_{p,\text{max}}=0.4764$, which occurs at a tip-speed ratio of approximately 7.33 (González et al., 2010). In the implemented model, the actual value of λ_i is determined from the operating rotor speed, which is limited by the maximum allowable blade-tip speed. Therefore, the turbine is not assumed to operate at the optimal tip-speed ratio under all wind speed conditions. Equation (5) describes the final constrained turbine power output used for the AEP calculation,

$$P_i = \begin{cases} 0, & v_i < v_{\text{ci}} \\ \min(P_{\text{aero},i}, P_r, T_r \omega_i), & v_{\text{ci}} \leq v_i \leq v_{\text{co}} \\ 0, & v_{\text{co}} < v_i \end{cases} \quad (5)$$

where P_i is the final turbine power in the wind speed interval i , P_r is the rated power, T_r is the rated torque, ω_i is the operating rotor speed, v_{ci} and v_{co} are the cut-in and cut-out wind speeds, respectively. In the implemented model, the cut-in speed is 3 m/s and the cut-out speed is 25 m/s. The rotor operation is constrained further by a maximum blade-tip speed of 80 m/s, which prevents unrealistic rotor speeds and reflects the practical operational limitations (Resor et al., 2014). The final power model therefore represents a constrained operational power curve rather than a simple rated-power-limited curve.

2.4 Economic Model

After calculating the AEP, the technical model is integrated with the economic model. The economic model estimates the capital expenditure (CAPEX), annual operating expenditure (OPEX), revenue from electricity sales, and the main economic indicators used to compare different turbine configurations. The capital expenditure is estimated using a component-based cost approach, following the National Renewable Energy Laboratory (NREL) wind turbine cost and scaling model (Fingersh et al., 2006), in which the main turbine and balance-of-system costs are related to the turbine size, rotor diameter, hub height, and rated power. Because the original cost equations are based on older cost data, escalation factors are applied using the producer price index data (Federal Reserve Bank of St. Louis, 2026). In the implemented model, this approach is used to estimate the total capital expenditure for each candidate turbine configuration, while the annual cash flows are evaluated using the electricity revenue, operation and maintenance costs, land lease costs, depreciation, profit tax, and discounted project cash flow. The annual revenue R from electricity sales is calculated using Equation (6),

$$R = p_{el} \cdot AEP \quad (6)$$

where p_{el} is the electricity selling price. The annual operating expenditure includes both operation and maintenance costs and land lease costs. The total annual operating expenditure C_{OPEX} is calculated using Equation (7),

$$C_{OPEX} = (c_{OM} + c_{lease}) \cdot AEP \quad (7)$$

where c_{OM} and c_{lease} are the specific operation and maintenance and land lease costs. The annual after-tax cash flow is calculated by accounting for the operating income, straight-line depreciation, taxable income, and profit tax. The depreciation is calculated over the project lifetime, and is used only for the tax calculation. Negative taxable income is not taxed. The annual after-tax cash flow CF is calculated using Equation (8),

$$CF = R - C_{OPEX} - \tau \cdot \max\left(R - C_{OPEX} - \frac{C_{CAPEX}}{N}, 0\right) \quad (8)$$

where τ is the profit tax rate, N is the project lifetime and C_{CAPEX} is the total capital expenditure. NPV is used to evaluate the lifetime profitability of each turbine configuration, by discounting the uniform annual after-tax cash flow over the project lifetime. It is calculated using Equation (9), where r is the discount rate.

$$NPV = -C_{CAPEX} + CF \cdot \frac{1 - (1 + r)^{-N}}{r} \quad (9)$$

This formulation assumes uniform annual cash flows occurring at the end of each year. The levelized cost of energy (LCOE) is calculated by annualizing the capital expenditure using the capital recovery factor, and adding the annual operating expenditure. It is given by Equation (10).

$$LCOE = \frac{C_{CAPEX} \cdot \frac{r}{1 - (1 + r)^{-N}} + C_{OPEX}}{AEP} \quad (10)$$

3 Model Implementation and Case Study Setup

This section defines the case study setup and computational implementation used to apply the previously described model to selected Slovenian wind energy areas.

3.1 Selected Slovenian Wind Areas and Input Data

Figure 1 shows the selected Slovenian study areas used in the case study, and indicates the wind speed zones above 5.5 m/s and above 7 m/s at 100 m above ground level.

Table 1: Wind resource input parameters for the selected Slovenian study areas

Area	A_{100} [m/s]	k [-]	α [-]
1	7.50	1.89	0.116
2	7.47	1.24	0.128
3	6.42	1.30	0.231
4	8.14	1.62	0.145
5	6.38	1.50	0.230
6	5.46	1.81	0.0566
7	6.65	1.52	0.158
8	7.41	1.50	0.0760
9	7.17	1.41	0.100

3.2 Optimization Module

The optimization was implemented in General Algebraic Modeling System (GAMS) as a nonlinear programming problem. The hub height, rotor diameter, and rated power were treated as continuous design variables within the admissible bounds, and subject to the geometric and operational constraints described in Section 2. The technical and economic equations were formulated directly in GAMS, linking the design variables and wind-resource parameters to the turbine power, AEP, CAPEX, OPEX, NPV, and LCOE. The resulting nonlinear programming problems were solved in GAMS using the CONOPT solver. The same mathematical model was applied to all nine study areas. MATLAB passed the area-specific parameters A_{100} , k , and a to GAMS, where an optimization run was performed for each area. Four optimization problems were considered: maximization of AEP (maxAEP), maximization of NPV (maxNPV), minimization of LCOE (minLCOE), and maximization of a weighted combined objective. Because AEP, NPV, and LCOE have different units and numerical ranges, each criterion was normalized separately for each area, using its corresponding minimum and maximum values before calculating the combined score. The LCOE criterion was inverted during normalization, so that a higher normalized value represented better performance for all three criteria. Weights of 0.15, 0.50, and 0.35 were assigned to AEP, NPV, and

LCOE, respectively, in the combined objective. The greater weight assigned to NPV reflects the emphasis placed on project profitability, while AEP and LCOE account for energy production and cost efficiency, respectively. The combined-objective configuration was obtained by maximizing the resulting weighted score, thereby providing a compromise between energy production, investment profitability, and cost of energy, rather than optimizing any individual indicator exclusively.

The optimization initially treated hub height, rotor diameter, and rated power as continuous variables. To obtain practically interpretable turbine configurations, nearby feasible rounded configurations were evaluated subsequently using the same technical and economic model. The best rounded candidate was selected separately for each optimization case, according to the corresponding objective criterion: highest AEP for maxAEP, highest NPV for maxNPV, lowest LCOE for minLCOE, and highest combined score for the combined objective. The resulting configurations were then used as the basis for the subsequent deterministic sensitivity analysis and Monte Carlo uncertainty analysis.

3.3 Deterministic Sensitivity Analysis

A deterministic sensitivity analysis was performed to evaluate the isolated influence of the selected input parameters on the main economic indicators. In this approach, one input parameter is varied, while all the other parameters remain fixed at their base values. This allows the individual effect of each parameter to be assessed without the interaction effects that occur when several uncertain inputs are varied simultaneously. The sensitivity analysis was conducted for the optimized turbine configuration obtained using the combined objective function.

The varied parameters included the Weibull scale parameter A_{100} , Weibull shape parameter k , electricity price p_{el} , discount rate r , CAPEX multiplier M_{CAPEX} , and OPEX multiplier M_{OPEX} . Each parameter was varied from -30 % to +30 % around its base value in 1 % increments. For each variation, the model recalculated the AEP, NPV, and LCOE.

This sensitivity analysis provides a deterministic assessment of parameter importance, and helps identify which assumptions have the strongest effect on project profitability and production cost. It also supports the interpretation of the

broader uncertainty assessment, by showing which individual parameters are most influential when varied independently.

3.4 Monte Carlo Uncertainty Analysis

A Monte Carlo analysis was used to assess the robustness of the optimized turbine configurations under uncertainty in the wind resource, technical, and economic parameters. Instead of evaluating each configuration only once using nominal input values, the model sampled uncertain parameters from predefined triangular distributions repeatedly, and recalculated the technical and economic performance for each scenario. The uncertain input parameters used in each Monte Carlo realization were grouped into the input vector shown in Equation (11),

$$\theta^{(m)} = \left[A_{100}^{(m)}, k^{(m)}, \alpha^{(m)}, \rho^{(m)}, p_{el}^{(m)}, r^{(m)}, M_{CAPEX}^{(m)}, M_{OPEX}^{(m)}, N^{(m)} \right] \quad (11)$$

where the superscript (m) denotes the sampled value in Monte Carlo realization m , and $\theta^{(m)}$ is the corresponding input vector. The uncertainty ranges used in the Monte Carlo analysis are summarized in Table 2. The wind resource parameters were varied relative to the nominal values for each selected area, and the technical and economic parameters were varied around the base assumptions of the deterministic model. The base electricity selling price was set to 105 €/MWh by rounding the average baseload day-ahead electricity price of 104.64 €/MWh recorded in Slovenia in 2025 (Agencija za energijo, 2026). A base discount rate of 6 % was adopted, consistent with the values applied in previous economic assessments of wind energy projects (Mijakovski et al., 2018; Mikindani et al., 2025).

Table 2: Input parameters varied in the Monte Carlo analysis

Parameter	Base value	Range in analysis	Description
A_{100} [m/s]	Area-specific	± 20 %	Weibull scale parameter
k [-]	Area-specific	± 10 %	Weibull shape parameter
α [-]	Area-specific	± 20 %	Wind shear exponent
ρ [kg/m ³]	1.225	± 5 %	Air density
p_{el} [€/MWh]	105	± 20 %	Electricity selling price
r [-]	0.06	0.04-0.08	Discount rate
M_{CAPEX} [-]	unmodified (1)	0.8-1.2	CAPEX multiplier
M_{OPEX} [-]	unmodified (1)	0.8-1.2	OPEX multiplier
N [years]	20	15-25	Project lifetime

For each sampled input vector, the optimized turbine geometry and deterministic capital expenditure obtained from the GAMS optimization were retained as the basis for evaluation, while the sampled parameters were used to recalculate the technical and economic performance. The sampled multipliers M_{CAPEX} and M_{OPEX} were applied to their corresponding deterministic values. The turbine geometry was not reoptimized during the individual Monte Carlo realizations. The resulting distributions of AEP, NPV, LCOE, and related economic indicators were summarized using deterministic values, percentile ranges, and the probability of achieving a positive NPV.

4 Case Study Results

This section presents the deterministic optimization, sensitivity analysis, and Monte Carlo uncertainty analysis for the nine selected Slovenian study areas. The deterministic results first show how the selected objective function affects the turbine sizing and techno-economic performance. A deterministic sensitivity analysis is then used to identify the wind resource and economic parameters with the greatest influence on the selected configurations. Finally, the Monte Carlo analysis evaluates their robustness when the uncertain parameters vary simultaneously.

4.1 Deterministic Optimization Results

The deterministic optimization problem was solved separately for each of the nine sets of area-specific wind-resource parameters. Four optimization problems were solved for each set of area-specific input parameters: maxAEP, maxNPV, minLCOE, and the combined objective. The combined objective was selected as the main reference, because it accounts simultaneously for energy production, profitability, and electricity generation cost. The corresponding turbine dimensions are shown in Figure 2, with the dashed lines representing the lower and upper optimization bounds.

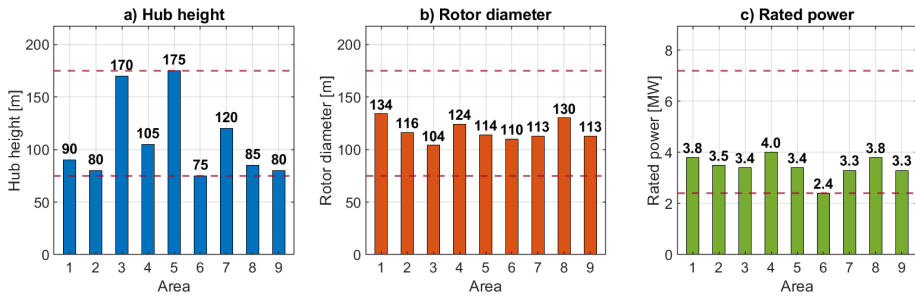


Figure 2: Rounded combined-objective turbine configurations for the nine study areas: a) hub height, b) rotor diameter, and c) rated power

The selected configurations differed substantially between the areas, particularly in hub height. The configurations obtained for Areas 3 and 5 had the greatest hub heights, at 170 and 175 m, whereas the configuration obtained for Area 6 had a hub height at the lower bound of 75 m. The rotor diameters ranged from 104 to 134 m and rated power from 2.4 to 4.0 MW. The results therefore showed that optimization using the combined objective did not yield the largest turbines systematically, but, instead, yielded configurations adapted to the local wind resource and the associated investment cost. The main technical and economic indicators of the selected configurations are presented in Figure 3.

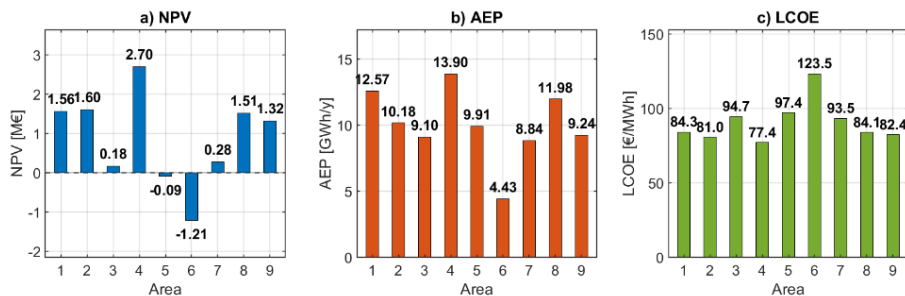


Figure 3: Deterministic performance of the rounded combined-objective configurations for the nine study areas: a) NPV, b) AEP, and c) LCOE

Under the combined objective, the most favorable overall results were obtained for Area 4, with an NPV of 2.70 M€, an AEP of 13.90 GWh/year, and the lowest LCOE of 77.4 €/MWh. Favorable results were also obtained for Areas 1, 2, 8, and 9, with

NPVs between 1.32 and 1.60 M€ and LCOE values between approximately 81 and 84 €/MWh. The configurations obtained for Areas 3 and 7 were only marginally profitable, with NPVs of 0.18 and 0.28 M€, respectively. The configuration obtained for Area 5 yielded an AEP of 9.91 GWh/year but had a slightly negative NPV of −0.09 M€. The least favorable results were obtained for Area 6, with an NPV of −1.21 M€, an AEP of 4.43 GWh/year, and an LCOE of 123.5 €/MWh. The optimization therefore yielded the minimum rated power of 2.4 MW for Area 6.

The influence of the optimization criterion on turbine sizing is compared in Figure 4.

Maximization of the AEP yielded solutions at the upper bounds of all three design variables in every area, corresponding to a hub height and rotor diameter of 175 m and a rated power of 7.2 MW. This was expected, because the maxAEP objective accounts for increased energy capture without accounting for the associated investment cost directly. In contrast, the maximization of NPV and minimization of LCOE yielded substantially smaller configurations. The minimization of LCOE yielded the minimum rated power of 2.4 MW in every area, whereas the maximization of NPV yielded rated powers between 2.4 and 3.7 MW. The resulting differences in NPV, AEP, and LCOE are shown in Figure 5.

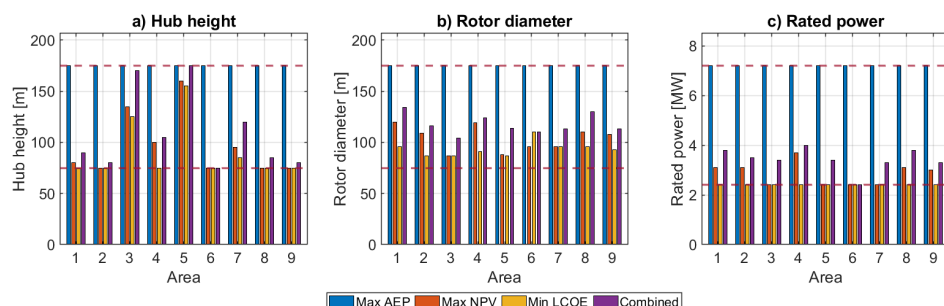


Figure 4: Comparison of the rounded turbine configurations obtained using the maxAEP, maxNPV, minLCOE, and combined objective functions: a) hub height, b) rotor diameter, and c) rated power

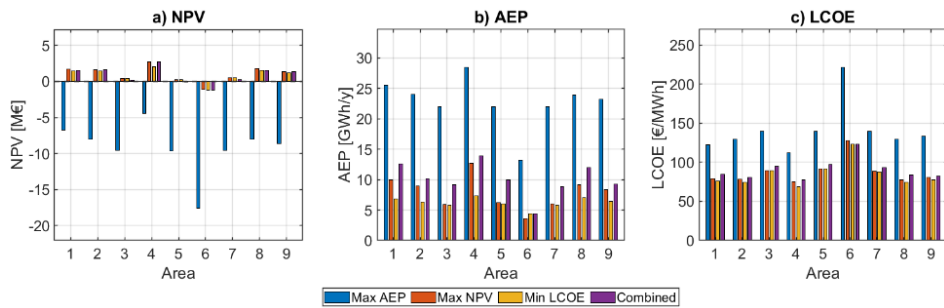


Figure 5: Comparison of the deterministic performance obtained using the rounded maxAEP, maxNPV, minLCOE, and combined objective configurations: a) NPV, b) AEP, and c) LCOE

The maxNPV and minLCOE solutions yielded similar economic outcomes, although the resulting turbine dimensions differed. The minLCOE solutions resulted in smaller turbines, whereas the maxNPV solutions tended to retain somewhat larger configurations. For the more favorable areas, the combined-objective solutions yielded higher AEP with only a limited reduction in NPV relative to the maxNPV solutions. For example, in Area 4, the AEP increased from 12.71 GWh/year for the maxNPV configuration to 13.90 GWh/year for the combined configuration, while NPV decreased only slightly from 2.74 to 2.70 M€. In Area 1, the AEP increased from 9.94 to 12.57 GWh/year, while NPV remained similar at 1.56 M€ for the combined configuration compared with 1.72 M€ for the maxNPV configuration. The trade-off was less favorable in the marginal areas. For Areas 3 and 7, the solutions obtained using the combined objective had substantially higher AEP but lower NPV than the corresponding maxNPV solutions. For Area 5, the configuration obtained using the combined objective increased AEP from 6.20 to 9.91 GWh/year, but shifted the NPV from a slightly positive 0.29 M€ to -0.09 M€. The economic penalty associated with increased energy production was therefore relatively small in the more favorable areas, but became more pronounced in the marginal areas.

Overall, the deterministic results showed that the optimization criterion affected both turbine sizing and project viability strongly. The solutions obtained by maximizing AEP were oversized and economically inefficient consistently, whereas those obtained by maximizing NPV and minimizing LCOE were smaller and

exhibited stronger financial performance. The combined-objective solutions yielded higher AEP than the purely economic solutions, with the associated NPV penalty depending on the site quality. The deterministic results identified Area 4 as the most favorable location, followed by Areas 1, 2, 8, and 9. The results for Areas 3 and 7 indicated only marginal economic attractiveness, the combined-objective configuration for Area 5 was slightly uneconomic, and the results for Area 6 indicated unfavorable economic feasibility under the deterministic assumptions. The combined-objective configurations were therefore retained as the reference designs for the subsequent uncertainty and sensitivity analyses.

4.2 Deterministic Sensitivity Analysis

A deterministic sensitivity analysis was performed for the rounded combined-objective configurations. The sensitivity trends were qualitatively similar across the nine study areas. To avoid presenting repetitive and visually congested figures, Area 4 was selected as an illustrative case for detailed discussion. It was chosen because the deterministic results obtained for this area indicated the strongest techno-economic performance, and provided a clear representation of the relative influence of the investigated parameters. The sensitivity of NPV for Area 4 is shown in Figure 6. The red dotted line represents the economic break-even point at which NPV equals zero.

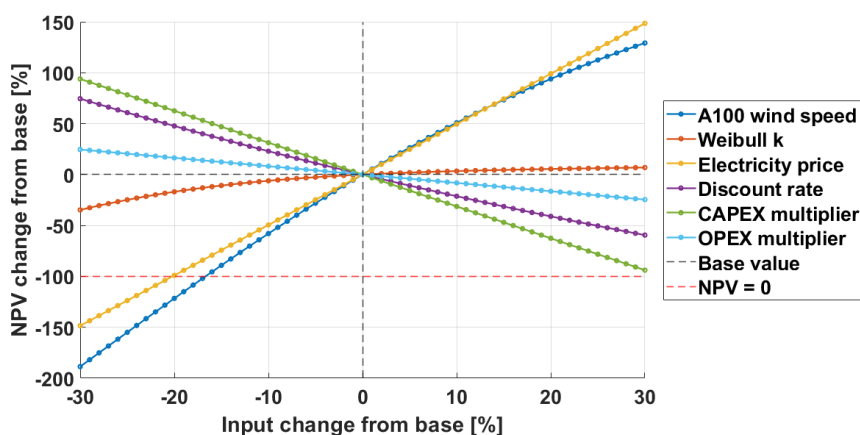


Figure 6: Deterministic sensitivity of NPV for the rounded combined-objective configuration in Area 4

The NPV was affected most strongly by A_{100} , p_{el} , and CAPEX. The increased wind resource intensity or electricity price increased NPV, whereas a higher CAPEX or r reduced it. Relative to the base case, a 30 % increase in p_{el} increased NPV by 149 %, while a 30 % decrease reduced NPV by 146 %. Across the investigated ± 30 % range, the variation in A_{100} changed NPV by -188 % to $+129$ % relative to the base value. CAPEX also had a pronounced effect: a 30 % reduction increased NPV by 94 %, whereas a 30 % increase reduced it by 93 %. The influence of r was smaller, but still substantial, whereas variations in OPEX and k had comparatively limited impacts. The Area 4 configuration remained economically viable over most of the investigated range; NPV became negative only when A_{100} decreased by 17 % or p_{el} decreased by 20 %. Even with a 30 % increase in CAPEX NPV remained close to the economic break-even point, indicating comparatively robust deterministic performance for the evaluated configuration. The corresponding LCOE sensitivity is shown in Figure 7.

The parameter A_{100} had the strongest influence on LCOE. A 30 % decrease increased LCOE by 65 % relative to the base value, whereas a 30 % increase reduced it by 18 %. This asymmetric response results from the nonlinear influence of the wind speed on energy production. CAPEX was the second most influential parameter: a ± 30 % variation in CAPEX changed LCOE by ± 23 %. The parameter r changed LCOE by -11 % to $+12$ %, while OPEX caused a smaller variation of ± 7 %. The parameter k had only a limited effect. Electricity price p_{el} does not affect LCOE, because it influences project revenue rather than the cost or quantity of generated electricity.

