JET

Journal of ENERGY TECHNOLOGY

University of Maribor Press

VOLUME 18
ISSUE 2
SEPTEMBER 2025

JET

Editor-in-Chief Jurij Avsec
(University of Maribor, Slovenia)

Co-editors Amor Chowdhury
(University of Maribor, Slovenia)

Brigita Ferčec
(University of Maribor, Slovenia)

Matej Fike
(University of Maribor, Slovenia)

Miralem Hadžiselimović
(University of Maribor, Slovenia)

Gorazd Hren
(University of Maribor, Slovenia)

Zdravko Praunseis
(University of Maribor, Slovenia)

Sebastijan Seme
(University of Maribor, Slovenia)

Bojan Štumberger
(University of Maribor, Slovenia)

Peter Virtič
(University of Maribor, Slovenia)

Technical Editors Jan Perša
(University of Maribor, University of Maribor Press, Slovenia)

Sonja Krajnc
(University of Maribor, Slovenia)

Lecturer in English Shelagh Margaret Hedges

Cover designer Jan Perša
(University of Maribor, University Press, Slovenia)

Cover graphics photo: Jurij Avsec, 2025

Graphics material Sources are own unless otherwise noted.

Publication type E-publication

EDITORIAL OFFICE ADDRESS
University of Maribor
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

PUBLISHED BY
University of Maribor
University Press
Slomškov trg 15, 2000 Maribor, Slovenia
e-mail: zalozba@um.si, zalozba.journals@um.si
https://press.um.si/, https://journals.um.si

ISSN 2463-7955 (electronic)
ISSN 2630-2535 (printed)

The **Journal of Energy Technology** is a peer-reviewed journal published in May, August, November and December by University of Maribor Press and issued by University of Maribor, Faculty of Energy Technology (Slovenia). The journal is indexed and abstracted in database INSPEC©, Proquest, EBSCO. For more information, please visit our website at https://journals.um.si/index.php/jet

University of Maribor Press

Slovenian Research and Innovation Agency

Journal of Energy Technology is co-funded by Slovenian Research and Innovation Agency

Journal of Energy Technology

Volume 18 Number 2 September 2025

JOURNAL OF ENERGY TECHNOLOGY
Vol. 18, No. 2, September 2025

Editorial

JURIJ AVSEC
Editor-in-Chief

The JET – Journal of Energy Technology magazine, has been covering a wide range of energy issues successfully for the past 18 years. During this time, it has become an important source of knowledge, information and professional content for all those interested in the development and future of energy technologies. Its role is especially important today, when we are faced with the challenges of energy transformation, sustainable development, the transition to green and alternative technologies and the ever-increasing need for innovation.

This year, we have switched to a new system of sending, processing and reviewing articles, which is more sustainably acceptable.

With the start of the new study year, I would like to wish all students a lot of success, motivation and curiosity. May each of you find an area that truly interests you, and may your knowledge lead you to new insights and achievements.

We wish all readers of the magazine a pleasant and successful reading. May the contents of the JET magazine encourage you to think, research and find new paths in the world of energy.

Uvodnik

Revija JET – Journal of Energy Technology že osemnajsto leto uspešno pokriva široko področje energetike. V tem času se je uveljavila kot pomemben vir znanja, informacij in strokovnih vsebin za vse, ki jih zanima razvoj ter prihodnost energetskih tehnologij. Njena vloga je še posebej dragocena danes, ko se soočamo z izzivi energetske preobrazbe, trajnostnega razvoja, prehoda na zelene in alternativne tehnologije ter vse večje potrebe po inovacijah.

V tem letu smo uvedli nov sistem pošiljanja, obdelave in recenzije člankov, ki je trajnostno prijaznejši.

Ob začetku novega študijskega leta želim vsem študentkam in študentom veliko uspeha, motivacije in radovednosti. Naj vsak izmed vas odkrije področje, ki ga resnično zanima, in naj vas znanje vodi k novim spoznanjem ter dosežkom.

Vsem bralkam in bralcem revije pa želimo prijetno in navdihujoče branje. Naj vas vsebine revije JET spodbudijo k razmišljanju, raziskovanju in iskanju novih poti v svetu energetike.

JOURNAL OF ENERGY TECHNOLOGY
Vol. 18, No. 2, pp. 65–74, September 2025

Original Scientific Article

TOWARDS DIGITAL TWINNING OF ELECTRICAL MOTORS – SIMULATION MODELS

GORAN KURTOVIĆ,[1] LUKA ŽIVKOVIĆ,[1] TIN BENŠIĆ,[1] ŽELJKO HEDERIĆ,[1] MARINKO STOJKOV[2]

[1] Josip Juraj Strossmayer University of Osijek, Faculty of Electrical Engineering, Computer Science and Information Technology Osijek, Osijek, Croatia
goran.kurtovic@ferit.hr, luka.zivkovic@ferit.hr, tin.bensic@ferit.hr, zeljko.hederic@ferit.hr
[2] University of Slavonski Brod, Mechanical Engineering Faculty, Slavonski Brod, Croatia
mstojkov@unisb.hr

CORRESPONDING AUTHOR
goran.kurtovic@ferit.hr

Submitted
4. 9. 2025

Accepted
8. 9. 2025

Published
26. 9. 2025

Abstract This paper presents a methodological framework for building a digital shadow of an induction motor based on standardised tests and a two-axis (dq) simulation model. The tests were carried out according to IEEE Std 112 and IEC 60034-2-1. The parameters of the equivalent circuit were identified and entered into the model. Validation was performed by comparing the torque–speed and current–speed curves at 180 V and 220 V, while the nominal behaviour at 400 V was estimated using the model and voltage scaling. The model was then calibrated to reduce the discrepancy between the simulation and measurements, and the error was quantified using the root-mean-square error (RMSE) and mean absolute percentage error (MAPE). An automated load-simulation setup that reproduces the torque test is also presented, enabling rapid evaluation of parameter influence. The results show a very good match in the current channel, with larger deviations in the prediction of characteristic torque points, indicating the limitations of linearised parameters and motivating nonlinear model extensions. The approach enables summarised reliable estimates at nominal voltage when direct measurements are not feasible.

Keywords
induction motor, digital shadow, standardised tests, dq model, torque test, automated load simulation, model calibration

https://doi.org/10.18690/jet.18.2.65-74.2025

University of Maribor Press

1 Introducton

Digital twins (DT) and digital shadows (DS) for electric drives are active research topics. A digital shadow is a one-way representation of a physical system in a digital environment, whereas a digital twin extends this by establishing a two-way link with forecasting and optimisation capabilities in real time. A DS is, therefore, the first step towards a DT, as it enables systematic data collection and analysis, as well as validation of simulation models prior to industrial deployment. This paper focuses on the DS level for an induction machine (IM), where the simulation model is validated using standardised tests and laboratory measurements.

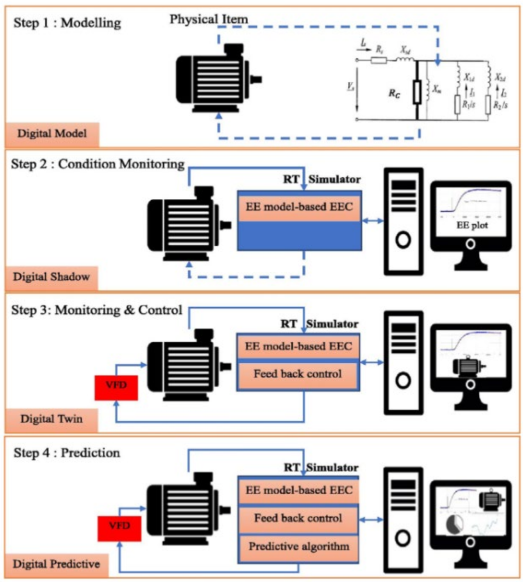


Figure 1: Reference hierarchy for IM DT/DS development.
Source: adapted from [1].

Within this hierarchy, the present work addresses the second level—the digital shadow—bridging the measured data and a simulation model, to obtain trustworthy estimates and to prepare the ground for closed-loop DT functions.

Recent literature emphasises energy efficiency and reliability in electric-machine DS/DT development [1, 2, 3], torque-test methodologies and torque/speed characterisation [4, 5, 6, 7], and both dynamic simulation and in-field speed measurement using low-cost tools [8, 9]. However, few works combine parameter identification from standardised tests with a torque-test-based validation and standard voltage scaling (IEEE 112) (SVS) to nominal voltage within one coherent workflow—this is the gap our paper addresses.

The standardised tests defined in IEEE Std 112 and IEC 60034-2-1 [10, 11] are essential for obtaining motor parameters and validating models. They include DC resistance measurement, no-load test (NLT), locked-rotor test (LRT), load test (LT), optimal-voltage test (OVT) and the torque test (TT). The TT yields torque–speed and current–speed characteristics, and allows extracting key points: starting torque (T_s), maximum torque (T_{max}), and breakdown speed (n_{bd}). These serve as reference markers when comparing simulations against laboratory results. In this work, the standardised tests were carried out in a certified laboratory, and the identified parameters were entered into a dq-frame simulation model implemented in MATLAB/Simulink.

Our validation strategy is two-pronged. First, the laboratory and simulation results are compared at reduced voltages (180 V and 220 V). Second, the nominal behaviour at 400 V was estimated using SVS (simulation-assisted voltage scaling) from the reduced-voltage data and the corresponding simulations. Quantitative agreement is reported using root-mean-square error (RMSE) and mean absolute percentage error (MAPE), providing an objective assessment across the operating ranges. The approach also supports rapid sensitivity studies by reproducing the TT conditions in the simulation.

The remainder of the paper is organised as follows. Section 2 details the methodology, including the standardised testing, the 400 V scaling procedure, the simulation model and the error metrics. Section 3 presents the measurement and simulation results with the associated tables and figures. Section 4 discusses the findings in the context of DS development and the transition towards a full DT. Section 5 concludes with the main contributions and outlines directions for future work.

2 Methodology

Standardised tests were carried out to develop the digital shadow (DS) of the induction motor. The resulting parameters were entered into a dq simulation model. Comparing the simulation and laboratory results at 180 V and 220 V enabled model calibration and extraction of characteristic points (T_s, T_{max}, n_{bd}). Finally, SVS was used to estimate the performance at the nominal 400 V.

2.1 Standardised tests

The following standardised tests (IEEE Std 112) were used to obtain the parameters for the equivalent circuit and to provide reference curves for model validation.

2.2 Scaling to 400 V

An SVS procedure was applied to estimate operation at the nominal 400 V. Measurements at the reduced voltages (180 V, 220 V) were combined with the pointwise ratio of simulated curves at 400 V and at the corresponding reduced voltage, for each speed n (see (1)–(2)).

$$T_{400}(n) = T_{lab,V_1}(n) \cdot \left(\frac{T_{sim,400}(n)}{T_{sim,V_1}(n)}\right) \tag{1}$$

$$I_{400}(n) = I_{lab,V_1}(n) \cdot \left(\frac{I_{sim,400}(n)}{I_{sim,V_1}(n)}\right) \tag{2}$$

Procedure: (1) laboratory curves T(n) and I(n) at 180 V and 220 V are interpolated onto a common speed grid; (2) from the simulation, $T_{sim,400}(n)$, $I_{sim,400}(n)$, $T_{sim,V1}(n)$ and $I_{sim,V1}(n)$ are obtained, with $V_1 \in \{180, 220\}$; (3) the ratio above is computed pointwise over speed and applied to the measured curves. Because the method is multiplicative, the relative errors (MAPE) at 400 V equal to those at the source voltage, while the absolute errors (RMSE) scale with the level of the variables. Parameters are treated as constants (no explicit saturation or skin effect); nonlinearities are assumed to be moderate. Scaling from both source voltages (180→400 and 220→400) was used, and the 400 V reference points (T_s, T_{max}, n_{bd}) were taken as the average of the two estimates.

Table 1: Standardised tests and abbreviations.

Test (abbr.)	Description	Obtained parameters / characteristics
DC test (DC)	Measurement of stator winding resistance using a DC current	Stator resistance R_s
No-load test (NLT)	Motor running without mechanical load at a rated voltage	Magnetising reactance X_m; core-loss resistance R_{fe}; constant losses
Locked-rotor test (LRT)	Rotor locked mechanically; supply at reduced voltage	Rotor resistance R'_2; total leakage reactance $X_1+X'_2$; split into stator and rotor components
Load test (LT)	Motor loaded at a rated voltage and frequency	Efficiency; power factor; limiting operating points
Optimal Voltage Test (OVT)	Adjust supply voltage to an optimal value for the given operating point (without exceeding the allowed limits)	Trade-off among current/losses/torque; not an over-voltage test
Torque test (TT)	Progressive loading up to near-synchronous speeds at 180 V and 220 V	Torque–speed T(n) and current–speed I(n); key points: T_s, T_{max}, n_{bd}

2.3 Simulation model

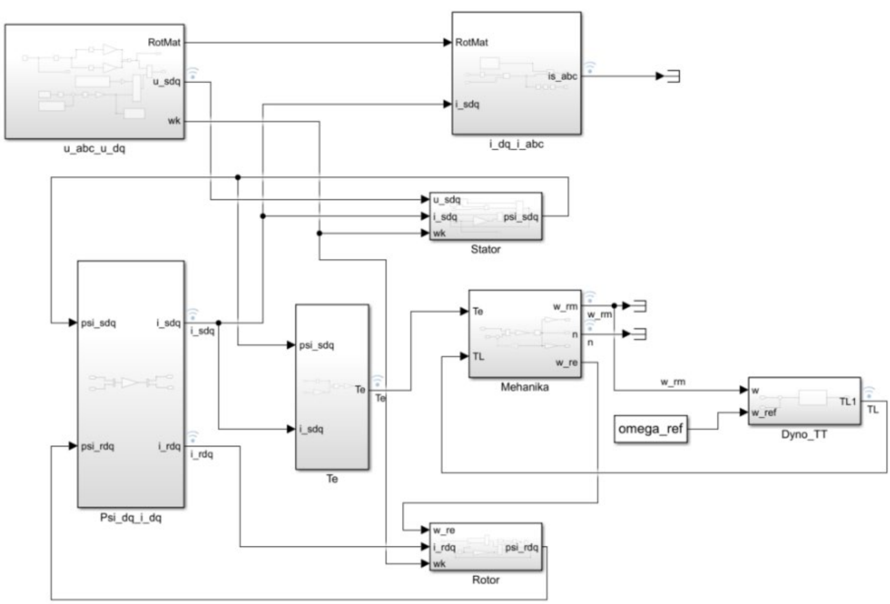


Figure 2: dq-model structure implemented in MATLAB/Simulink.

A dq-frame induction-motor model with constant parameters (R_s, R'_2, X_m, X_1, X'_2) identified from standardised tests was implemented in MATLAB/Simulink. A simple mechanical sub-model of the load is included. The model generates torque–speed and current–speed curves at 180 V, 220 V, and 400 V for direct comparison with the torque test (TT). The parameters are treated as constants with respect to temperature and frequency; nonlinear phenomena (magnetic saturation, skin effect, temperature dependence) are not modelled explicitly. Despite this simplification, empirical parameter tuning provides sufficient agreement for DS validation (see Figure 2). The approach follows the standard dq formulation and modelling practice reported in the literature [2].

2.4 Metrics for quantitative comparison

For quantitative comparison of the laboratory and simulation results we used RMSE (root-mean-square error) and MAPE (mean absolute percentage error) defined in (3)-(4). RMSE emphasises the absolute deviations between paired curves (large deviations weigh more), whereas MAPE expresses the average relative error in percent, enabling comparison across magnitudes and test conditions.

$$\mathrm{RMSE}_X = \sqrt{\frac{1}{N} \cdot \sum_{i=1}^{N} (\mathrm{X}_{\mathrm{sim,i}} - \mathrm{X}_{\mathrm{lab,i}})^2} \tag{3}$$

$$\mathrm{MAPE}_X = \frac{100}{N} \cdot \sum_{i=1}^{N} \left| \frac{X_{sim,i} - X_{lab,i}}{X_{lab,i}} \right| \tag{4}$$

3 Results

This section reports the results of the standardised tests (ST) and the torque-test (TT) comparison between the laboratory measurements and the dq simulation model. First, the parameters identified from ST are summarised, followed by the T–n and I–n curves at 180 V and 220 V and 400 V estimates obtained via SVS. For fair comparison, all the data were interpolated onto a common speed grid (n = 0–1500 rpm, step 10 rpm), with a threshold n ≥ 100 rpm to avoid initial transients. Quantitative metrics (RMSE, MAPE) are then presented, and the key TT points (T_s, T_{max}, n_{bd}) are indicated.

3.1 Identified parameters

Identified parameters used in the dq model and in the comparisons are summarised below.

Table 2: Identified parameters of the induction motor from standardised tests.

Parameter	Value	Test method
R_s [Ω]	1.912	DC
R'_2 [Ω]	1.50	LRT
X_m [Ω]	80.0	NLT
$X_1 + X'_2$ [Ω]	8.0	LRT

3.2 Torque test — measurements vs. simulation

The I–n and T–n curves are compared and discussed at 180 V and 220 V, together with the 400 V estimates obtained by SVS. Characteristic points T_s, T_{max}, and n_{bd} are marked on each curve. See Figures 3–4.

Table 3: Key TT points — 180 V (Lab vs. Sim)

Quantity	Lab	Sim	Abs. diff	Rel. diff [%]
T_s [Nm]	4.96	3.91	-1.06	-21.29
T_{max} [Nm]	7.06	9.45	2.38	33.74
n_{bd} [rpm]	1280.00	1200.00	-80.00	-6.25

Table 4: Key TT points — 220 V (Lab vs. Sim)

Quantity	Lab	Sim	Abs. diff	Rel. diff [%]
T_s [Nm]	8.39	5.84	-2.55	-30.44
T_{max} [Nm]	11.64	14.11	2.47	21.26
n_{bd} [rpm]	1250.00	1200.00	-50.00	-4.00

3.3 Quantitative agreement

RMSE and MAPE were computed over the common speed grid (n = 0-1500 rpm, step 10 rpm), with $n \geq 100$ rpm. The following values are reported by voltage level.

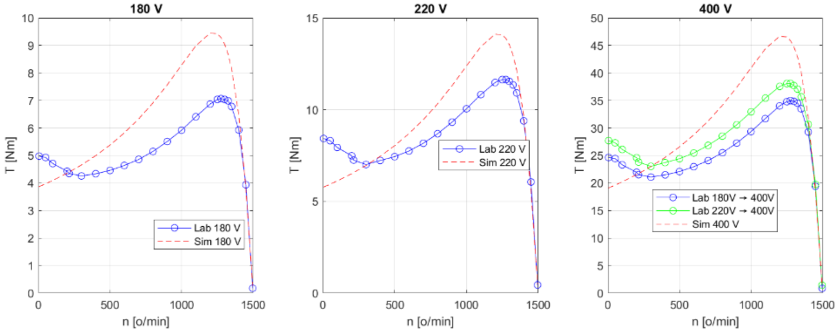


Figure 3: Comparison of T–n curves (180 V, 220 V and 400 V scaled).

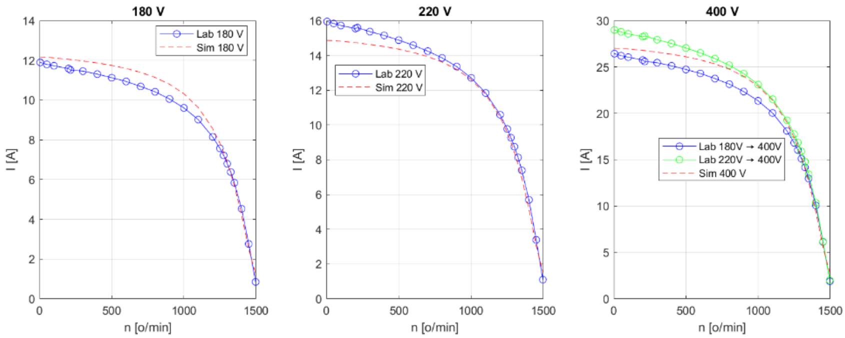


Figure 4: Comparison of I–n curves (180 V, 220 V and 400 V scaled).

Table 5: Error metrics (RMSE, MAPE) by voltage level for the TT comparisons.

Voltage	$RMSE_T$ [Nm]	$MAPE_T$ [%]	$RMSE_I$ [A]	$MAPE_I$ [%]
180 V	1.60	24.79	0.56	5.68
220 V	1.63	14.91	0.47	3.50
400 V (180→400, scaled)	7.89	24.79	1.25	5.68
400 V (220→400, scaled)	5.38	14.91	0.86	3.50

Note on abbreviations: $RMSE_T$ — RMSE for torque [Nm]; $MAPE_T$ — MAPE for torque [%]; $RMSE_I$ — RMSE for current [A]; $MAPE_I$ — MAPE for current [%].