Overall, the deterministic sensitivity analysis identified wind resource intensity, p_{el} , and CAPEX as the principal determinants of economic performance. The same general parameter ranking was observed across the study areas, although the magnitude of the responses and the distance from economic break-even differed. The results for Areas 3, 5, and 7 were more sensitive to relatively small adverse changes, while the configuration for Area 6 remained economically unfavorable over much of the investigated range. The configuration evaluated for Area 4, in contrast, remained comparatively robust under moderate deviations from the base assumptions. Because the deterministic sensitivity analysis varied each parameter independently, the combined effects of simultaneous uncertainty were evaluated subsequently using Monte Carlo analysis.

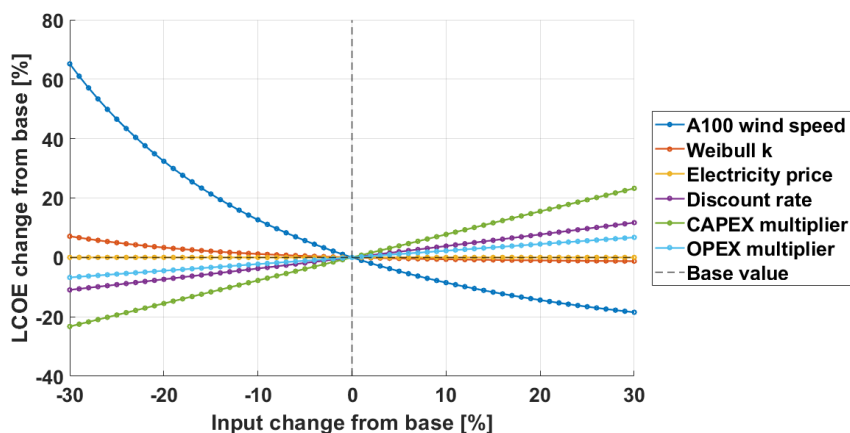


Figure 7: Deterministic sensitivity of LCOE for the rounded combined-objective configuration in Area 4

4.3 Monte Carlo Uncertainty Analysis

The Monte Carlo analysis was used to evaluate the robustness of the rounded combined-objective configurations when the wind resource and economic inputs varied simultaneously. For each study area 10,000 simulations were performed, using triangular distributions centered on the deterministic assumptions. Although AEP was calculated in every simulation, its uncertainty is not presented separately. Only the wind resource and technical parameters affect energy production directly, while p_{el} , r , CAPEX, OPEX, and N affect only the economic indicators. The deterministic AEP values also remained close to the center of the corresponding percentile intervals in all areas. The effect of the AEP uncertainty is therefore represented more meaningfully through its influence on NPV and LCOE.

The resulting uncertainty in NPV is presented in Figure 8. P05 and P95 denote the 5th and 95th percentiles, respectively, and therefore define the central 90 % range of the simulated results, while the base value represents the corresponding deterministic result.

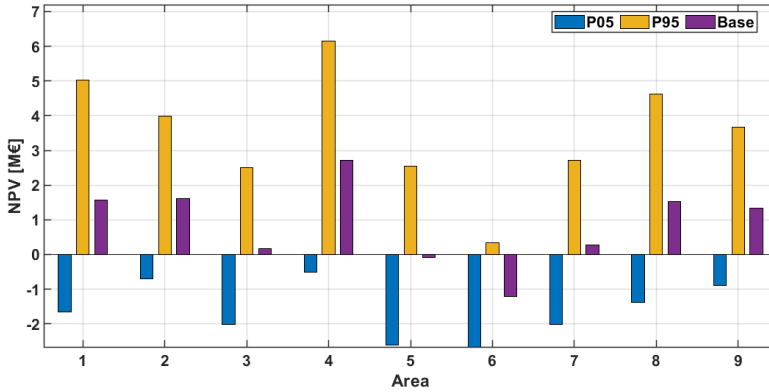


Figure 8: Base, P05, and P95 values of the NPV obtained from the Monte Carlo analysis

The strongest economic performance under uncertainty was obtained for Area 4. The NPV distribution for Area 4 ranged from -0.50 M€ at P05 to 6.14 M€ at P95, compared with a deterministic value of 2.71 M€. Comparatively favorable NPV results were also obtained for Area 2, with an NPV range from -0.70 to 3.98 M€. The NPV distributions for Areas 1, 8, and 9 were wider, but predominantly favorable, with P95 values of 5.02 , 4.62 , and 3.67 M€, respectively. Nevertheless, the P05 NPV was negative for every area, including the best performing configurations. This indicated that sufficiently unfavorable combinations of wind resource and economic conditions could make all the investigated projects uneconomic. The downside risk was particularly important for Areas 3, 5, 6, and 7, whose deterministic NPVs were already close to, or below zero. The least favorable NPV distribution was obtained for Area 6, with an NPV range from -2.68 to only 0.33 M€.

The resulting uncertainty in LCOE is shown in Figure 9.

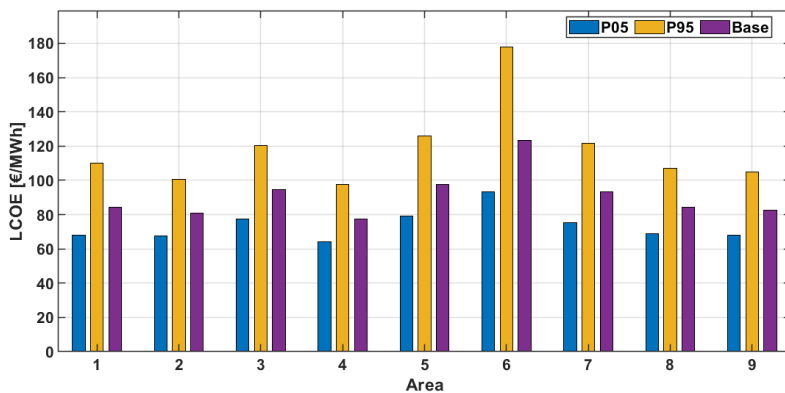


Figure 9: Base, P05, and P95 values of LCOE obtained from the Monte Carlo analysis

The lowest LCOE values under uncertainty were obtained for Area 4, with values ranging from 64.0 €/MWh at P05 to 97.7 €/MWh at P95. The LCOE distributions for Areas 1, 2, 8, and 9 were also comparatively favorable, although their upper percentiles generally exceeded 100 €/MWh. For example, the LCOE for Area 2 ranged from 67.6 to 100.5 €/MWh, while the corresponding LCOE for Area 8 ranged from 68.9 to 107.0 €/MWh. The results for the weaker locations were characterized by both higher deterministic values and less favorable upper tails. The highest LCOE values throughout the analysis were obtained for Area 6, ranging from 93.3 to 177.7 €/MWh. The P95 values obtained for Areas 3, 5, and 7 also exceeded 120 €/MWh. The larger upward deviation under unfavorable conditions was consistent with the deterministic sensitivity analysis, and resulted mainly from the nonlinear effect of reduced wind availability on electricity production.

A direct measure of economic robustness is provided by the probability of achieving a positive NPV, as presented in Figure 10.

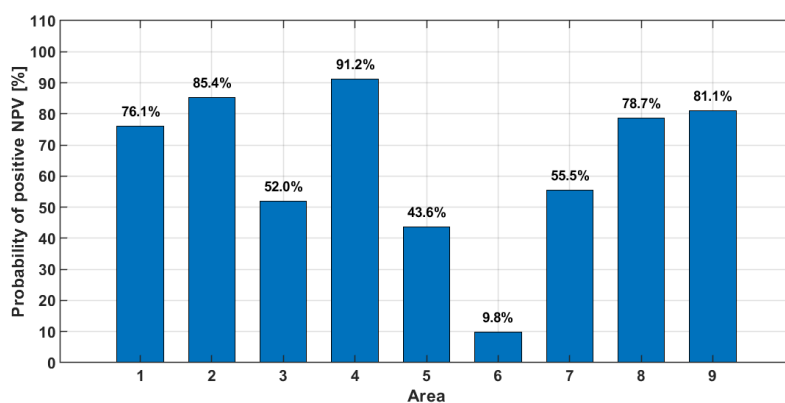


Figure 10: Probability of positive NPV for the rounded combined-objective configurations under the Monte Carlo analysis

The highest probability of a positive NPV was obtained for Area 4, at 91.2 %, indicating the greatest economic robustness among the evaluated locations. The second highest probability was obtained for Area 2, at 85.4 %, while the corresponding probabilities for Areas 9, 8, and 1 were 81.1 %, 78.7 %, and 76.1 %, respectively. The corresponding configurations therefore remained profitable in most simulated scenarios, although their negative P05 values showed that economic risk was not eliminated. The probabilities of a positive NPV for Areas 3 and 7 were 52.0 % and 55.5 %, respectively. Their outcomes were therefore approximately divided evenly between profitable and unprofitable scenarios, which were consistent with their marginal deterministic results. A positive NPV was obtained in only 43.6 % of the simulations for Area 5, indicating that unfavorable outcomes were more likely than favorable ones. The probability of a positive NPV for Area 6 was only 9.8 %. Although positive results occurred under a limited number of favorable scenarios, the configuration remained economically unattractive under most combinations of uncertain inputs.

Overall, the Monte Carlo analysis preserved the general ranking obtained from the deterministic optimization, but showed that deterministic values alone did not describe the project risk adequately. The Monte Carlo results identified Area 4 as the most favorable and robust location, followed by Areas 2, 9, 8, and 1. The results for Areas 3 and 7 indicated marginal economic feasibility, while those for Areas 5, and particularly 6, indicated substantial economic risk. These findings were consistent

with the deterministic sensitivity analysis, which identified wind resource intensity, p_{el} , and CAPEX as the principal drivers of project performance.

5 Discussion and Study Limitations

The results demonstrate that turbine selection cannot be based on energy production alone. Because the investment cost was not penalized, maximization of AEP resulted in hub height, rotor diameter, and rated power approaching their upper bounds, whereas the maximization of NPV and minimization of LCOE yielded smaller configurations. The combined-objective solution represented a compromise between production and economic performance, particularly in stronger-wind areas such as Areas 1 and 4. However, in marginal areas, increasing the turbine size could raise AEP while reducing NPV. The combined solution should therefore not be interpreted as universally optimal; a final selection should consider the individual values of AEP, NPV, and LCOE together with the associated uncertainty.

Across the investigated locations, the wind resource quality remained the principal technical determinant of feasibility. The sensitivity analysis identified the Weibull scale parameter, electricity price, CAPEX, and discount rate as the most influential inputs. The Monte Carlo results showed further that favorable deterministic values do not necessarily indicate robust profitability, emphasizing the importance of percentile ranges and the probability of positive NPV when evaluating marginal projects.

Several limitations must be considered. Each area was represented by modeled Weibull parameters at a representative point rather than long-term measurements at a confirmed turbine location, so local effects related to complex terrain, turbulence, wind direction, atmospheric stability, and icing were not captured in detail. The single-turbine model excludes manufacturer-specific power curves, dynamic control behavior, structural and fatigue loads, wake effects, wind farm layout, electrical losses, curtailment, and grid constraints. The economic assessment relies on escalated NREL cost-scaling relationships and simplified financial assumptions that omit project-specific transport, installation, financing, degradation, component replacement, decommissioning, and future electricity-price changes. The Monte Carlo analysis also assumes independent triangular distributions, although correlations may exist among the uncertain parameters. The framework should

therefore be regarded as a preliminary screening and configuration-selection tool, with detailed project development requiring site measurements, manufacturer-specific data, updated cost information, and wind-farm-level spatial, structural, environmental, and grid assessments.

6 Conclusion

The case study demonstrates that wind turbine size should not be selected independently of site quality and the chosen optimization objective. The maximization of AEP resulted consistently in hub height, rotor diameter, and rated power approaching their upper bounds, but the resulting increase in electricity generation was generally insufficient to compensate for the considerably higher CAPEX. The maximization of NPV and minimization of LCOE yielded smaller configurations. The weighted combined-objective solution was intermediate, retaining a substantial share of the achievable economic performance while increasing AEP. However, this compromise was most effective at locations with stronger wind resources, whereas larger configurations at marginal locations could increase production while reducing NPV.

Across the nine study areas, the strongest overall results were obtained for Area 4, with an AEP of approximately 13.90 GWh/year, an NPV of 2.70 M€, an LCOE of 77.4 €/MWh, and a 91.2 % probability of positive NPV. The second favorable group comprised Areas 1, 2, 8, and 9, for which positive deterministic NPVs were obtained and probabilities of positive NPV between 76.1 % and 85.4 %. The configurations evaluated for Areas 3 and 7 were only marginally profitable under the deterministic assumptions, and remained close to the economic threshold under uncertainty, with positive-NPV probabilities of 52.0 % and 55.5 %, respectively. The configuration evaluated for Area 5 was slightly uneconomic under the deterministic assumptions, and a positive NPV was achieved in only 43.6 % of the simulations. The least favorable results were obtained for Area 6, with an NPV of -1.21 M€, an LCOE of 123.5 €/MWh, and only a 9.8 % probability of positive NPV. The comparison demonstrates that turbine scaling alone cannot compensate for an insufficient wind resource, and that site quality remains fundamental to project feasibility.

The sensitivity analysis identified the Weibull scale parameter, electricity price, CAPEX, and discount rate as the most influential model inputs. The Monte Carlo analysis demonstrated further that favorable deterministic indicators do not necessarily represent robust investment performance, because negative outcomes remained possible, even at comparatively attractive locations. The probability of a positive NPV and the corresponding percentile ranges should therefore be considered together with deterministic NPV and LCOE, particularly when assessing marginal projects.

The developed framework provides a systematic basis for preliminary turbine-configuration and site screening, by linking energy production, economic performance, and uncertainty within a common assessment workflow. It also distinguishes between locations where the additional turbine scale creates sufficient value, and locations where it increases primarily investment exposure. Nevertheless, the results should be interpreted as screening-level estimates, because the analysis relies on modeled wind resource parameters, a simplified single-turbine representation, generalized cost-scaling relationships, and predefined uncertainty distributions.

Future work should focus on the following areas:

- **Dynamic turbine performance:** Evaluate the selected configurations using chronological wind speed data and dynamic models that account for variable-speed operation, pitch and torque control, start-up and shutdown behavior, curtailment, and operation near rated conditions.
- **Higher-fidelity technical modeling:** Compare the simplified power coefficient model with the manufacturer-specific power curves, blade element momentum models, and aeroelastic simulations that include turbulence, fatigue, extreme loading, blade deflection, and turbine class requirements.
- **Site-specific wind assessment:** Supplement the modeled Weibull parameters with long-term site-specific wind measurements, and account for complex terrain, wind direction, atmospheric stability, turbulence intensity, seasonal variability, and icing.
- **Wind-farm-level optimization:** Extend the framework to include wake interactions, turbine spacing, layout optimization, electrical losses, availability, access requirements, curtailment, and grid connection constraints.

- **Improved economic representation:** Incorporate updated turbine and balance-of-system costs, financing structures, degradation, component replacement, decommissioning, residual value, grid connection expenditure, and electricity price evolution.
- **Advanced optimization under uncertainty:** Consider correlations among uncertain parameters, and compare the weighted combined objective with Pareto-based multi-objective, stochastic, and robust optimization approaches.
- **Spatial and environmental integration:** Incorporate geographic information system data directly into the optimization, to represent protected areas, settlement distances, terrain accessibility, infrastructure, visual impact, and other practical siting constraints.

These extensions would allow the framework to progress from preliminary configuration screening toward a more comprehensive decision-support tool for site-specific wind energy planning and investment assessment.

Acknowledgment

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Povzetek s slovenskem jeziku

Optimizacijsko osnovana tehno-ekonomska ocena kopenskih vetrnih turbin v Sloveniji ob upoštevanju negotovosti. Sistemi za izrabo obnovljivih virov energije zahtevajo izbor tehnologije, ki ustreza posameznim lokacijam in zagotavlja visoko proizvodnjo energije ter ekonomsko upravičenost. V okviru raziskave je bil razvit splošen, na optimizaciji osnovan tehno-ekonomski okvir za ocenjevanje konfiguracij kopenskih vetrnih turbin, ki je bil uporabljen na devetih reprezentativnih lokacijah v Sloveniji. Spremenljivke optimizacije so bile višina pesta, premer rotorja in nazivna moč, ciljne funkcije pa letna proizvodnja energije, neto sedanja vrednost (NSV), izravnani stroški električne energije (ang. levelized cost of energy, krajše LCOE) ter utežen sestavljen cilj. Izbrane konfiguracije so bile ovrednotene z deterministično analizo občutljivosti in simulacijo Monte Carlo za oceno vpliva negotovosti vetrnega vira ter tehničnih in ekonomskih parametrov. Maksimiranje zgolj proizvodnje energije je privedlo do predimenzioniranih in ekonomsko neučinkovitih konfiguracij, medtem ko je optimiranje na podlagi ekonomskih ciljev (NSV in LCOE) privedlo do manjših vetrnih turbin, sestavljena ciljna funkcija pa je omogočila bolj uravnoteženo trženje. Kakovost vetrnega vira, cena električne energije, investicijski stroški in diskontna stopnja so se izkazali kot glavni dejavniki dobičkonosnosti, pri čemer ugodni deterministični rezultati ob upoštevanju negotovosti niso vedno izkazali ekonomske robustnosti.

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EXPERIMENTAL VALIDATION OF A SIMPLIFIED MODEL OF A CURRENT TRANSFORMER

JERNEJ ČERNELIČ,¹ ERMIN RAHMANOVIĆ,¹
BOŠTJAN POLAJŽER,¹ GAŠPER HABJAN,² MATEJ PETEK,²
DARINKO STICH²

¹ University of Maribor, Faculty of Electrical Engineering and Computer Science,
Maribor, Slovenia

jernej.cernelic@um.si, ermin.rahmanovic@um.si, bostjan.polajzer@um.si

² Dravske elektrarne Maribor d.o.o., Maribor, Slovenia

gasper.habjan@dem.si, matej.petek@dem.si, darinko.stich@dem.si

CORRESPONDING AUTHOR

jernej.cernelic@um.si

Abstract Modeling of current transformers (CTs) is essential for assessing their transient performance, as the nonlinear magnetizing characteristic of the iron core can lead to severe secondary current waveform distortion. Such effects are particularly critical for the measurement accuracy of protection relays, whose reliable and fast operation depends on the faithful reproduction of the secondary current. This paper presents the experimental validation of a simplified dynamic CT model that includes only the nonlinear (anhysteretic) magnetizing characteristic, while neglecting the winding resistance and leakage inductance. The magnetizing characteristic was measured using a commercial CT analyzer. To align the measured and simulated secondary currents, an optimization procedure was used to determine the initial value of the remanent magnetic flux. The optimization was applied to a transient condition, in which a primary current contains an aperiodic component, typical for power system faults. The simulated secondary current was then compared to the measured current using the range-normalized Root-Mean Square Error (NRMSE) method. After optimization, an NRMSE value ranging from 2% to 5% was achieved for the CT under consideration across six validation scenarios.

Keywords

validation,
current transformer,
model,
magnetizing
characteristic,
saturation,
NRMSE

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1 Introduction

Current transformers (CTs) are essential components in power-system measurement and protection, where accurate reproduction of the primary current is required for reliable operation. During fault conditions and certain transients, a high current magnitude and the presence of an aperiodic (DC) component may drive the iron core into saturation, causing substantial distortion of the secondary current waveform. Such distortion is known to degrade the performance of protection relays and may lead to delayed or incorrect tripping (Whang et al.; 2017, Wiszniewski et al., 2008). Different CT iron-core saturation detection and compensation methods have been developed, because this can have a major impact on power system operation stability and reliability (Naseri et al., 2019; Yang et al., 2022).

Therefore, CT models are indispensable for analyzing CT behavior during such transient events. Several modeling approaches exist, ranging from detailed electromagnetic models that include magnetic hysteresis and winding impedance, to simplified models that include only a nonlinear magnetizing characteristic (Afonso et al., 2020a), and some in between (Guo et al., 2017). While detailed models offer higher accuracy, they require more extensive parameter identification and can be computationally more demanding. Simplified models, in contrast, preserve only the dominant nonlinear magnetizing characteristic, while neglecting winding resistance and leakage inductance (Zhang et al., 2013). There are many different approaches to modeling the nonlinear magnetizing characteristic, which remain very challenging to describe accurately (Zhang et al., 2013; Ayyadurai et al., 2014). These simplified models provide a good compromise between accuracy and time-consuming parameter estimation, and are used widely in protection studies, where the key requirement is reproducing the onset and severity of iron core saturation (Yin et al., 2016; Afonso et al., 2020a).

Despite the practicality, all CT models should be validated experimentally, to ensure accurate reproduction of the real transformer's behavior under the most relevant conditions. The CT saturation depends strongly on the true magnetizing characteristic, residual flux, and the waveform of the driving current (Yin et al., 2016; Afonso et al., 2020b). Consequently, experimental validation is necessary to confirm that a simplified model provides sufficient accuracy for the desired case studies. This paper, therefore, focuses on the experimental validation of a simplified CT model

based solely on the measured nonlinear magnetizing characteristic, using a commercially available CT analyzer to speed up model parameter estimation and increase model usability.

2 Simplified model of a current transformer

The simplified model of the CT in this paper aims to reproduce only the dominant nonlinear behavior of the iron core, while avoiding the complexity associated with full electromagnetic representations (Zhang et al., 2013). The balance of magnetomotive force (MMF) produced by the primary and secondary windings can be described as:

$$\theta = N_1 i_1 - N_2 i_2 \quad (1)$$

where N_1 and N_2 denote the primary and secondary winding turns, while i_1 and i_2 denote the primary and secondary winding currents. The resulting net MMF drives the magnetic flux according to the static nonlinear magnetizing characteristic:

$$\phi = f(\theta) \quad (2)$$

which is introduced in the model as a look-up table instead of the more commonly used parametric hysteresis models (Zhang et al., 2013; Ayyadurai et al., 2014).

The time variation of magnetic flux induces a voltage in the secondary winding according to:

$$e_2 = -N_2 \frac{d\phi}{dt} = i_2 R_2 \quad (3)$$

which drives the secondary current over the secondary resistance (R_2), which consists of secondary winding resistance and burden resistance. The MATLAB/Simulink model presented in Figure 1 was built based on equations (1), (2), and (3).

In steady-state and non-saturated operation of the CT, the induced voltage (e_2) is sufficiently large to drive a secondary current i_2 that generates the secondary ampere-turns ($N_2 i_2$), which balance out the primary ampere-turns ($N_1 i_1$) almost exactly,

according to equation (1). As a result, the net MMF (θ) remains small, and the iron core operates in the linear region of its magnetizing characteristic.

However, when the magnetic flux exceeds the linear region, i.e., enters the saturation region, the incremental permeability of the iron core decreases rapidly, and the magnetic flux no longer follows the primary excitation proportionally. This loss of proportionality, reflected in amplitude reduction and waveform distortion, marks the onset of current-transformer saturation, which can occur during transient conditions, or when the burden resistance or current exceeds the rated values.