4 Analysis and discussion

Across 180 V and 220 V, the model reproduced I–n more accurately than T–n consistently. The largest deviations occurred in the vicinity of T_s, T_{max}, and n_{bd}, which is consistent with the omission of nonlinear phenomena (magnetic saturation, skin effect) and temperature-dependent parameters. SVS to 400 V yielded physically credible curves in the linear region, but for the DS→DT transition the model should be extended with nonlinear magnetising characteristics $X_m=f(i_m)$ (or f(U)), frequency-dependent rotor resistance R'_2 (skin effect), and a thermal sub-model to track the parameter drift. Integrating real-time telemetry and control closes the loop towards a full DT capable of online optimisation of efficiency, reliability and safety.

5 Conclusion

We presented a methodology for developing a digital shadow (DS) of an induction motor based on standardised tests and comparison of laboratory measurements with a dq simulation model. The measurements were carried out per IEEE Std 112 and IEC 60034-2-1 [10, 11] (DC, NLT, LRT, LT, OVT, TT). The parameters identified from these data were used in the model. Emphasis was placed on the TT at reduced voltages (180 V and 220 V) and on estimating nominal behaviour at 400 V through SVS. We observed good agreement in the current prediction (e.g., $MAPE_I \approx 5.7\%$ at 180 V and 3.5% at 220 V; $RMSE_I \approx 0.56$ A and 0.47 A), with larger discrepancies in torque ($MAPE_T \approx 24.8\%$ and 14.9%; $RMSE_T \approx 1.60$ Nm and 1.63 Nm). Under scaling to 400 V, the relative errors remained unchanged, whereas the absolute errors increased proportionally to the signal level (e.g., $RMSE_T \approx 7.9$ Nm for 180→400 and 5.38 Nm for 220→400). The characteristic TT points corroborated the pattern: T_s was underestimated (≈ −21% to −30%), T_{max} was overestimated (≈ +21% to +34%), and n_{bd} was shifted by about −50 to −80 rpm compared with the measurements. Future work will introduce nonlinear magnetisation, frequency-dependent rotor resistance, and thermal effects, and will integrate telemetry and control towards a DT platform.

References

[1] A. A. Adamou: Energy efficiency model-based digital shadow for induction motors: Towards the implementation of a digital twin, *Engineering Science and Technology, an International Journal*, 2023, doi:10.1016/j.jestch.2023.101469.

[2] P. F. Le Roux, M. K. Ngwenyama: Static and dynamic simulation of an induction motor using MATLAB/Simulink, *Energies*, Vol. 15, No. 10, Art. 3564, 2022, doi:10.3390/en15103564.

[3] H. Esen, M. O. Göl, H. M. Ertugrul: A new field test method for determining energy efficiency of induction motor, *IEEE Transactions on Instrumentation and Measurement*, Vol. 66, No. 11, pp. xxxx–xxxx, 2017, doi:10.1109/TIM.2017.2735718.

[4] R. L. Spasov, E. Rachev: Determining the equivalent circuit parameters of three-phase induction motor from the manufacturer's technical data, *Proc. 14th Electrical Engineering Faculty Conference (BulEF)*, 2022, doi:10.1109/BULEF56479.2022.10021178.

[5] E. B. Agamloh: Accurate determination of induction machine torque and current characteristics, *Proc. IEEE Energy Conversion Congress and Exposition (ECCE)*, 2016, doi:10.1109/ECCE.2016.7854812.
[6] K. A. Makinde: Simulation-based testing and performance investigation of induction motor drives using MATLAB/Simulink, *SN Applied Sciences*, Vol. 5, Art. xxxx, 2023, doi:10.1007/s42452-023-05296-w.
[7] A. Veyrat Durbex, Y. Nachajon Schwartz, H. Tacca: Solutions for torque and speed measurement on electric machine controllers test benches, *Elektron*, Vol. 5, No. 1, pp. xx–xx, 2021, doi:10.37537/rev.elektron.5.1.131.2021.
[8] M. Dems, K. Komeza, J. Szulakowski, W. Kubiak: Dynamic simulation of high-speed induction motor, *Energies*, Vol. 14, No. 9, Art. 2713, 2021, doi:10.3390/en14092713.
[9] P. Paramo-Balsa, J. M. Roldan-Fernandez, M. Burgos-Payan, J. M. Riquelme-Santos: A low-cost non-intrusive method for in-field motor speed measurement based on a smartphone, *Sensors*, Vol. 21, No. 13, Art. 4317, 2021, doi:10.3390/s21134317.
[10] IEEE Std 112-2004: *IEEE standard test procedure for polyphase induction motors and generators*, IEEE Power Engineering Society, 2004.
[11] IEC 60034-2-1:2014: *Rotating electrical machines—Part 2-1: Standard methods for determining losses and efficiency*, International Electrotechnical Commission, 2014.

Povzetek v slovenskem jeziku

Proti digitalnemu dvojčku električnih motorjev – simulacijski modeli. Članek predstavlja metodološki okvir za gradnjo digitalnega dvojčka asinhronskega motorja na podlagi standardiziranih preskusov in dvoosnega (dq) simulacijskega modela. Preskusi so bili izvedeni v skladu s standardoma IEEE Std 112 in IEC 60034-2-1. Parametri ekvivalentnega vezja so bili določeni in vneseni v model. Validacija je bila izvedena s primerjavo krivulj navor–hitrost in tok–hitrost pri 180 V in 220 V, medtem ko je bilo nazivno obnašanje pri 400 V ocenjeno z uporabo modela in skaliranja napetosti. Model je bil nato umerjen za zmanjšanje razlike med simulacijo in meritvami, napaka pa je bila kvantificirana z uporabo srednje kvadratne napake (RMSE) in povprečne absolutne odstotne napake (MAPE). Predstavljena je tudi avtomatizirana merilna postavitev za simulacijo obremenitve, ki ponazarja preskus navora in omogoča hitro oceno vpliva parametrov. Rezultati kažejo zelo dobro ujemanje v kanalu toka, pri napovedi značilnih točk navora pa so večja odstopanja, kar nakazuje omejitve lineariziranih parametrov in spodbuja razširitve modela na nelinearne. Pristop omogoča zanesljive povzetke ocen pri nazivni napetosti, kadar neposredne meritve niso izvedljive.

JOURNAL OF ENERGY TECHNOLOGY
Vol. 18, No. 2, pp. 75–84, September 2025

Original Scientific Article

SIMULATION-BASED STUDY OF STRUCTURAL CHANGES IN ELECTRICAL TIME-SERIES SIGNALS

LUKA ŽIVKOVIĆ,[1] ŽELJKO HEDERIĆ,[1] TIN BENŠIĆ,[1] GORAN KURTOVIĆ,[1] MARINKO STOJKOV[2]

[1] Josip Juraj Strossmayer University of Osijek, Faculty of Electrical Engineering, Computer Science and Information Technology Osijek, Osijek, Croatia
luka.zivkovic@ferit.hr, zeljko.hederic@ferit.hr, tin.bensic@ferit.hr, goran.kurtovic@ferit.hr
[2] University of Slavonski Brod, Mechanical Engineering Faculty, Slavonski Brod, Croatia
mstojkov@unisb.hr

CORRESPONDING AUTHOR
luka.zivkovic@ferit.hr

Submitted
4. 9. 2025

Accepted
12. 9. 2025

Published
26. 9. 2025

Abstract This paper uses statistical indicators to address the detection of changes in electrical signals typical of industrial and power systems. A dedicated MATLAB algorithm was developed to identify change points by tracking shifts in signal behaviour and statistical properties. To evaluate the method, synthetic signals were generated through simulation to reproduce the common patterns observed in these systems, allowing testing under different operating conditions and varying noise levels. The results demonstrate that the algorithm detects change points reliably across multiple scenarios, showing flexibility and robustness. This study highlights the value of simulation-based signal generation as a controlled environment for testing detection methods. It provides a foundation for future applications to more complex real-world electrical signal analysis tasks.

Keywords
break points, energy system, noise, segmentation, signals, simulation, time series

https://doi.org/10.18690/jet.18.2.75-84.2025

University of Maribor Press

1 Introducton

Analysing signals from electrical and energy systems has represented a significant challenge in recent years due to their inherent complexity, variability and noise. Simulation-based approaches have become increasingly important, as they allow reliable monitoring and testing of methods for the timely detection of changes in such signals, essential for maintaining the stability, efficiency and safety of modern energy and industrial infrastructures [1]. Structural changes, often called breakpoints, may reflect events such as faults, switching operations, or load variations, and detecting them accurately is important for system diagnostics and control.

Detecting structural changes in these signals is challenging, and statistical methods are used widely to support this process [2]. These methods quantify how much each data point differs from typical behaviour and can account for multiple variables simultaneously [3]. In addition to classical statistical approaches, recent research has explored machine learning techniques [4], including clustering [5], classification [6] and deep learning methods [7], to detect changes in more complex or high-dimensional signals. Various approaches have been presented in the literature, differing in their assumptions, the types of signals they analyse, and how changes are detected [8]. This classification helps in selecting the most suitable method for a given application. Figure 1 shows a diagram summarising this taxonomy of techniques, providing an overview of the main strategies for identifying breakpoints in time-series signals. As shown in Figure 1, methods can be classified into three main categories: supervision, data type, and detection mode. Supervised methods use labelled training data and typically apply classification or regression techniques, while unsupervised methods rely on statistical tests or clustering without prior labels. Methods can handle univariate signals with a single variable or multivariate signals involving multiple sensors or features [9]. Finally, they operate in either offline/batch mode, analysing data after collection, or in online/real-time mode, detecting changes as new data arrives.

This study uses a MATLAB-based simulation framework to investigate the detection of structural changes in synthetic electrical time-series signals. The signals were generated to resemble patterns found commonly in energy and industrial systems, providing a controlled environment to test different detection approaches. Various scenarios are explored, including step changes, ramp variations and shifts in noise levels, allowing an assessment of how the methods respond under different conditions. This framework is a practical basis for developing and evaluating change detection techniques before applying them to real-world electrical signals.

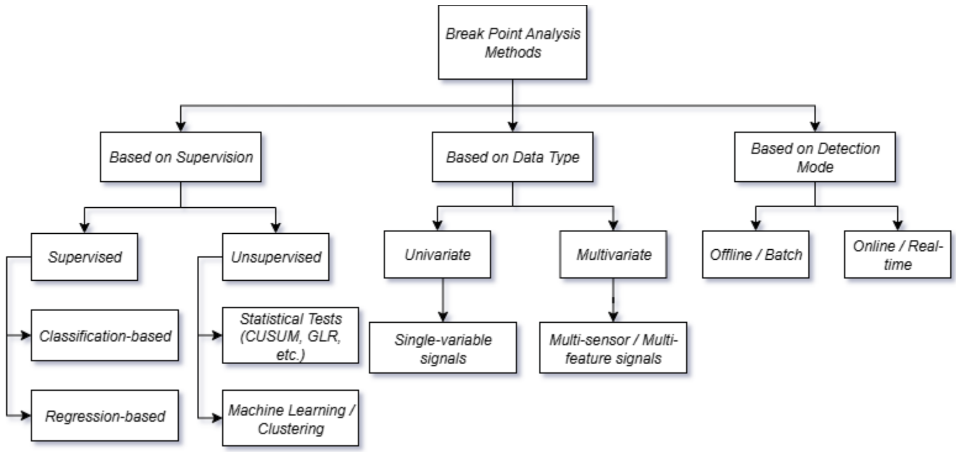


Figure 1: Overview of Structural Break Analysis Techniques

2 Detecting structural changes in data

Understanding the local behaviour of signals is crucial for identifying changes in their structure. Structural signal changes are detected by analyzing key statistical descriptors, such as the mean, variance, and covariances between signal components.

The mean of a signal segment is calculated using equation 2.1:

$$\mu = \frac{1}{m}\sum_{i=1}^{m} x_i \tag{2.1}$$

where x_i are the individual data points in the signal segment and m is the total number of points in the segment.

The variance of the signal segment is calculated using equation 2.2:

$$\sigma^2 = \frac{1}{m-1}\sum_{i=1}^{m} (x_i - \mu)^2 \tag{2.2}$$

The covariance between two signal components is calculated using equation 2.3:

$$\mathrm{Cov}(X,Y) = \frac{1}{m-1}\sum_{i=1}^{m}(x_i - \mu_X)(y_i - \mu_Y) \tag{2.3}$$

where x_i and y_i represent the individual data points in the signal segment, and μ_X and μ_Y are the mean values of the respective signal components. Covariance measures how two signal components vary together, indicating whether they tend to increase or decrease simultaneously. A positive covariance means that both components generally increase together, while a negative covariance indicates that they tend to move in opposite directions.

Significant deviations in these statistical descriptors are used to decide whether a structural change has occurred. The approach monitors how these descriptors evolve and flags potential breakpoints when meaningful shifts are observed.

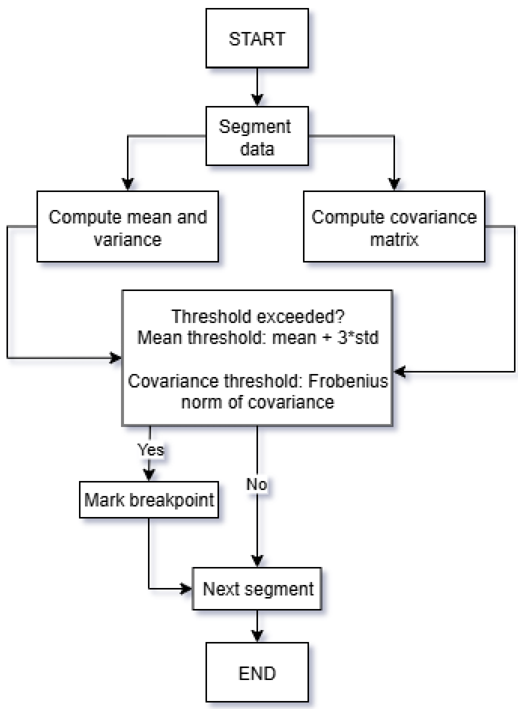


Figure 2: Flowchart of the proposed method

To provide a clearer overview of the method, Figure 2 illustrates a flowchart of the proposed method. The algorithm processes the signal in consecutive segments and monitors structural changes continuously. For each new segment, statistical descriptors including the mean, variance and covariance matrix are computed not only for the current segment but also in combination with the preceding n segments, establishing a local baseline that captures recent signal behaviour. The descriptors of the current segment are then compared against this baseline. A breakpoint is flagged if the mean deviates beyond the predefined threshold, or if the covariance matrix exceeds its threshold (measured via the Frobenius norm). This simultaneous evaluation ensures that both magnitude changes and shifts in component relationships are detected promptly.

3 Testing and analysis of the simulated signals

The validation of the proposed approach is conducted on signals generated in MATLAB and designed to capture the characteristics typical of electric drive systems and energy applications. These simulated signals provide a controlled environment for observing structural changes and evaluating the method's responsiveness under varying conditions. For this purpose, three representative data series are considered, each forming the basis for a separate case. The following list presents these cases, which are analysed individually in the subsequent sections:

- **Case 1**: Step change analysis
- **Case 2**: Noise variation analysis
- **Case 3**: Complex signal dynamics

3.1 Analysis of Step Changes in Signal

Step changes are sudden shifts in a signal that appear commonly in electrical and energy systems, such as when a load suddenly changes or a switch is activated. One common example of step changes occurs in PWM signals of voltage and current pulses in inverters. Analysing these shifts provides insight into the system response, identifies potential issues, and supports the design of effective control strategies. In power systems, step changes are associated frequently with switching events, grid disturbances, or fault occurrences, where detecting variations in the mean value of signals plays a key role in system monitoring and protection. Figure 3 shows the simulated step signals with added Gaussian noise with a Standard Deviation of 15. The proposed algorithm identified seven breakpoints, corresponding to the moments of sudden change in the signal.

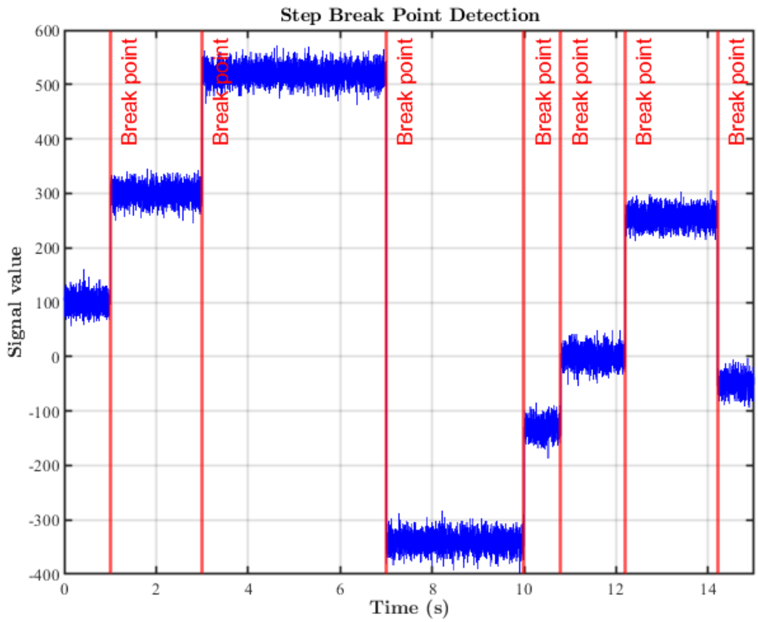


Figure 3: Identification of step changes in the signal mean

3.2 Analysis of Noise Variations in a Signal

Every measurement in power systems is inevitably affected by noise, originating from imperfections in the equipment and the surrounding environment. It is typically represented as Gaussian white noise, and its presence is evident in almost all voltage and current recordings across transmission and distribution networks. Variations in noise intensity can point to changes in operating conditions, disturbances in the grid, or transient events that affect the measurement quality. Figure 4 shows a simulated signal with Gaussian noise of varying intensity, where the algorithm identified two breakpoints corresponding to transitions in variance. In contrast, the mean value of the signal remained unchanged.

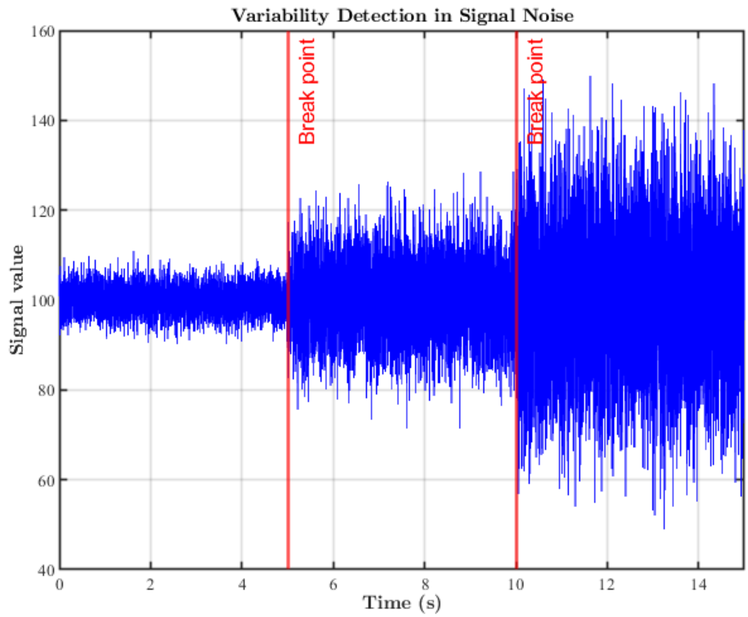


Figure 4: Identification of step changes in signal variance

3.3 Analysis of Complex Signal Dynamics

A more complex signal was simulated, to evaluate the algorithm further, consisting of multiple segments with different mean values. At the same time, the variance remained constant, reflecting variations observed commonly in power system measurements. The signal can represent the rotor speed of a generator or electric motor, where operating conditions or load changes shift the average value over time, while the measurement noise remains relatively constant. It includes an upward ramp, two step segments at constant levels, and a downward ramp, as illustrated in Figure 5.

During the ramp segments, the mean changes continuously, leading the algorithm to detect multiple breakpoints. While these may appear as false positives, they reflect actual changes in the signal metrics over time. In contrast, the step segments produce distinct, isolated breakpoints that indicate abrupt shifts in the mean. This behaviour shows that the algorithm can distinguish between gradual and abrupt changes. At the same time, the constant variance ensures that the detected breakpoints correspond to actual shifts in the signal level rather than to random fluctuations.