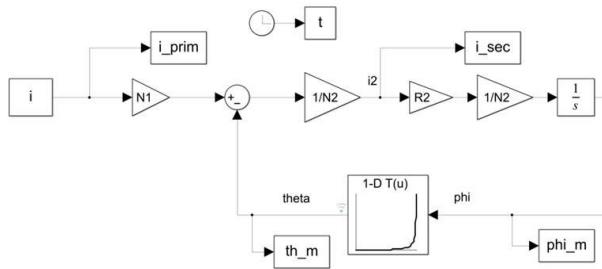


Figure 1: Simplified model of a current transformer in Matlab Simulink

Source: own.

3 Determining the parameters of the current transformer model

A measurement-class CT, the Circutor TA 210, was used to validate the simplified CT model experimentally. The rated values and parameters of the simplified CT model are presented in Table 1. The secondary resistance (R_2) was obtained by measuring only the secondary winding resistance with the GW INSTRUK GOM-802 Ohmmeter.

Table 1: Rated values and parameters of current transformer TA 210

	Value	Unit	Description
I_1	10	A	Primary rated current (RMS)
I_2	5	A	Secondary rated current (RMS)
S_r	15	VA	Rated apparent power
N_1	40		Primary winding turns
N_2	80		Secondary winding turns
R_2	99,3	mΩ	Secondary (winding) resistance

Source: own.

The secondary winding terminals were shorted out with a very short wire, and no additional burden was used in the following experiment. The magnetizing characteristic $\phi(\theta)$ was determined using the Omicron CT Analyzer, which measures the induced voltage and magnetizing current according to four different Standards: IEC 61869-2, 60044-1, 60044-6, and IEEE C57.13. Each of these Standards defines the magnetizing characteristic using different calculations of the measured induced voltage (E) and the magnetizing current (I_m). The magnetizing characteristic $\phi(\theta)$ presented in Figure 1 can be, according to the IEEE C57.13 Standard, obtained by the calculation of MMF using equation (4) and magnetic flux using equation (5). In Figure 2, the magnetic flux saturation level is indicated for illustrative purposes as ϕ_{sat} at the value of 0.35 mVs.

$$\hat{\theta} = \sqrt{2} \cdot I_m \cdot N_2 \quad (4)$$

$$\hat{\phi} = \frac{\sqrt{2} \cdot E}{2\pi \cdot f \cdot N_2} \quad (5)$$

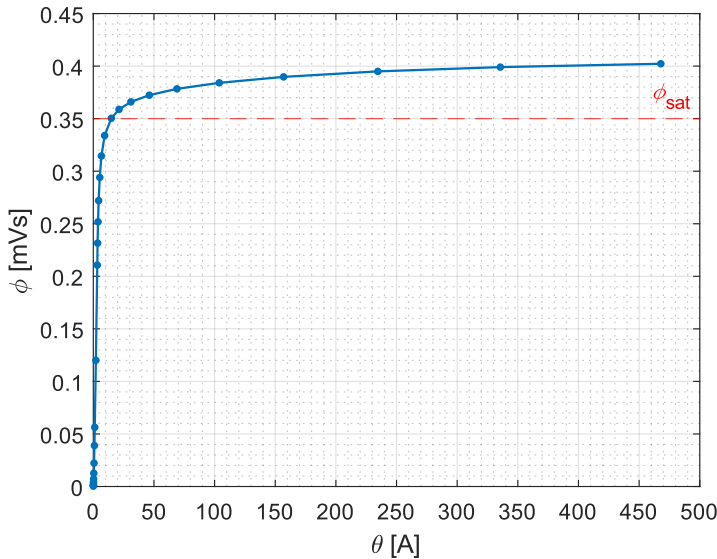


Figure 2: Magnetizing characteristic

Source: own.

4 The experimental validation of the current transformer model

The proposed simplified CT model was validated experimentally, with the CT primary winding supplied using the Omicron CMC 256-6 test and calibration device (Figure 3). The secondary winding terminals were shorted with a very short wire, allowing measurement of the secondary current while adding the least burden to the secondary resistance. The primary and secondary currents (i_1 and i_2) were measured using a LEM IT 60-S current transducer with a 60 A DC current range and the Dewesoft Sirius data acquisition system with a sampling rate of 20 kHz.

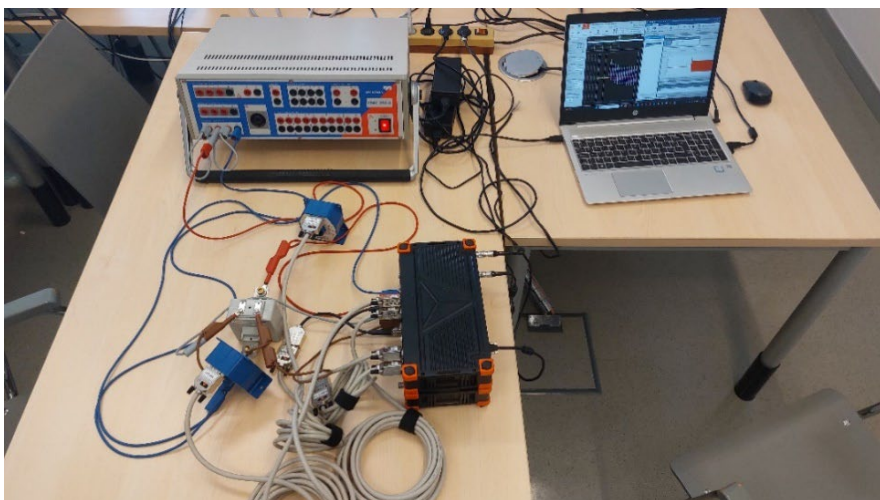


Figure 3: Experimental setup with an Omicron CMC 256-6 power supply, LEM IT 60-S current transducer, and Dewesoft Sirius data acquisition system

Source: own.

The primary winding of the CT was supplied with the primary current, (i_1), which consisted of two time sequences that represent the typical transient behavior of the power line's fault current. The first sequence, denoted with $i_{1,1}$ in equation (6), represents normal operating conditions with a constant current $I_{1,1}$ of 2 A, the angular frequency ω of $2\pi 50$ rad/s, and a fault inception angle φ equal to 90 degrees. The second sequence, denoted with $i_{1,2}$ in equation (7), represents the short-circuit current with a steady-state value $I_{1,2}$ of 10 A and contains an aperiodic component, which represents the short-circuit conditions. The angular frequency and inception angle remained unchanged, while $\delta = (\varphi - \tan^{-1}(\omega\tau))$. The time constant of the

decay τ was set to a value that caused saturation of the CT iron core without exceeding the measured range of the magnetizing characteristic shown in Figure 2. The decay time constant τ value of 60 ms was found by trial and error. Note that each sequence was simulated for a time period of 5 seconds.

$$i_{1,1} = \sqrt{2} \cdot I_{1,1} \sin(\omega t + \varphi); \quad t \in [t_o, t_1] \quad (6)$$

$$i_{1,2} = \sqrt{2} \cdot I_{1,2} \left(\sin(\omega t + \varphi) - \sin(\delta) e^{-\frac{t}{\tau}} \right); \quad t \in [t_1, t_2] \quad (7)$$

The described primary current (i_1) drives the magnetic flux of the CT into the nonlinear region of the magnetizing characteristic, which causes the increase of magnetizing current (i_m) and the distortion of the secondary current (i_2). Figure 4 shows all the described currents, where the secondary current is reduced to the primary side using the current ratio K_I , as given by:

$$i'_2 = K_I \cdot i_2 = \frac{I_1}{I_2} \cdot i_2 = \frac{N_2}{N_1} \cdot i_2 \quad (8)$$

An additional comparison was performed using the normalized peak-to-peak Root Mean Square Error (NRMSE) metric, which is calculated over a sliding time window of one fundamental period with N samples using equation (9). The $I_{1\max}$ and $I_{1\min}$ are the maximum and minimum values of the primary current (i_1), respectively, also calculated over a sliding window of N samples.

$$\text{NRMSE}_1 = \frac{\text{RMSE}_1}{I_{1\max} - I_{1\min}} = \frac{\sqrt{\frac{1}{N} \sum_{j=1}^N (i'_2(j) - i_1(j))^2}}{I_{1\max} - I_{1\min}} \quad (9)$$

The applied NRMSE provides a scale-invariant measure of the secondary current waveform distortion. The maximum value of NRMSE_1 obtained in this comparison was 18.9%, which occurred in the 4th period after the aperiodic component was applied to the primary current (Figure 4). This indicates the severe saturation of the iron core, because the secondary current no longer reproduces the primary current waveform accurately.

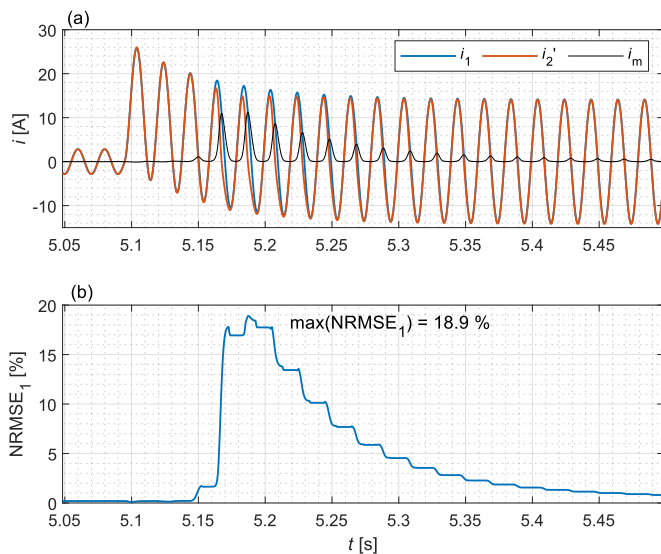


Figure 4: Measured primary, secondary, and magnetizing current of current transformer (a) and NRMSE of secondary current (b)

Source: own.

The above-described experiment was also used to validate the simplified model of the CT, by comparing the measured secondary current, denoted as i_{2m}' , with the simulated one, denoted as i_{2s}' , in Figure 5. This comparison uses the same NRMSE metric described in (9), where i_2' was replaced by i_{2m}' and i_1 was replaced by i_{2s}' . The newly calculated NRMSE is denoted with NRMSE₂.

Figure 5 shows all the currents, where the simulated secondary current was obtained using a demagnetized iron core in a CT model. This assumption (demagnetized iron core) was incorrect, and produced a large difference between the measured i_{2m}' and simulated secondary current i_{2s}' , exceeding 4.53 A, resulting in an NRMSE₂ for the simulated secondary current exceeding 14.63%. This large difference between the simulated and measured secondary current appeared only in the 4th period after the application of the aperiodic component. During the observed period, waveform distortion occurred only in the measured secondary current, indicating iron-core saturation, whereas, in the simulated secondary current, it was not observed, and the model showed that the magnetic flux was barely saturated (Figure 5). Furthermore,

the waveform distortion (iron-core saturation) in the simulated and measured secondary currents occurred at different times.

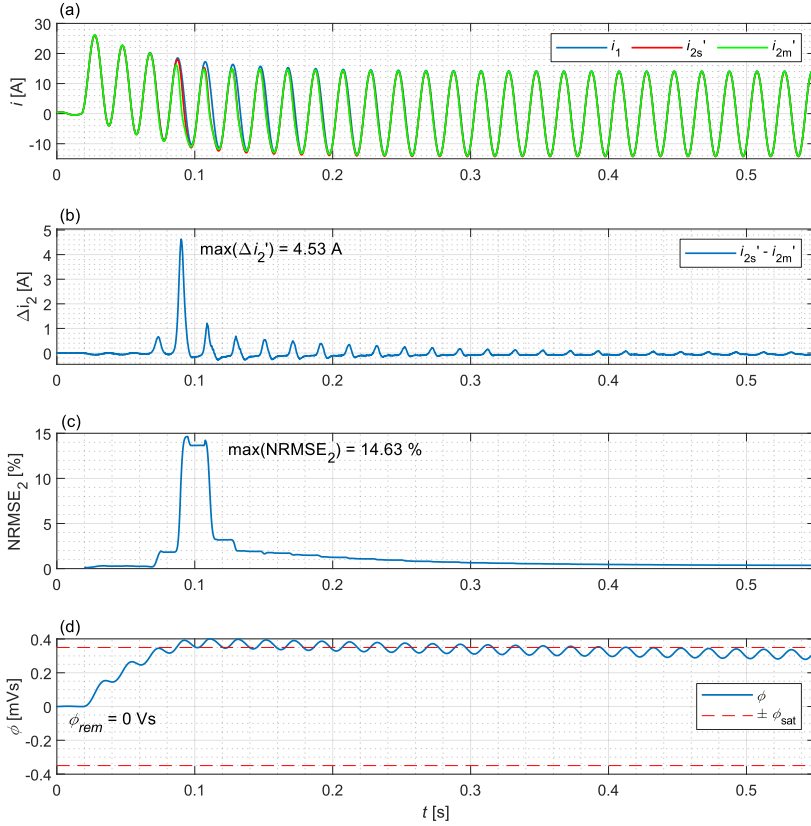


Figure 5: Simulated and measured primary and secondary currents of current transformer (a), difference between the simulated and measured secondary current (b), NRMSE (c), and magnetic flux without the remanent magnetic flux (d)

Source: own.

To match the measured and simulated secondary currents, an optimization procedure was employed to determine the remanent magnetic flux (initial value). The objective function was defined as the minimization of the RMSE between the measured and the simulated secondary current waveforms. In this case, the RMSE in (10) was calculated over the entire timeframe shown in Figure 5, which is 0.55 s long. This timeframe defines the total number of samples N used in the RMSE calculation.

$$RMSE = \sqrt{\frac{1}{N} \sum_{j=1}^N (i'_{2m,j} - i'_{2s,j})^2} \quad (10)$$

The optimization problem was solved using the "fminsearch" function from the Matlab Optimization Toolbox, where the only decision variable was the remanent magnetic flux denoted as ϕ_{rem} , while all the other model parameters were kept constant. The variable tolerance was set to 10^{-7} , since the remanent magnetic flux is in the range of μ Vs.

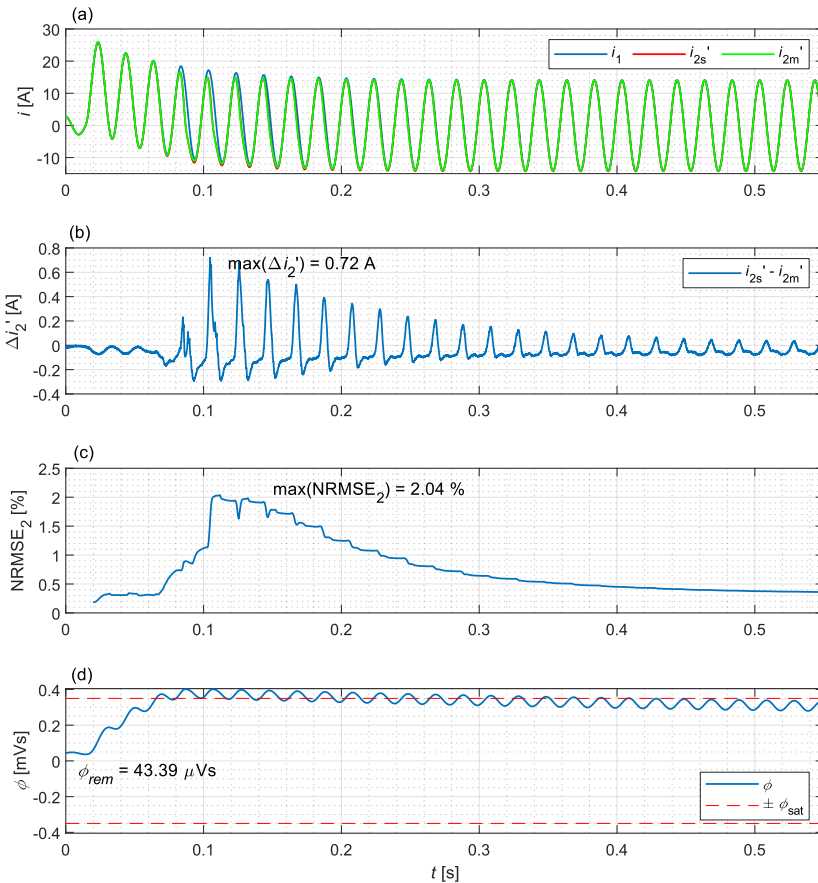


Figure 6: Measured and simulated primary and secondary currents of the current transformer (a), difference between the simulated and measured secondary current (b), NRMSE (c), and magnetic flux with remanent magnetic flux (d)

Source: own.

By applying the described optimization procedure, a remanent magnetic flux value of $43.39 \mu\text{Vs}$ was obtained for the discussed case. It must be emphasized that the actual value may differ, as it was not measured. Furthermore, the determined remanent magnetic flux value may not reflect the iron core's physical state accurately, but it can help address model simplifications, such as the omission of hysteresis and other nonlinear phenomena. However, the obtained remanent magnetic flux reduced the maximum NRMSE_2 of the newly simulated secondary current to only 2.04%. The maximum NRMSE_2 was again observed during the period with the most severe saturation, when the difference between the secondary and primary currents was greatest (Figure 6).

This low NRMSE_2 value confirms that the simplified model, based solely on the nonlinear magnetization characteristic, can capture the essential iron-core saturation dynamics with sufficient accuracy. Note that the NRMSE_2 exceeded 1.5% for only approximately 4 fundamental periods.

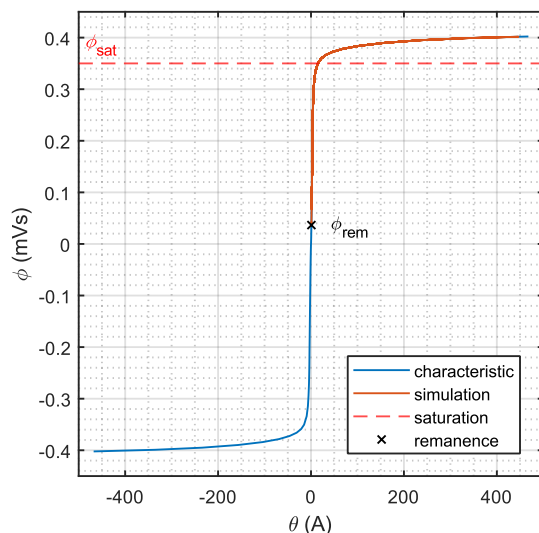


Figure 7: Measured magnetizing characteristic with simulated magnetic flux and magnetic flux saturation level

Source: own.

Figure 7 shows the measured magnetizing characteristic and the simulated magnetic flux, with a remanent magnetic flux of $43.39 \mu\text{Vs}$. The maximum value of magnetic flux in this simulation was $401.7 \mu\text{Vs}$, which is within the range of the measured

magnetizing characteristic, which as 402.2 μVs . Thus, it eliminates the need for extrapolation, which can introduce additional extrapolation errors to the results.

Table 2: NRMSE values at different remanent flux values and primary current parameters

	τ [ms]	$I_{1,1}$ [A]	$I_{1,2}$ [A]	ϕ_{rem} [μVs]	ϕ_{max} [μVs]	NRMSE ₁ [%]	NRMSE ₂ [%]
1	60	2.0	10	43.39	401.7	18.9	2.04
2	55	0.367	10	51.06	401.8	18.2	1.76
3	90	1.5	9	28.81	403.8	25.5	2.0
4	90	1.5	9	269.4	410.2	40.3	3.63
5	130	1.5	9	28.14	408.1	35.1	2.63
6	130	1.5	9	270.1	411.3	44.8	4.52

Source: own

Additional experiments were performed with different remanent magnetic flux ϕ_{rem} values and different primary current i_1 parameters, such as decay time constant τ , pre-fault current amplitude $I_{1,1}$, and short-circuit current amplitude $I_{1,2}$. For each experiment, the NRMSE₁ and NRMSE₂ were calculated, with NRMSE₂ computed from the remanent magnetic flux obtained by the optimization algorithm.

In the first two tests presented in Table 2 the magnetic flux remained within the measured range, resulting in an NRMSE₂ of approximately 2%, despite the relatively high saturation levels, which led to an NRMSE₁ of up to 19%. In the subsequent four tests, the decay time constant was increased to 90 ms and 130 ms, heightening the severity of the saturation further. It is important to note that the distinction between tests Nos. 3 and 4 lies in the degree of demagnetization prior to testing. The same distinction applies to tests Nos. 5 and 6. In tests Nos. 4 and 6, the optimization method yielded a remanent magnetic flux linkage value of around 270 μVs , which is approximately 75% of the saturation level indicated at 350 μVs . In these two tests, the saturation was at its highest, with the NRMSE₁ exceeding 40%. However, the NRMSE₂ remained below 5%, even in these cases, where the magnetizing characteristics were extrapolated using linear extrapolation.

5 Conclusion

This paper presents a simplified nonlinear model of a CT intended for analyzing saturation effects during transient conditions. The model incorporates only the nonlinear magnetizing characteristic of the iron core, which captures the dominant magnetic behavior responsible for iron core saturation. Experimental validation

using a primary current with an aperiodic component showed that the transformer operated in a state of severe saturation, as confirmed by a high NRMSE_1 of 18.9% between the measured primary current and the secondary current referred to the primary side. Despite this pronounced saturation, the comparison between the measured and simulated secondary currents yielded an NRMSE_2 of about 2% when the magnetic flux remained within the range of the measured magnetizing characteristic. In the tests where the magnetic flux exceeded the range of the measured magnetizing characteristic, the NRMSE_2 increased with the severity of iron core saturation, but remained below 5% in all the tests.

These experiments demonstrate that the simplified model reproduces the essential features of the saturation effect successfully. These results indicate that the model is sufficiently accurate for practical studies of CT transient performance, including scenarios that may lead to non-selective or misoperation of the protection relays. The described approach, therefore, provides a useful basis for further investigations, such as extending the model to include hysteresis, or analyzing the impact of burden variations, or introducing more complex excitation waveforms. Further investigations should include measurements of the remanent magnetic flux and analysis of the different types of current transformers, e.g., protection classes TPX, TPY, and TPZ.

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Povzetek s slovenskem jeziku

Eksperimentalna validacija poenostavljenega modela tokovnega transformatorja. Modeliranje tokovnih transformatorjev (TT) je ključnega pomena za ocenjevanje njihovega odziva med prehodnimi pojavi, saj lahko nelinearna magnetilna karakteristika železnega jedra povzroči izrazito popačenje sekundarne tokovne oblike. Takšni pojavi so še posebej kritični za merilno natančnost zaščitnih relejev, katerih zanesljivo in hitro delovanje je odvisno od verodostojne reprodukcije sekundarnega toka. V članku je predstavljena eksperimentalna validacija poenostavljenega dinamičnega modela TT, ki vključuje le nelinearno magnetilno karakteristiko brez upoštevanja histereze, upornost primarnega navitja in razpisna induktivnost pa sta zanemarejeni. Magnetilna karakteristika je bila izmerjena s komercialnim analizatorjem TT. Za uskladitev izmerjenih in simuliranih sekundarnih tokov je bil uporabljen optimizacijski postopek za določitev začetne vrednosti preostalega magnetnega pretoka. Optimizacija je bila izvedena za prehodno stanje, pri katerem primarni tok vsebuje aperioidično komponento, značilno za okvare v elektroenergetskem sistemu. Simulirani sekundarni tok je bil nato primerjan z izmerjenim tokom z uporabo metode korena povprečne kvadratne napake, normirane z razponom vrednosti (angl. NRMSE). Po izvedeni optimizaciji je bila za obravnavani TT v šestih validacijskih scenarijih dosežena vrednost NRMSE med 2% in 5%.