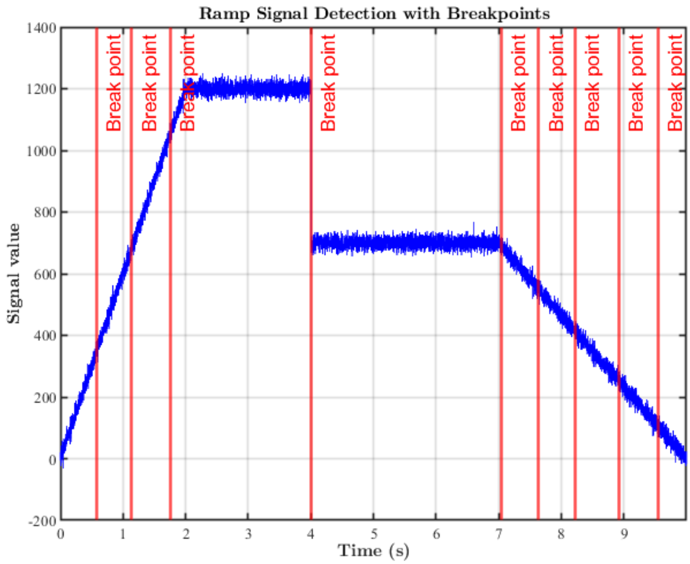


Figure 5: Identification of ramp changes in the signal structure

4 Conclusion

This paper presented a statistical approach for detecting changes in electrical signals encountered commonly in industrial and power systems. The proposed MATLAB algorithm was evaluated using simulated signals that included step changes, ramps and variations in variance, representing scenarios such as sudden load changes, switching events and rotor speed fluctuations. The results indicate that the algorithm can distinguish between abrupt and gradual changes and identify breakpoints corresponding to actual shifts in the signal mean or variance, while minimising the influence of measurement noise, although continuous transitions such as ramps may lead to multiple detected breakpoints. Several limitations were observed, as the evaluation relied on simulated signals that do not capture the complexity of real-world environments fully. The algorithm depends on basic statistical measures which may reduce robustness in the presence of fast or irregular changes, and outliers can affect detection accuracy further. These limitations motivate the proposed directions for future research directly. Future research should therefore extend the validation to real-world power system data, investigate methods to improve robustness to outliers, and explore adaptive strategies for handling varying signal characteristics. Comparative studies with alternative breakpoint detection and machine learning-based techniques would help clarify the relative advantages of the proposed approach, while also providing benchmarks for assessing performance under different operating conditions. Despite these limitations, the method offers notable advantages: its reliance on simple statistical descriptors ensures low computational effort and straightforward implementation, making it suitable for lightweight or embedded monitoring applications where real-time performance is essential. Overall, the study demonstrates that simulation-based signal generation provides a controlled environment to evaluate detection methods and supports the potential application of the algorithm to practical power system monitoring and analysis.

References

[1] A. Benigni, T. Strasser, G. De Carne, M. Liserre, M. Cupelli and A. Monti, "Real-Time Simulation-Based Testing of Modern Energy Systems: A Review and Discussion," in *IEEE Industrial Electronics Magazine*, vol. 14, no. 2, pp. 28-39, June 2020.

[2] S. Aminikhanghahi and D. J. Cook, "A Survey of Methods for Time Series Change Point Detection," *Knowledge and Information Systems*, vol. 51, no. 2, pp. 339–367, 2016.

[3] A. Hazra, N. Gogtay, "Biostatistics Series Module 10: Brief Overview of Multivariate Methods," *Indian J. Dermatol.*, Jul-Aug 2017.

[4] C. Truong, L. Oudre, and N. Vayatis, "Selective review of offline change point detection methods," *Signal Processing*, vol. 167, p. 107299, 2020.

[5] T. Dawn, A. Roy, A. Manna, and A. K. Ghosh, "Some clustering-based change-point detection methods applicable to high dimension, low sample size data," *Journal of Statistical Planning and Inference*, vol. 234, 2025.

[6] A. Pushkar, M. Gupta, R. Wadhvani, and M. Gyanchandani, "A Comparative Study on Change-Point Detection Methods in Time Series Data," in *2022 2nd International Conference on Intelligent Technologies (CONIT)*, Hubli, India, pp. 1–7, 2022.

[7] A. Ryzhikov, M. Hushchyn, and D. Derkach, "Latent Stochastic Differential Equations for Change Point Detection," *IEEE Access*, vol. 11, pp. 104700–104711, 2023.

[8] S. Liu, M. Yamada, N. Collier, and M. Sugiyama, "Change-point detection in time-series data by relative density-ratio estimation," *Neural Networks*, vol. 43, pp. 72–83, 2013.

[9] X. Ding, J. Wang, Y. Liu, and U. Jung, "Multivariate time series anomaly detection using working memory connections in bi-directional long short-term memory autoencoder network," *Appl. Sci.*, vol. 15, no. 2861, 2025.

Povzetek v slovenskem jeziku

Simulacijska študija strukturnih sprememb v časovnih vrstah električnih signalov. V tem članku so za zaznavanje sprememb v električnih signalih, značilnih za industrijske in energetske sisteme, uporabljeni statistični kazalniki. Razvit je bil namenski MATLAB-ov algoritem za prepoznavanje točk sprememb z beleženjem premikov v obnašanju signala in njegovih statističnih lastnostih. Za oceno metode so bili s simulacijo ustvarjeni sintetični signali, ki ponazarjajo pogoste vzorce v teh sistemih, kar je omogočilo testiranje pri različnih obratovalnih pogojih in različnih ravneh šuma. Rezultati kažejo, da algoritem zanesljivo zazna točke sprememb v številnih scenarijih ter s tem izkazuje prilagodljivost in robustnost. Študija poudarja vrednost simulacijskega ustvarjanja signalov kot nadzorovanega okolja za preizkušanje metod zaznavanja. S tem postavlja temelje za prihodnje uporabe pri zahtevnejši analizi realnih električnih signalov.

JOURNAL OF ENERGY TECHNOLOGY
Vol. 18, No. 2, pp. 85–98, September 2025

Original Scientific Article

BIOMASS GASIFICATION POTENTIAL FOR SLOVENIA'S GREEN TRANSITION: E-MOBILITY

NEJA HADŽISELIMOVIĆ,[1] TJAŽ HADŽISELIMOVIĆ[2]
[1] TU Graz, Graz, Austria
neja.hadziselimovic@student.tugraz.at
[2] II. Gymnasium of Maribor, Maribor, Slovenia
tjaz.hadziselimovic@druga.si

CORRESPONDING AUTHOR
neja.hadziselimovic@student.tugraz.at

Submitted
2. 9. 2025

Accepted
10. 9. 2025

Published
26. 9. 2025

Abstract In 2024, approximately fifty percent of the total kilometers driven by passenger vehicles in Slovenia were attributed to diesel-powered automobiles, underscoring the persistent dependence of the transportation sector on fossil fuels, which are major contributors to greenhouse gas emissions and global warming. Research further substantiates that the transportation sector constitutes the nation's predominant source of greenhouse gas emissions. In this context, e-mobility emerges as a key strategy for Slovenia's green transition in transportation. Additionally, biomass gasification represents a sustainable and environmentally friendly energy pathway that could support the country in achieving its environmental targets, while promoting the principles of the circular economy.

Keywords
green transition, renewable energy, forest biomass, biomass gasification, e-mobility

https://doi.org/10.18690/jet.18.2.85-98.2025

1 Introducton

It could be said that, throughout history, the main driving force behind most significant developments has been the generation and use of energy. Since lignocellulosic materials (biomass) were the primary energy source, the world has evolved to a point where fossil fuels, especially crude oil and natural gas, produce energy predominantly [1]. The excessive use of fossil fuels in coal- and gas-based power plants has contributed to one of the most significant challenges of our time: global warming, causing a significant ecological imbalance. Biomass is estimated to contribute 10–14% of the world's power supply [1]. Increasing this contribution is a key goal for sustainable energy development, as the biomass gasification process has been proven to be environmentally friendly due to its neutral effect on atmospheric greenhouse gas accumulation [1]. The study explores Slovenia's energy situation, and discusses the potential benefits of implementing biomass gasification processes.

In Slovenia in 2024, roughly half of all the electric energy produced was from renewable energy sources (hydro-, wind- and solar power plants), and the other half was generated from the Nuclear power plant Krško, or thermal power plants. The exact contributions and percentages for the year 2024 are shown in Table 1 and Figure 1 [2].

Table 1: Sources of electric energy in Slovenia by annual electricity production

Source	Contribution	Percentage
Thermal power plants	3639 GWh	27.2%
Nuclear power plants	2772 GWh	20.7%
Renewable energy sources	6961 GWh	52.1%

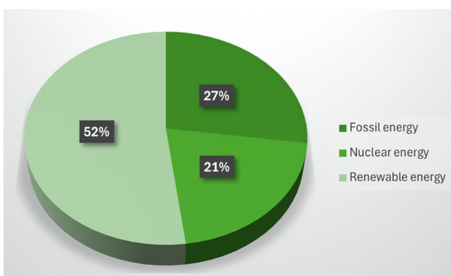


Figure 1: Sources of electric energy in Slovenia by annual electricity production

Although there is a high percentage of electricity that comes from renewables, the current mix, climate-wise, is still not optimal, as shown in Figure 1. The reason for this is that fossil fuel-based electricity releases CO_2 that has been locked underground for millions of years, adding net carbon to the atmosphere [3]. The question is – how is biomass as a source of energy different? In contrast to fossil fuels, the CO_2 released from biomass burning was previously absorbed by plants, forming a closed carbon cycle [3]. Biomass also emits lower levels of sulfur (SO_2) and heavy metals compared to coal [4], reducing acid rain and pollution. Unlike nuclear energy, biomass plants do not produce radioactive waste; they are smaller, cheaper, and more versatile in location [5, 6]. Although hydroelectric power is renewable, it can disrupt river ecosystems, block fish migration [7], and depend on fluctuating water levels. On the other hand, one of its crucial advantages is that biomass can be burned on demand. However, biomass combustion (burning biomass to produce heat that drives a steam turbine to produce electricity) is just one option for its usage. It turns out that, even though combustion presents higher generation efficiencies, gasification of biomass offers more benefits from an environmental point of view, since the CO_2 emissions are similar, but the amount of NO_x produced is much lower [8].

It is important to highlight that gasification also offers a diversity of co-products that could be of great use, such as syngas, which, typically, contains H_2, CO, CO_2, CH_4, H_2O, and trace amounts of higher hydrocarbons. Syngas is an important source for producing diesel or gasoline, hydrogen, fertilizers, methanol, and other chemicals. Furthermore, the product of biomass gasification is also a hydrogen-enriched gas, which is of great significance, because, among all the renewable energy sources, only biomass gasification can produce hydrogen directly. With a higher contribution of biomass gasification as a renewable source of electric energy, could the production of hydrogen through fossil fuels, which is currently 96%, be minimized [9].

Furthermore, Slovenia is one of Europe's most forested countries, with about 58% of its land (nearly 1.18 million hectares) covered by forests [10, 11]. The annual gross increment (annual forest growth) is around 8.7 million m^3 [12], from which approximately 3.8 million m^3 are conifers and roughly 5 million m^3 are non-conifers. Based on the data for 2020 from the Ministry of Agriculture, Forestry and Food of Slovenia, the annual potential (allowable) felling in Slovenia is 7.1 million m^3, however, in 2020, the total felling was only 4.2 million m³ (59% of the potential felling), of which 2.4 million m³ were non-conifers and 1.8 million m³ conifers [13]. Similar results were also presented by the Statistical Office of the Republic of Slovenia [14]. Based on these facts, it could be concluded that Slovenia has a significant unharvested potential of roughly 2 million m³ of conifers and 2.6 million m³ of non-conifers annually, totaling 4.6 million m³.

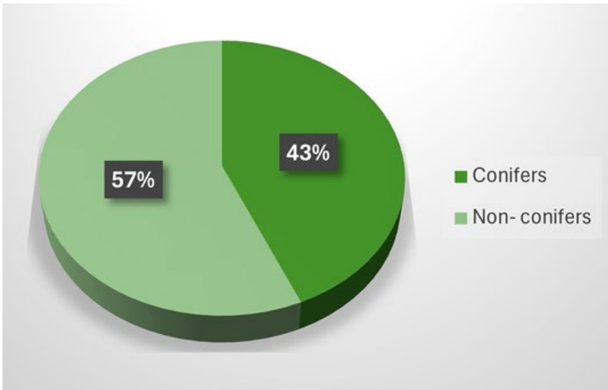


Figure 2: Unharvested potential of conifers and non-conifers

Studies have shown that removing mature, diseased, or overcrowded trees allows younger trees to thrive [15], enhances biodiversity [16], and reduces wildfire risks [17]. Moreover, young, fast-growing forests absorb more CO_2 than older, stagnant ones [18]. Harvesting wood and enabling new growth can sustain the forest-carbon cycle. These facts suggest that biomass is a highly suitable energy source for Slovenia, but the question remains: where could its use be implemented to maximize the benefits?

According to Slovenia's National Inventory Document (NID) for 2024 [19], the transport sector remains the most significant contributor to the country's greenhouse gas (GHG) emissions. Furthermore, according to the Statistical Office of the Republic of Slovenia, in 2024, national and foreign vehicles drove 22 billion kilometers-vkm on Slovenian road territory, of which 90% was by national vehicles. A total of 8.6 billion vkm (39%) were driven on motorways and highways. On Slovenian and foreign road territories, national vehicles drove 22.8 billion vkm, of which 79%, or approximately 18 billion vkm, were driven by passenger cars. Among these, diesel passenger cars represented the largest share (47%), equaling 10.7 billion vkm [20]. It is important to note that, in the context of green transition and minimizing the emissions from the transport sector to reduce the effects of global warming, the age of vehicles is relevant, as it was shown that over-aged vehicles emit a higher percentage of CO and other hydrocarbons [20]. Figures 3, 4, 5, and 6 show the number of vkm registered annually in Slovenia on the Slovenian and foreign road territory by type and age of vehicle.

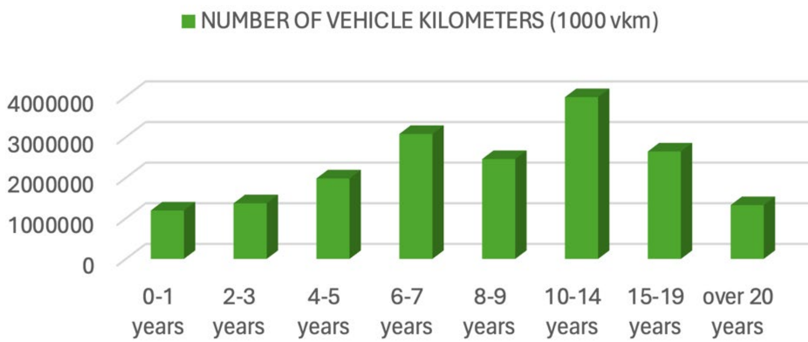


Figure 3: Number of vkm made by all passenger vehicles registered in Slovenia annually by age of vehicles

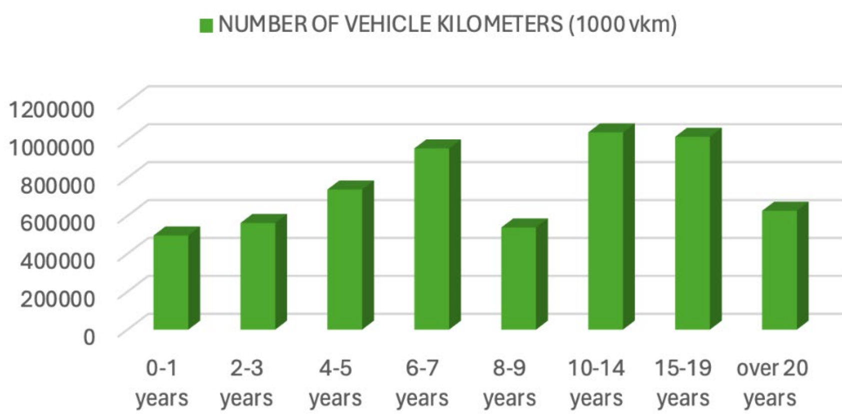


Figure 4: Number of vkm made by petrol-fueled passenger vehicles registered in Slovenia annually by age of vehicles

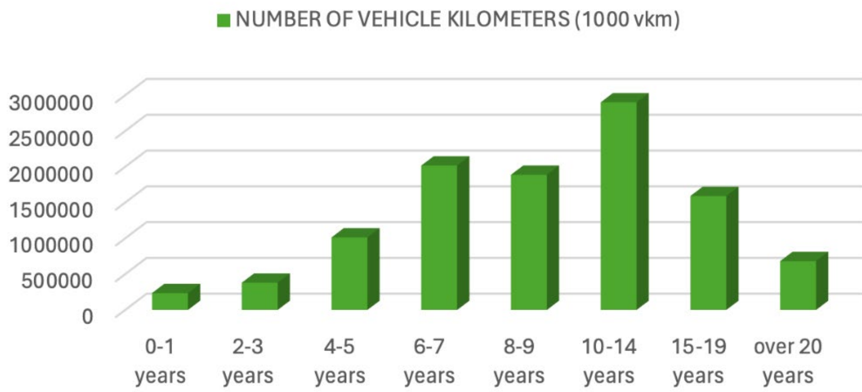


Figure 5: Number of vkm made by diesel-fueled passenger vehicles registered in Slovenia annually by age of vehicles

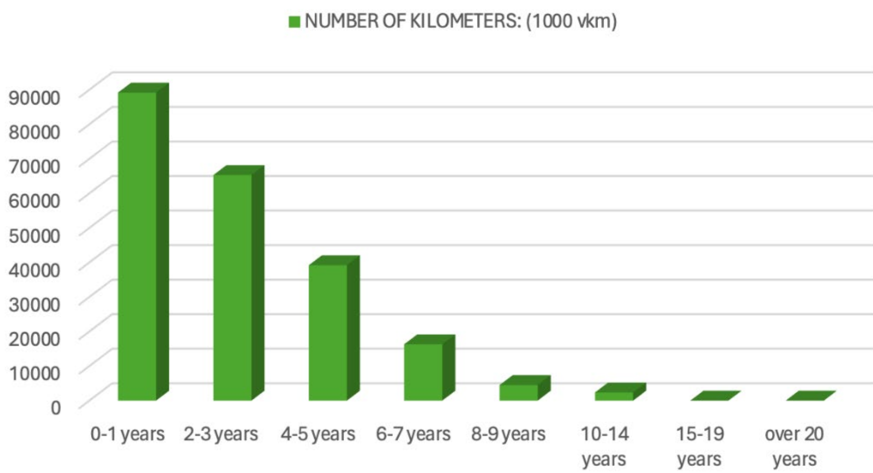


Figure 6: Number of vkm made by electric-fueled passenger vehicles registered in Slovenia annually by age of vehicles

These Figures illustrate how strongly Slovenia's transport sector still depends on fossil fuels, with nearly half of all vkm driven by diesel vehicles in 2024. This mobility pattern contributes substantially to greenhouse gas emissions, and highlights the country's reliance on imported petroleum. Biomass gasification offers a potential pathway to reduce fossil fuel dependency, providing green energy and supporting the transition toward e-mobility.

2 Methods

As stated above, roughly 22 billion vkm were made by Slovenian and foreign passenger vehicles on the Slovenian road-territory. The strategy for green transition in the transport sector via e-mobility would be to lower the number of vkm made by non-electric vehicles. To achieve that goal, a suitable infrastructure should be provided for the transition, such as enough electric energy and charging spots. The question is how much biomass gasification could contribute, in other words, how many vkm could be made by electric vehicles using the electric energy produced by biomass gasification? The Alternative Fuels Infrastructure Regulation (AFIR, EU 2023/1804) mandates fast-charging stations every 60 km along the TEN-T core road network by 2025 [21]. Slovenian highways and motorways are vital to the TEN-T core road network. Slovenia is an important transit country at the crossroads of the Baltic–Adriatic, Mediterranean, and Alpine-Western Balkans corridors. This is why the following calculations focus on Slovenian highways and motorways, where 8.6 billion vkm were driven by national and foreign vehicles [20]. To find out what percentage of electric energy is needed for driving 8.6 billion vkm with electric vehicles that could be covered by biomass gasification, it is first necessary to look at the Slovenian capacities, such as how much biomass is available for gasification. For the latter process non-confiners are beneficial, because they fall into the so-called hardwood species [22], which, in comparison to softwood species, have higher density and greater reactivity [23], which are critical properties in gasification. Slovenia has an unharvested potential of 2.6 million m^3 of non-conifers annually [13]. Beech represents approximately 33% of growing stock in Slovenia [24]; therefore, it is a dominant species. Its density at 12-15% moisture content is 710 kg/m3 [25]. With these data available, the weight of unharvested potential of hardwood could be calculated by Equation 1.

$$m = \rho V \tag{1}$$

From the weight of biomass available for gasification, the sum of electric energy yield can be determined by equation 2.

$$E = \eta m \tag{2}$$

However, the precise data for energy yield η weren't available directly for the data used for this study, which is why it had to be determined before proceeding with Equation 2. The first step for calculating the energy yield was determining the low heating value of 1 kg of wood used. The biomass LHV describes the energy density of the forestry residues, and determines the maximum amount of energy that can be extracted in the gasification process. This property depends on the type of wood, and mainly on the moisture content [26]. LHV can be determined as [27]:

$$LHV = HHV(1 - MC) - 2.447MC \tag{3}$$

In Equation 3 HHV represents the high heat value of the dry biomass based on [26], **and** the values range between 17 MJ/kg and 21 MJ/kg for dry wood. The average 19 MJ/kg was used. MC is the moisture content, which based on [28], in commercial plants, usually only allowed up to 15%. For this study, 12% MC was used.

The LHV = 16.42636 MJ/kg was determined after inserting these properties in Equation 3. Indirectly relevant to producing electric energy in a biomass gasification power plant is the energy of syngas, which can be determined from the LHV of the biomass using the value of cold gas efficiency, which measures how effectively a gasification process converts solid fuel (biomass) into combustible gases by comparing the energy in the produced gas (syngas) to the energy in the initial solid feedstock. The average cold gas efficiency is 70% [29], which means that LHV = 16.42636 MJ/kg has to be multiplied by a factor of 0.7, resulting in the energy of syngas roughly 11.5 MJ/kg. Finally, generator efficiency should be taken into consideration. Based on [30] the generator efficiency ($MJ_{electricity}/MJ_{syngas}$) ranges from 20-35%, and the average factor 0.275 was used for this study. After multiplying the energy of syngas (11.498452 MJ/kg) by the generator efficiency, we are left with an energy yield of round η = 3.16 MJ/kg.

Now η = 3.16 MJ/kg can finally be used in Equation 2.

$$E = \eta m \tag{2}$$

resulting in total energy of 5 837 189 157.8 MJ or 1 621 441 432.7 kWh from 1 846 000 000 kg unharvested hardwood potential.

The last step is converting the power (kWh) to kilometers. Equation 4 respects the fact that, for 100 km of driving with an electric passenger car, 20 kWh are necessary based on [31], where it is stated that an electricity consumption of up to 20 kWh/100 km should be realistic for a European mid-size car moving in urban areas or extra-urban at limited speeds.

$$d = E\,\frac{100\ km}{20\ \mathrm{kWh}} \tag{4}$$

For better transparency, all the data used are shown in Table 2.

Table 2: Data used for calculations

	Data
Low heating value of biomass at 12% MC	16.42636 MJ/kg
Generator efficiency ($MJ_{electricity}/MJ_{syngas}$)	0.275
Cold gas efficiency	70%
Energy yield	3.1620743 MJ/kg

3 Results and analysis

Table 3 shows all the calculation results based on an initial input of 1 ton of biomass at 12% MC. In Table 4, the results are based on all the unharvested hardwood potential in Slovenia at the same moisture content.

Table 3: Results for 1 ton

	Value
Mass of wood at 12% MC	1000 kg
Total energy content of biomass	16 430 MJ
Energy yield	878.55 kWh
Number of kilometres	4392.75 km

Table 4: Results for all unharvested hardwood potential

	Value
Mass of unharvested hardwood potential at 12% MC	1 846 000 000 kg
Total energy content of biomass	30 329 780 000 MJ
Produced electric	1 621 803 736.1 kWh
Number of kilometres	8 107 207 163.6 km

Table 4 shows that, from the gasification of 1,846,000,000 kg of unharvested hardwood, enough electric energy would be generated for approximately 8.1 billion kilometers made by passenger vehicles. This is 94.27**%** of all the kilometers made by national and foreign vehicles on Slovenian motorways and highways (for the year 2024), which are, as already mentioned above, an essential part of the TEN-T core road network. Furthermore, the calculated number of kilometers that could be made in the future with electric vehicles with electricity produced from the biomass gasification process is equal to 45.04% of all the kilometers made by national passenger vehicles on Slovenian and foreign road territories in 2024.

Integrating biomass gasification power plants near the highways and motorways would be the most effective way to install charging stations at highway rest stops, complying with European Regulations. It is important to highlight that optimal locations should be considered, which means the best areas would be the ones that are near the sources of biomass (forests), and also not too far from potential charging spots, to minimize additional carbon emissions due to the transportation of biomass and practically cancel out the electric energy losses for distribution.

4 Discussion and conclusion

With one of the highest forest coverages in Europe, Slovenia has a great potential for implementing the biomass gasification process as a source for electricity production. Not only would that lower carbon and NO_x emissions that are heating our planet, but a mixture of other valuable and important chemical components would be synthesized. As the traffic sector is known to be the most significant pollutant in Slovenia, the study focused on how implementing such power plants could reduce the number of kilometers driven by non-electric passenger vehicles. It is important to highlight that data, especially energy yield, depend on the type of gasifier, the type of biomass, its moisture content, and cold gas efficiency. The study used the average of these values; therefore, more detailed calculations should be made based on the previously stated data for a concrete example of a biomass gasification power plant. This paper also didn't consider charging stations and battery charging efficiency. In all cases, even if the energy yield would be somewhat lower, this strategy would still be efficient for Slovenia’s green transition in the transport sector via e-mobility. To conclude, it was proved by the calculations in the study that biomass gasification technology has a great potential to become the primary source of electric energy for transport sector in Slovenia – it could cover roughly 94% of the kilometers made on highways and motorways, in other words, 45% of all the kilometers that were made by national passenger vehicles on Slovenian and foreign road territories in 2024. Biomass could, in the future, serve as an important complementary source to existing renewable energy systems, enabling synergies such as with hydrogen technologies and combined heat and power generation. Furthermore, additional research is needed, including pilot projects along highway corridors and comparisons of different biomass share scenarios in the energy mix, in order to assess its long-term role realistically in Slovenia's green transition. This potential not only supports Slovenia's energy independence, but also aligns with the European Union's broader goals for decarbonization and sustainable transport solutions [32].

References

[1] Erakhrumen, A. A. (2012). Biomass Gasification: Documented Information for Adoption/Adaptation and Further Improvements toward Sustainable Utilisation of Renewable Natural Resources. *ISRN Renewable Energy*, *2012*, 1–8. https://doi.org/10.5402/2012/536417

[2] Agencija za energijo (2024). *Poročilo o stanju na področju energetike v Sloveniji.*

[3] Kashif, U., Abbas, S., Kousar, S., & Lu, H. (2025). Linking of bio-energy and carbon neutrality: Navigating economic policy uncertainty and climate change policy in the USA. *Energy*, 136012. https://doi.org/10.1016/j.energy.2025.136012

[4] Trivedi, K., Sharma, A., Kanabar, B. K., Arunachalam, K. D., & Gautam, S. (2024). Comparative Analysis of Coal and Biomass for Sustainable Energy Production: Elemental Composition, Combustion Behavior and Co-Firing Potential. *Water, Air, & Soil Pollution*, *235*(11). https://doi.org/10.1007/s11270-024-07509-3

[5] U. S. Environmental Protection Agency, Energy and Environmental Analysis, Inc., an ICF International Company, & Eastern Research Group, Inc. (ERG). (2007). *Biomass Combined Heat and Power Catalog of Technologies: Vol. v.1.1*. https://www.epa.gov/sites/default/files/2015-07/documents/biomass_combined_heat_and_power_catalog_of_technologies_v.1.1.pdf

[6] IRENA (2022), Renewable power generation costs in 2022, International Renewable Energy Agency, Abu Dhabi.

[7] Benitez, J. P., Sonny, D., Colson, D., Dierckx, A., & Ovidio, M. (2025). Hydroelectric power plant and upstream fish migration: evaluation of the efficiency of a behavioural barrier. *Journal of Ecohydraulics*, 1–14. https://doi.org/10.1080/24705357.2025.2533868

[8] Carotenuto, A., Di Fraia, S., Uddin, M. R., & Vanoli, L. (2022). Comparison of Combustion and Gasification for Energy Recovery from Residual Woody Biomass. *International Journal of Heat and Technology*, *40*(4), 888–894. https://doi.org/10.18280/ijht.400404

[9] Farzad, S., Mandegari, M. A., & Görgens, J. F. (2016). A critical review on biomass gasification, co-gasification, and their environmental assessments [Review Paper]. *Biofuel Research Journal*, *483–495*. https://doi.org/10.18331/BRJ2016.3.4.3

[10] Tend, O. (n.d.). *Forest cover - Slovenia Forest Service*. Slovenia Forest Service. https://www.zgs.si/en/slovenian-forests/forest-

cover#:~:text=Forests%20are%20the%20dominant%20landscape,forested%20area%20is%20in%20Prekmurje.

[11] *Forest area (ha) by AREA and YEAR-PxWeb.* (n.d.). PxWeb. https://pxweb.stat.si/SiStatData/pxweb/en/Data/Data/1673105S.px/table/tableViewLayout2/

[12] *Growing stock and annual gross increment by STOCK AND INCREMENT, TYPE OF WOOD, MEASURES and YEAR-PxWeb.* (n.d.). PxWeb. https://pxweb.stat.si/SiStatData/pxweb/en/Data/Data/1673110S.px/table/tableViewLayout2/

[13] Slovenia Forest Service & Ministry of Agriculture, Forestry and Food of Slovenia. (2021). PUBLIC FORESTRY SERVICE IN SLOVENIA: FORESTS AND FORESTRY IN SLOVENIA. In *Slovenia.* https://www.zgs.si/assets/uploads/files/vsebine/1/8/3/zgs_gozd_in_gozdarstvo_v_sloveniji_zlo_a4_en_press-compressed.pdf

[14] *Removals (m3) by REMOVALS, TYPE OF TREES and YEAR-PxWeb.* (n.d.). PxWeb. https://pxweb.stat.si/SiStatData/pxweb/en/Data/Data/1673135S.px/table/tableViewLayout2/

[15] Saarinen, N., Kankare, V., Yrttimaa, T., Viljanen, N., Honkavaara, E., Holopainen, M., Hyyppä, J., Huuskonen, S., Hynynen, J., & Vastaranta, M. (2020). Assessing the effects of thinning on stem growth allocation of individual Scots pine trees. *Forest Ecology and Management*, *474*, 118344. https://doi.org/10.1016/j.foreco.2020.118344

[16] Verschuyl, J., Riffell, S., Miller, D., & Wigley, T. B. (2010). Biodiversity response to intensive biomass production from forest thinning in North American forests – A meta-analysis. *Forest Ecology and Management*, *261*(2), 221–232. https://doi.org/10.1016/j.foreco.2010.10.010

[17] Ott, J. E., 1, Kilkenny, F. F., 1, Jain, T. B., 2, USDA Forest Service, & Rocky Mountain Research Station. (2023). Fuel treatment effectiveness at the landscape scale: a systematic review of simulation studies comparing treatment scenarios in North America. *Fire Ecology*, 2–29. https://doi.org/10.1186/s42408-022-00163-2

[18] Pugh, T. a. M., Lindeskog, M., Smith, B., Poulter, B., Arneth, A., Haverd, V., & Calle, L. (2019). Role of forest regrowth in global carbon sink dynamics. *Proceedings of the National Academy of Sciences*, *116*(10), 4382–4387. https://doi.org/10.1073/pnas.1810512116

[19] Ministry of the Environment and Spatial Planning of the Republic of Slovenia. (2024). *National inventory document 2024: GHG emissions inventories 1986–2022* [Submission under the United Nations Framework Convention on Climate Change]. Government of the Republic of Slovenia.

[20] *Number of vehicle kilometres and average number of vehicle kilometres per vehicle by TYPE OF VEHICLE, AGE OF VEHICLE, YEAR and MEASURES-PxWeb.* (n.d.). PxWeb. https://pxweb.stat.si/SiStatData/pxweb/en/Data/Data/2282005S.px/

[21] European Union. (2023). *Regulation (EU) 2023/1804 of the European Parliament and of the Council of 13 September 2023 on deploying alternative fuels infrastructure, and repealing Directive 2014/94/EU. Official Journal of the European Union*, L 229, 1–85. https://eur-lex.europa.eu/eli/reg/2023/1804/oj

[22] Food and Agriculture Organization of the United Nations. (1997). *Wood: Hardwoods and softwoods.* In *Introduction to wood as a material* (Chapter 2).

[23] Asmadi M., Kawamoto H., Saka S. (2009) Gasification characteristics of some softwood and hardwood species.

[24] FORESTS and forestry in Slovenia. (2020). In M. Čater & P. Železnik (Eds.), *Studia Forestalia Slovenica.*

[25] Čufar, K., 1, Gorišek, Ž., 1, Merela, M., 1, Kropivšek, J., 1, Gornik Bučar, D., 1, & Straže, A., 1. (2017). Properties of Beechwood and its Use. In *Les/Wood: Vol. 66* (Issue No. 1, pp. 27–39) [Journal-article]. https://doi.org/10.26614/les-wood.2017.v66n01a03

[26] Camarero Lema, S. I. (2022). IMPACT OF CHANGES IN THE SYNGAS-BIOCHAR MIX AND PLANT SIZE ON THE ECONOMICS AND ENVIRONMENTAL PERFORMANCE OF DISTRIBUTED BIOMASS GASIFICATION SYSTEMS. In J. Alfaro & P. Vaishnav, *University of Michigan*.

[27] Abouemara, K., Shahbaz, M., McKay, G., & Al-Ansari, T. (2024). The review of power generation from integrated biomass gasification and solid oxide fuel cells: Current status and future directions. *Fuel, 360*, 130511

[28] Frisinghelli, P., Zachl, A., Buchmayr, M., Gruber, J., Anca–Couce, A., Scharler, R., & Hochenauer, C. (2025). Extending the operational limit for fuel water content in a stratified downdraft gasifier from 15 to 22 m% by increasing the reactor height. *Fuel*, *395*, 135167. https://doi.org/10.1016/j.fuel.2025.135167

[29] Aguado, R., Escámez, A., Jurado, F., & Vera, D. (2023). Experimental assessment of a pilot-scale gasification plant fueled with olive pomace pellets for combined power, heat, and biochar production. *Fuel*, *344*, 128127. https://doi.org/10.1016/j.fuel.2023.128127

[30] Roise, J. P., Catts, G., Hazel, D., Hobbs, A., & Chris Hopkins. (2013). *Balancing biomass harvesting and drying tactics with delivered payment practice*.

[31] Helmers, E., Marx, P., & Institut für angewandtes Stoffstrommanagement (IfaS) am Umwelt-Campus Birkenfeld, Trier University of Applied Sciences. (2012). Electric cars: technical characteristics and environmental impacts. In *Environmental Sciences Europe* [Journal-article]. http://www.enveurope.com/content/24/1/14

[32] Morselli, N., Puglia, M., Ottani, F., Pedrazzi, S., Noussan, M., Laveneziana, L., Prussi, M., Talluri, G., Allesina, G., & Tartarini, P. (2024). Gasification of agricultural residues to support the decarbonization of the transport sector via electricity generation: a case study. Journal of Physics. https://doi.org/10.1088/1742-6596/2893/1/012001

Nomenclature

Symbol	Meaning
m	mass
ρ	density
V	volume
E	energy
η	energy yield
HHV	High heating value
LHV	Low heating value
MC	Moisture content
d	distance

Povzetek v slovenskem jeziku

Uplinjanje biomase za zeleni prehod Slovenije: e-mobilnost. Skoraj polovica vseh s potniškimi avtomobili prevoženih kilometrov v Sloveniji je bila v letu 2024 prevožena z dizelskimi avtomobili, kar nakazuje na odvisnost transporta od fosilnih goriv, ki zaradi emisij toplogrednih plinov med drugim prispevajo k globalnemu segrevanju. Raziskave prav tako potrjujejo, da tudi v letu 2024 transportni sektor ostaja največji vir emisij toplogrednih plinov v državi. Kot izjemno sredstvo zelenemu prehodu Slovenije v transportnem sektorju preko e-mobilnosti se zaradi obdanosti Slovenije z gozdnimi viri uplinjanje biomase ponuja kot trajnosten in okolju prijazen vir energije, ki bi lahko Slovenijo posredno pripeljal do želenih okoljskih ciljev s poudarkom na krožnem gospodarstvu.

JOURNAL OF ENERGY TECHNOLOGY
Vol. 18, No. 2, pp. 99–122, September 2025

Professional Article

Submitted
10. 9. 2025

Accepted
15. 9. 2025

Published
26. 9. 2025

ASSESSMENT OF HARMONIC DISTORTION IN SCHOOL BUILDINGS EQUIPPED WITH GRID-CONNECTED PV SYSTEMS

FRANJO PRANJIĆ
University of Maribor, Faculty of Energy Technology, Krško, Slovenia
franjo.pranjic@um.si

CORRESPONDING AUTHOR
franjo.pranjic@um.si

Abstract The integration of photovoltaic systems into power grids can impact power quality, particularly concerning voltage and current harmonics. This study investigates the power quality of a photovoltaic system integrated into the electrical system of an educational facility, focusing on harmonic distortion in both voltage and current. Comprehensive measurements were conducted across three phases and analysed according to the EN 50160 and IEEE 519 Standards. The results demonstrated that, while the voltage quality meets EN 50160 requirements consistently, indicating stable voltage levels, the current measurements revealed significant harmonic distortion. Notably, Phase 2 exhibited Total Harmonic Distortion values substantially above the acceptable limits, with Phase 1 and Phase 3 also showing elevated Total Harmonic Distortion. To address these issues, the study recommends the implementation of advanced harmonic filters and optimisation of inverter technologies. These measures are crucial for enhancing power quality, and ensuring compliance with the industry Standards in high photovoltaic penetration scenarios.

Keywords
power quality analysis, grid-connected PV systems, EN 50160 standard, IEEE 519 Standard, IEC 61000 standard, voltage harmonics, current harmonics, harmonic distortion, renewable energy integration, compliance assessment

https://doi.org/10.18690/jet.18.2.99-122.2025

1 Introducton

The integration of photovoltaic (PV) systems into building infrastructures has seen a significant increase, driven by the need for sustainable energy solutions and the declining cost of solar technology. However, while PV systems offer substantial environmental benefits, their integration poses challenges related to power quality, particularly concerning voltage harmonics and current distortion.

The impact of PV systems on power quality has been studied widely. Various research works have highlighted the issues and proposed solutions to mitigate them. For instance, harmonic resonance, which can arise from the interaction between the PV inverters and the grid, has been a focal point. Studies have shown that using LCL filters and advanced impedance modelling techniques can suppress harmonic resonance effectively and enhance system stability [1 – 6].

Moreover, the integration of PV systems often leads to the generation of harmonics at the point of common coupling (PCC). [7] This issue is exacerbated by fluctuations in solar irradiance, which can cause significant variations in power quality parameters. Research has demonstrated that sophisticated control strategies, such as zero sequence current adjusters and hybrid optimisation techniques, can mitigate these effects. [5-10]

Experimental evaluations of distortion effects in grid-connected PV systems have provided valuable insights into the behaviour of these systems under different conditions. For example, studies have utilised real-time simulation platforms to analyse the impact of solar radiation levels and controller tuning on harmonics, revealing that proper system design and control can improve the power quality significantly [11,12]. Additionally, the use of various harmonic compensation strategies, including the proportional-integral resonance controllers with harmonic and lead compensators, has shown promising results in reducing total harmonic distortion (THD) and improving the overall performance of grid-connected PV systems [13-16].

Studies have also addressed the impact of high PV penetration on power quality, finding that the current harmonics generated by PV systems can exceed the thresholds set by Standards like IEEE 519. This can lead to issues such as overheating of transformers and increased losses in the distribution network [17].

EN 50160 outlines the voltage characteristics of electricity supplied by public distribution systems, and defines acceptable limits for voltage variations and harmonic distortion. On the other hand, IEEE 519 provides guidelines for harmonic control in electrical power systems, specifying acceptable limits for current and voltage harmonics in different types of electrical systems. For compliance in Europe, the IEC 61000-3-6 Standards are also highly relevant for managing current harmonics in PV systems.

In educational buildings the integration of PV systems presents unique challenges, due to variable load profiles and the influence of student activities on power consumption patterns. Research suggests that tailored solutions, including the use of passive and active filtering techniques, are essential for mitigating harmonic issues in such environments. [18, 19]

Compliance with the EN 50160 and IEEE 519 Standards is crucial for ensuring the safe and efficient operation of PV systems. EN 50160 focuses on the quality of voltage supplied by the public distribution system, specifying limits for parameters such as voltage magnitude, frequency and harmonics. IEEE 519, on the other hand, sets standards for harmonic distortion in electrical power systems, providing limits for both voltage and current harmonics based on the size of the electrical system and the point of common coupling (PCC). The IEC 61000-3-6 standards are also applicable in Europe for managing the current harmonics in PV systems. These standards are essential for mitigating the adverse effects of harmonics, such as equipment overheating, reduced efficiency and potential damage to sensitive electronic devices. [20,21]

Given the rigorous nature of these Standards, they are appropriate for current harmonics analysis in PV systems. However, continuous monitoring and adaptive control strategies are necessary to maintain compliance, especially in environments with fluctuating power demands, such as school buildings. Future research might also explore additional Standards and Guidelines that could complement EN 50160 and IEEE 519, enhancing the power quality in systems with high PV penetration further.