Ključne besede: validacija, tokovni transformator, model, magnetilna karakteristika, nasičenje, NRMSE

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WASTE HEAT UTILISATION IN SLOVENIA: SOURCE-SINK MATCHING AND ECONOMIC SCREENING

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NEJA HADŽISELIMOVIĆ,¹
MARVIN CHOWDHURY HAQUE²

¹ Graz University of Technology, Graz, Austria
neja.hadzelimovic@student.tugraz.at

² University of Maribor, Faculty of Chemistry and Chemical Technologies, Maribor, Slovenia
marvin.chowdhury@student.um.si

CORRESPONDING AUTHOR
neja.hadzelimovic@student.tugraz.at

Abstract Waste heat can contribute to heat supply only where the source characteristics match local demand and integration costs remain acceptable. This paper develops a source-sink framework for Slovenia that combines thermal quality, recoverable capacity, temporal availability, spatial proximity, demand characteristics, infrastructure requirements and delivered-heat cost. It distinguishes theoretical, technically recoverable, and economically usable heat, and examines data centres as an emerging source with limited internal thermal demand. For Slovenia's existing data-centre stock, recoverable heat is nationally modest and relevant mainly locally; scenarios for 15 and 30 MWth systems at 3,000 equivalent full-load hours yield about 45 and 90 GWh annually. Economic screening shows that the viability improves with a higher source temperature and utilisation, shorter connections, and moderate integration costs, whereas the delivered heat may exceed 100 €/MWh under unfavourable conditions, even when the source heat is free. The results support selective site-specific assessment and early heat-reuse planning for the future energy-intensive infrastructure.

Keywords

waste heat,
source-sink matching,
district heating,
Slovenia,
heat pump,
economic screening,
heat reuse

1 Introduction

1.1 Waste heat as a system-level energy resource

Waste heat is an unavoidable consequence of energy conversion and industrial activity, but its existence does not imply that it can be used economically. The practical value of a waste-heat source depends on its temperature, thermal capacity, temporal availability, spatial relation to heat demand and the infrastructure required for recovery and delivery. Consequently, the theoretical waste-heat availability, technically recoverable heat and economically usable heat, represent different quantities and should not be treated interchangeably (Brueckner et al., 2014; Forman et al., 2016; Papapetrou et al., 2018; Woolley et al., 2018).

Industrial waste-heat studies have focused traditionally on energy-intensive manufacturing sectors, including ferrous and non-ferrous metallurgy, chemicals, mineral processing, paper production and other high-temperature processes (Brueckner et al., 2014; Forman et al., 2016; Papapetrou et al., 2018). Historically, these activities generated large concentrated heat flows, because substantial quantities of primary energy were converted at elevated process temperatures.

The structure of industrial energy use, however, is not static. Over several decades, rising energy costs, process optimisation, environmental requirements and energy-efficiency regulation have strengthened incentives for equipment modernisation, heat integration and the recovery of process energy. In many conventional process industries, an additional advantage is that significant thermal demand is present on the same industrial site. Recovered energy can therefore often be redirected internally for preheating, drying, steam generation, process water heating, or other thermal loads (Papapetrou et al., 2018; Woolley et al., 2018).

This historical development is relevant for the interpretation of waste heat as an energy resource. Technically available heat does not become useful merely because it exists. Its utilisation becomes more likely when the technological capability, economic incentives and regulatory conditions develop simultaneously. Industrial modernisation has therefore reduced specific energy consumption in many applications, and increased the internal use of recoverable energy where process conditions permit. The remaining waste-heat resource is, consequently, determined

not only by the production volume, but also by the degree of energy integration already achieved within the process.

Where internal reuse is not possible or sufficient, external heat demand becomes necessary. District-heating systems are particularly relevant, because they aggregate the spatially concentrated demand and can connect otherwise independent thermal sources and consumers. The feasibility of such integration nevertheless remains source- and site-specific. Previous studies have shown that spatial proximity, temperature compatibility and temporal matching influence both the technically usable potential and economic performance strongly (Bühler et al., 2017, 2018).

1.2 Waste-heat utilisation in the Slovenian context

Slovenia combines geographically dispersed waste-heat sources with an established, but heterogeneous district-heating sector. In 2024, 122 heat distribution systems operated in 68 municipalities, supplying heat to more than 150,000 consumers. This infrastructure provides the potential for external heat utilisation, but the national aggregate statistics alone cannot determine whether individual sources and sinks are technically compatible.

A national assessment must therefore avoid two simplifying assumptions. The aggregate sectoral energy consumption cannot be converted directly into recoverable waste heat without information on the process conditions and existing internal recovery, and an identified waste-heat source cannot be considered usable independently of the receiving demand.

This distinction is especially relevant in a small and spatially heterogeneous energy system. A nationally modest source can be important to an individual local network, while a larger source may have limited value when no suitable sink is nearby. The relevant scale of assessment is therefore often regional or site-specific rather than purely national.

1.3 Data Centres as an Emerging Waste-Heat Source and Objective of the Paper

The transition towards a more digital economy introduces a new class of energy-intensive infrastructure. Data centres consume substantial amounts of electricity, most of which is, ultimately, converted into heat that must be removed continuously (Wahlroos et al., 2017; Yuan et al., 2025). Unlike many conventional process industries, however, data centres generally have little internal thermal demand, and therefore depend on external heat sinks to use the recovered heat.

This makes them particularly relevant from a planning perspective. For new facilities, the location, cooling architecture and external heat integration can still be influenced before a long-lived infrastructure is fixed. Proximity to a suitable heat demand can therefore be considered alongside access to the electricity grid, telecommunications infrastructure, land availability and cooling requirements.

The European Energy Policy reflects this issue increasingly. Directive (EU) 2023/1791 and the associated reporting framework strengthen the consideration of data-centre heat recovery, subject to technical and economic feasibility (European Parliament and Council of the European Union, 2023; European Commission, 2024).

Data centres are examined in this paper, not because they currently represent the largest waste-heat resource in Slovenia, but because they constitute an emerging form of energy-intensive infrastructure, for which several decisive source–sink variables can still be influenced during the project’s development.

The paper develops a source–sink screening framework for the Slovenian heat-supply context, formulates an economic assessment based on consistent system boundaries and the cost of the heat supply actually displaced, and applies the framework quantitatively to the current and prospective role of data-centre waste heat in Slovenia.

2 Waste Heat as a System Resource

Waste heat is not a uniform energy source. Its practical value depends on the physical characteristics of the rejected heat, the operating conditions of the source process, and the requirements of the receiving heat demand. The temperature provides an initial indication of heat quality and influences the recovery technology strongly, but thermal capacity, annual availability, temporal profile, heat-transfer medium, continuity of operation and location are equally relevant (Brueckner et al., 2014; Papapetrou et al., 2018; Woolley et al., 2018; Bühler et al., 2017, 2018; Jouhara et al., 2018).

A system-level assessment must therefore distinguish between source characterisation and utilisation potential. Two sources with similar annual rejected energy can have very different practical values if they differ in temperature, continuity, location, or compatibility with nearby demand (Table 1).

2.1 Classification of Waste Heat

Waste heat can be classified using several complementary criteria. The temperature is the most direct indicator of thermodynamic quality. Reviews of industrial waste-heat recovery commonly distinguish low-, medium-, and high-temperature sources, although numerical boundaries vary across applications (Brueckner et al., 2014; Papapetrou et al., 2018; Jouhara et al., 2018). For screening purposes, the following ranges are used:

- low-temperature waste heat: below approximately 40 °C;
- medium-temperature waste heat: approximately 40–100 °C;
- high-temperature waste heat: above approximately 100 °C.

These ranges are engineering screening categories rather than strict thermodynamic boundaries. Low-temperature heat generally requires temperature upgrading for conventional district heating or industrial applications. Medium-temperature heat can support process preheating, return-line integration, heat-pump upgrading, or direct use in lower-temperature systems. High-temperature sources offer a wider range of direct recovery options, and can also enable steam production or power recovery when the temperature and thermal capacity are sufficient (Table 2).

The thermal capacity describes the instantaneous magnitude of the source. If $Q_{\text{source}}(t)$ denotes source thermal power, the corresponding annual rejected energy is

$$E_{\text{source}} = \int_0^{8760} Q_{\text{source}}(t) dt \quad (1)$$

The annual energy alone does not describe usability. A nearly continuous source and an intermittent high-power source can deliver the same annual energy while requiring different strategies for recovery, storage and integration.

Temporal availability should therefore be treated as a separate source characteristic. Waste-heat sources can be continuous, cyclic, production-dependent, intermittent, or seasonal. The operating profile determines whether the source availability coincides with the heat demand at the receiving end.

The heat-transfer medium also affects recoverability. Waste heat can occur in cooling water, process liquids, steam, exhaust gases, ventilation air, or other process streams. Liquid streams generally simplify the heat exchange and transport, while gaseous, contaminated, or chemically aggressive streams can require larger heat-transfer surfaces, intermediate circuits, or specialised materials (Jouhara et al., 2018).

Table 1: Principal characteristics of waste-heat sources relevant to utilisation

Characteristic	Parameter	Relevance
Temperature	T_{source}	Determines the heat quality and required temperature upgrading
Thermal capacity	$Q_{\text{source}}(t)$	Determines the instantaneous contribution to a heat sink
Annual availability	E_{source}	Indicates the total annual thermal energy available
Temporal profile	Operating profile	Determines coincidence with the heat demand
Heat-transfer medium	Liquid, gas, vapour, air, other	Affects the recovery and heat-exchanger configuration
Continuity	Continuous, cyclic, intermittent, seasonal	Affects the utilisation and storage requirements
Location	Source coordinates and distance to the sink	Determines the transport and connection requirements

The location determines the practical relevance of low- and medium-temperature heat, because external use requires a dedicated thermal transport infrastructure. Increasing the source–sink separation generally increases the pipeline investment, pumping requirements and thermal losses. Spatial studies of industrial excess heat, therefore, combine source characteristics with the location of potential users (Bühler et al., 2017, 2018).

Table 2: Indicative temperature classification of waste heat

Temperature class	Indicative range	Typical sources	Typical utilisation routes
Low temperature	<40 °C	Cooling water, refrigeration, wastewater and conventional cooling systems	Heat pumps, low-temperature heating and preheating
Medium temperature	40–100 °C	Warm cooling water, compressors, condensers, process cooling	District heating, process preheating and heat pumps
High temperature	>100 °C	Furnaces, kilns, exhaust gases, high-temperature process streams	Direct process heat, steam production, district heating and power recovery, where appropriate

Temperature classification provides only the first screening step. The recovery technology must be selected based on the source temperature, sink temperature, source capacity, operating profile and source–sink distance.

2.2 Theoretical, Technical and Economic Potential

Waste-heat assessments must distinguish between the heat rejected by a process and the fraction that can be recovered and used. Regional and national studies commonly separate the theoretical, technical and economic potential (Brueckner et al., 2014; Papapetrou et al., 2018):

$$E_{\text{theoretical}} \geq E_{\text{technical}} \geq E_{\text{economic}} \quad (2)$$

The theoretical potential represents the thermal energy rejected within the selected system boundary. For rejected thermal power Q_{rejected} ,

$$E_{\text{theoretical}} = \int_0^{8760} Q_{\text{rejected}}(t) dt \quad (3)$$

This quantity describes the gross thermal stream leaving the process, and does not imply technical recoverability or practical use.

The technical potential is the fraction that can be recovered under technically feasible operating conditions:

$$E_{\text{technical}} = \int_0^{8760} Q_{\text{recoverable}}(t) dt$$

$$Q_{\text{recoverable}}(t) \leq Q_{\text{rejected}}(t) \quad (4)$$

The technical recoverability depends on the process outlet-temperature limits, heat-transfer characteristics, heat-carrier properties, source variability, heat-exchanger constraints, required temperature upgrading, and the availability of a technically compatible sink. Sector- and temperature-specific analyses show that this step can reduce gross waste-heat estimates substantially (Papapetrou et al., 2018).

The economic potential is the technically recoverable fraction for which recovery and delivery remain economically preferable to the relevant alternative heat supply. It depends on the recovery equipment, temperature upgrading, thermal transport, connection infrastructure, auxiliary electricity, operation and maintenance, and, where applicable, the contractual value assigned to the source heat.

Economic potential is therefore not an intrinsic property of the source. Changes in electricity prices, investment cost, annual utilisation, heat demand, or the cost of alternative heat production can alter the economically usable fraction without changing the physical source itself.

National or regional aggregation should therefore be interpreted cautiously. Summing the estimated process heat losses can indicate the gross resource magnitude, but it can overstate the amount that can be contributed to an actual heat-supply system (Brueckner et al., 2014; Papapetrou et al., 2018). A defensible assessment must establish the source–sink compatibility before evaluating the economic feasibility.

2.3 Source–Sink Matching Framework

The transition from technically recoverable heat to usable heat requires simultaneous evaluation of the source and the receiving demand. The framework used here considers four dimensions: temperature compatibility, capacity compatibility, temporal coincidence and spatial proximity (Woolley et al., 2018; Bühler et al., 2017, 2018; Dorotić et al., 2022).

Temperature compatibility

The source temperature must be compared with the temperature required by the receiving system. A simplified temperature lift is

$$\Delta T_{\text{lift}} = T_{\text{sink}} - T_{\text{source}} \quad (5)$$

Direct heat exchange can be possible when the source temperature exceeds the required sink temperature by a sufficient margin. Temperature upgrading is required if the source temperature is lower.

For heat-pump integration, a larger temperature lift generally reduces COP and increases electricity consumption. The same source can therefore have different values in different receiving systems.

Capacity compatibility

At any time t , the directly usable heat cannot exceed either the available source power or simultaneous demand:

$$Q_{\text{use}}(t) = \min[Q_{\text{source}}(t), Q_{\text{sink}}(t)] \quad (6)$$

Nominal capacities alone are therefore insufficient for sizing. Oversizing relative to the maximum source output can reduce the annual utilisation if the receiving demand is low for much of the year.

Temporal compatibility

The annual usable heat is

$$E_{\text{use}} = \int_0^{8760} Q_{\text{use}}(t) dt \quad (7)$$

$$E_{\text{use}} \leq E_{\text{source}} \quad (8)$$

A simple utilisation indicator is

$$f_{\text{use}} = \frac{E_{\text{use}}}{E_{\text{source}}} \quad (9)$$

A source with a high theoretical or technical potential can still have a low utilisation fraction if heat is available when the demand is absent. Short-term storage can reduce short-duration mismatches, but does not necessarily resolve a seasonal imbalance.

Spatial compatibility

External utilisation requires thermal transport between the source and the sink. The source–sink distance can be denoted as

$$d = d(\text{source}, \text{sink}) \quad (10)$$

Increasing the distance generally raises the pipeline investment, pumping requirements and heat losses. The economic effect also depends on the thermal capacity, operating hours, temperature level and the physical connection route.

A straight-line distance alone is therefore insufficient. The practical feasibility can depend on the road and utility corridors, the terrain, property constraints, network geometry and the feasible hydraulic connection point.

The temperature, capacity, time and distance must be considered jointly. A large source can have limited value if it is remote from the demand; a nearby source can remain unattractive if it requires excessive temperature upgrading; and a technically compatible source can still achieve low annual utilisation if its operating profile does not coincide with the demand.

Figure 1 summarises the framework developed in Section 2, showing how the waste-heat source characteristics and receiving-sink requirements are filtered progressively through source–sink matching, technical recovery and integration and economic screening, to distinguish the theoretical potential from the technically recoverable and economically usable heat.

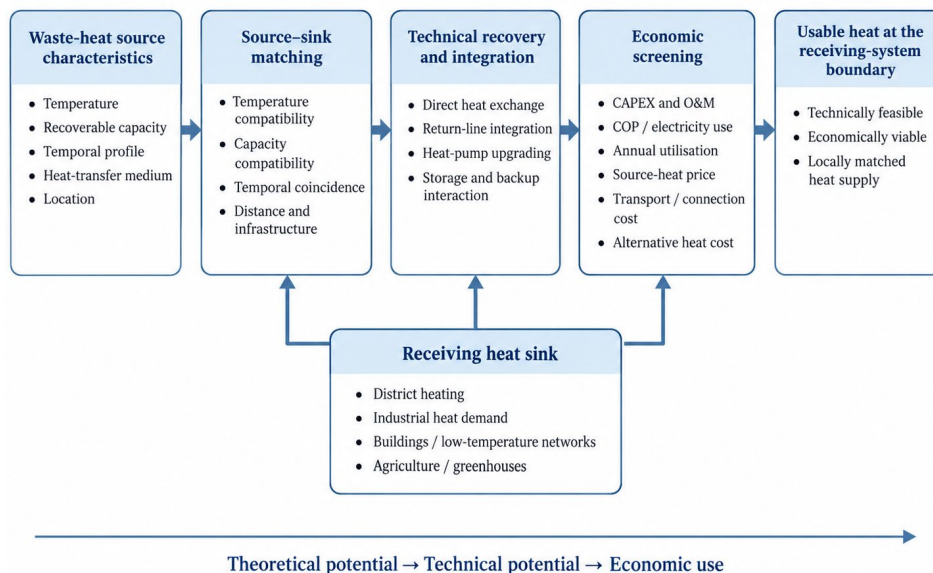


Figure 1: Source–sink matching and economic screening framework for waste-heat utilisation

3 Waste-Heat Sources and Heat Sinks in Slovenia

The national statistics describe the sectoral energy use and infrastructure more reliably than site-level waste-heat flows. The purpose of this section is therefore to identify the relevant source categories and potential heat sinks in Slovenia, rather than to derive a national total for waste heat. Quantitative recovery estimates require site-level information on temperature, flow, operating profile and location.

3.1 Main Categories of Waste-Heat Sources in Slovenia

Industrial processes

Industry remains one of the most important categories of potential waste-heat sources in Slovenia. In 2018, manufacturing accounted for 82% of the final energy consumption in the industrial activities covered by the national statistics. Detailed energy-use data were reported for food production, paper and paper products, chemicals and chemical products, non-metallic mineral products and basic metals. In almost all of these activities, heat production accounted for the largest share of energy use; basic metals were the main exception, due to the importance of electrochemical processes (Statistical Office of the Republic of Slovenia, 2019).

The technical characteristics of industrial waste heat vary substantially between sectors and processes. High-temperature sources can include furnaces, kilns, dryers and exhaust streams, whereas cooling circuits, condensers and process-water systems generally provide lower-temperature heat (Papapetrou et al., 2018; Jouhara et al., 2018). The operating profiles also differ between continuous and batch production. Site-specific data are therefore required before industrial energy consumption can be translated into recoverable heat.

Power and combined heat and power plants

Thermal power generation and combined heat and power plants can provide residual heat from cooling systems, condensers and flue gases. In CHP systems, however, the useful cogenerated heat is already an energy product, and must be separated from the residual waste heat to avoid double-counting.

The recoverable residual fraction depends on the plant configuration, operating regime and existing heat-recovery equipment. Electricity production or fuel consumption alone is therefore insufficient for estimating usable waste heat.

Refrigeration and cooling systems

Refrigeration and cooling systems reject heat through condensers and cooling circuits. The relevant applications include food processing, cold storage, logistics, supermarkets and other facilities with substantial cooling demand.

These sources are typically low- to medium-temperature and can operate for long periods, but their value depends on their proximity to a suitable heat sink and on the coincidence between the cooling demand and heat demand.

Wastewater

Wastewater represents a distributed low-temperature heat source. In 2023, 256.4 million m³ of wastewater entered the Slovenian public sewerage system, of which 185.7 million m³ was treated (Statistical Office of the Republic of Slovenia, 2024). The total volume includes sanitary wastewater, industrial discharges, infiltration, rainwater and other flows, so it cannot be converted directly into recoverable thermal energy.

Wastewater heat recovery requires site-specific information on the flow, temperature, treatment configuration and proximity to demand. Treatment plants and major sewer collectors are therefore more relevant screening locations than the national aggregate wastewater volume.

Commercial and service-sector cooling

Commercial and service activities can generate recoverable heat from cooling, refrigeration and ventilation systems. The Slovenian service-sector energy use was approximately 16,000 TJ in 2024, with trade, accommodation and food services, health and social care, education, transport and storage, information and communication and public administration among the principal activities (Statistical Office of the Republic of Slovenia, 2025a).

These statistics identify sectors where cooling and building-services loads can be significant, but they do not quantify waste heat directly. The practical potential remains building and site-specific.

Data centres

Data centres form a smaller, but increasingly relevant source category. In 2023, 41 surveyed Slovenian data centres had a combined rated electrical power of 7,554 MW and consumed 36,833 GWh of electricity. Most facilities were small: 61% had rated electrical power below 100 kW, while only 7% were rated at 1 MW or more (Statistical Office of the Republic of Slovenia, 2025b).

The existing stock is therefore fragmented, but the data centres are relevant because their electricity consumption is concentrated, and their waste-heat characteristics depend strongly on the cooling architecture (Table 3).

Table 3: Indicative characteristics of the principal waste-heat source categories in Slovenia

Source category	Typical temperature level	Typical continuity	Indicative scale	Potential use
High-temperature industrial processes	Medium to high	Process dependent	Medium to large	Direct process use, district heating, steam, or power recovery
Industrial process cooling and condensation	Low to medium	Process dependent	Small to large	Heat pumps, process preheating, district heating
Residual heat from power and CHP plants	Low to medium/high	Plant-operation dependent	Large	District heating, process heat
Refrigeration and cooling systems	Low to medium	Often long operating periods	Small to medium	Building heat, district heating, local heat recovery
Wastewater and treated effluent	Low	Relatively continuous	Site dependent	Heat pumps, low-temperature networks
Commercial and service-sector cooling	Low	Building-operation dependent	Small to medium	Local building heat, district heating where concentrated
Data centres	Low to medium	Relatively continuous	Small to potentially large	Heat pumps, return-line integration, district heating

The Table provides a screening classification rather than a quantified national inventory. The source temperature, capacity, continuity and location must be verified at the site level.

3.2 Main Heat Sinks

District heating

District-heating systems are the most evident large external heat sinks, because they aggregate the thermal demand and already provide a heat distribution infrastructure. External waste heat can substitute part of conventional heat production through direct exchange, return-line integration, or heat-pump upgrading.

The main limitation is seasonal demand. The minimum summer load and the load-duration curve are therefore more informative for waste-heat integration than the annual heat consumption alone.