This study investigates the power quality of a school building with an integrated PV system, focusing on voltage harmonics and current distortion. The measurements were taken over a one-week period with a ten-minute interval recording, providing a detailed insight into the power quality dynamics of the building. The primary objective was to assess the compliance of voltage harmonics with the EN 50160 standards and identify the extent of current distortion present.

The findings revealed that, while the voltage harmonics are within acceptable limits, there is a severe current distortion issue. By providing empirical data and analysis, the study aims to offer practical insights and recommendations for improving the integration of PV systems in similar settings.

2 Materials and Methods

The study analyses the measurement results for a school building located in Slovenia (EU). While specific details about the building, such as its surface area, are not relevant to this study, key details include the installed photovoltaic (PV) power on the rooftop (50 kW) and the nominal current rating of the building's circuit breakers (160 A). The school building is shown in Figure 1.

Figure 1: School building
Source: own.

The measurements were conducted in accordance with the EN 50160 Standard, with data collected at 10-minute intervals over a one-week period. The Metrel MI2892 instrument was used and connected at the point of common coupling (PCC) to the main distribution board, where the 3x160 A circuit breakers are installed. Measurements were taken for both the photovoltaic (PV) system and the school building. The data were analysed using the Metrel PowerView software (version 3.0.0.5936, 64-bit). The instrument is shown in Figure 2.

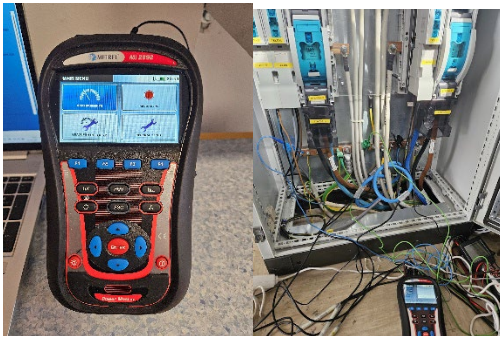


Figure 2: Measuring equipment and the setup: (a) Metrel MI 2892 Power Master Measuring instrument; (b) Connection setup at the point of common coupling (PCC) at the main distribution board.
Source: own.

Although the building has 3x160A circuit breakers the fundamental current harmonic does not go over 75A (as the results will show), so the current harmonics are analysed by the IEC 61000-3-6 Standard.

2.1 Standards for Power Quality in School Buildings with Integrated PV Systems

When integrating photovoltaic (PV) systems into school buildings, ensuring compliance with power quality standards is crucial to maintain a stable and efficient electrical system. Three primary Standards provide guidelines for voltage and current harmonics: EN 50160, IEEE 519, and IEC 61000. This section of the article reviews these Standards in the context of PV integration in school buildings, providing a comparative analysis and highlighting the relevant requirements.

Meeting the power quality Standards is essential for ensuring the reliability, safety, and efficiency of the electrical systems in the school building. It protects equipment, enhances energy efficiency, ensures regulatory compliance, and supports the effective integration of renewable energy sources. By adhering to these Standards, the school can provide a safe and conducive learning environment, while also achieving financial and environmental benefits.

2.1.1 EN 50160: Voltage Characteristics

EN 50160 specifies the voltage characteristics of electricity supplied by public distribution networks. It addresses primarily the voltage quality parameters, including frequency, magnitude, waveform, symmetry and the presence of disturbances. [20]

The integration of photovoltaic (PV) systems into buildings such as schools has become increasingly prevalent, due to the push for sustainable energy solutions. However, this integration brings challenges, particularly in maintaining power quality. The European Standard EN 50160 is pivotal in defining the voltage characteristics for electricity supplied by public distribution systems, ensuring stability and reliability. This chapter explores EN 50160's relevance in the context of our study, which examines the power quality of a school building with a grid-connected PV system.

EN 50160 covers the voltage characteristics of low, medium and high voltage public distribution systems. It applies to various buildings, including residential, commercial and educational institutions like the school in our study. The Standard provides a comprehensive framework for assessing and maintaining power quality, crucial for the seamless operation of electrical systems, especially when integrating renewable energy sources.

To evaluate compliance with EN 50160, we conducted measurements over a one-week period at 10-minute intervals. This methodology provides a detailed analysis of the voltage characteristics, identifying any deviations from the Standard. Our findings help in assessing whether the school's electrical system, influenced by the grid-connected PV system, meets these stringent requirements.

Key Requirements:

- Voltage Frequency: 50 Hz ± 1% for 95% of a week.

- Voltage Level: ±10% of the nominal voltage for 95% of a week.
- Voltage Harmonics: Total harmonic distortion (THD) should not exceed 8% for 95% of a week.
- Voltage Fluctuations: Voltage deviations should not exceed ±5%.
- Voltage Unbalance: Should not exceed 2% for 95% of a week.

Table 1 shows the voltage harmonic limits by the EN50160 Standard.

Table 1: Voltage Harmonic Limits (EN50160)

Harmonic Order	Maximum Individual Harmonic Voltage (% of fundamental)
1st	-
3rd	5
5th	6
7th	5
9th	1.5
11th	3.5
13th	3
15th	0.5
THD	8% (95% of the time)

Source: EN 50160: Voltage characteristics of electricity supplied by public distribution networks. European Committee for Electro-technical Standardization (CENELEC).

2.1.2 IEC 61000: Electromagnetic Compatibility

IEC 61000 series address the electromagnetic compatibility (EMC) requirements. IEC 61000-3-6, titled "Electromagnetic compatibility (EMC) – Part 3-6: Limits – Limits for harmonic currents," is a key Standard developed by the International Electrotechnical Commission (IEC) to regulate the harmonic distortion in electrical systems. This Standard is crucial for ensuring that the harmonic currents generated by electrical equipment do not affect the quality of the power supply and the operation of other equipment adversely. It limits the harmonic current emissions of equipment connected to public low-voltage systems with a rated current ≥ 16 A and ≤ 75 A. [21]

IEC 61000-3-6 sets out limits for harmonic currents in electrical systems, with a primary focus on controlling harmonic currents at various orders. The Standard targets specifically:

- The 5th Harmonic: typically, the permissible limit for the 5th harmonic current is around 20% of the fundamental current.
- The 7th Harmonic: the limit for the 7th harmonic current is generally about 14% of the fundamental current.

The Standard emphasises odd harmonics, because they are generated more commonly by typical non-linear loads, and can have a more significant impact on power systems. In contrast, even harmonics (such as the 2nd, 4th, and 6th) are addressed less frequently, as they are less prevalent in systems with standard non-linear loads. Detailed limits for harmonic currents are specified in the Standard, including in Table 2.

Table 2: Harmonic Current Limits (IEC 61000-3-6) for Equipment Rated Up to 75A

Harmonic Order	Current Limit (% of fundamental)
3rd	5
5th	20
7th	14
9th	7
11th	6
13th	5
15th	4
17th	4
19th	3
21th	3

Source: ELECTROMAGNETIC COMPATIBILITY (EMC) – Part 3-6: Limits – Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems

2.1.3 IEEE 519: Harmonic Control

IEEE 519 provides recommended practices for harmonic control in electrical power systems. It sets limits for both voltage and current harmonics, to minimise interference and ensure compatibility with sensitive electronic equipment. [22]
Key Requirements:

Voltage Distortion Limits:

- Systems below 69 kV: THD should not exceed 5%.
- Systems between 69 kV and 161 kV: THD should not exceed 2.5%.

– Systems above 161 kV: THD should not exceed 1.5%.

Current Distortion Limits:

– Vary depending on the short-circuit ratio (I_sc/I_L), ranging from 4% to

20% for individual harmonics and 5% to 20% for THD.

IEEE 519 is critical for managing the harmonic currents generated by PV inverters, ensuring that they do not exceed acceptable limits and affect other devices connected to the same grid.

Table 3 shows the general harmonic current limits by the IEEE 519 Standard.

Table 3: General Current Harmonic Limits (IEEE 519)

Short-Circuit Ratio $I_{\_sc}/I_{\_L}$	Maximum Individual Harmonic Current (%) h < 11	Maximum Total Harmonic Current (%)	Total Demand Distortion (TDD) (%) 11 ≤ h ≤ 17
<20	4	5	2.0
20 - 50	7	8	3.5
50 -100	10	12	4.5
100 - 1000	12	15	5.5
>1000	15	20	7.0

Source: IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems," in IEEE Std 519-2014 (Revision of IEEE Std 519-1992), vol., no., pp.1-29, 11 June 2014, doi: 10.1109/IEEESTD.2014.6826459.

Table 4 shows the specific values for harmonics (used for the $I_{\_sc}/I_{\_L}$<20).

Table 4: General Current Harmonic Limits (IEEE 519)

Harmonic Order	Current Limit (%)	Harmonic Order	Current Limit (%)
2	5	8	4
3	4	10	4
4	2	11-16	2
5	4	17-22	1.5
6	2	23-34	0.6
7	4	35-50	0.3

Source: IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems," in IEEE Std 519-2014 (Re-vision of IEEE Std 519-1992), vol., no., pp.1-29, 11 June 2014, doi: 10.1109/IEEESTD.2014.6826459.

Adhering to these Standards is essential for the effective integration of PV systems in school buildings. EN 50160 ensures voltage quality, IEEE 519 provides comprehensive guidelines for controlling harmonic distortions, and IEC 61000 addresses the EMC requirements. Together, these Standards help maintain a reliable and stable power supply, ensuring the safety and performance of electrical systems in educational facilities.

2 Results

In this section we present the measured results for current and voltage, including their waveforms and harmonic content. These results are then compared with the relevant Standards: EN 50160, IEEE 519, and IEC 61000-3-6.

2.1 Current and Voltage Measurements

The measured voltage was within the limits specified by the EN 50160 Standard consistently. This result aligns with expectations, as the voltage waveform was observed to be a stable sinewave across all three phases, with no significant fluctuations, as illustrated in Figure 3.

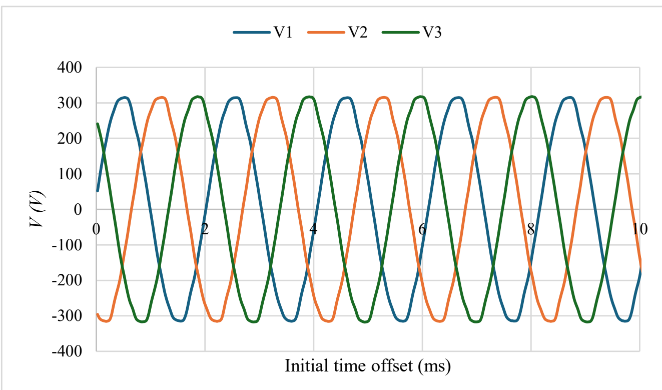


Figure 3: Measured voltage waveform.
Source: own.

Figures 4-6 illustrate the voltage Total Harmonic Distortion (THD) for each day of the week, separately for all three phases. These Figures confirm that the THD values remained within acceptable limits throughout the week, supporting the overall compliance with the EN 50160 requirements.

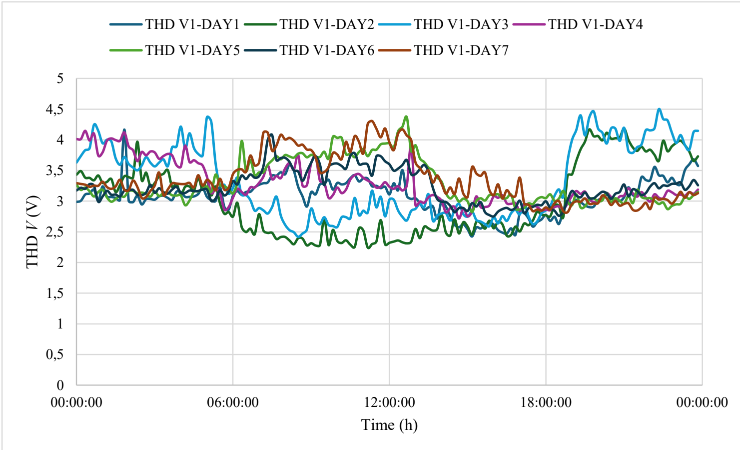


Figure 4: Voltage THD in phase 1.
Source: own.

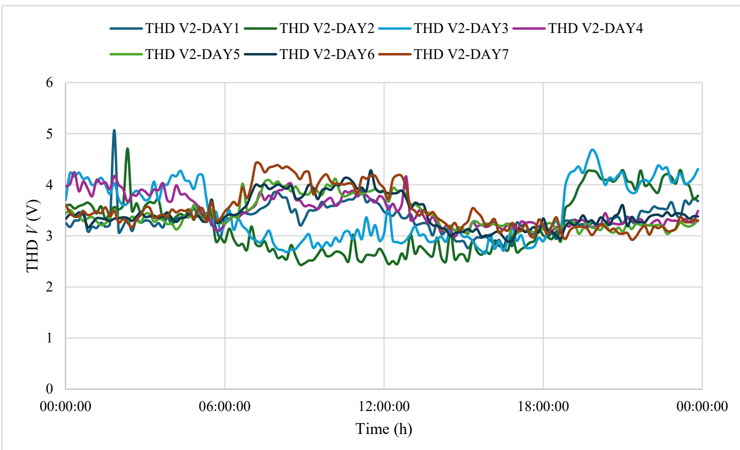


Figure 5: Voltage THD in phase 2.
Source: own.

THD was minimal throughout the measurement period. Based on these results, we limited our comparison of voltage harmonics to the EN50160 requirements up to the 10th harmonic, as detailed in Table 5.

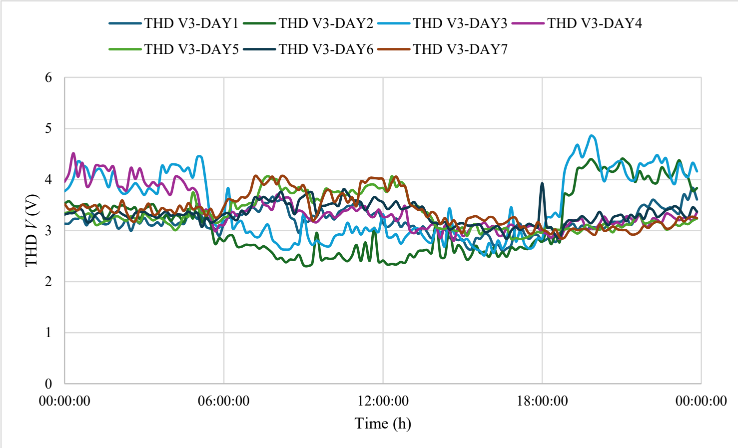


Figure 6: Voltage THD in phase 3.
Source: own.

Table 5: Voltage Harmonic Comparison to the EN50160 requirements

		PHASE L1		PHASE L2		PHASE L3	
Harmonic	Limit	Measured	Status	Measured	Status	Measured	Status
THD	< 8.00 %	1.62 %	Passed	1.64 %	Passed	1.63 %	Passed
2	< 2.00 %	0.05 %	Passed	0.05 %	Passed	0.05 %	Passed
3	< 5.00 %	0.59 %	Passed	0.70 %	Passed	0.54 %	Passed
4	< 1.00 %	0.04 %	Passed	0.04 %	Passed	0.04 %	Passed
5	< 6.00 %	0.93 %	Passed	0.90 %	Passed	0.95 %	Passed
6	< 0.50 %	0.04 %	Passed	0.03 %	Passed	0.04 %	Passed
7	< 5.00 %	1.11 %	Passed	1.07 %	Passed	1.17 %	Passed
8	< 0.50 %	0.03 %	Passed	0.03 %	Passed	0.03 %	Passed
9	< 1.50 %	0.74 %	Passed	0.80 %	Passed	0.71 %	Passed
10	< 0.50 %	0.02 %	Passed	0.02 %	Passed	0.02 %	Passed

Source: IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems," in IEEE Std 519-2014 (Re-vision of IEEE Std 519-1992), vol., no., pp.1-29, 11 June 2014, doi: 10.1109/IEEESTD.2014.6826459.

The harmonic analysis reveals that all the measured values are well within the EN50160 limits. Key results include that the THD was well below the 8.00% limit (1.62% - 1.64% across all phases) and all measurements (2nd to 10th harmonics) were significantly below their respective limits. Overall, the voltage quality is excellent, with all the harmonics meeting or exceeding the regulatory Standards.

The current measurement displayed a distorted waveform, as illustrated in Figure 7, with a clear presence of significant harmonics.

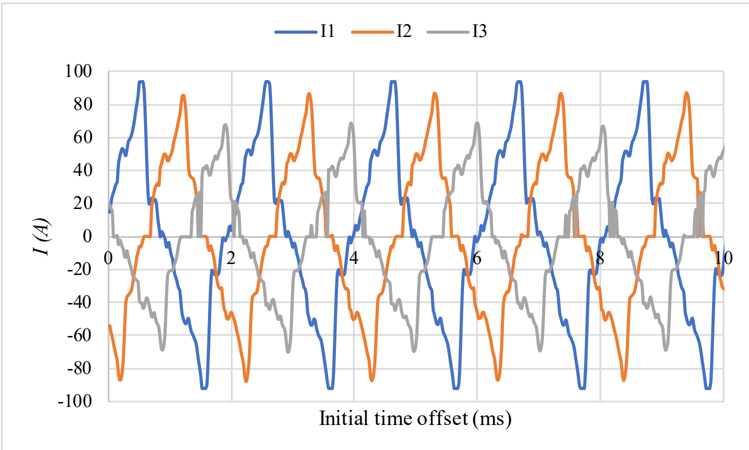


Figure 7: Measured current waveform.

Source: own.

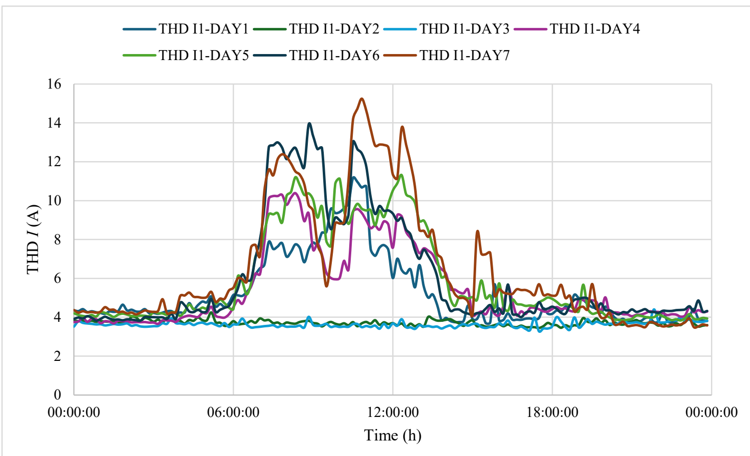


Figure 8: Current THD in phase 1 (A)

Source: own.

Figures 8-10 present the Total Harmonic Distortion (THD) in (A) for each day of the week, while Figures 11-13 show the THD in percentage, separately for all three phases. These Figures confirm that the THD values were consistently high.

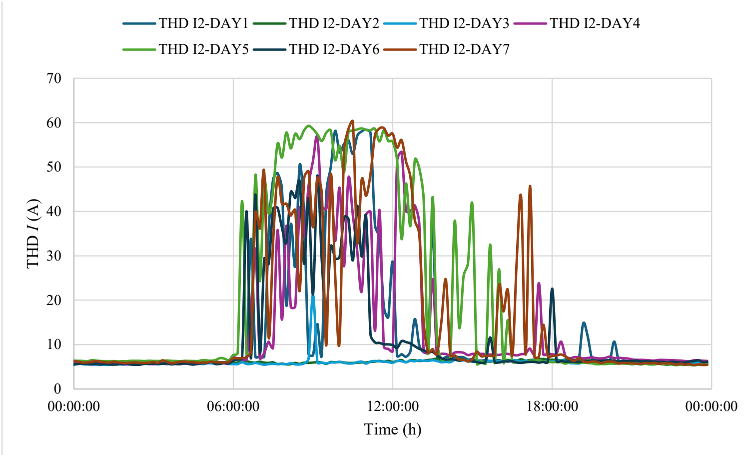


Figure 9: Current THD in phase 2 (A)

Source: own.

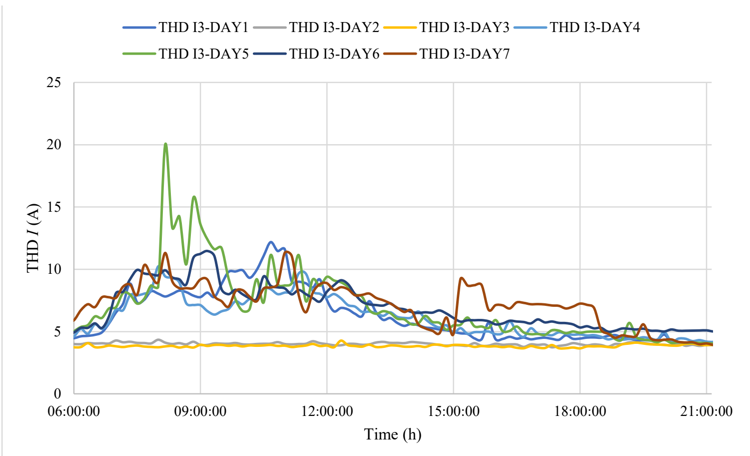


Figure 10: Current THD in phase 3 (A)

Source: own.