Industrial process heat

Industrial sites can act as sources and sinks simultaneously. Internal recovery is generally advantageous, because it avoids off-site transport, while cross-site exchange is relevant where neighbouring facilities have compatible temperature levels and operating schedules.

Public and commercial buildings

Hospitals, hotels, offices, educational complexes, shopping centres and similar buildings provide space-heating and domestic hot-water demand. The individual loads are smaller than major district-heating systems, but building clusters can provide useful local sinks, especially where the year-round hot-water demand improves utilisation.

Low-temperature heat networks

Low-temperature and ambient-loop networks can improve compatibility with low-grade waste heat by reducing the required temperature lift. Their value lies in improved source–sink matching rather than in increasing source availability (Puschnigg et al., 2021).

Agriculture and greenhouses

Greenhouses, drying, aquaculture and related agricultural applications can use low- and medium-temperature heat where suitable demand is located near the source. Their relevance is therefore primarily local.

Thermal storage

Thermal storage is not an independent final sink, because it does not create an annual heat demand. Short-term storage can reduce the hourly mismatch and support heat-pump operation, but it cannot compensate for a persistent seasonal surplus or insufficient annual demand.

3.3 District Heating in Slovenia

District heating is an established component of the Slovenian heat-supply system. In 2024, 122 heat-distribution systems operated in 68 municipalities through 51 distributors (Agencija za energijo, 2025). Distributors handled 1,955.7 GWh of heat for building heating and cooling, domestic hot water and industrial steam processes. Final consumers received 1,592.7 GWh, while the reported distribution losses amounted to 363.0 GWh. The systems supplied 156,754 consumers (Agencija za energijo, 2025).

The five systems with the longest recorded heat distribution networks in 2024 are Ljubljana, the Šaleška Valley, Maribor, Hrastnik, and Ravne na Koroškem. Their principal physical indicators are summarised in Table 4. The selection is based solely on network length, and does not constitute a ranking by annual heat demand, generation capacity, or the waste-heat absorption potential (Figure 2).

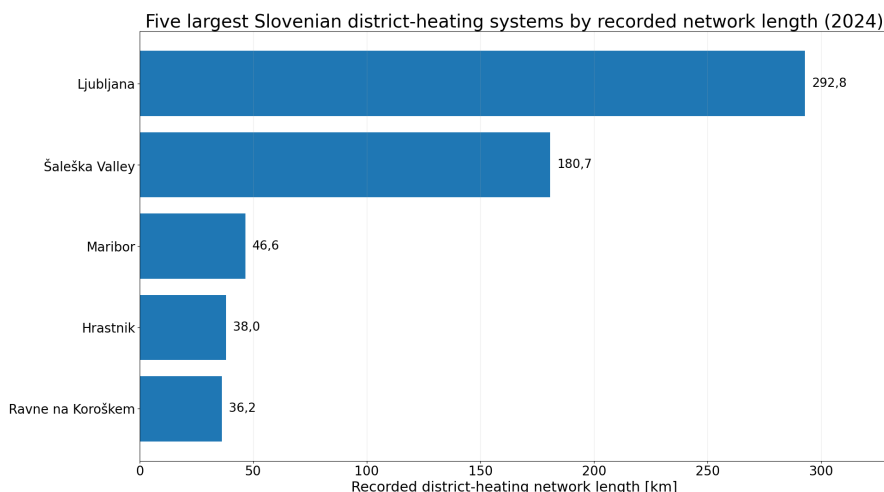


Figure 2: Five Slovenian district-heating systems with the longest recorded distribution networks in 2024.

Source: Agency for Energy (Agencija za energijo, 2025).

Table 4: Selected Slovenian district-heating systems used for system-scale comparison

System	Network length [km], 2024	Heat consumers, 2024	Published connection capacity [MW]	Capacity reference year
Ljubljana	292.8	71,772	1,177.4	2025
Šaleška Valley	180.7	12,220	184.0	2026
Maribor	46.6	16,165	114.40	2019
Hrastnik	38,0	1,693	n.a.	—
Ravne na Koroškem	36.2	2,674	33.5844	2019

Source: Network length and consumer data: Agencija za energijo (2025). Connection capacities: the individual operator and municipal sources are cited below.

The network length and consumer data come from the harmonised national source (Agencija za energijo, 2025). The aggregate connection capacity is not available in one comparable National Table, so the values originate from the latest public sources identified for individual systems: Ljubljana (Javno podjetje Energetika Ljubljana, 2026), the Šaleška Valley (Komunalno podjetje Velenje, 2026), Maribor (Mestna občina Maribor, Nadzorni odbor, 2021) and Ravne na Koroškem (Občina Ravne na Koroškem, 2023). For Hrastnik, a consistent aggregate connection-capacity value was not identified; the operator reports plant and system

characteristics instead (Petrol d.d., 2026). The generation capacity is therefore not substituted for connection capacity.

The five systems together account for 594.3 km of the recorded distribution network. Ljubljana and the Šaleška Valley account for 473.5 km, or approximately 79.7% of the group's combined network length. These figures illustrate the differences in the physical scale, but do not quantify the waste-heat absorption potential.

For waste-heat integration, the critical system parameters are the hourly heat demand, the load-duration curve, the minimum summer load, the supply and return temperatures, the network losses, pumping requirements, feasible hydraulic connection points, and the distance and route between the source and the network. The existing base-load, peak and backup production must also be considered.

A harmonised comparison of annual heat delivery for the five individual systems is not included, because comparable values using a common reporting year and system boundary were not available in the reviewed sources. Combining operator-specific annual data from different years or reporting conventions would imply a degree of comparability that the data do not support.

Slovenian district-heating systems should therefore be treated as heterogeneous potential heat sinks. Large networks may provide greater absorption opportunities, but smaller systems can also be attractive when the source and sink are close, temperatures are compatible and the demand is sufficiently stable.

4 Data Centres as an Emerging Waste-Heat Source

Data centres differ from many conventional waste-heat sources, because a large share of their electrical input ultimately manifests as heat that must be removed continuously. Their practical value as heat sources depends primarily on the cooling architecture, recoverable temperature, and compatibility with the receiving heat demand (Wahlroos et al., 2017; Yuan et al., 2025; Oltmanns et al., 2020; Feike et al., 2021).

4.1 Cooling Technologies and Recoverable Temperature Levels

Air cooling

Conventional air-cooled data centres transfer heat from information technology equipment to the room air, and, subsequently, to air- or water-based cooling systems. Recoverable temperatures around 25–35 °C are representative of room-air-based recovery configurations, although the actual values depend on the equipment and operating conditions (ASHRAE, 2023; Oltmanns et al., 2020).

Chilled-water systems

Chilled-water architectures provide a convenient hydraulic interface for external heat recovery, but the available water temperature is usually low. A representative useful recovery interface lies approximately in the 15–30 °C range (ASHRAE, 2023; Oltmanns et al., 2020).

Direct-to-chip liquid cooling

Direct-to-chip cooling transfers heat from high-heat-flux components to a liquid circuit, eliminating the intermediate heat-transfer steps and enabling higher coolant temperatures.

ASHRAE liquid-cooling classes include W17, W27, W32, W40, W45 and W+, where the number denotes the maximum facility supply-liquid temperature and W+ represents operation above 45 °C (ASHRAE, 2021, 2023). These classes describe the allowable facility supply temperatures, not the district-heating delivery temperatures.

Depending on the system configuration and heat load, return water temperatures of approximately 35–50 °C can be achieved (Oltmanns et al., 2020; Feike et al., 2021).

Warm-water liquid cooling

Warm-water liquid cooling operates deliberately at elevated coolant temperatures, and is therefore particularly favourable for heat recovery. (Oltmanns, et al., 2020) reported a recoverable heat source at approximately 45 °C in a hot-water-cooled HPC system, while (Feike, et al., 2021) evaluated heat-pump integration for a system operating at approximately 40–45 °C. Other high-temperature data-centre studies consider source-water temperatures of approximately 50–60 °C (Wang et al., 2024). The achievable temperature remains design dependent.

Table 5: Indicative data-centre cooling concepts and recoverable heat-temperature levels

Cooling concept	Indicative recoverable temperature	Implication for district heating
Air cooling / room-air recovery	~25–35 °C	Large temperature lift; a heat pump is normally required
Chilled-water architecture	~15–30 °C at a useful water interface	Technically usable, but a relatively high heat-pump electricity demand
Direct-to-chip liquid cooling	~35–50 °C return, design dependent	Reduced temperature lift; suitable heat-pump source
Warm-water liquid cooling	~45–60 °C return, design dependent	Favourable for return-line integration or smaller heat-pump lift

The ranges in Table 5 are screening values rather than design specifications. The actual values depend on the cooling-system configuration, coolant flow, and operating load (Figure 3).

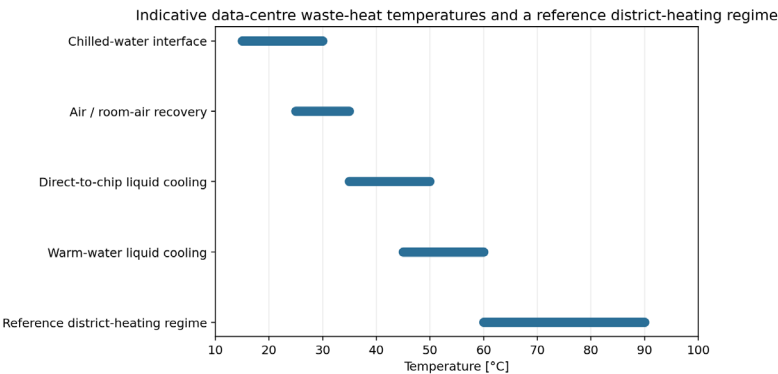


Figure 3: Indicative temperature ranges of data-centre waste-heat sources compared with a demanding 90/60 °C district-heating reference regime.

4.2 Integration Pathways

The integration pathway depends primarily on the relation between the recoverable source temperature and the temperature required by the receiving system.

Direct heat exchange

Direct heat exchange is possible when the available source temperature exceeds the required sink temperature by a sufficient margin. This condition is uncommon for conventional high-temperature district heating, but can occur in low-temperature networks or during periods of reduced network temperature.

Return-line integration

When the recoverable temperature approaches the district-heating return temperature, the data-centre heat can preheat the return line, reducing the duty of a subsequent heat-pump stage or a conventional heat source. (Feike, et al., 2021) demonstrated this concept using heat from a hot-water-cooled HPC system.

Heat-pump upgrading

When the source temperature is below the required delivery temperature, a heat pump provides the necessary temperature boost. The higher source temperature and lower sink temperature reduce the temperature lift and generally improve the coefficient of performance.

A GEA RedGenium operating point with a secondary source-water circuit of 37/32 °C and a heating-water circuit of 70/90 °C reports COP values of approximately 4.27–4.34 (GEA Group, 2026). A SABROE HeatPAC operating point with a cold-side water circuit of 40/35.9 °C and a hot-side circuit of 40/85 °C reports a COP of approximately 4,4 (Johnson Controls / SABROE, 2024).

When the source temperatures are lower or the target temperatures are higher, two-stage, cascade, or other advanced heat-pump configurations can become

advantageous. High-temperature heat-pump studies for data-centre recovery consider delivery temperatures up to approximately 120 °C (Wang et al., 2024), while trans critical CO₂ systems have also been analysed (Li et al., 2021).

Table 6: Indicative district-heating integration pathways according to the data-centre heat temperature

Recoverable heat temperature	Typical integration pathway	Main technical consideration
~15–30 °C	High-lift heat pump	High compressor electricity demand; a large source flow may be required
~25–40 °C	Heat-pump upgrading to the required delivery temperature	Conventional low-temperature waste-heat recovery case
~35–50 °C	Heat pump and/or return-line preheating	Reduced temperature lift and improved heat-pump performance
~45–60 °C	Return-line integration; booster heat pump where required	Favourable match to lower-temperature networks
≥60 °C	Direct exchange, where network conditions permit; booster heat pump, where required	Hydraulic separation, delivery temperature, and network control

The ranges are indicative rather than rigid thresholds, because the heat-exchanger approach temperatures, network operating conditions and seasonal variations can shift the preferred integration pathway (Table 6).

Thermal storage and peak supply

Data-centre heat is generally better suited to base-load or intermediate-load supply than to peak demand. Short-term storage can reduce the hourly mismatch and heat-pump cycling, while the existing or dedicated peak and backup sources remain necessary during high-load periods or source outages. Storage does not eliminate the persistent seasonal surplus, so the recovery capacity should be sized against usable demand rather than the maximum recoverable source power.

4.3 Heat-Pump Energy Balance

In the following analysis, recoverable waste heat refers to the thermal energy recovered from the data-centre cooling system at the heat pump's source side. Useful delivered heat refers to the thermal energy supplied at the heat-pump outlet or, more generally, at the receiving-system boundary. For heat-pump integration, useful

delivered heat therefore consists of the recovered source heat and the electrical energy supplied to the heat pump.

Where a heat pump is required, the coefficient of performance in the heating mode is defined as

$$COP = \frac{Q_{DH}}{P_{el,HP}} \quad (11)$$

where COP is the heat-pump coefficient of performance in the heating mode, Q_{DH} is the useful thermal power delivered at the heat-pump outlet, and $P_{el,HP}$ is the electrical power input to the heat pump.

Neglecting the auxiliary losses outside the heat-pump control volume,

$$Q_{DH} = Q_{WH} + P_{el,HP} \quad (12)$$

where Q_{WH} denotes the thermal power recovered from the data-centre cooling system.

Combining (11) and (12) gives

$$Q_{WH} = Q_{DH} \left(1 - \frac{1}{COP}\right) \quad (13)$$

and

$$P_{el,HP} = \frac{Q_{DH}}{COP} \quad (14)$$

The formulation is independent of the absolute data-centre size, and can therefore be normalised to 1 MW_{th} of useful heat output.

For the illustrative reference value COP of 4.3, equations (13) and (14) give

$$Q_{WH} = 0,767 Q_{DH}$$

and

$$P_{\text{el,HP}} = 0,233 Q_{\text{DH}}$$

Thus, each 1 MW_{th} of useful delivered heat requires approximately 0.767 MW_{th} of recovered data-centre heat and 0.233 MW_{el} of heat-pump electricity (Figure 4).

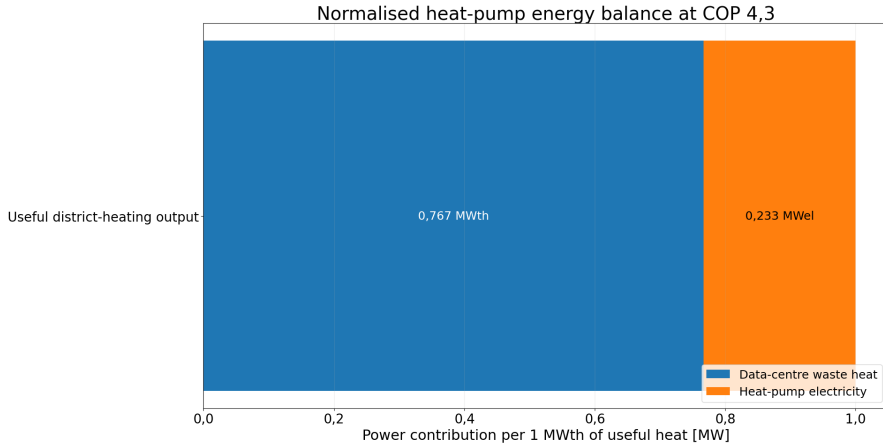


Figure 4: Normalised heat-pump energy balance at COP = 4.3 per 1 MW_{th} of useful delivered heat.

The COP value of 4.3 is used only as a reference scenario. It is consistent with the selected manufacturer's operating points, but is not a validated design COP for a particular data centre or district-heating system. The actual performance depends on the source and sink temperature profiles, heat-pump configuration, part-load behaviour and auxiliary consumption.

4.4 Temporal Characteristics of Data-Centre Heat

Data-centre waste heat is comparatively continuous, whereas the district-heating demand is strongly seasonal. This mismatch can limit the annual utilisation, even when the source availability is high (Wahlroos et al., 2017; Olthmanns et al., 2020; Feike et al., 2021; Li et al., 2021; Jürgens et al., 2024).

For a simplified annual assessment, the operation can be represented by the equivalent full-load hours. For an installed useful heat-output capacity Q_{HP} ,

$$E_{\text{DH}} = Q_{\text{HP}} h_{\text{eq}} \quad (15)$$

where h_{eq} denotes the equivalent full-load hours.

At constant reference COP,

$$E_{WH} = E_{DH} \left(1 - \frac{1}{COP}\right) \quad (16)$$

and

$$E_{el,HP} = \frac{E_{DH}}{COP} \quad (17)$$

For a normalised useful heat-output capacity of 1 MW_{th} and a COP of 4.3:

Table 7: Normalised annual energy balance per 1 MW_{th} of useful heat-pump output at COP = 4.3

Equivalent full-load hours [h/a]	Useful delivered heat [GWh/a]	Data-centre waste heat [GWh/a]	Heat-pump electricity [GWh/a]
2.000	2,000	1,535	0,465
3.000	3,000	2,302	0,698
4.000	4,000	3,070	0,930

At 3,000 equivalent full-load hours, 1 MW_{th} of installed useful heat-output capacity therefore supplies 3,000 GWh/a, requiring approximately 2.302 GWh/a of recovered source heat and 0,698 GWh/a of heat-pump electricity (Table 7).

Equivalent full-load hours are useful for screening, but do not capture the actual temporal interaction between the source and the sink. Project design, therefore, requires hourly, or sub-hourly source and demand profiles, in which the seasonal mismatch, part-load COP, or storage operation affects utilisation materially.

5 General Economic Framework for Waste-Heat Utilisation

The economic assessment of waste-heat utilisation requires a system boundary that is consistent with the technical source–sink framework. The relevant quantity is not the nominal heat value at the source, but the cost of useful heat delivered to the receiving system. Recovery equipment, temperature upgrades, transport, connection infrastructure, auxiliary electricity, and operation and maintenance can all contribute

materially to this cost. Large-scale heat-pump projects also show that a substantial fraction of the investment can arise outside the heat-pump unit itself, including source-side equipment, civil works, piping and other balance-of-plant components (Pieper et al., 2018).

In the present framework, the economic system boundary extends from the recoverable waste-heat interface at the source to the point where useful heat is delivered to the receiving heat system. The costs downstream of this boundary are excluded, such as the existing district-heating distribution, retail billing, taxes and consumer-side charges. This distinction prevents a direct comparison between a generation or integration cost and a final household tariff, since the two quantities represent different system boundaries.

The resulting levelised cost should be interpreted as a screening indicator. Project-specific investment costs can vary substantially with the heat source, temperature level, capacity, distance, route conditions and connection requirements (Pieper et al., 2018). Technology catalogues can provide reference values where project-specific quotations are unavailable, but such values do not replace the engineering design or supplier data (Danish Energy Agency, 2026).

5.1 Cost Components

The levelised cost of useful heat recovered from a waste-heat source can be decomposed into the components of recovery, upgrading, transport, integration and operation. Using a common delivery boundary,

$$LCOH_{WH} = C_{\text{recovery}} + C_{\text{upgrade}} + C_{\text{transport}} + C_{\text{integration}} + C_{\text{operation}} \quad (18)$$

where all the terms are expressed per unit of useful heat delivered at the receiving-system boundary.

For a project using a heat pump and dedicated connection infrastructure, a more explicit formulation is

$$LCOH_{WH} = \frac{(CAPEX_{rec} + CAPEX_{HP} + CAPEX_{pipe} + CAPEX_{conn})CRF + OPEX_{fix}}{E_{use}} + OPEX_{var} + C_{el} + C_{source} \quad (19)$$

where $CAPEX_{rec}$ is the source-side recovery investment; $CAPEX_{HP}$ is the heat-pump investment; $CAPEX_{pipe}$ is the thermal transport investment; $CAPEX_{conn}$ is the receiving-system connection and hydraulic integration; $OPEX_{fix}$ and $OPEX_{var}$ are the fixed and variable operation and maintenance costs; E_{use} is the net annual useful heat delivered at the selected receiving-system boundary after losses within that boundary; C_{el} is the specific heat-pump electricity cost; and C_{source} is the contractual cost assigned to the recovered waste heat.

The pumping electricity, transport losses and other auxiliaries must be represented consistently with this boundary, either explicitly, or within the corresponding variable-cost and energy terms.

The capital recovery factor is

$$CRF = \frac{r(1+r)^n}{(1+r)^n - 1} \quad (20)$$

where r is the real discount rate, and n is the economic lifetime in years.

The project investment boundary should extend beyond the heat-pump package itself. Pieper et al. (2018) showed for large-scale district-heating heat-pump projects that a substantial part of the total investment can arise from the source systems, civil works, piping and other project components. The reported allocation should not be transferred as a universal percentage to other projects, but it demonstrates why the heat-pump purchase cost alone is an insufficient proxy for the total project investment.

The transport cost is particularly site-dependent. The pipeline length, thermal capacity, pipe diameter, route conditions, operating temperature and utilisation all affect the specific cost of the delivered heat. A short connection between a source and an existing district-heating main can therefore have a substantially different cost

structure than that of an otherwise similar source located several kilometres from the receiving network.

The denominator E_{use} is equally important. The fixed investment is recovered over the useful heat actually delivered rather than over the theoretical annual heat available at the source. Low annual utilisation, therefore, increases the capital component of $LCOH_{\text{WH}}$, even if the installed capacity and source availability remain unchanged.

5.2 Heat-Pump Electricity Cost

For the heat-pump control volume defined by the useful heat output, the required compressor electricity per unit of useful heat delivered is $1/\text{COP}$. At a constant electricity acquisition price p_{el} , the corresponding specific electricity cost is

$$C_{\text{el}} = \frac{p_{\text{el}}}{\text{COP}} \quad (21)$$

Equation (21) shows directly why both electricity prices and heat-pump performance influence the waste-heat economics strongly. The same increase in electricity prices produces a larger increase in heating costs when COP is low than when COP is high.

The relationship also links the economic model to the source and sink temperatures. The COP should not be treated as an independent economic parameter: it is determined by the operating temperatures, heat-pump configuration and part-load behaviour (Pieper et al., 2021). A fixed COP is therefore appropriate only for a clearly identified reference scenario.

For screening purposes, sensitivity should, at a minimum, consider the electricity acquisition price, the heat pump COP, and the annual useful heat delivered, or the equivalent full-load hours. The electricity prices and COP affect the operating costs directly, whereas the annual utilisation affects primarily the specific contribution of fixed investment and fixed O&M.

If the installed thermal capacity is Q_{HP} and annual operation is represented by equivalent full-load hours h_{eq} ,

$$E_{\text{use}} = Q_{\text{HP}} h_{\text{eq}} \quad (22)$$

and the annualised capital component is

$$C_{\text{cap}} = \frac{CAPEX_{\text{tot}} CRF}{Q_{\text{HP}} h_{\text{eq}}} \quad (23)$$

where

$$CAPEX_{\text{tot}} = CAPEX_{\text{rec}} + CAPEX_{\text{HP}} + CAPEX_{\text{pipe}} + CAPEX_{\text{conn}}.$$

Equation (23) explains the strong economic importance of utilisation. An installation designed for a large nominal source capacity but used for relatively few hours can have a high specific capital cost, even where the waste heat itself has no contractual purchase price.

The equivalent full-load hours remain a simplified representation. A detailed feasibility analysis should use time-dependent electricity prices, heat-pump performance, and source–sink profiles where available. Hourly modelling of large heat pumps has been used to account explicitly for seasonal source temperatures, capacity constraints and variations in the COP (Pieper et al., 2019).

5.3 Cost of the Waste-Heat Source

Waste heat is described frequently as free, because it is a by-product of another process. This assumption is not generally valid from a project-economic perspective.

If the source owner provides recovered heat without a transfer payment,

$$p_{\text{WH}} = 0 \quad (24)$$

This does not imply that the useful heat delivered is free, as recovery, upgrading, transport, connection and operating costs still apply.

Where the source owner charges for recovered heat, the source term depends on the amount of source heat required per unit of useful heat. For the idealised heat-pump balance,

$$C_{\text{source}} = p_{\text{WH}} \left(1 - \frac{1}{\text{COP}} \right) \quad (25)$$

Equation (25) assumes that the contractual measurement boundary coincides with the waste-heat input to the heat pump, and that the additional losses between the commercial source boundary and the heat pump are negligible, or accounted for elsewhere.

For a more general project with recovery or transport losses, the source term can be written as

$$C_{\text{source}} = p_{\text{WH}} \frac{E_{\text{WH,purchased}}}{E_{\text{use}}} \quad (26)$$

Here, $E_{\text{WH,purchased}}$ denotes the thermal energy purchased at the contractual waste-heat transfer point. This form is preferable when the commercial transfer point, heat-pump source boundary and final delivery boundary do not coincide.

The source price can reflect different contractual arrangements. The source owner may provide heat at zero price, charge for it as an energy product, or contribute to the recovery infrastructure if the heat export reduces its own cooling requirement. Conversely, the receiving heat utility may finance the source-side recovery equipment in return for a lower long-term heat price. The economic value of waste heat is therefore both contractual and thermodynamic (Jerez Monsalves et al., 2024; Moser & Jauschnik, 2023).

No universal source price should be assigned to waste heat. Its acceptable value depends on the receiver's avoided heat-production cost, the investment allocation between the parties and any avoided cooling cost at the source.

5.4 Economic Decision Criterion

The economic viability should be evaluated against the cost of the heat supply that the waste heat actually displaces. The relevant condition is

$$LCOH_{WH} < C_{\text{alternative}} \quad (27)$$

where $C_{\text{alternative}}$ represents the comparable cost of supplying the same useful heat from the relevant alternative.

Depending on the receiving system, the alternative can be heat from a gas-fired boiler, biomass heat, heat from an existing or new CHP plant, purchased external heat, another large-scale heat pump, or another planned replacement technology.

The comparison must use consistent system boundaries. If $LCOH_{WH}$ includes the investment, fixed O&M and variable operation over the project lifetime, it should not be compared only with the fuel component of an alternative new-build technology. Conversely, if the decision concerns short-term dispatch against an already installed boiler, the relevant comparator can be the avoidable marginal cost rather than the full levelised cost of that boiler.

Two economic decisions should therefore be distinguished. Operational substitution refers to waste heat displacing variable production from an existing installed capacity. Investment substitution refers to waste-heat recovery, avoiding or replacing investment in another heat-production technology. For operational substitution, $C_{\text{alternative}}$ should represent the avoidable costs that vary with the output, including fuel, the relevant variable O&M, and, where applicable, the emission costs. For investment substitution, an annualised or levelised full cost of the alternative is the more appropriate benchmark.

The same principle explains why household heat tariffs are not suitable as the primary economic comparator. Retail tariffs may remain unchanged after a new source is introduced, covering network operations, fixed infrastructure, regulation, taxation and consumer billing. Economic attractiveness should therefore be

interpreted relative to the displaced heat-supply cost rather than the final consumer tariff.

5.5 Break-Even Waste-Heat Price

The contractual value of source heat can be expressed through a break-even condition. Let C_0 denote the levelised cost of useful heat excluding payment for the waste-heat source:

$$C_0 = \frac{CAPEX_{\text{tot}}CRF + OPEX_{\text{fix}}}{E_{\text{use}}} + OPEX_{\text{var}} + C_{\text{el}} \quad (28)$$

For the simplified heat-pump source-price formulation,

$$LCOH_{\text{WH}} = C_0 + p_{\text{WH}} \left(1 - \frac{1}{COP}\right) \quad (29)$$

The break-even source price is obtained by imposing

$$LCOH_{\text{WH}} = C_{\text{alternative}} \quad (30)$$

which gives

$$p_{\text{WH,max}} = \frac{C_{\text{alternative}} - C_0}{1 - \frac{1}{COP}} \quad (31)$$

The result represents the maximum price that can be paid per unit of source heat while keeping the recovered-heat option economically equivalent to the selected alternative, under the assumptions used to determine C_0 .

If $C_{\text{alternative}} \leq C_0 \Rightarrow p_{\text{WH,max}} \leq 0$. In that case, the project is not competitive, even when the waste heat itself is provided free of charge. The economic feasibility would then require lower capital and electricity costs, higher COP, higher utilisation, lower transport costs, or another improvement in the project configuration.

Conversely, a positive $p_{WH,max}$ indicates economic headroom that can, potentially, be allocated between the source owner and the heat utility. The resulting value is not a universal market value of waste heat. It is specific to the selected alternative, source–sink configuration, annual utilisation, electricity price, COP, transport distance, investment allocation and financial assumptions. It should therefore be interpreted as a project-specific negotiation boundary rather than as a nationally applicable waste-heat price.

6 Application to the Slovenian Context

Application of the source–sink framework to Slovenia requires distinguishing between theoretical heat generation, technically recoverable heat, and heat that can actually be delivered to a compatible sink. The national statistics support an order-of-magnitude assessment, but do not provide the spatial, thermal, and temporal resolution required for project-level feasibility.

For data centres, the available statistical basis allows a first national screening estimate. In 2023, 41 surveyed Slovenian data centres consumed 36,833 GWh of electricity and had a combined rated electrical capacity of 7,554 MW (Statistical Office of the Republic of Slovenia, 2025b). Since nearly all the electricity consumed ultimately appears as heat, the annual theoretical heat output is of the same order as electricity consumption.

Using an illustrative literature-based recovery envelope of 70–80% (International Energy Agency, 2025),

$$E_{WH,tech} = \eta_{rec} E_{el,DC} \quad (32)$$

With $\eta_{rec} = 0.70$ – 0.80 , Equation (32) gives approximately 25.8–29.5 GWh/a.

This range represents the technically recoverable source heat, not the national utilisation potential. The facilities are dispersed geographically; most are small, and the national statistics do not provide the source temperatures, cooling architectures, nearby heat demand, or feasible connection routes needed to determine the usable fraction.

If all the technically recoverable heat could be supplied to a suitable sink through a heat pump operating at the reference value $COP = 4.3$,

$$E_{DH} = \frac{E_{WH}}{1 - \frac{1}{COP}} \quad (33)$$

the corresponding useful-heat envelope would be approximately 33.6–38.4 GWh/a. This value indicates the technical scale only, and should not be interpreted as a forecast of the annual heat reuse.

6.1 Screening Criteria and Numerical Boundaries

Seven criteria are used for Slovenian screening: source temperature, recoverable thermal capacity, temporal availability, source–sink distance, heat-demand magnitude, the required temperature upgrading and the existing infrastructure.

Several criteria are effectively non-compensatory. Insufficient heat demand, an infeasible connection route, or an inability to achieve the required delivery temperature can prevent utilisation, regardless of the otherwise favourable source characteristics (Table 8).

Table 8: Technical screening criteria for Slovenian waste-heat projects

Criterion	Favourable	Conditional	Unfavourable
Source temperature	>45 °C or a small required lift	30–45 °C	<30 °C for conventional DH
Recoverable capacity	Well matched to the base or intermediate load	Partial utilisation expected	Exceeds the local usable demand strongly
Temporal availability	High coincidence with the sink demand	Moderate seasonal mismatch	Persistent mismatch
Source–sink distance	Short and technically simple connection	Moderate route length or complexity	Long or technically difficult connection
Heat-demand magnitude	High base-load absorption	Adequate only seasonally	Insufficient local heat demand
Expected COP	≈4 or higher	Approximately 3–4	Below 3
Existing infrastructure	Suitable network and electrical capacity available	Moderate adaptation required	Major new infrastructure required

The thresholds in Table 8 are screening values rather than design limits. The source temperature and expected COP indicate the likely difficulty of integration with conventional district heating, while the acceptable distance depends jointly on the thermal capacity, utilisation, route conditions and connection cost (Bühler et al., 2017, 2018). The project appraisal must therefore replace these screening categories with measured data on sources and sinks.

6 Realistic Project-Scale Scenarios

Aggregating the existing Slovenian data-centre stock into a single hypothetical heat source would be unrealistic, as the facilities are distributed spatially. Project-scale scenarios provide a more useful basis for examining future or expanded facilities.

Three useful delivered-heat capacities are considered: 5, 15, and 30 MW_{th}. They represent small, medium and relatively large recovery projects in the Slovenian context without assuming a hyperscale facility (Table 9).

At COP of 4.3, the heat-pump balance gives:

Table 9: Data-centre heat-recovery project scales at COP = 4.3

Useful heat output	Required DC source heat	Heat-pump electricity
5 MW _{th}	3.84 MW _{th}	1.16 MW _{el}
15 MW _{th}	11.51 MW _{th}	3.49 MW _{el}
30 MW _{th}	23.02 MW _{th}	6.98 MW _{el}

The annual useful heat depends on the utilisation. Continuous full-load operation throughout the year would be unrealistic for a district-heating sink with a strongly seasonal demand. A screening value of 3,000 equivalent full-load hours is therefore used to illustrate the annual scale, rather than as a universal utilisation assumption (Table 10).

Table 10: Annual useful heat at 3,000 equivalent full-load hours

Useful capacity	Annual useful heat
5 MW _{th}	15 GWh/a
15 MW _{th}	45 GWh/a
30 MW _{th}	90 GWh/a

The values show why the maximum theoretical source output should not be interpreted as the annual useful heat. Higher utilisation is possible where the receiving system provides sufficient base-load demand, but the published case studies also show strong dependence on the actual network load and operating conditions (Wahlroos et al., 2017; Socci et al., 2024).

6.3 Economic Screening Under Slovenian Conditions

Technical recoverability does not imply economic viability. The official Slovenian reference retail electricity price for an average non-household consumer in the second quarter of 2026 was 169.5 €/MWh, including VAT. For a VAT-registered project evaluated before recoverable VAT, the corresponding reference used here is 138.93 €/MWh (Ministry of Infrastructure and Energy, Portal Energetika, 2026). This value serves as a national screening input rather than a project-specific procurement price.

A complete recovery project includes more than the heat-pump package. Source-side recovery, hydraulic integration, piping, electrical connections and other balance-of-plant components can contribute materially to the total investment (Pieper et al., 2018; Danish Energy Agency, 2026). Three total-investment scenarios are therefore used: 800, 1,200, and 1,800 €/kW_{th}.

These are not quoted project costs in Slovenia. They represent progressively more demanding integration configurations for sensitivity analysis. The total CAPEX follows the investment boundary defined in Equation (19) and includes source-side recovery, heat-pump, piping and connection infrastructure.

Using a 20-year economic life, a 5% real discount rate, fixed O&M of 2,000 €/MW_{th}·a, variable O&M of 2 €/MW_{th}, and the electricity price above, the screening costs in Table 11 are calculated according to Equations (19)–(23).

The screening scenarios do not resolve source–sink distance, pipeline length and diameter, pumping electricity, or thermal transport losses explicitly. These site-specific effects are represented only through the assumed aggregate integration cost. The results should therefore be interpreted as screening values rather than project-specific feasibility estimates. A detailed assessment requires the actual connection

route, hydraulic design, operating temperatures, pumping requirements and transport losses.

Table 11: Screening cost of useful heat, excluding payment for the waste-heat source

Scenario	COP	Total CAPEX [€/kW _{th}]	EFLH [h/a]	C ₀ [€/MWh _{th}]
Favourable	4.5	800	3,500	51.8
Conditional	3.5	1,200	3,000	74.5
Difficult	3.0	1,800	2,500	106.9

The spread is substantial. Before payment for the source heat, the C_0 ranges from approximately 52 €/MWh in the favourable case to approximately 107 €/MWh in the difficult case.

If an illustrative source-heat transfer price of $p_{WH} = 20$ €/MWh_{WH} is included according to Equation (29), useful-heat costs increase to approximately 67.3, 88.7, and 120.2 €/MWh for the favourable, conditional, and difficult configurations, respectively. Here, MWh_{WH} denotes a megawatt-hour of recovered waste heat measured at the contractual source boundary. The source price affects the result, but poor source–sink matching can dominate the total cost, even when the waste heat itself is inexpensive.

6.4 Break-Even Interpretation

The acceptable source-heat price depends on the cost of the heat supply that the recovered heat displaces. For an illustrative alternative heat cost of $C_{\text{alternative}} = 80$ €/MWh, the break-even relation gives approximately 36.3 €/MWh_{WH} for the favourable configuration, 7.8 €/MWh_{WH} for the conditional configuration, and –40.4 €/MWh_{WH} for the difficult configuration.

A negative break-even value indicates that the project is not economically viable relative to the selected alternative, even when the source heat is supplied free of charge. The feasibility would then require lower investment, higher utilisation, higher COP, lower electricity or transport cost, or a higher avoided heat-supply cost.

The 80 €/MWh value is an illustrative benchmark rather than a national Slovenian replacement-heat cost. The appropriate comparator depends on the receiving system, and on whether the waste heat displaces a short-run production, or substitutes a long-run investment.

The break-even value, therefore, represents the residual economic value of the source heat after accounting for the costs of recovery and delivery, not the inherent market price of the waste heat.

6.5 Data Centres as a Slovenian Opportunity

The quantitative screening indicates that the existing Slovenian data-centre stock represents primarily a local, rather than a national, heat-supply opportunity. Even the upper technical recovery envelope remains small relative to the national district-heating delivery, while the geographical fragmentation reduces the share that is practically usable further.

Future larger facilities can nevertheless become material heat sources for individual networks where sufficient coincident demand and acceptable integration conditions exist. Their main planning advantage is that the siting and cooling-system design can still be coordinated with potential heat reuse before the infrastructure is fixed.

Proximity to the district heating should therefore be treated as one siting criterion rather than an overriding requirement. The electricity grid access, telecommunications infrastructure, land, cooling requirements and sufficiently large heat demand must be considered simultaneously.

The cooling architecture affects the external heat value directly. Higher-temperature liquid cooling reduces the required temperature lift and heat-pump electricity demand relative to conventional low-temperature cooling (Yuan et al., 2025; Oltmanns et al., 2020; Feike et al., 2021; Wang et al., 2024). The benefit remains conditional on the receiving network having sufficient base-load demand; where the summer load is low, the recovery capacity should be sized against usable demand rather than the maximum source output.

7 Discussion and Conclusions

7.1 Discussion

The results show that the usefulness of waste heat in Slovenia cannot be inferred from the aggregate resource estimates alone. The national statistics can identify relevant source categories and approximate energy scales, but economically usable heat emerges only from specific source–sink combinations. Therefore, temperature, demand, temporal coincidence, and spatial proximity determine the practical potential more directly than the gross annual heat availability does.

This distinction is particularly important for data centres. Their present contribution to the Slovenian heat-supply system is limited by the small, geographically fragmented existing stock. However, the future facilities differ from many legacy industrial sources, in that several decisive integration parameters can still be influenced during project development. The siting, cooling-system selection, and the choice of the receiving heat system. can therefore affect recoverability before the long-lived infrastructure is fixed.

The economic screening also shows that feasibility is highly sensitive to project configuration. Under favourable combinations of source temperature, COP, annual utilisation and integration cost, the recovered heat can compete with the plausible alternative heat sources. When several conditions deteriorate simultaneously, however, the useful-heat cost can exceed 100 €/MWh, even before any payment for the source heat is included. The economic penalty is therefore cumulative rather than attributable to a single variable.

The break-even source-heat price provides a useful interpretation of this result. Waste heat does not possess an intrinsic economic value independent of its use. Its acceptable price is the residual value remaining after deducting the recovery, temperature upgrading, transport, auxiliary electricity and other integration costs from the cost of the displaced heat supply. A negative break-even price indicates that the source–sink combination is unattractive, even when the waste heat itself is free.

The results, therefore, favour early integration of heat-reuse considerations into the planning of the future energy-intensive infrastructure. For large new data centres, the value of heat recovery can depend as much on siting and cooling architecture as on the efficiency of the recovery equipment itself. The waste-heat policy should consequently prioritise technically compatible and economically justified source–sink combinations, rather than pursue heat recovery as an objective in isolation from local system conditions.

7.2 Conclusions

Waste-heat utilisation can contribute to the Slovenian heat supply, but its role is inherently selective. The strongest cases combine favourable thermal quality, persistent nearby demand and limited integration burden; the weakest cases combine low source temperature, long distance, seasonal mismatch, low utilisation and high project cost.

The results do not support a general policy of connecting every available waste-heat source to district heating. They support a targeted screening approach, followed by a detailed analysis only for source–sink combinations that satisfy both the technical and economic criteria.

The principal finding is therefore not that Slovenia has a large generic waste-heat resource, but that specific, well-matched waste-heat sources can provide an economically relevant local heat supply. In contrast, poorly matched sources remain unattractive despite their theoretical energy content.

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Povzetek v slovenskem jeziku

Izraba odpadne toplote v Sloveniji: povezovanje virov in ponorov ter ekonomski screening .

Odpadna toplota lahko prispeva k oskrbi s toploto le tam, kjer so značilnosti vira usklajene z lokalnim povpraševanjem in so stroški integracije sprejemljivi. Članek razvija okvir za presojo izrabe odpadne toplote v Sloveniji, ki povezuje toplotno kakovost, izkoristljivo zmogljivost, časovno razpoložljivost, prostorsko bližino, značilnosti toplotnega povpraševanja in infrastrukturne zahteve z ekonomsko presojo na podlagi stroška dobavljene toplote. Analiza razlikuje med teoretično razpoložljivo, tehnično izkoristljivo in ekonomsko uporabno odpadno toploto. Obravnavan je tudi razvoj energetske intenzivnih dejavnosti: tradicionalne procesne industrije so postopno izboljševale notranjo integracijo toplote, medtem ko digitalna infrastruktura ustvarja nove koncentrirane porabnike električne energije z omejenim lastnim toplotnim povpraševanjem. Podatkovni centri so zato obravnavani kot nastajajoča kategorija virov za zunanjo izrabo toplote. Za obstoječi slovenski fond podatkovnih centrov je izkoristljiva toplota na nacionalni ravni omejena in pomembna predvsem lokalno. Scenarijski izračuni kažejo, da bi sistema s toplotno močjo 15 in 30 MW pri 3,000 ekvivalentnih urah polne obremenitve letno dobavila približno 45 oziroma 90 GWh toplote. Ekonomski screening pokaže, da odpadna toplota ni nujno poceni vir. Upravičenost izboljšujejo višja temperatura vira, večja izraba, krajša razdalja in zmerni stroški integracije. V neugodnih pogojih lahko strošek dobavljene toplote preseže 100 €/MWh tudi pri brezplačni toploti na viru. Rezultati podpirajo selektiven in lokacijsko specifičen pristop.

THE IMPACT OF POWER LINES ON WILDLIFE – A LITERATURE REVIEW AND EXPERIENCES FROM THE FIELD

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AMANDA POPLAS, KATARINA FLAJŠMAN

Slovenian Forestry Institute, Ljubljana, Slovenia
amanda.poplas@gmail.com, katarina.flajzman@gozdis.com

CORRESPONDING AUTHOR

amanda.poplas@gmail.com

Abstract Power lines can have a significant impact on the environment both during construction and operation, particularly within right-of-way (RoW) zones or corridors beneath power lines, where the vegetation is maintained regularly. As part of this study, we reviewed recent research on the impacts of power lines on wildlife and game species, and examined two field examples from Slovenia. The research indicates that power lines can have both negative and positive impacts on the environment, depending on the animal species and environmental conditions. Common negative impacts include, for example, habitat degradation and fragmentation, as well as the barrier effect of safety corridors, which affect animal movement and ecosystem connectivity most significantly. Nevertheless, several studies indicate that RoWs can also serve as valuable habitats for many animal species. Our field observations confirmed these findings, as numerous signs of animal presence and activity were recorded beneath the power lines.

Keywords

power lines,
Right-of-Way,
wildlife,
habitat,
environmental impacts

1 Introduction

The global demand for electricity and electricity consumption is on the rise. From 1980 to 2023, electricity consumption has more than tripled, coinciding with the milestone of 8 billion people on the planet. The spread of industrialization and greater and easier access to electricity across much of the globe have also contributed to the increased demand for electricity (Statista Research Department, 2025). Electricity consumption is expected to continue to rise in the coming years, particularly due to the growing production of electric vehicles (Galvin, 2021), drastic cold fronts and heatwaves, which will lead to increased use of central heating and cooling systems (Van Ruijven et al., 2019; Safdie, 2024), as well as continued population growth and technological development (Van Ruijven et al., 2019).

The demand for the construction of transmission lines, which carry electricity from power plants to consumers, is therefore proportional to this demand (Biasotto and Kindel, 2018). To date, a considerable number of studies have been conducted on their significant impact on the environment and biodiversity. Both negative and positive impacts arising during the construction and operation phases of such structures have been described (Bagli et al., 2011; Biasotto and Kindel, 2018; der Boghossian, 2024), while some studies even mention neutral impacts (Biasotto and Kindel, 2018).

In this study, we reviewed recently published studies on the impact that power lines have—from initial construction through to active operation—on various species of wildlife and the natural environment. In addition to reviewing the research, we also examined and analyzed two practical examples in Slovenia – the case in the Laze hunting ground (Zasavje Hunting Management Area (Zasavsko lovsko upravljavsko območje)) and the case in the Dolce-Komen hunting ground (Primorska Hunting Management Area (Primorsko lovsko upravljavsko območje)).

1.1 General about electricity and transmission lines

At present, it is not yet possible to store electricity in large quantities, which is why continuous production is necessary. On land, electricity is transmitted via underground or overhead transmission lines and distribution lines (Biasotto and Kindel, 2018; European Commission, 2018). The former are designed to transmit

electricity from power plants to main substations, while the latter transmit it from the substations to consumers (Biasotto and Kindel, 2018; Department for Energy and Mining, 2024).