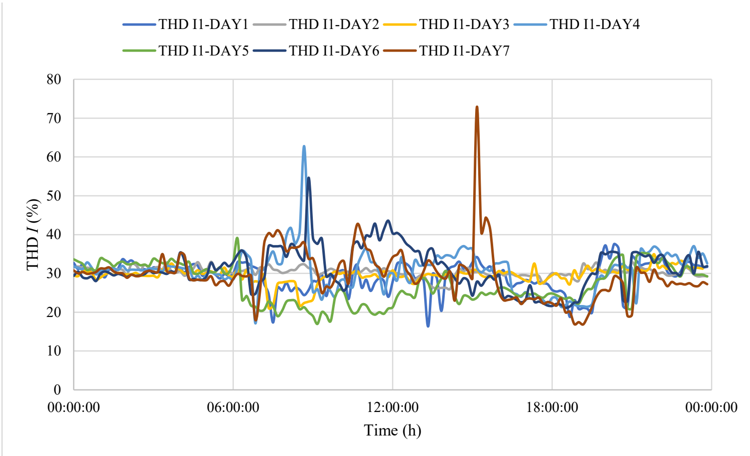


Figure 11: Current THD in phase 1 (%)

Source: own.

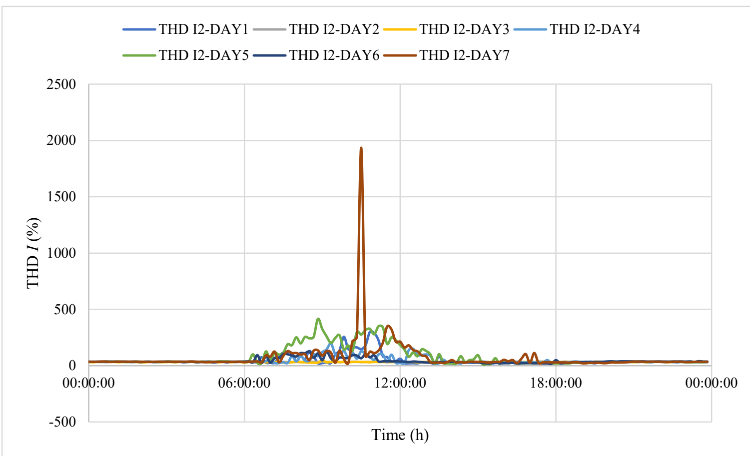


Figure 12. Current THD in phase 2 (%)

Source: own.

Figures 14 and 15 display the Total Harmonic Distortion (THD) in both amperes (A) and percentage (%) for all the phases combined. These Figures reveal a significant level of distortion, with Phase 2 showing particularly high levels of harmonic distortion.

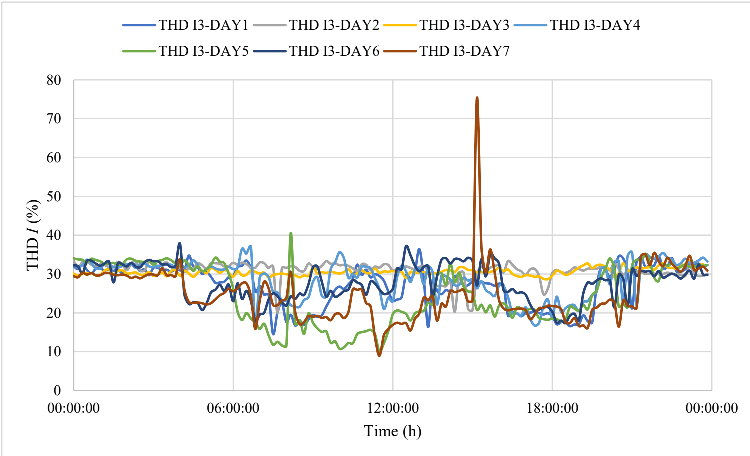


Figure 13: Current THD in phase 3 (%)
Source: own.

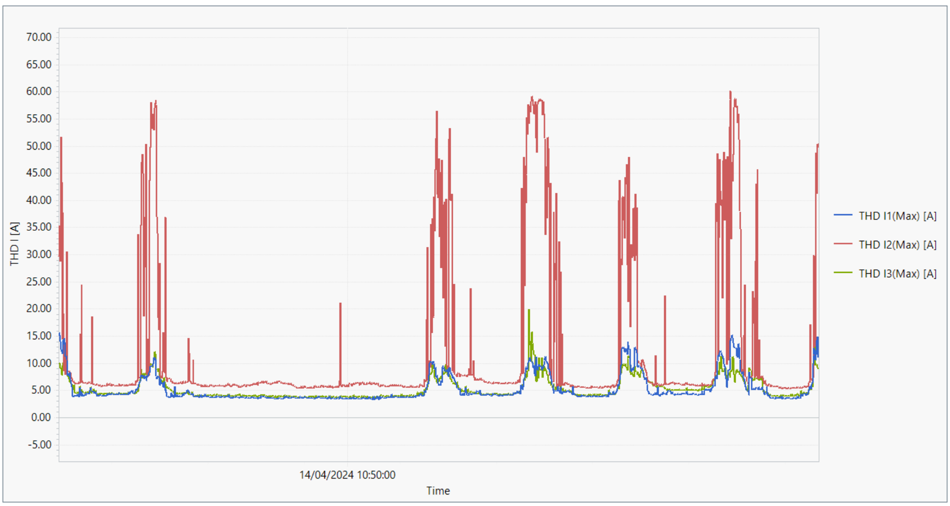


Figure 14: Current THD for all phases (A)
Source: own.

Figures 14 and 15 illustrate clearly that Phase 2 exhibited the highest levels of current harmonics. To address this, the measured harmonic data for each phase have been compared to the Standards outlined in IEEE 519. The detailed comparison of individual phases is presented in Tables 6-8.

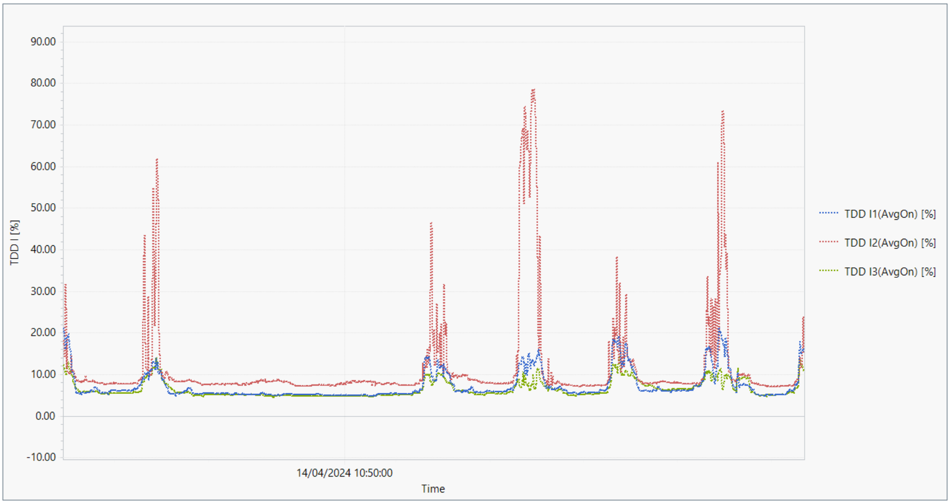


Figure 15: Current THD for all phases (%)
Source: own.

Table 6: Current Harmonic Comparison to the IEEE 519 requirements – Phase 1

h	Limit (%)	Measured (%)	Status
TDD	5.00	9.97	Failed
2	2.00	0.40	Passed
3	4.00	6.93	Failed
4	2.00	0.18	Passed
5	4.00	4.66	Failed
6	2.00	0.11	Passed
7	4.00	3.68	Passed
8	4.00	0.09	Passed
9	4.00	3.24	Passed
10	4.00	0.07	Passed
11	2.00	2.09	Failed
12	2.00	0.07	Passed
13	2.00	1.33	Passed
14	2.00	0.06	Passed
15	2.00	0.95	Passed

Table 7: Current Harmonic Comparison to the IEEE 519 requirements – Phase 2

h	Limit (%)	Measured (%)	Status
TDD	5.00	24.46	Failed
2	2.00	9.24	Failed
3	4.00	8.78	Failed
4	2.00	8.13	Failed
5	4.00	7.04	Failed
6	2.00	6.73	Failed
7	4.00	5.54	Failed
8	4.00	5.19	Failed
9	4.00	4.24	Failed
10	4.00	3.95	Passed
11	2.00	3.75	Failed
12	2.00	3.48	Failed
13	2.00	3.27	Failed
14	2.00	3.12	Failed
15	2.00	3.26	Failed

Table 8: Current Harmonic Comparison to the IEEE 519 requirements – Phase 3

h	Limit (%)	Measured (%)	Status
TDD	5.00	8.31	Failed
2	2.00	0.40	Passed
3	4.00	5.75	Failed
4	2.00	0.19	Passed
5	4.00	3.71	Passed
6	2.00	0.12	Passed
7	4.00	2.93	Passed
8	4.00	0.10	Passed
9	4.00	2.78	Passed
10	4.00	0.07	Passed
11	2.00	1.47	Passed
12	2.00	0.08	Passed
13	2.00	1.77	Passed
14	2.00	0.06	Passed
15	2.00	0.90	Passed

The Total Harmonic Distortion (THD) for Phase 1 measured at 9.97%, which is notably above the allowable limit of 5.00%. This indicates a severe level of distortion in this phase, leading to potential issues such as increased heating and energy losses in the electrical equipment. For Phase 2, the THD was even higher at 24.46%, exceeding the limit by a substantial margin. This extreme level of distortion suggests significant harmonic interference, which could cause operational problems and reduce the lifespan of connected devices.

The THD for Phase 3 stood at 8.31%, which is also above the permissible limit of 5.00%. This indicates that, while not as severe as Phase 2, Phase 3 still experiences considerable harmonic distortion that could impact system performance.

The harmonic measurements for lower-order harmonics showed varying results. For instance, the 2nd harmonic was significantly high in Phase 2 (9.24%), indicating potential issues with non-linear loads or rectifiers in this phase. Similarly, the 3rd harmonic, which is often associated with non-linear devices, was elevated across all the phases, suggesting widespread harmonic distortion sources.

The higher-order harmonics (e.g., the 5th, 7th, and above) generally exhibited lower percentages, but still presented some level of distortion, particularly in Phase 2, where the 5th harmonic was at 7.04%, and the 7th was at 5.54%. The higher percentage of these harmonics contributes to the overall THD, and underscores the need for corrective measures.

Phase 1 shows mostly passed measurements for the individual harmonics but failed in the overall THD. This indicates that, while individual harmonics may be within acceptable limits, their cumulative effect leads to excessive THD.

Phase 2 failed to meet harmonic limits consistently across several orders and the overall THD. This phase is the most problematic, suggesting significant sources of harmonic generation or inadequate filtering.

While having some passed measurements for individual harmonics in Phase 3, the overall THD was still above the limit, pointing to potential issues that, although less severe than in Phase 2, still warrant attention.

The measurements revealed that harmonic distortion is a prevalent issue across all the phases, with Phase 2 experiencing the most significant distortion. The overall THD values exceeding the permissible limits in all phases indicate a need for harmonic mitigation strategies, such as installing filters, or improving power factor correction, to ensure system reliability and compliance with the Standards.

Comparison of the measured current harmonics was compared to the IEC 6100-3-6 requirements and is presented in Table 9.

Table 9: Current Harmonic Comparison to the IEC 6100-3-6 requirements

Harmonic Order	Limit (%)	Measured (L1, L2, L3)	Status (L1, L2, L3)
3	5	6.93%, 8.78%, 5.75%	Failed (L1, L2), Passed (L3)
5	20	4.66%, 7.04%, 3.71%	Passed (L1, L3), Failed (L2)
7	14	3.68%, 5.54%, 2.93%	Passed (L1, L3), Failed (L2)
9	7	3.24%, 4.24%, 2.78%	Passed (L1, L3), Failed (L2)
11	6	2.09%, 3.75%, 1.47%	Failed (L1, L2), Passed (L3)
13	5	1.33%, 3.27%, 1.77%	Passed (L1, L3), Failed (L2)
15	4	0.95%, 3.26%, 0.90%	Passed (L1, L3), Failed (L2)
17	4	0.60%, 2.71%, 0.64%	Passed (L1, L3), Failed (L2)
19	3	1.15%, 2.49%, 1.19%	Failed (L1, L2, L3)
21	3	0.71%, 2.17%, 0.44%	Passed (L1, L3), Failed (L2)

Overall, the measured harmonics for some orders are significantly above the specified limits in one or more phases, especially for the 3rd, 5th, 7th, 9th, 11th, 13th, 19th, and 21st harmonics. These discrepancies suggest that corrective actions or mitigation strategies are required, particularly for the phases exceeding the harmonic limits. Addressing these issues can improve the overall power quality and system performance.

4 Discussion

The results of this study provide a comprehensive analysis of the power quality in a school building equipped with a grid-connected photovoltaic (PV) system. Our findings revealed a dual scenario: while the voltage quality adheres to the EN 50160 Standards, the current quality exhibits significant deviations from the IEEE 519 and IEC 61000-3-6 Standards.

4.1. Voltage Quality Analysis

The voltage measurements throughout the study period showed consistent compliance with the EN 50160 Standard. The Total Harmonic Distortion (THD) in voltage was well within the acceptable limit of 8%, and the individual harmonic components were below the specified thresholds. This stability in voltage quality suggests that the integration of the PV system has not affected the voltage characteristics of the building's power supply adversely. The results indicate that the voltage harmonics introduced by the PV system are managed effectively, aligning with the European Standard for Voltage Quality.

4.2 Current Quality Analysis

Conversely, the current measurements revealed notable issues with harmonic distortion. The THD values for current were significantly higher than the limits set by IEEE 519 and IEC 61000-3-6. Particularly in Phase 2, the distortion was pronounced, with the Total Demand Distortion (TDD) exceeding the permissible limit of 5%. This elevated level of distortion is a concern, as it can lead to potential operational issues such as overheating of transformers, increased losses in distribution networks, and potential interference with sensitive electronic equipment.

The elevated harmonic distortion in current, especially in Phase 2, suggests that the PV system's inverters may be introducing harmonics that are not mitigated adequately by the existing filtering mechanisms. This could be due to a variety of factors, including the inverter design, the interaction of multiple inverters, or the characteristics of the load profile in the school building.

4.3 Implications for Power Quality Management

The discrepancy between voltage and current quality highlights the need for a more nuanced approach to power quality management in systems with high PV penetration. While the voltage quality remains within acceptable limits, the current distortion underscores the necessity for continuous monitoring and adaptive control strategies.

The installation of advanced harmonic filters could help in mitigating the excessive current harmonics. Both passive and active filters can be employed to address specific harmonic orders that exceed acceptable levels.

The optimisation of inverter settings and possibly employing more sophisticated inverter technologies with better harmonic suppression capabilities could be beneficial. Ensuring that the inverters are sized and configured properly to match the load characteristics can also help reduce harmonic generation.

Implementing a real-time monitoring system to track the power quality parameters continuously can facilitate early detection of issues and enable timely corrective actions. Regular maintenance and calibration of equipment are crucial to ensure ongoing compliance with the power quality Standards.

4.4 Educational Facility Considerations

Educational buildings, with their variable load profiles and frequent fluctuations in power demand, present unique challenges for power quality management. The study underscores the importance of tailored solutions that consider the dynamic nature of these environments. Strategies such as load management, peak shaving, and integration of energy storage systems, may also contribute to more stable power quality.

5 Conclusions

This study provides valuable insights into the power quality implications of integrating grid-connected PV systems in educational facilities. While the voltage quality in the school building adheres to the EN 50160 Standards, significant challenges were identified with current harmonic distortion. The findings emphasise the need for a comprehensive approach to power quality management, including advanced filtering solutions, optimised inverter configurations and continuous monitoring.

Future research should focus on exploring additional strategies and Standards that could enhance power quality further in high-PV penetration scenarios. By addressing the identified issues and implementing recommended measures, educational institutions can integrate renewable energy systems better, while maintaining stable and reliable power quality.

Overall, the study underscores the importance of ongoing evaluation and adaptation in managing the interplay between PV systems and power quality, ensuring that the benefits of renewable energy integration are realised without compromising system performance or equipment safety.

References

[1] Peiris, K.; Elphick, S.; David, J.; Robinson, D. Impact of Multiple Grid-Connected Solar PV Inverters on Harmonics in the High-Frequency Range. *Energies* 2024, *17*, 2639. https://doi.org/10.3390/en17112639

[2] Zhu, T.; Huang, G.; Ouyang, X.; Zhang, W.; Wang, Y.; Ye, X.; Wang, Y.; Gao, S. Analysis and Suppression of Harmonic Resonance in Photovoltaic Grid-Connected Systems. *Energies* 2024, *17*, 1218. https://doi.org/10.3390/en17051218

[3] Liu, Y.; Li, L.; Shan, P.; Yu, H.; Zhang, S.; Huang, M.; Liu, W.; You, X.; Zhang, P.; Sun, Y.; et al. Coordinated Mitigation Control for Wideband Harmonic of the Photovoltaic Grid-Connected Inverter. *Appl. Sci.* 2023, *13*, 7441. https://doi.org/10.3390/app13137441

[4] Naderipour, A.; Abdul-Malek, Z.; Miveh, M.R.; Hadidian Moghaddam, M.J.; Kalam, A.; Gandoman, F.H. A Harmonic Compensation Strategy in a Grid-Connected Photovoltaic System Using Zero-Sequence Control. *Energies* 2018, *11*, 2629. https://doi.org/10.3390/en11102629

[5] Liu, Y.; Li, L.; Shan, P.; Yu, H.; Zhang, S.; Huang, M.; Liu, W.; You, X.; Zhang, P.; Sun, Y.; et al. Coordinated Mitigation Control for Wideband Harmonic of the Photovoltaic Grid-Connected Inverter. *Appl. Sci.* 2023, *13*, 7441. https://doi.org/10.3390/app13137441

[6] Yoon, S.-J.; Tran, T.V.; Kim, K.-H. Stability Assessment of Current Controller with Harmonic Compensator for LCL-Filtered Grid-Connected Inverter under Distorted Weak Grid. *Appl. Sci.* 2021, *11*, 212. https://doi.org/10.3390/app11010212

[7] X. Liang and C. Andalib -Bin- Karim, "Harmonics and Mitigation Techniques Through Advanced Control in Grid-Connected Renewable Energy Sources: A Review," in *IEEE Transactions on Industry Applications*, vol. 54, no. 4, pp. 3100-3111, July-Aug. 2018, doi: 10.1109/TIA.2018.2823680.

[8] Bandahalli Mallappa, P.K.; Garcia, H.M.; Quesada, G.V. Power Quality Enhancement in a Grid-Integrated Photovoltaic System Using Hybrid Techniques. *Appl. Sci.* 2021, *11*, 10120. https://doi.org/10.3390/app112110120

[9] Naidu, T.A.; Ali Ahmed Albeshr, H.M.; Al-Sabounchi, A.; Sadanandan, S.K.; Ghaoud, T. A Study on Various Conditions Impacting the Harmonics at Point of Common Coupling in On-Grid Solar Photovoltaic Systems. *Energies* 2023, *16*, 6398. https://doi.org/10.3390/en16176398

[10] Pereira, J.L.M.; Leal, A.F.R.; Almeida, G.O.d.; Tostes, M.E.d.L. Harmonic Effects Due to the High Penetration of Photovoltaic Generation into a Distribution System. *Energies* 2021, *14*, 4021. https://doi.org/10.3390/en14134021

[11] Ikić, M.; Mikulović, J. Experimental Evaluation of Distortion Effect for Grid-Connected PV Systems with Reference to Different Types of Electric Power Quantities. *Energies* 2022, *15*, 416. https://doi.org/10.3390/en15020416

[12] C. Dufour and J. Bélanger, "On the Use of Real-Time Simulation Technology in Smart Grid Research and Development," in *IEEE Transactions on Industry Applications*, vol. 50, no. 6, pp. 3963-3970, Nov.-Dec. 2014, doi: 10.1109/TIA.2014.2315507.

[13] Jahan, S.; Biswas, S.P.; Hosain, M.K.; Islam, M.R.; Haq, S.; Kouzani, A.Z.; Mahmud, M.A.P. An Advanced Control Technique for Power Quality Improvement of Grid-Tied Multilevel Inverter. *Sustainability* **2021**, *13*, 505. https://doi.org/10.3390/su13020505

[14] K. D. Souza, M. Baran and A. Vukojevic, "Maximizing the Benefits of Dynamic VAR Compensators on Distribution Systems with High Penetration PV," *2022 IEEE 13th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, Kiel, Germany, 2022, pp. 1-5, doi: 10.1109/PEDG54999.2022.9923214.

[15] M. Angulo, D. A. Ruiz-Caballero, J. Lago, M. L. Heldwein and S. A. Mussa, "Active power filter control strategy with implicit closed-loop current control and resonantcontroller", *IEEE Trans. Ind. Electron.*, vol. 60, no. 7, pp. 2721-2730, Jul. 2013.

[16] M. Castilla, J. Miret, A. Camacho, J. Matas and L. G. de Vicuna, "Reduction of current harmonic distortion in three-phase grid-connected photovoltaic inverters via resonant current control", *IEEE Trans. Ind. Electron.*, vol. 60, no. 4, pp. 1464-1472, Apr. 2013.

[17] Arangarajan Vinayagam, Asma Aziz, Balasubramaniyam PM, Jaideep Chandran, Veerapandiyan Veerasamy, Ameen Gargoom, Harmonics assessment and mitigation in a photovoltaic integrated network, Sustainable Energy, Grids and Networks, Volume 20, 2019, 100264, ISSN 2352-4677, https://doi.org/10.1016/j.segan.2019.100264.

[18] Mohit Bajaj, and Amit Kumar Singh, "Enhancing grid stability by maintaining power quality in distribution network using FOPID and ANN controlled shunt active filter," Environment, Development and Sustainability, vol. 104, pp. 7551-7578, June 2022, doi: 10.1007/s10668-021-01643-2.

[19] Mahmoud M. Elkholy, M. A. El-Hameed, and Attia A. El- Fergany, "Harmonic analysis of hybrid renewable microgrids comprising optimal design of passive filters and uncertainties," Electric Power Systems Research, vol. 163, pp 491-501, 2018, doi: 0.1016/j.epsr.2018.07.023

[20] EN 50160: Voltage characteristics of electricity supplied by public distribution networks. European Committee for Electrotechnical Standardization (CENELEC).

[21] ELECTROMAGNETIC COMPATIBILITY (EMC) – Part 3-6: Limits – Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems

[22] IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems," in *IEEE Std 519-2014 (Revision of IEEE Std 519-1992)* , vol., no., pp.1-29, 11 June 2014, doi: 10.1109/IEEESTD.2014.6826459.

[23] Hasan Eroğlu, Erdem Cuce, Pinar Mert Cuce, Fatih Gul, Abdulkerim Iskenderoğlu, Harmonic problems in renewable and sustainable energy systems: A comprehensive review, Sustainable Energy Technologies and Assessments, Volume 48, 2021, 101566, ISSN 2213-1388, https://doi.org/10.1016/j.seta.2021.101566.

[24] PowerView documentation

Povzetek v slovenskem jeziku

Ocena harmonskega popačenja v šolskih stavbah s fotonapetostnimi sistemi. Integracija fotonapetostnih sistemov v elektroenergetska omrežja lahko vpliva na kakovost električne energije, zlasti glede napetostnih in tokovnih harmonikov. Ta študija obravnava kakovost električne energije v šolski stavbi z integriranim fotonapetostnim sistemom, s poudarkom na harmonskem popačenju napetosti in toka. Izvedene so bile obsežne meritve v vseh treh fazah, analiza pa je potekala v skladu s standardoma EN 50160 in IEEE 519. Rezultati kažejo, da kakovost napetosti dosledno izpolnjuje zahteve standarda EN 50160, kar potrjuje stabilne napetostne ravni, medtem ko meritve toka razkrivajo izrazito harmonsko popačenje. Posebej izstopa faza 2, kjer vrednosti celotnega harmonskega popačenja bistveno presegajo dovoljene meje, povišane vrednosti pa se pojavljajo tudi v fazi 1 in fazi 3. Za obvladovanje teh težav študija priporoča uporabo naprednih harmonskih filtrov in optimizacijo pretvornikov. Ti ukrepi so ključni za izboljšanje kakovosti električne energije in zagotavljanje skladnosti s strokovnimi standardi v scenarijih z visokim deležem obnovljivih virov energije.

JOURNAL OF ENERGY TECHNOLOGY
Vol. 18, No. 2, pp. 123–142, September 2025

Original Scientific Article

CONSUMER PROTECTION IN THE ELECTRICITY MARKET IN THE EUROPEAN UNION AND SLOVENIA: VULNERABLE CUSTOMERS AND EMERGENCY SUPPLY

Submitted
31. 8. 2025

Accepted
1. 9. 2025

Published
26. 9. 2025

NINA SOTOŠEK, PETER VIRTIČ
University of Maribor, Faculty of Energy Technology, Krško, Slovenia
nina.sotosek@student.um.si, peter.virtic@um.si

CORRESPONDING AUTHOR
nina.sotosek@student.um.si

Abstract The article examines consumer protection in the electricity market, focusing on vulnerable customers and the right to emergency supply. At EU level, it outlines the development from the energy legislative packages to Directive (EU) 2019/944, which strengthens consumer rights and requires Member States to define and protect vulnerable groups. In Slovenia, these issues are regulated by Article 33 of the Electricity Supply Act (ZOEE), implemented through the System Operating Instructions (SONDSEE) and the Energy Agency's act on criteria for ensuring emergency supply. The article applies normative and comparative legal analysis, reviews the Energy Agency's Annual Reports, and analyzes case law. The findings reveal a gap between regulation and practice, as only one request for emergency supply was approved in Slovenia, in 2019. It proposes clearer criteria, simpler procedures, and more effective consumer information, particularly for vulnerable groups, to ensure the right to emergency supply is realized in practice.

Keywords
consumer protection, vulnerable customers, emergency supply, electricity market, ZOEE, Directive (EU) 2019/944, energy poverty, Energy Agency

https://doi.org/10.18690/jet.18.2.123-142.2025

University of Maribor Press

1 Introduction

The European legislative framework of the internal electricity market is based on a balance between competition, security of supply, and consumer protection, with consumer rights strengthened explicitly in the more recent legislative reforms of the European Union. In the context of electricity market liberalization, the integration of electricity networks, and fluctuations in electricity prices, it is essential that market reforms do not undermine the protection of the most vulnerable market participants. A special place in this framework is reserved for vulnerable customers, who are entitled to an emergency electricity supply.

At the level of the European Union (hereinafter: EU), the conceptual and normative framework for the protection of household customers – consumers in the field of electricity – was shaped through four energy packages, reaching its peak with Directive (EU) 2019/944[1], which imposed clear rules on consumer rights, the protection of vulnerable groups, and mechanisms for addressing energy poverty on Member States.

Slovenia transposed these foundations into its national legal order primarily through the Energy Act (Energetski zakon, EZ-1), which entered into force in 2014, and, subsequently, through the Electricity Supply Act (Zakon o oskrbi z električno energijo, ZOEE) of 2021, which implemented Directive (EU) 2019/944. Article 33 of the ZOEE regulates specifically the concept of a vulnerable customer and the right to an emergency electricity supply. An emergency supply represents a measure which, under certain conditions, postpones the disconnection of electricity, and is intended for cases where the life and health of a vulnerable customer are at risk.

Nevertheless, empirical insights into practice, particularly in the reports of the national regulator – the Energy Agency, an independent body responsible for regulating the energy market – reveal a gap between the legal framework and the implementation of the institution of emergency supply in practice. The right to an emergency supply is recognized extremely rarely in Slovenia; the procedures are demanding for customers, and the evidentiary standards are high. The cost burden

[1] Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU.

of the emergency supply is transferred to distributors, who, at the same time, decide on the recognition of this right, which leads to restrictive use of the institution. Such a situation raises doubts as to whether the existing legal framework actually achieves its basic purpose, namely, to prevent electricity disconnection in situations where the life and health of the most vulnerable customers would be endangered.

The purpose of the article is threefold: to present the European legal framework of consumer protection systematically, with an emphasis on vulnerable customers and the right to an emergency supply, to analyze the implementation of the European legislation in the Slovenian legal order, and to assess the implementation of an emergency supply in practice critically. Methodologically, the article is based on normative and comparative legal analysis, a review of case law, as well as reports of the national regulator and publicly available data.

The article proceeds from the assumption that the institution of emergency supply in Slovenia is not implemented appropriately; therefore, the discussion identifies key shortcomings, and the conclusion proposes implementation improvements aimed at more effective realization of the rights of vulnerable customers.

2 Methodology

The research is based on qualitative methods, in particular, normative legal analysis and comparative legal analysis. In the normative legal analysis, classical methods of interpretation (linguistic, systematic, and teleological) were applied, to examine the provisions of the European Union law and national legislation in the field of Electricity Supply. The comparative legal analysis served to identify the consistencies and differences between the EU law and its implementation in the Slovenian legal order.

In the empirical part, the article relies on the analysis of the Annual Reports of the national regulator, i.e., the Energy Agency, as well as on the content analysis of case law. In addition, where appropriate, it also includes a descriptive presentation of publicly available data, such as the number of applications and approvals of emergency supply and indicators of energy poverty. These data make it possible to place the research findings adequately in the broader context of the functioning of the electricity market and the protection of final customers.

3 Consumer protection in the field of electricity

The electricity market is a system that encompasses all activities related to the generation, transmission, distribution, and supply of electricity to final users. Within the internal energy market of the EU, it enables the free flow of electricity between Member States, which increases competition, enhances grid stability, and ensures the availability of energy at competitive prices for consumers. Following Slovenia's accession to the EU, Slovenian consumers became part of the EU market with 447 million inhabitants.

Among the participants in the electricity market are also consumers who, due to a lack of knowledge and information, belong to the weakest market participants, and therefore require special protection. Rapid legislative changes often make it difficult for consumers to be informed about their rights properly and to enforce them effectively [1].

The fields of Consumer Protection and Energy fall within the areas regulated by the EU together with the Member States, with legislative competence being shared. If the EU adopts legislation in these areas (e.g., a Regulation or a Directive), the Member States are obliged to comply with it and, where necessary, transpose it into their national legal order. Compared to earlier periods, the EU devotes considerable attention in the field of the electricity market precisely to consumer protection and the more vulnerable groups of customers. A vulnerable customer is a household customer who lacks the means to meet minimum living needs at a level that ensures survival, including electricity [1].

3.1 The concept of final, household, and vulnerable customers

A final customer is a natural or legal person who purchases energy for their own final use. In point 32 of Article 4 of the ZOEE, it is defined broadly and encompasses household, small business, and business final customers [2].

A household customer of electricity is a customer who purchases electricity for their own use in a household, which excludes use for the performance of commercial or professional activities (e.g., carrying out craft activities, catering, office activities, or other service activities performed as part of a gainful activity). Their rights are protected by regulations governing the energy market, while they also enjoy consumer rights under the Consumer Protection Act (Zakon o varstvu potrošnikov - ZVPot-1), which, as the fundamental legal act, regulates consumer rights in relation to businesses and against unfair commercial practices, as well as the field of the fair business conduct of companies in relation to consumers. The EZ-2 in Article 4 defines a household customer as a customer who purchases electricity, natural gas, heat, or another energy gas for their own use in a household, which excludes use for the performance of commercial or professional activities [3].

The ZOEE also defines a household customer as a customer who purchases electricity for their own use in a household, excluding commercial or professional activities, with the definition being identical to that in Directive (EU) 2019/944. In defining a household customer in point 22 of Article 4 of the ZOEE, the essential legal element is own use in a household, which equates the household customer substantively with a consumer within the electricity system [2].

The concept of a vulnerable customer is defined in paragraph 1 of Article 33 of the ZOEE (entitled vulnerable customers and emergency supply), which defines a vulnerable customer as a household customer who, due to their financial situation, the share of energy expenditure in disposable income, and other social circumstances and living conditions, cannot secure another source of energy for household use that would entail the same or lower costs for the most basic household use. Paragraph 33 defines the right to an emergency supply further [4].

3.2 Development of the EU legislation

The legal framework of the EU internal electricity market began with the adoption of the first energy package in the period 1996–1998. Directive 96/92/EC[2], which was part of the first energy package, concerned common rules for the internal market in electricity, and its main objective was the liberalization of the electricity market in the EU, which included the gradual opening of the market and increased competition, while ensuring consumer protection, although it did not address consumer protection specifically [5].

---

[2] Directive 96/92/EC of the European Parliament and of the Council of 19 December 1996 concerning common rules for the internal market in electricity.

This framework was replaced in 2003 by the second energy package, on the basis of which the market was opened to all business customers in 2004, and the energy market was fully opened in 2007, when the market was opened to all household customers – consumers [6].

Since 2007, household customers have also been able to choose their supplier of electricity or natural gas freely among the providers on the market. The second energy package introduced numerous new concepts focused on strengthening consumer protection, ensuring security of supply, labeling of green energy, etc. The concept of the vulnerable customer also appeared for the first time as a specially protected consumer. Within the framework of the second energy package, the EU Member States were required to ensure a high level of consumer protection, and to adopt appropriate measures to protect vulnerable customers [7].

A turning point in consumer protection in the field of Electricity was the adoption of the third energy package in 2009, which also included Directive 2009/72/EC[3] on common rules for the internal market in electricity [8].

The third energy package focused mainly on consumer protection, imposing on Member States the obligation to define the group of vulnerable customers in the field of Electricity, to expand information to consumers, to establish a single point of contact for consumers, and to set up systems for complaint handling and out-of-court dispute resolution [9].

At this point, it is also necessary to mention Directive 2011/83/EU[4] on consumer rights, adopted in 2011, which provides a broader legal framework for consumer protection in the EU. The Directive defines the concept of a consumer clearly, and its provisions also apply to contracts for the supply of gas and electricity. In the Slovenian legal order, the provisions of Directive 2011/83/EU were transposed initially into the Consumer Protection Act (Zakon o varstvu potrošnikov – ZVPot), and today they are included in the applicable ZVPot-1 [10].

---

[3] Directive 2009/72/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in electricity and repealing Directive 2003/54/EC.

[4] Directive 2011/83/EU of the European Parliament and of the Council of 25 October 2011 on consumer rights, amending Council Directive 93/13/EEC and Directive 1999/44/EC of the European Parliament and of the Council and repealing Council Directive 85/577/EEC and Directive 97/7/EC of the European Parliament and of the Council.

In 2019, the fourth EU energy package "Clean Energy for All Europeans" was adopted, aiming to accelerate the use of clean technologies, increase market competitiveness, and improve energy efficiency. The fourth energy package strengthened the role of the active customer who can participate in the production, storage, and sale of energy (the so-called prosumer), and introduced new obligations for Member States to combat energy poverty and protect vulnerable groups [11].

The central legislative act of the fourth energy package is Directive (EU) 2019/944, which provides consumers with numerous rights, including the right to choose their supplier freely (Article 4), the right to clear and transparent bills (Article 18), the right to be informed through the establishment of single points of contact (Article 25), the right to out-of-court dispute resolution (Article 26), the right to basic supply (Article 27), while additional measures were also adopted to protect vulnerable customers (Article 28), and to prevent energy poverty (Article 29) [12].

After the fourth EU energy package, additional legislative reforms were adopted, which continue to shape the development of the EU energy policy and enhance consumer protection, such as "Fit for 55" and the "European Green Deal".

3.3 Implementation of the EU legislation in the Slovenian legal order

The development of energy law in Slovenia began with the adoption of the first Energy Act (Energetski zakon - EZ) in 1999, which established the fundamental legal framework in the field of the energy market. With it, Slovenia began implementing the policy of market liberalization and consumer protection in line with the European guidelines. On this basis, the Energy Agency (Agencija za energijo) was established, assuming the role of the national regulator. The EZ introduced the electricity market and the gradual opening of the electricity market, set the objectives of energy policy, and established rules for consumer protection in the field of Energy [13].

Due to Slovenia's accession to the EU, the national legislation had to be harmonized with the EU legislation, which led to the adoption of amendments to the Energy Act (EZ-A), which also included new provisions concerning consumer protection. In 2004, the concept of a household customer appeared in Slovenia for the first time, comparable to the definition of a consumer, and protected further through the provisions of the EZ. The amendment to the Act also introduced the institution of emergency supply, which prevents the operator from stopping the supply of energy below the amount that could endanger the life or health of customers. Measures were introduced to protect consumers in relation to supply contracts and general Terms and Conditions, and the complete opening of the market was envisaged by 2007, when all customers could choose their energy supplier in the energy markets freely [14].

As an EU Member State, Slovenia was also required to implement the changes from the third energy package, which brought extensive reforms in the field of Consumer Protection. These changes required a new regulation of customer protection, the definition of vulnerable customers, the regulation of informing electricity and natural gas customers, and the reshaping of provisions regarding business conditions between suppliers and customers [9].

In accordance with these requirements, a new Energy Act (Energetski zakon - EZ-1) was adopted in 2014, with which Slovenia transposed the third energy package fully, i.e., the content of ten Directives and specific provisions of five EU Regulations. The EZ-1 introduced in the field of Consumer Protection the obligation to inform customers about changes in contractual conditions, prices, and other important information, amended business conditions between suppliers and customers, introduced provisions on out-of-court dispute resolution between household customers and electricity and natural gas suppliers. Article 51 of the EZ-1 also defined vulnerable customers and measures for their protection, thereby implementing Article 3(7) of Directive 2009/72/EC [15].

Following the adoption of the fourth EU energy package, Slovenia had to adopt numerous legislative changes to align its legislation with the European objectives, particularly in the fields of Energy Efficiency and Sustainable Energy Supply. Key changes were introduced through new Acts that replaced the existing EZ-1, which, over the years, had become very extensive and unclear. Thus, the Slovenian legislator dispersed the substance of energy law between several Acts. With the latest major reform of energy law in Slovenia, which resulted from the fourth EU legislative package, Slovenia adopted the Energy Efficiency Act (Zakon o učinkoviti rabi energije - ZURE) of 2020, the Electricity Supply Act (Zakon o oskrbi z električno energijo - ZOEE) of 2021, the Gas Supply Act (Zakon o oskrbi s plini - ZOP) of

2021, the Renewable Energy Sources Promotion Act (Zakon o spodbujanju rabe obnovljivih virov energije - ZSROVE) of 2021, the Heat Supply from Distribution Systems Act (Zakon o oskrbi s toploto iz distribucijskih sistemov - ZOTDS) of 2022, and the new Energy Act (Energetski zakon - EZ-2) of 2024, which, together, replaced the previously valid systemic act EZ-1 of 2014 [2].

The fundamental EU legislative instruments in the field of Electricity Supply today are Directive (EU) 2019/944 and Regulation (EU) 2019/943. These instruments were implemented fully into the Slovenian legal order through the ZOEE, which is also of key importance from the perspective of consumer protection and vulnerable customers in the electricity market. The ZOEE was adopted in November 2021 and amended in 2025 (Amendment ZOEE-A) [16]. The ZOEE introduced important rights for consumers into the Slovenian legal order, as, in its new Chapter 2, which regulates in detail the rights of system users, it provides, inter alia, the right to choose a supplier freely, the right to change suppliers easily, and the introduction of dynamic pricing reflecting the market. In addition, the ZOEE granted final customers the right to conclude contracts with multiple suppliers simultaneously, ensured greater transparency of contractual terms and information for consumers, introduced single contact points, and the right to dispute resolution. In Section 3, the ZOEE also defines backup supply, vulnerable customers, and emergency supply [4].

4 Vulnerable customers and emergency supply

Directive 2009/72/EC, which was part of the third energy package, required Member States to define the concept of a vulnerable customer in the field of Electricity. The Directive highlighted the growing problem of energy poverty, and obliged Member States to adopt measures to protect final customers, particularly the vulnerable ones, to define the concept of energy poverty, and to prohibit the disconnection of electricity for poor customers in cases of endangerment [2].

The EU's normative approach[5] was relatively loose, as it established mainly legal obligations at a general level without a uniform and detailed definition. It required Member States in particular to define the concept of a vulnerable customer in their national legislation and to ensure protection [17].

The protection of vulnerable customers is one of the most important forms of customer protection. The essence of the institution of the vulnerable customer and emergency supply is that a customer who, due to poor financial circumstances, is unable to pay the costs of electricity supply and whose life and health or that of the persons living with them are endangered due to special circumstances (e.g., season, temperature, place of residence, health condition, or other similar circumstances), may apply for a postponement of disconnection and exercise the right to an emergency supply. An emergency supply is a measure that, under certain conditions, postpones the disconnection of electricity, and is intended for extreme cases of endangerment of the life and health of the vulnerable customer.

The emergency supply must be distinguished from the backup supply, which is regulated in Article 32 of the ZOEE, where the operator ensures an uninterrupted electricity supply to those customers whose supply contract has expired due to reasons on the supplier's side, such as illiquidity, insolvency, or other reasons leading to the exclusion of the supplier from the balance scheme [4].

Although the original Energy Act (EZ) did not define the concept of a vulnerable customer explicitly, Article 76 contained a provision that the system operator was not allowed to reduce or interrupt the supply below the quantity which, considering the specific circumstances (season, living conditions, place of residence, financial situation, etc.), was necessary to prevent endangerment of the life and health of the customer and the persons living with them. The costs incurred by the supplier due to such an obligation were covered by the network usage fee [13].