Overhead power lines, also known as transmission lines, are electrical lines that run above ground. Their most recognizable features are the tall, lattice-style towers made of steel that carry high voltages (ALTEGRA, 2024). Both power lines and underground cables are required by law to have a corridor of cleared, almost bare ground without (tall) vegetation, known as a Right-of-Way (RoW) or transmission corridor. The RoW allows maintenance crews to operate safely and continuously, and facilitates access to the electrical infrastructure during repairs and general maintenance. Shrubs and trees within the RoW can pose the greatest obstacle to access and maintenance, which is why utility companies clear and maintain all vegetation regularly (Ituen and Sohn, 2010; Right of Way, n.d.).

Like all other development activities within the European Union, the energy transmission infrastructure must also comply with the EU environmental policy, including the Habitats Directive and the EU Birds Directive. Natura 2000 sites are not established to impose a total ban on access, or to prevent all development within them. It just means that development projects must be carried out in a way that protects the rare and endangered species and habitats for the conservation of which the site was designated. This can be achieved through careful planning, open and extensive consultation, and, if necessary, the implementation of appropriate risk mitigation measures to prevent or reduce, from the outset, the individual and cumulative negative impacts that could affect the (original) conservation objectives of a site (European Commission, 2018). The establishment of power lines within the territory of the Republic of Slovenia must also comply with the national legal frameworks, such as the Spatial Planning Act, the Environmental Protection Act, the Energy Act, and the Construction Act. In addition to laws, subordinate regulations and other legal acts must also be followed (Eles, n.d.²).

1.2 Electricity and transmission infrastructure in Slovenia

The Slovenian high-voltage transmission grid consists of infrastructure at three voltage levels – 110 kV, 220 kV and 400 kV – and transmits electrical energy from generators (hydroelectric, nuclear, and thermal power stations) to distribution

substations (RTP), from where it is fed into distribution networks and on to the end consumers. These end users are connected either at the medium-voltage level, which is around 20 kV, or at the low-voltage level, i.e. 0.4 kV (Eles, n.d.¹; iEnergija, n.d.). Part of the high-voltage electricity is also supplied directly to large industrial consumers operating at the high-voltage level (Eles, n.d.¹).

Our transmission network also facilitates the transit of electricity between the power systems of our neighboring countries. We are connected to Austria by two 400 kV transmission lines and one 220 kV transmission line, and to Croatia by four 400 kV transmission lines, two 220 kV transmission lines and three 110 kV transmission lines; with Italy, one 400 kV transmission line and one 220 kV transmission line; and with Hungary, just one 400 kV transmission line (Eles, n.d.¹).

2 Results of a review of studies on the impacts of power lines on wildlife

The construction of power lines and their subsequent operation have an impact on the ecosystem and the animal species living within it. After reviewing recent studies, we have categorized these impacts into potentially negative and potentially positive effects. Some of them are described briefly below.

2.1 Potential negative impacts

2.1.1 Fragmentation, degradation and (functional) loss of habitat

The construction of power lines and associated infrastructure for electricity transmission requires land clearing and the removal of surface vegetation. During this process the existing habitat may become fragmented into several smaller habitats, altered, damaged, or even degraded or destroyed. The extent of degradation and loss depends on the design, location, and size of the project, as well as on the sensitivity of the habitat itself (European Commission, 2018).

Studies conducted in Norway and Canada have found that power lines can disrupt the use of nearby habitats by ungulates, but that the nature of the impact depends on the species, the terrain, and other environmental factors. Several studies have shown that wild and semi-domesticated reindeers (*Rangifer tarandus*) avoid areas near power lines—their density or presence is reduced significantly within a 1–4 km radius of a power infrastructure, particularly during sensitive periods such as calving

(Vistnes and Nellemann, 2001; Panzacchi et al., 2013). However, the authors emphasized that the results may also partially reflect other environmental influences occurring during the study period, such as snow conditions, lower predation rates at higher elevations, farther from the power lines (Reimers and Colman, 2009), or changes in the landscape (e.g., the study by Nellemann et al. (2003) took place during dam construction). However, some studies have also reported exceptions. In the work by Vistnes et al. (2008), it was found that, at high elevations, there were more moose near power lines during the summer. Other ungulates, such as moose (*Alces alces*) and white-tailed deer (*Odocoileus virginianus*), avoided power lines only slightly or not at all, which supports the theory that responses to power lines depend on the species and context (Bartzke et al. 2014a; Bartzke et al. 2014b).

2.1.2 Right-of-Ways as an ecological trap

RoWs can act as ecological traps (Battin, 2004). This phenomenon occurs when animals, in response to rapid environmental changes, choose habitats that appear favorable but, compared to other available options, actually reduce their ability to survive (Hale and Swearer, 2016). Thus, Right-of-Ways are attractive due to the abundance of different food sources, but potentially harmful to individual animal species, as they pose a greater risk of disturbance and predation (Frid and Dill, 2002). Power lines and the maintenance roads leading to them serve as walkways and locations where natural predators wait and watch for their prey (e.g., golden eagles (*Aquila chrysaetos*) (Steenhof et al., 1993; Nybakk et al., 2002; Norberg et al., 2006; Johnsen et al., 2007; Hamel and Côté, 2009; Prather and Messmer, 2010; Nadjafzadeh et al., 2013). Power lines also increase accessibility for hunters (Perry et al., 1997; Bartzke et al., 2014a). Thus, buffer zones may benefit certain wild ungulates locally by providing them with more food, but they also increase the predation and fragmentation pressure on selected species, which affects the population dynamics negatively (Bartzke et al., 2014a). Power lines and Right-of-Way corridors can thus create so-called ecological “winners and losers”, by altering the dynamics between predators and prey and reducing the effectiveness of prey refuges (Lovich and Ennen 2013; DeMars and Boutin 2017; Cunningham et al., 2015).

2.1.3 Barrier and corridor effect

Power lines and the RoWs beneath them can act as barriers to animal movement or migration. The effects vary among species. Wild reindeer may avoid crossing under power lines, as indicated by the uneven grazing patterns on lichens near power lines; however, these patterns could also be attributed to the presence of other factors, such as roads, other nearby infrastructure, and human activities (Vistnes et al., 2004; Reimers et al., 2007). If the needs for migration were high (due to differences in food accessibility and availability, risks of predation, etc.), researchers observed that some northern deer individuals did cross these artificial barriers formed by power lines (Bartzke et al., 2014a). Based on the research conducted, moose, Canadian elk or wapiti (*Cervus canadensis*), and white-tailed deer generally had no difficulty crossing power line corridors of various widths and voltages; however, the number of crossings decreased in locations where animals felt overly exposed due to insufficient vegetation cover, or where the corridors were (too) wide (Bartzke et al., 2014a). In general, the animals' willingness to cross power line routes depends on factors such as corridor width, vegetation cover, and ecological needs for migration (Bartzke et al., 2014a).

2.14 Collisions with infrastructure and the risk of electric shock

These are a range of negative impacts that, according to research, affect birds in particular most noticeably. In Norway, approximately 26,000 black grouse (*Lyrurus tetrix*), 20,000 Western capercaillies (*Tetrao urogallus*), and 50,000 Willow Ptarmigans (*Lagopus lagopus*) were lost—these figures exceed the losses caused by hunting (Bevanger, 1995; Bevanger and Brøseth, 2004). The negative impacts are also believed to be linked to a significant decline in the populations of European birds of prey, such as buzzards or Bonelli's eagle (*Aquila fasciata*), the Eurasian eagle-owl (*Bubo bubo*), and the Spanish imperial eagle (*Aquila adalberti*), which is considered a native species of the Iberian Peninsula (Sergio et al., 2004; Mariano González et al., 2007; Schaub et al., 2010; Hernández-Matías et al., 2015; Bennett et al., 2025). Power lines also pose a threat to migratory birds along their migration routes (Uddin et al., 2021).

2.1.5 Electromagnetic radiation

All electric currents, including those flowing through electrical wires, generate electromagnetic fields (EMFs) (Ferne and Reynolds, 2005). Some animal and plant species possess sensory receptors and mechanisms that enable them to detect and respond to electric or magnetic fields—a phenomenon known as magnetoreception or electroreception (Johnsen and Lohmann, 2008; England and Robert, 2021; Levitt et al., 2022;; “Magnetoreception,” n.d.; “Possible Effects of Electromagnetic Fields on Plants and Animals,” n.d.)

Electric and magnetic fields decrease exponentially with the distance from the power line axis. Figures 2 and 3, obtained and summarized from the Inis.si portal, show how the intensity of these fields changes as we move away from the axis of the power line for the most common types of power lines in Slovenia. The highest values are near 400 kV power lines, while they are noticeably lower near 220 and 110 kV power lines. The results shown in the figures below apply to locations where the conductors (power lines) sag the most and are therefore closest to the ground. The electric and magnetic field values are highest at these locations—the results thus show the situation under the most unfavorable conditions.

Cattle and roe deer (*Capreolus capreolus*) tend to align their bodies along the north-south geomagnetic axis while resting and feeding. The mechanisms behind this phenomenon are not yet known, but it is known that the electromagnetic fields of power lines can disrupt this magnetic alignment in animals (Burda et al., 2009; Shukla, 2025). Researchers have not yet reached a consensus on this issue (Bartzke et al., 2014a).

Some experts have concluded that fluctuations in the electric fields of high-voltage power lines had no effect on the behavior of domestic animals or their production (Ganskopp et al., 1991; Burchard et al., 1996; Wenzel et al., 2020), while other researchers have documented that proximity to power lines and their electromagnetic radiation can cause reduced milk production and milk fat content in cows, respiratory problems, abnormally low fertility rates in pigs, and noticeable mortality in piglets, stunted growth in heifers, occasional bleedings, and miscarriages (Bhuvane et al., 2023). In one study, semi-domesticated reindeers housed in pens near power lines showed increased restlessness, and, at higher transmission loads,

even avoidance of the power lines; however, the results were said to be inconclusive (Flydal et al., 2009).

2.2 Potential positive impacts

2.2.1 New (feeding) habitats

RoWs, which are often maintained in the early-succession stage of a habitat type, support various species from the communities of adjacent habitats (Geibert, 1980; Wagner et al., 2019; Hrouda and Brlík, 2021). Regenerating vegetation in these zones and along their edges can create valuable foraging habitats for wild ungulates by providing them with abundant and nutritious food (Bramble and Byrnes, 1979; Ricard and Doucet, 1999; Milligan and Koricheva, 2013; Bartzke et al., 2014a). Vegetation density and diversity are typically greater within 3–10 meters of the edges of RoWs than deeper within the forest (Luken et al., 1991; Luken et al., 1992; Rieucan et al., 2007; Powell and Lindquist, 2011). According to the results of some studies, it is often possible to find tracks or footprints of white-tailed deer in the peripheral areas of buffer zones, where they go to feed on shrubs and young trees, while their droppings are observed more frequently in nearby forests, as there is more cover (Bartzke et al., 2014a).

Regularly mowed and trimmed vegetation in buffer zones can provide higher-quality grazing, as those plant species prioritize (regrowth) rather than defense against herbivore grazing (through the production of secondary metabolites) (Rea and Gillingham, 2001). However, it should be noted that the increased availability of light in buffer zones, resulting from reduced vegetation density, can stimulate both defense and growth in newly emerging vegetation (Nybakken et al., 2012). Herbaceous vegetation in buffer zones has a higher mineral and protein content and lower fiber content compared to woody plants. In general, both the availability and nutritional quality of the food are what make these zones so attractive to ungulates (Bartzke et al., 2014a).

The edge effect that buffer zones have on vegetation can create new habitats for wild rabbits, hares, and other herbivorous small mammals, which, in turn, attracts their predators, such as red foxes (*Vulpes vulpes*), golden jackals (*Canis aureus*), and brown bears (*Ursus arctos*), thereby enhancing the species diversity of the new habitat (Berger, 2010)

With appropriate vegetation management, RoWs can also improve the ecological quality of suburban environments, as they support diverse and often more varied plant communities (Garfinkel et al., 2022).

2.2.2 Corridor for connecting habitats

RoWs can sometimes facilitate the movement of ungulates by providing them with pathways to move between habitats or by offering forest edges rich in food (Bartzke et al., 2015). Studies thus report that some ungulate species move along RoWs frequently, albeit with regard to transmission lines (Jackson and Hecklau, 1995; Bartzke et al., 2015). Despite these observations, evidence of consistent RoWs` use by ungulates remains quite scarce, and movement is thus more dependent on the local terrain and habitat conditions (Bruggeman et al., 2006; Bartzke et al., 2014).

2.2.3 A place for nesting and resting

Although power lines are believed to have a significant impact on bird mortality (electrocution, collisions) and their migration routes, certain species actually use these structures to their advantage. Examples include the pied crow (*Corvus albus*) in Africa, common ravens (*Corvus corax*), and white storks (*Ciconia ciconia*), which use power lines for nesting and as resting sites (Moreira et al., 2017). Bird species considered generalist predators also exploit power lines as vantage points from which to scout for prey. This can lead to increased predation pressure, representing a negative impact of power lines on animals that are often preyed upon by birds of prey (as described previously) (DeMars and Boutin, 2017; Cunningham et al., 2015; Bennett et al., 2025).

In Table 1 we gathered all the presented potential impacts that power lines can have on wildlife, which animal species are reported to be affected by them, and studies from which we got that information.

Table 1: Potential negative and positive impacts that power lines can have on the wildlife, animal species on which those impacts were reported on, and studies from where we got that info.

NEGATIVE IMPACTS		
Type of negative impact	Documented in the following animal species	Reference
Fragmentation, degradation and (functional) loss of habitat	– Reportedly high impact on: wild and semi-domesticated reindeer (<i>Rangifer tarandus</i>) – Reportedly low impact on: moose (<i>Alces alces</i>), white-tailed deer (<i>Odocoileus virginianus</i>)	Vistnes and Nellemann, 2001; Panzacchi et al., 2013; Bartzke et al. 2014a; Bartzke et al. 2014b
Right-of-Ways as an ecological trap	Prey species and game species like hares (<i>Lepus</i> sp.), roe deer (<i>Capreolus capreolus</i>), red deer (<i>Cervus elaphus</i>), wild boar (<i>Sus scrofa</i>), grouse,...	Steenhof et al., 1993; Perry et al., 1997; Nybakk et al., 2002; Norberg et al., 2006; Johnsen et al., 2007; Hamel and Côté, 2009; Prather and Messmer, 2010; Nadjafzadeh et al., 2013; Bartzke et al., 2014a
Barrier and corridor effect	Wild reindeer	Vistnes et al., 2004; Reimers et al., 2007
Collisions with infrastructure; electrocution	Black grouse (<i>Lyrurus tetrix</i>), Western capercaillies (<i>Tetrao urogallus</i>), Willow Ptarmigans (<i>Lagopus lagopus</i>), Bonelli's eagle (<i>Aquila fasciata</i>), Eurasian eagle-owl (<i>Bubo bubo</i>), Spanish imperial eagle (<i>Aquila adalberti</i>), various migratory bird species...	Bevanger, 1995; Bevanger and Brøseth, 2004; Sergio et al., 2004; Mariano González et al., 2007; Schaub et al., 2010; Hernández-Matías et al., 2015; Uddin et al., 2021; Bennett et al., 2025
Electromagnetic radiation	Domestic animal species (e.g., domestic pigs, sheep, cattle...), semi-domesticated reindeer, roe deer	Flydal et al., 2009; Bhuvane et al., 2023
POSITIVE IMPACTS		
Type of positive impact	Documented in the following animal species	Reference
New (feeding) habitats	Wild ungulates, mesocarnivores (e.g. red fox (<i>Vulpes vulpes</i>), golden jackal (<i>Canis aureus</i>)) and top predators (e.g. brown bears (<i>Ursus arctos</i>))	Bramble and Byrnes, 1979; Ricard and Doucet, 1999; Berger, 2010; Milligan and Koricheva, 2013; Bartzke et al., 2014a
Corridor for connecting habitats	Wild ungulates	Jackson and Hecklau, 1995; Bartzke et al., 2015
A place for nesting and resting	Pied crow (<i>Corvus albus</i>), common ravens (<i>Corvus corax</i>), white storks (<i>Ciconia ciconia</i>), various birds of prey (e.g. common buzzard (<i>Buteo buteo</i>))	Cunningham et al., 2015; DeMars and Boutin, 2017; Moreira et al., 2017; Bennett et al., 2025

3 Case studies or field examples

We also observed the impact of power lines and their associated RoWs in practice, specifically in the Laze hunting ground (Zasavsko LUO), through which part of the 400 kV Beričevo-Krško power line runs, and in the Dolce-Komen (Primorsko LUO), through which the 400 kV Divača-Redipuglia power line runs. In accordance with the Energy Act (EZ-1), for such voltages (400 kV), the width of the safety zone is 40 m on each side of the axis of the power line or from the outer fence of the substation or transformer station.

Clearing of vegetation along the power line in the Laze hunting grounds began between 2006 and 2009 (Figure 1). Construction of the line began in 2011 and was completed in 2013 (»Slavnostno Odprtje DV 2x400 kV Beričevo-Krško«, 2014). Construction of the Divača-Redipuglja power line began in 1979 and was completed in 1980 (IBE, d.d., 2009). Vegetation clearing likely took place several years earlier.

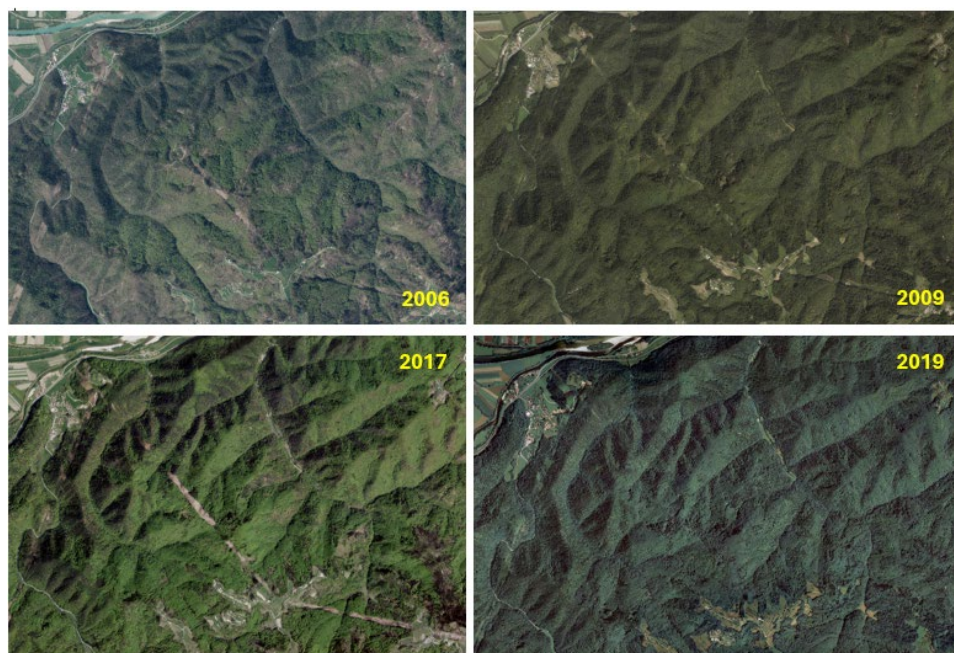


Figure 1: Progress of vegetation clearing along the Beričevo-Krško power line route in the Laze hunting ground.

Source: Pregledovalnik ZGS, zajem zaslona, 2025

The sites where the two power lines were constructed were originally forested areas. Part of both forests had to be cleared to make way for the power lines. The resulting clearing is now being overgrown by pioneer tree and shrub species, such as silver birch (*Betula pendula*) and european aspen (*Populus tremula*), saplings of tree species from peripheral habitats (in the Karst region, these include pine, oak, acacia), blackberry, eagle fern (*Pteridium aquilinum*), and various grass species; however, invasive or non-native species are also thriving here, such as American pokeweed (*Phytolacca americana*), himalayan balsam (*Impatiens glandulifera*), Japanese knotweed (*Fallopia japonica*), and Canada goldenrod (*Solidago canadensis*)...



Figure 2 and 3: Animals captured by camera traps in the hunting area Dolce – Komen.

Source: Slovenian Forestry Institute

In both hunting grounds, we have at least one location near power lines where we have set up trap cameras as part of various projects to monitor the presence of wildlife. Using these cameras, as well as signs of wild animal presence (droppings, tracks, and grazed vegetation), we were able to confirm that animals use the areas beneath the power lines for crossing, foraging, feeding, and caring for their young. We recorded ungulates such as wild boar (*Sus scrofa*), roe deer (*Capreolus capreolus*), and red deer (*Cervus elaphus*) (Figures 2, 3, 4 and 5), and the presence of other animal species was also confirmed—european badger (*Meles meles*), fox, jackal, red squirrel (*Sciurus vulgaris*)... In the case of the power line in the Laze hunting ground, we also contacted the managers (hunters) of that hunting ground to obtain additional information. According to their observations, the presence of wildlife in the area where the power lines were installed declined noticeably during and immediately after construction. This was particularly noticeable in the case of the previously present red deer, which had withdrawn from the area for several years. However, as

vegetation began to regrow and food availability increased, that species also began to return to the area.



Figure 4 and 5: Animals captured by camera traps in the hunting area Laze.

Source: Slovenian Forestry Institute

4 Conclusion

Power lines are one of the inevitable human interventions in the environment driven by our needs. They come with numerous negative impacts, yet there are also some positive ones.

They primarily affect wildlife through collisions and electrocution—these alone kill millions of birds and bats every year. Habitat fragmentation and changes resulting from the construction and subsequent maintenance of power lines also impact wildlife negatively. Power lines act as barriers that prevent animal movement, and, in the safety zones beneath them, conditions are created that encourage the proliferation of invasive plant and animal species, while native species are more threatened in these areas. Electromagnetic radiation from power lines and the barrier effect of safety zones also have a significant impact on animals.

However, even though we are aware of all the potential negative impacts these elements have on wildlife, it is also important to focus on the positive effects that result from them. With proper management of buffer zones and edge habitats near power lines, it is possible to provide an attractive habitat for wild ungulates, as well as likely for many other animal species. Due to their function as ecological corridors

that facilitate species movement in urban or human-altered landscapes, buffer zone areas can support greater species diversity of plants, birds, and pollinators compared to suburban or urban meadows or mowed areas. In regions where (flowering) meadows are in decline, they provide foraging habitats for pollinators, thereby ensuring the survival of all the subsequent elements in the food chain.

In reviewing reports and studies on the impact of electrical infrastructure on animals, particularly wildlife, we observed that most studies focus on birds. Studies on the impact of power lines on mammals are few in number. A systematic review of studies on this topic would likely be even more difficult to conduct if it focused on smaller and less mobile taxa, such as amphibians, reptiles, molluscs, and insects, even though these are also sensitive to the impacts that power lines have on their natural habitats. We have observed a lack of research on the impacts of power lines on wildlife, particularly ungulates, in Slovenia. According to our data, such analyses have not yet been conducted in Slovenia, although it would be sensible to carry them out in the future

A review of research and practical examples shows that, with proper management of safety zones and edge habitats near power lines, we can ensure an attractive habitat for wildlife. Electricity has become an integral part of our daily lives, so, unfortunately, we cannot do without the infrastructure that enables its production and use. It is important that we strive to mitigate the impacts of such interventions as much as possible, and enable wild animals to live as undisturbed as possible in the altered landscape.