In Slovenia, the concept of a vulnerable customer was first introduced by the Energy Act (EZ-1), which entered into force on 22 March 2014. Article 51 of the EZ-1 stipulated that a vulnerable customer is a household customer who, due to their

[5] The normative approach means regulating a specific area through legal rules and obligations, whereby, in the case at hand. the EU sets only the general requirements for Member States, while leaving the detailed regulation to the national legislation.

financial circumstances, income, other social circumstances, and living conditions, cannot secure another source of energy for household use that would entail the same or lower costs for the most basic household use. Thus, Article 51 of the EZ-1 effectively implemented the provisions of point 7 of Article 3 of Directive 2009/72/EC and Article 3 of Directive 2009/73/EC, which regulated the field of Natural Gas [18].

The new Energy Act (EZ-2), which entered into force on 8 May 2024, no longer provides a legal definition of vulnerable customers, although it still refers to them in certain places. The concept of a vulnerable electricity customer and the measures for their protection – the right to an emergency supply – are now regulated specifically by Article 33 of the ZOEE, which entered into force on 13 November 2021 and implemented Directive (EU) 2019/944. The concept of a vulnerable natural gas customer is regulated by the Gas Supply Act (ZOP), but this aspect was not part of the research, which focuses solely on the field of Electricity.

4.1 Energy poverty

The ZOEE in Article 34 regulated energy poverty for the first time. Energy poverty occurs in cases where a household cannot heat or cool its dwelling adequately and cover other energy needs, such as hot water, lighting, and similar. Energy poverty most often affects the most vulnerable groups, such as the unemployed, pensioners, and people with low incomes. Combating energy poverty at the EU level is linked closely to the definition of vulnerable customers and the introduction of appropriate public policies aimed at assisting individuals who, due to limited financial resources, cannot ensure an adequate energy supply and heating [2].

4.2 Analysis of Article 33 of the ZOEE

Vulnerable customers and emergency supply are today regulated by Article 33 of the ZOEE. Paragraph 1 of Article 33 of the ZOEE defines the concept of a vulnerable customer. These are persons who, due to their financial circumstances, the share of energy expenditure in disposable income, other social circumstances, and living conditions, cannot secure another source of energy for household use that would entail the same or lower costs for the most basic household use. It should be noted that, according to the definition in point 22 of Article 4 of the ZOEE, only household customers (consumers) can be vulnerable customers [2].

Paragraph 2 of Article 33 further provides that the distribution system operator may not disconnect a vulnerable customer from electricity or limit consumption below the amount or capacity that, given the circumstances (season, temperature conditions, place of residence, health condition, and other similar circumstances), is necessary to prevent endangerment of the life and health of the customer and the persons living with them. The main objective is, therefore, the protection of the goods of life and health, with the key expression being "endangerment of life and health" [17].

This provision is special in relation to paragraph 1 of Article 33, and understanding its content depends on when the life and health of the customer and persons living with them are endangered, which involves medical aspects, and must be assessed in each individual case. Endangerment of life and health occurs in particular during the winter months, when the temperature in the dwelling remains below 10 °C for several hours, which usually happens in most residential buildings that are without heating for several days. According to the Annual Reports of the distribution system operator SODO and the Energy Agency, the institution of emergency supply is used only exceptionally in practice, while data from the Statistical Office of the Republic of Slovenia (SURS) show that household energy poverty in 2024 was as high as 7.3%, which indicates a discrepancy between the legal provision of Article 33 of the ZOEE and actual practice. The reason for this may also lie in the fact that the approval of the right to an emergency supply and the cost burden of emergency supply are transferred to the distribution system operator, who has an interest in keeping costs as low as possible [2].

Paragraph 5 of Article 33 provides explicitly that the cost of the emergency supply in the field of Electricity is an eligible cost of the electricity distribution system operator [4].

Paragraph 3 of Article 33 provides further that the distribution system operator must inform the customer prior to disconnection of the possibility of emergency supply, of the evidence that the customer must submit to the operator in order for the operator to approve the emergency supply, and of the deadlines for submitting such evidence. The operator prescribes more detailed conditions and the price of the emergency supply, which covers the cost of energy procurement, in the System Operating Instructions under Article 136 of the ZOEE in accordance with the rules and criteria prescribed by the Energy Agency [4]. The implementing regulations of Article 33 of the ZOEE are thus the System Operating Instructions for the Electricity Distribution System (Sistemska obratovalna navodila za distribucijski sistem električne energije, SONDSEE) and the Act of the Energy Agency on the Criteria and Rules for Ensuring Emergency Electricity Supply (Akt o kriterijih in pravilih za zagotavljanje nujne oskrbe z električno energijo Agencije za energijo). The eligibility for an emergency supply is assessed by the electricity distribution system operator under the procedure laid down in the SONDSEE and in accordance with the rules and criteria determined by the Energy Agency [4, 19]

The Act of the Energy Agency on the Criteria and Rules for Ensuring an Emergency Electricity Supply sets out the criteria and rules on the basis of which the distribution system operator prescribes in detail the conditions for ensuring the emergency supply and the price of the emergency supply in the System Operating Instructions. The Act consists of five chapters, covering the general provisions, the criteria for assessing eligibility for the emergency supply, the rules and the procedure for approval of the emergency supply, the costs of the emergency supply, and the final provision. In assessing eligibility for an emergency supply, the distribution system operator must first establish whether the applicant is a vulnerable customer, and then, on the basis of the evidence, assess whether disconnection of electricity would endanger the life and health of the vulnerable customer. A vulnerable customer may exercise the right to an emergency supply only in the case where the distribution system operator would otherwise disconnect them because the supplier terminated the supply contract, or due to non-payment of network charges [20].

Since the distribution system operator has no authority to verify the financial situation of the customer, this is carried out within the procedure for eligibility for regular social assistance at the Social Work Center. The endangerment of the life and health of the vulnerable customer is assessed by the distribution system operator on the basis of the Act according to two criteria:

– during the heating season from 1 October to 30 April, on the basis of evidence of heating in the customer's dwelling, from which it must be clearly apparent whether electricity is necessary for heating (criterion 1: season, temperature conditions);

– on the basis of a medical certificate that the vulnerable customer needs medical devices or equipment powered by electricity urgently in order to preserve life and health (criterion 2: health condition of the vulnerable customer and the persons living with them) [20].

Furthermore, paragraph 4 of Article 33 of the ZOEE provides that, if the distribution system operator finds that the conditions for emergency supply are met, it must immediately inform the customer and submit a contract on emergency supply for signature. If the distribution system operator concludes that the conditions for emergency supply are not met, it must notify the customer in writing immediately and proceed with the disconnection [4].

Disputes concerning eligibility for an emergency supply are decided by the Energy Agency under the dispute resolution procedure provided by the Act regulating the agency, i.e., the EZ-2. If the conditions for an emergency supply are met, the distribution system operator is therefore subject to a duty to contract – the obligation to conclude a contract when the conditions are fulfilled. As a holder of public authority, the distribution system operator issues a declaratory decision in this respect [2].

4.3 Case law in the field of Emergency Supply

Case law regarding vulnerable customers is still scarce. In the decision of the Higher Court in Maribor (Višje sodišče v Mariboru), case no. I Cp 995/2018 of 4 December 2018, it was established that the distribution system operator may not disconnect a vulnerable customer who does not have a valid electricity supply contract if the conditions for emergency supply of electricity are met under the (then applicable) Article 51 of the EZ-1. It is also essential that the customer submits a timely request for emergency supply and provides the necessary supporting documents, such as a medical certificate regarding the use of medical devices. Case law emphasizes the obligation of the distribution system operator to inform the customer duly about the possibility of claiming an emergency supply and to request the necessary documentation. If the customer does not file the request in time, the disconnection is not unlawful. Furthermore, the emergency supply is limited to the period between the planned disconnection and the final decision on social assistance. In this particular case, the court confirmed that the distribution system operator did not act unlawfully when disconnecting the electricity, since the customer failed to exercise the right to an emergency supply in a timely manner [21].

In contrast, the judgment of the Higher Court in Ljubljana (Višje sodišče v Ljubljani), case no. I Cp 2918/2017 of 30 May 2018, held that the concept of a vulnerable customer does not include persons who are not connected to the electricity grid legally, such as residents of illegal constructions. The right of access to the network is conditional upon compliance with the technical and ownership requirements, as stipulated by Articles 147 and 149 of the EZ-1. The court stressed explicitly that the special rights claimed by members of the Roma community in relation to access to electricity in illegal buildings cannot prevail over the constitutional right to safety and the technical reliability of the electricity system. Therefore, the legislation does not allow exceptions for illegal connections, which represents a significant limitation in the protection of vulnerable groups. In this case, the court rejected the claim for the right of access to the electricity grid for an illegal construction, and confirmed that the rights of a vulnerable customer do not extend to unlawful connections [22].

4.4 Emergency Supply in Practice

Data from the Annual Reports of the Energy Agency on the state of the energy sector in Slovenia show that the institute of emergency supply is applied extremely rarely in practice. The Agency's reports indicate that a request for the approval of emergency supply in Slovenia was granted only once, namely, in 2019. Data on the number of approved requests for emergency supply prior to 2009 are not available publicly [23].

In 2019, the electricity distribution system operator received five requests for the approval of emergency supply, of which one was granted. In 2020, the operator received two requests, both of which were rejected; in 2021, one request, which was also rejected; in 2022, four requests, all rejected; and in 2023, again four requests, all rejected, with one applicant actually disconnected in that year [23–27].

In 2024, the operator received three requests, none of which were approved, despite official data from the Statistical Office of the Republic of Slovenia (SURS) showing that the energy poverty rate among households in Slovenia in 2024 was as high as 7.3% (approximately 63,000 households, or 110,000 individuals) [28].

It is also important to highlight that the Annual Reports of the electricity distribution system operator (SODO) for the period 2013–2022 indicate that not a single emergency supply was granted during this time, which demonstrates an inconsistency between the publicly available data [29–38].

While SODO's reports for the period 2013–2022 state that no emergency supply was approved, the Energy Agency's report for 2019 shows that one request was granted for an emergency supply. For the purposes of this analysis, we therefore proceed from the assumption that one emergency supply was approved in 2019.

5 Conclusion

In legislation, emergency supply is embedded within the broader framework of measures for supply reliability and the protection of vulnerable customers, representing one of the most important forms of consumer protection. In principle, it is intended to safeguard households in specific living or health conditions, where the interruption of the electricity supply would endanger health or basic living conditions. In practice, however, the exercise of this right is often limited significantly, and conditional upon strict requirements and evidence (e.g., Social Work Center confirmation, season and temperature conditions, and the health status of the customer and household members), as stipulated in the System Operating Instructions for the Distribution System of Electricity (SONDSEE) and the Act on Criteria and Rules for Ensuring Emergency Supply of the Energy Agency, which, together, constitute the implementing regulations in the field of Emergency Electricity Supply.

This creates a discrepancy between the legal framework, which recognizes special protection for vulnerable customers, and its actual implementation in practice, where the eligibility threshold for emergency supply is set extremely high and the procedures are burdensome for customers. Consequently, it can be concluded that the implementing regulations, by establishing additional, stricter rules and criteria, narrow the rights defined in the law significantly, since, according to the available practical data, it is extremely difficult, or even impossible, to meet these requirements. As a result, the implementing regulations and their practical application do not provide vulnerable customers with the protection granted to them by law [17]. If the previously valid provision of Article 51 of the EZ-1 and the currently valid provision of Article 33 of the ZOEE are not applied in practice, this represents a deviation from the principle of legal clarity and certainty, as well as from the principle of legality, which requires authorities to act in accordance with and enforce the applicable law.

This discrepancy is also reflected in the data of the Energy Agency, which shows that, in Slovenia from 2009 to the present, only one customer was granted an emergency supply, namely, in 2019. Even more concerning is the fact that each year only a small number of household customers apply for the right to an emergency supply, despite the relatively high level of energy poverty among Slovenian households. This also points to a lack of consumer awareness and understanding of their rights, which, in practice, hinders the effective exercise of the intended protective mechanisms further.

Recent legislative regulation in Slovenia does preserve and build upon the principles of social cohesion, transparency, and the protection of vulnerable customers. However, the statistics on rejected applications for emergency supply and warnings from practice show that implementation challenges remain, since we have a legal provision that does not function in practice. Normative regulation without adequate implementation cannot achieve its purpose, which is to prevent households facing health or living risks from being left without electricity. For the effective operation of the emergency supply mechanism, clear and practical criteria, simpler procedures for exercising the right to an emergency supply, and consistent alignment between the law, implementing regulations, and operational decision-making, are therefore essential. Furthermore, consumers - especially the most vulnerable - should be better informed about the existence and content of their rights, as the lack of information contributes significantly to the ineffective enforcement of protections.

It is essential that the provision of Article 33 of the ZOEE be implemented in practice effectively and not remain merely theoretical. For this reason, it would be advisable to introduce certain legislative changes aimed at ensuring the more effective realization of the rights of the most vulnerable customers in practice.

References

[1] Resolucija o nacionalnem programu varstva potrošnikov 2024–2029 (ReNPVP24 29), Uradni list RS, št. 45/24
[2] Bratina, B. (ur.), et al. (2025), Zakon o oskrbi z električno energijo (ZOEE): s komentarjem. Ljubljana: Lexpera, GV Založba
[3] Energetski zakon (EZ-2), Uradni list RS, št. 38/24 in 47/25 – ZOEE-A
[4] Zakon o oskrbi z električno energijo (ZOEE), Uradni list RS, št. 172/21 in 47/25
[5] Directive 96/92/EC of the European Parliament and of the Council of 19 December 1996 concerning common rules for the internal market in electricity, OJ L 27, 30.1.1997, p. 20–29
[6] Directive 2003/54/EC of the European Parliament and of the Council of 26 June 2003 concerning common rules for the internal market in electricity and repealing Directive 96/92/EC, OJ L 176, 15.7.2003, p. 37–56
[7] Cameron, P. (2005), Legal aspects of EU energy regulation: Implementing the new directives on electricity and gas across Europe, Oxford University Press
[8] Directive 2009/72/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in electricity and repealing Directive 2003/54/EC, OJ L 211, 14.8.2009, p. 55–93
[9] Pirnat, R. (2009), Pravna vprašanja prenosa tretjega paketa energetskih predpisov EU v slovensko pravo. V Strateško srečanje udeležencev energetskega trga »Inovacije energetika?« Prosperia, Brdo pri Kranju
[10] Directive 2011/83/EU of the European Parliament and of the Council of 25 October 2011 on consumer rights, amending Council Directive 93/13/EEC and Directive 1999/44/EC, and repealing Council Directive 85/577/EEC and Directive 97/7/EC, OJ L 304, 22.11.2011, p. 64–88
[11] European Commission, Directorate-General for Energy, (2019, May 22), Clean energy for all Europeans package completed: Good for consumers, good for growth and jobs, and good for the planet. Brussels. Available: https://commission.europa.eu/news-and-media/news/clean-energy-all-europeans-package-completed-good-consumers-good-growth-and-jobs-and-good-planet-2019-05-22_en (16.8.2025)
[12] Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU, OJ L 158, 14.6.2019, p. 125–199
[13] Energetski zakon (EZ), Uradni list RS, št. 27/07 (uradno prečiščeno besedilo), 70/08, 22/10, 10/12, 94/12 – ZDoh-2L in 17/14 – EZ-1
[14] Zakon o spremembah in dopolnitvah Energetskega zakona – EZ-A, Uradni list RS, št. 51/04 z dne 7. 5. 2004
[15] Predlog Energetskega zakona – EZ-1, Poročevalec Državnega zbora RS, 23. 10. 2013
[16] Zakon o spremembah in dopolnitvah Zakona o oskrbi z električno energijo (ZOEE-A), Uradni list RS, št. 47/25
[17] Tomažič, L. M., Bračič Tomažič, S., & Bratina, B. (2018), Vulnerable consumers, their health and urgent supply of electrical energy in Slovenian legal framework. Medicine, Law & Society, 11(2), 91–106. https://doi.org/10.18690/mls.11.2.91-106.2018

[18] Energetski zakon (EZ-1), Uradni list RS, št. 60/19 (uradno prečiščeno besedilo), 65/20, 158/20 – ZURE, 121/21 – ZSROVE, 172/21 – ZOEE, 204/21 – ZOP, 44/22 – ZOTDS, 38/24 – EZ-2 in 56/25
[19] Sistemska obratovalna navodila za distribucijski sistem električne energije (SONDSEE), Uradni list RS, št. 77/24
[20] Akt o kriterijih in pravilih za zagotavljanje nujne oskrbe z električno energijo, Uradni list RS, št. 48/16 in 172/21 – ZOEE
[21] Višje sodišče v Mariboru, Sklep I Cp 995/2018 z dne 4. 12. 2018
[22] Višje sodišče v Ljubljani, Sodba I Cp 2918/2017 z dne 30. 5. 2018
[23] Agencija za energijo, Poročilo o stanju na področju energetike v Sloveniji v letu 2019
[24] Agencija za energijo, Poročilo o stanju na področju energetike v Sloveniji v letu 2020
[25] Agencija za energijo, Poročilo o stanju na področju energetike v Sloveniji v letu 2021
[26] Agencija za energijo, Poročilo o stanju na področju energetike v Sloveniji v letu 2022
[27] Agencija za energijo, Poročilo o stanju na področju energetike v Sloveniji v letu 2023
[28] Agencija za energijo, Poročilo o stanju na področju energetike v Sloveniji v letu 2024
[29] SODO d.o.o., Revidirano letno poročilo družbe SODO d.o.o. za leto 2013
[30] SODO d.o.o., Revidirano letno poročilo družbe SODO d.o.o. za leto 2014
[31] SODO d.o.o., Revidirano letno poročilo družbe SODO d.o.o. za leto 2015
[32] SODO d.o.o., Revidirano letno poročilo družbe SODO d.o.o. za leto 2016
[33] SODO d.o.o., Revidirano letno poročilo družbe SODO d.o.o. za leto 2017
[34] SODO d.o.o., Revidirano letno poročilo družbe SODO d.o.o. za leto 2018
[35] SODO d.o.o., Revidirano letno poročilo družbe SODO d.o.o. za leto 2019
[36] SODO d.o.o., Revidirano letno poročilo družbe SODO d.o.o. za leto 2020
[37] SODO d.o.o., Revidirano letno poročilo družbe SODO d.o.o. za leto 2021
[38] SODO d.o.o., Revidirano letno poročilo družbe SODO d.o.o. za leto 2022

Povzetek v slovenskem jeziku

Varstvo potrošnikov na trgu z električno energijo v Evropski uniji in Sloveniji: ranljivi odjemalci in nujna oskrba. Članek obravnava varstvo potrošnikov na trgu z električno energijo s posebnim poudarkom na ranljivih odjemalcih in pravici do nujne oskrbe. Na ravni Evropske unije prikazuje razvoj od energetskih zakonodajnih svežnjev do Direktive (EU) 2019/944, ki krepi pravice odjemalcev ter državam članicam EU nalaga opredelitev in zaščito ranljivih skupin. Pojem ranljivega odjemalca in institut nujne oskrbe na področju električne energije v Sloveniji ureja 33. člen Zakona o oskrbi z električno energijo (ZOEE), njegova izvedba pa poteka prek sistemskih obratovalnih navodil (SONDSEE) in akta Agencije za energijo o kriterijih in pravilih za zagotavljanje nujne oskrbe. Metodološko članek uporablja normativno in primerjalno-pravno analizo, pregled letnih poročil Agencije za energijo ter vsebinsko analizo sodne prakse. Ugotovitve kažejo na razhajanje med zakonsko ureditvijo instituta nujne oskrbe in izvedbo v praksi, saj je bila v Sloveniji odobrena le ena zahteva, in sicer leta 2019. Članek zato predlaga oblikovanje jasnejših in življenjsko naravnanih kriterijev, poenostavitev postopkov ter učinkovitejše obveščanje potrošnikov, zlasti ranljivih skupin, da bi se pravica do nujne oskrbe dejansko uresničevala v praksi.

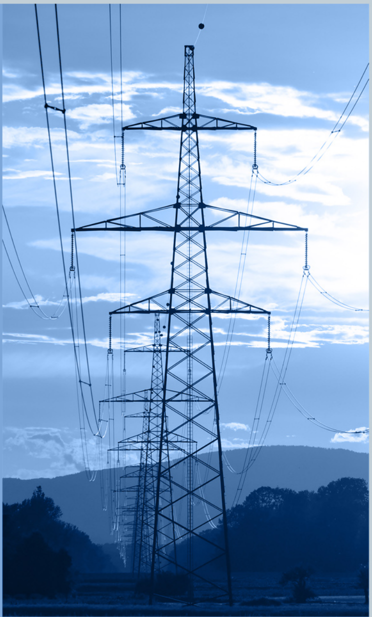
University of Maribor

Faculty of Energy Technology

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

jet@um.si

ISSN 2463-7815



JET