End notes

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Povzetek v slovenskem jeziku

Vpliv daljnovodov na prostoživeče živali – pregled literature in izkušnje s terena. Daljnovodi lahko znatno vplivajo na okolje tako v fazi izgradnje kot tudi v fazi obratovanja, zlasti na območju varovalnih pasov ali transmisijjskih koridorjev (ang. Right-of-Way; RoW), ki potekajo pod daljnovodi. V okviru te študije smo pregledali novejšo raziskavo o vplivih daljnovodov na prostoživeče živali in divjad ter preučili dva praktična primera s terena v Sloveniji. Raziskave kažejo, da imajo daljnovodi lahko tako negativne kot pozitivne vplive na okolje, odvisno od vrste živali in okoljskih razmer. Med pogostimi negativnimi vplivi so denimo degradacija in razdrobljenost habitatov ter barierni učinek, ki ga povzročajo čistine pod daljnovodi, kateri od vseh negativnih dejavnikov najbolj vplivajo na premike živali ter povezanost ekosistemov. Kljub temu številne študije kažejo, da lahko ti transmisijjski koridorji služijo tudi kot dragoceni habitati za številne živalske vrste. Naša terenska opazovanja so te ugotovitve potrdile, saj smo pod daljnovodi zabeležili številne znake prisotnosti in aktivnosti živali.

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TINE VIRTič,¹ DARKO OBRETAN²

¹ SERŠ – Secondary School of Electrical Engineering and Computing, Maribor, Slovenia

tine.virtic1@gmail.com

² University of Maribor, Faculty of Energy Technology, Krško, Slovenia

darko.obretan@gmail.com

CORRESPONDING AUTHOR

tine.virtic1@gmail.com

Abstract Photovoltaic (PV) systems are an important source of renewable energy, and their electricity production is influenced strongly by the weather conditions. The aim of this study was to investigate the influence of global solar irradiance, air temperature and cloud cover on electricity production from a residential photovoltaic system during a seven-day observation period. Electricity production data obtained from the SolarEdge Monitoring Platform were compared with meteorological data provided by the Slovenian Environment Agency (ARSO), and the results were analysed using Tables and graphs created in Microsoft Excel. The analysis showed that global solar irradiance had the greatest influence on PV electricity production, while cloud cover reduced the energy output and the air temperature had a smaller effect. The findings improve the understanding of how weather conditions influence electricity production from residential photovoltaic systems, and highlight the importance of solar irradiance for PV performance.

Keywords

photovoltaic system,
weather, production,
solar irradiance,
electricity production,
renewable energy

1 Introduction

Renewable energy sources are becoming increasingly important, because they help reduce greenhouse gas emissions and decrease the dependence on fossil fuels. Among the renewable energy technologies, photovoltaic (PV) systems are one of the fastest-growing methods of electricity generation. According to the International Energy Agency (International Energy Agency, 2024) the global use of solar energy continues to increase, due to its environmental and economic benefits.

The analysed residential photovoltaic system is monitored using the SolarEdge Monitoring Platform, which provides detailed information about electricity production throughout the day (SolarEdge Technologies, 2026). The weather data used in this study were obtained from the Slovenian Environment Agency (ARSO), which provides reliable meteorological measurements, including global solar irradiance and air temperature (Slovenian Environment Agency, 2026).

The electricity production of a photovoltaic system depends strongly on the weather conditions. Messenger and Ventre (Messenger & Ventre, 2010) explained that the amount of electricity generated is determined primarily by the intensity of the incoming solar radiation, while environmental factors such as air temperature and cloud cover also influence the performance of photovoltaic modules. Furthermore, Dubey et al. (Dubey et al., 2013) highlighted the importance of environmental conditions when evaluating the performance of PV systems. Their findings support the need to analyse weather conditions when assessing PV system performance.

The aim of this study was to investigate the influence of weather conditions on electricity production from a residential photovoltaic system. Electricity production data collected from the PV system were compared with meteorological data, including global solar irradiance and air temperature, over a seven-day observation period. The results were analysed, to determine how changes in the weather conditions affected the electricity production of the residential PV system.

2 Materials and Methods

The analysed photovoltaic system is installed on a residential building in Slovenia. The basic technical characteristics of the analysed PV system are presented in the following Table.

Table 1: Basic technical characteristics of the analysed PV system

Installed capacity - PV modules peak power (kWp)	Module orientation - Azimuth (°)	Tilt (°)	Inverter/ system configuration	Shading
15.725	129 (for 36 modules) 309 (for 1 module)	28	3-phase 16 kW inverter, with 19 optimisers, 37 monocrystalline 425 W PV modules, one string	two chimneys

The distance between the PV installation and the ARSO meteorological station is approximately 2.14 km. The limitation of the study is also the global irradiance measured at a meteorological station rather than irradiance in the plane of the PV modules.

The air temperature was used as an available meteorological parameter. However, it should be noted that the air temperature does not represent the PV module temperature directly, which is the parameter related more directly to temperature-induced changes in PV efficiency.

The electricity production data were obtained from the SolarEdge monitoring platform. The PV production data had a temporal resolution of 15 minutes, while the meteorological data obtained from the ARSO weather station were recorded at 10-minute intervals. The datasets were aligned according to their date and time information for comparison. No missing data were identified in either dataset during the analysed seven-day period. The analysed period covered seven consecutive days, from 15 June to 21 June, 2026. The selected period included both clear and cloudy days, allowing the influence of different weather conditions to be evaluated on PV electricity production.

The meteorological data were obtained from the nearest ARSO weather station, which is located in the village of Šmartno pri Slovenj Gradcu. Two weather parameters were selected for the analysis: global solar irradiance (W/m^2) and air temperature ($^{\circ}\text{C}$). These parameters were selected because they are relevant meteorological factors affecting photovoltaic electricity production and were available for the analysed period.

The electricity production and weather data were organised and processed using Microsoft Excel. Graphs were created to compare the changes in PV electricity production with the changes in solar irradiance and air temperature throughout each day.

3 Results

3.1 Daily analysis of PV production

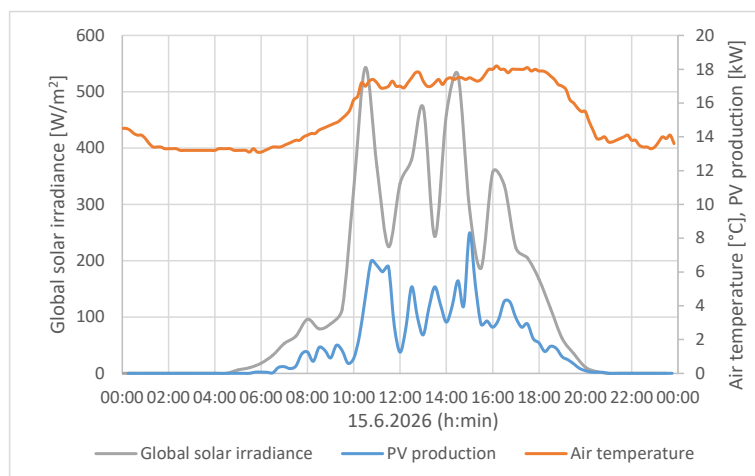


Figure 1: Relationship between the weather conditions and PV power production on 15 June, 2026

Figure 1 shows the relationship between the global solar irradiance, air temperature and PV power production on 15 June, 2026. The global solar irradiance increased during the morning and reached its maximum around midday. The PV system responded similarly, although several short-term drops in power production

occurred due to temporary reductions in solar irradiance, caused most likely by passing clouds. The air temperature increased steadily throughout the day and reached its highest value in the afternoon. The results indicate that the solar irradiance had the greatest influence on PV power production.

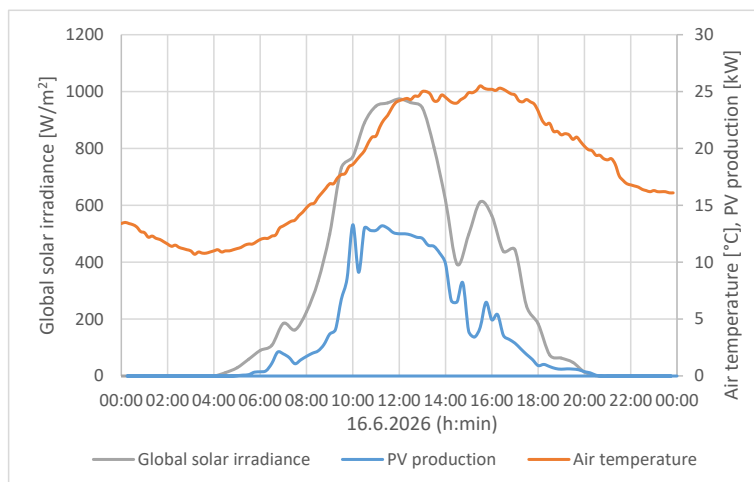


Figure 2: Relationship between the weather conditions and PV power production on 16 June, 2026

Figure 2 presents the weather conditions and PV power production on 16 June, 2026. The solar irradiance increased rapidly during the morning and remained relatively high until the afternoon. These changes were reflected in the PV production, which followed the irradiance pattern closely. The air temperature increased gradually during the day and remained high for several hours. The strong similarity between the irradiance and PV production confirms that solar radiation was the dominant factor affecting power generation.

Figure 3 illustrates the weather conditions and power production on 17 June, 2026. Compared with the previous day, the global solar irradiance showed more frequent fluctuations, indicating variable cloud cover. Consequently, the PV system produced power less steadily, with several noticeable decreases during the day. The air temperature increased continuously and reached its maximum in the afternoon. The results suggest that the changing cloud conditions affected the power production significantly.

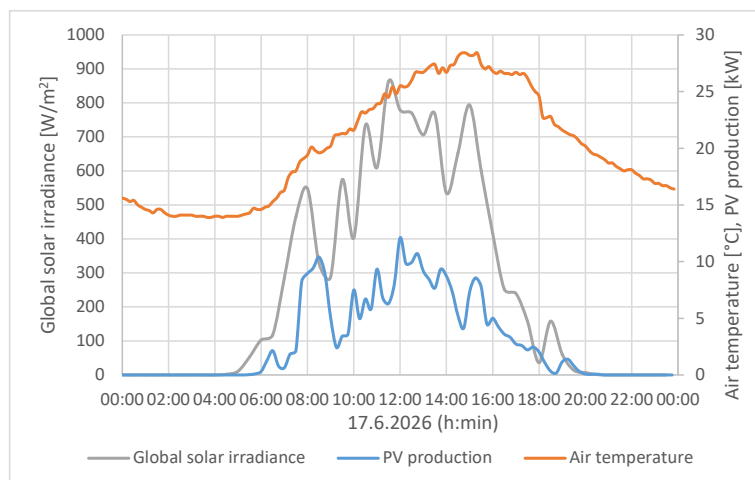


Figure 3: Relationship between the weather conditions and PV power production on 17 June, 2026

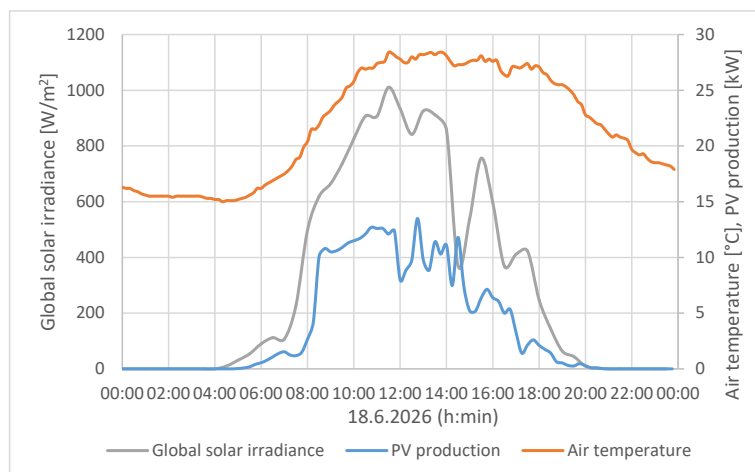


Figure 4: Relationship between the weather conditions and PV power production on 18 June, 2026

Figure 4 shows relatively favourable weather conditions throughout most of the day. The global solar irradiance reached high values during the late morning and early afternoon, resulting in stable power production by the PV system. Short-term reductions in irradiance were reflected immediately in lower power production. The air temperature remained high during the afternoon, but did not produce sudden

changes in PV output. This confirms that solar irradiance had a more direct influence on power production than air temperature.

Figure 5 represents one of the most stable days during the observation period. The global solar irradiance followed a smooth daily pattern with only minor fluctuations, resulting in relatively constant PV power production. The air temperature increased gradually and reached approximately 30 °C during the afternoon. Because the cloud cover was limited, the PV system operated under favourable conditions and produced power continuously throughout the day.

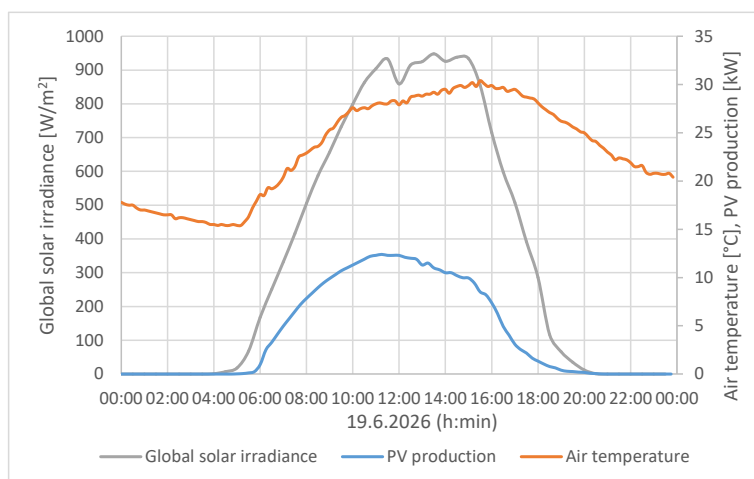


Figure 5: Relationship between the weather conditions and PV power production on 19 June, 2026

Figure 6 differs from the previous days because the power production decreased sharply during the afternoon at relatively high air temperatures. This reduction corresponded to a rapid decline in the global solar irradiance, indicating increased cloud cover or changing weather conditions. As a result, the PV production dropped significantly within a short period. The graph again demonstrates that solar irradiance has a much stronger influence on power production than air temperature alone.

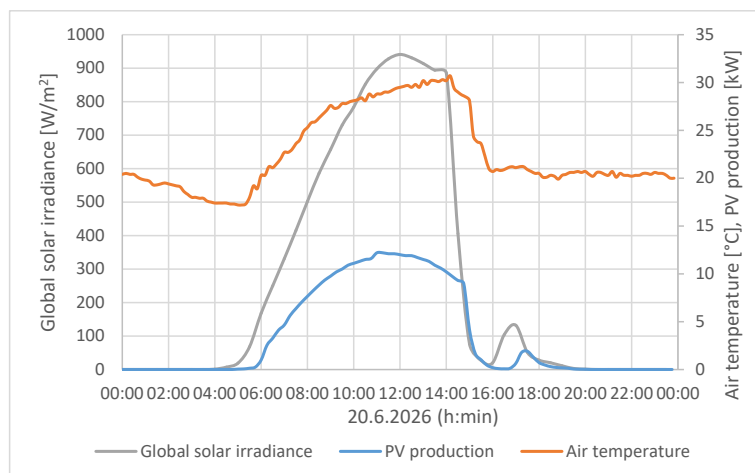


Figure 6: Relationship between the weather conditions and PV power production on 20 June, 2026

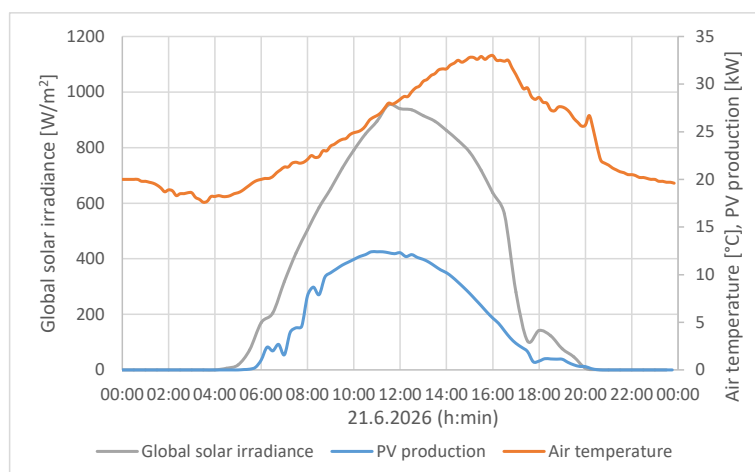


Figure 7: Relationship between the weather conditions and PV power production on 21 June, 2026

Figure 7 presents the weather conditions and PV power production on the final day of the observation period. The global solar irradiance increased gradually during the morning, and reached its maximum around midday before decreasing in the afternoon. The PV system followed this trend closely, and produced its highest output during periods of maximum irradiance. The air temperature continued to rise

throughout the afternoon, when the power production decreased due mainly to lower solar irradiance. This demonstrates that the availability of solar radiation is the primary factor determining photovoltaic power production.

3.2 Comparison of Daily Energy Production

Table 2: Summary of the daily PV power production and cloudiness [3]

	Daily Energy Production (kWh)	Cloudiness at 7 AM	Cloudiness at 2 PM
15 June	38.3	Cloudy	Cloudy
16 June	81.8	Cloudy	Partly cloudy
17 June	74.3	Partly cloudy	Mostly cloudy
18 June	92.4	Cloudy	Mostly cloudy
19 June	107	Clear	Clear
20 June	90.1	Clear	Clear
21 June	101	Clear	Clear

Table 2 summarises the daily PV energy production together with the observed cloudiness at 7 AM and 2 PM during the seven-day observation period. The highest daily energy production was recorded on 19 June (107 kWh), when the weather remained clear throughout the day. Similarly, high energy production was observed on 21 June (101 kWh) and 20 June (90.1 kWh), both of which also had clear weather conditions. In contrast, the lowest daily production was recorded on 15 June (38.3 kWh), when cloudy conditions in the morning and in the afternoon reduced the available solar radiation. Overall, the data indicate that clearer weather conditions generally resulted in higher daily PV energy production, while increased cloudiness was associated with lower energy output.

3.3 Overall results

During the seven-day observation period the daily energy production ranged from 38.3 kWh to 107 kWh. The highest production was recorded on 19 June under clear weather conditions, while the lowest production occurred on 15 June, when cloud cover reduced the available solar irradiance. These results are consistent with the trends observed in all daily graphs.

4 Discussion

The results show clearly that the global solar irradiance was the most important factor affecting the electricity production of the residential photovoltaic system. On all the analysed days PV production increased shortly after sunrise, reached its highest values around midday and decreased gradually towards the evening. This trend followed the changes in global solar irradiance closely.

Several short-term decreases in electricity production occurred during periods when the solar irradiance declined rapidly. These changes were most likely caused by temporary cloud cover, which reduced the amount of sunlight reaching the photovoltaic panels. The close agreement between the irradiance and PV production curves indicates a strong relationship between these two variables. The Pearson correlation coefficient was calculated to assess the relationship between solar irradiance and PV electricity production quantitatively. A strong positive correlation was obtained ($r = 0.95$), indicating that the higher global solar irradiance was associated with higher PV electricity production during the analysed period.

The air temperature also changed during the observation period, generally increasing from the morning until the afternoon. The air temperature was also analysed separately. The results suggest that its apparent influence on PV power was weaker than that of solar irradiance during the analysed period. However, the available data do not allow the independent effect of the air temperature to be separated quantitatively from the effect of solar irradiance. It is well known that an increase in PV module temperature reduces its efficiency, and, consequently, its electricity production. This trend can also be observed in Figure 5. In several cases the air temperature continued to increase while the PV electricity production was already decreasing, mainly because the solar irradiance had started to decline.

The comparison of all seven days also revealed that the stable weather conditions resulted in smoother electricity production, while variable weather conditions caused frequent fluctuations in the PV output. These observations agree with the theoretical principles of photovoltaic electricity generation described in the literature.

A limitation of this study is the short seven-day observation period, which does not capture seasonal variations in the PV system operation. Therefore, the results should be interpreted as a short-term case study, rather than as representative of residential photovoltaic systems under different seasonal conditions.

Overall, the results for the analysed seven-day period indicate that solar irradiance was the main observed weather factor associated with PV power variations in the investigated residential photovoltaic system.

5 Conclusion

This study investigated the influence of weather conditions on electricity production from a residential photovoltaic system during a seven-day observation period.

The results show that global solar irradiance had the strongest influence on electricity production. This is supported by the strong positive correlation between global solar irradiance and PV electricity production ($r = 0.95$) during the analysed seven-day period. The PV system produced the highest amount of electricity during periods with high solar irradiance, while cloud cover caused immediate reductions in electricity generation. The air temperature also changed during the day, but its effect on electricity production was less significant than the effect of solar irradiance. However, the effect of PV module temperature cannot be quantified independently because the PV module temperature was not measured.

The findings of this study, based on the seven-day observation period and the analysed residential PV system, demonstrate that weather conditions should be considered when evaluating photovoltaic system performance. The results should be interpreted as a short-term case study, as the seven-day observation period does not cover seasonal variations in weather conditions and PV performance. Understanding the relationship between weather conditions and electricity production can help improve the analysis and operation of residential solar power systems.

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Povzetek v slovenskem jeziku

Vpliv vremenskih pogojev na proizvodnjo električne energije iz stanovanjske fotonapetostne elektrarne. Fotonapetostni (PV) sistemi predstavljajo pomemben vir obnovljive energije, njihova proizvodnja električne energije pa je močno odvisna od vremenskih razmer. Namen raziskave je bil preučiti vpliv globalnega sončnega obsevanja, temperature zraka in oblačnosti na proizvodnjo električne energije iz hišnega fotonapetostnega sistema v sedemdnemnem obdobju opazovanja. Podatki o proizvodnji električne energije, pridobljeni s platforme SolarEdge Monitoring Platform, so bili primerjani z meteorološkimi podatki Agencije Republike Slovenije za okolje (ARSO), rezultati pa analizirani s pomočjo tabel in grafov, izdelanih v programu Microsoft Excel. Analiza je pokazala, da ima globalno sončno obsevanje največji vpliv na proizvodnjo električne energije fotonapetostnega sistema, medtem ko oblačnost zmanjšuje proizvodnjo, temperatura zraka pa ima manjši vpliv. Ugotovitve raziskave prispevajo k boljšemu razumevanju vpliva vremenskih razmer na proizvodnjo električne energije iz hišnih fotonapetostnih sistemov ter poudarjajo pomen globalnega sončnega obsevanja za njihovo učinkovito delovanje.



University of Maribor

Faculty of Energy Technology

<https://journals.um.si/index.php/jet>

jet@um.si



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