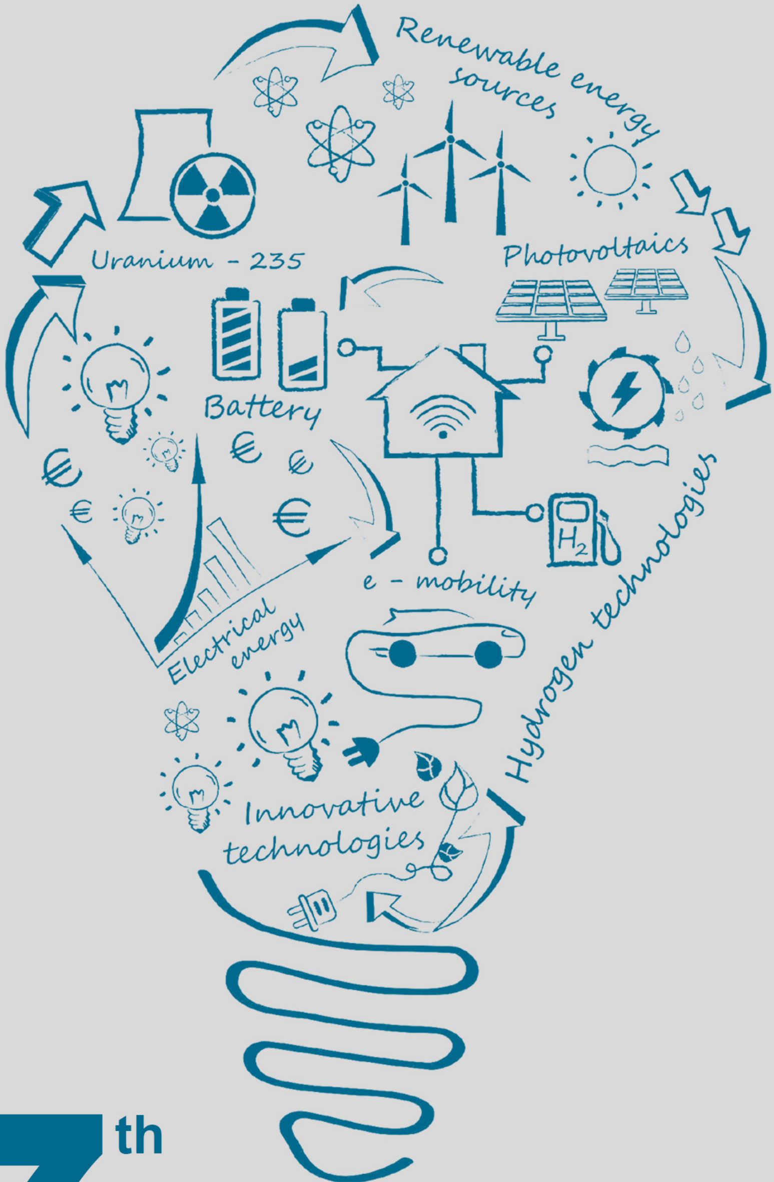

7th INTERNATIONAL CONFERENCE

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energy & responsibility

Book of Extended Abstracts

edited by
Sebastijan Seme & Klemen Sredenšek

University of Maribor Press


Renewable energy sources
Uranium - 235
Photovoltaics
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Innovative technologies

University of Maribor

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Sebastijan Seme
Klemen Sredenšek

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Klemen Sredenšek
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Table of Contents

Organizers:

Invited Lectures

Renewable energy sources
Uranium - 235
Photovoltaics
Battery
Electric energy
e - mobility
Hydrogen technologies
Innovative technologies

Defossilisation of the Heating Sector with an Integrated Energy System Approach

UROŠ SALOBIR, MARKO BAHOR
ELES, d.o.o., Ljubljana, Slovenia
uros.salobir@eles.si, marko.bahor@eles.si

A study titled "Defossilisation of the heating sector with an integrated energy system approach" has been prepared in cooperation between the companies ELES, d.o.o., the Combined electricity transmission and distribution network operator of the Republic of Slovenia and ENERGINET the Danish Transmission System Operator (ELES, 2022). We have approached the defossilisation of the heating sector in Europe, looking at the EU's current approach, the technologies already available and those under development, and the likely effects of policies on the energy grids as a whole. In doing so, we have presented a new conceptual approach to heating and its importance to the entire energy system.

The robust, long-term security of supply at sustainable prices will benefit, with multiple, simultaneously available sources matched to local requirements rather than any single source. To satisfy consumption, the generation capacity will also need to be paired, where possible, with energy storage solutions that match the local situation. In addition, efficient maximisation should be included of all waste heat sources. District heating can, in an integrated energy system, deliver on many of these elements. The latest 4th and 5th generation district heating solutions can provide a source-agnostic backbone onto which multiple future solutions and networks can be connected. The latest technologies also make operating such systems (even with few connections) economical, so that reliable, sustainable and cost-optimal heating can be provided for communities of various sizes.

Keywords: district heating, integrated energy systems, defossilisation, security of supply, flexibility

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District Heating Challenges in the Context of the Transformation of the District Heating System in the Šaleška Valley

Gregor Cvet
Komunalno podjetje Velenje, Velenje, Slovenia
gregor.cvet@kp-velenje.si

The key activities of the Velenje Municipal Company have been focused recently on the transformation of the district heating of the Šaleška Valley. The key objectives of the transformation are temperature optimization of the network, renovation of critical sections of the hot water and hot water system in order to reduce heat losses, modernization of the heating stations, and the implementation of alternative green heat energy sources. In order to achieve the goals of the transformation, simultaneous energy renovation of the buildings to achieve a transition to a lower temperature heating regime is of the utmost importance for the end consumers.

The implementation of the transformation follows the outlined timeline, as, by 2024, we had already renovated 240 meters of the TEŠ-CEP main hot water pipeline.

In 2025, we began the renovation of the hot water network in the Gorica Velenje supply area with a total length of 1,170 meters, and in the Cankarjeva cesta supply area in Šoštanj, we continued with the renovation of the secondary network and the construction of 8 internal heating stations.

In 2026, we are completing the works from 2025, and continuing the renovation of the remaining primary sections of the network and the construction of internal heating stations in the Velenje area. The completion of the renovation is scheduled for the end of 2028.

The article presents the technical, spatial, environmental, and landscape challenges in the renovation of district heating as part of the transformation of the district heating system in the Šaleška dolina, which we are encountering during the implementation of the works.

Keywords: district heating, network renovation, renovation of heating stations, alternative renewable sources of heat energy, spatial-environmental-landscape challenges in the implementation of works

SESSION

1

Electric Machines, Drives and Power Electronics


Renewable energy sources
Uranium - 235
Photovoltaics
Battery
e - mobility
Electrical energy
Hydrogen technologies
Innovative technologies

Controllability of an Electrically Excited Synchronous Generator

KLARA ŽUNIĆ, BOŠTJAN POLAJŽER
University of Maribor, Faculty of Electrical Engineering and Computer Science, Maribor, Slovenia
klara.zunic@student.um.si, bostjan.polajzer@um.si

The growing share of variable renewable generation is also increasing the share of variable-speed systems, such as pumped-hydro and wind power plants. Synchronous generators (SGs) in variable-speed systems are connected to the grid through full-size power converters. Wind power plants use mainly SGs with permanent magnets (Chen, 2021), while pumped-hydro power plants use electrically excited SGs (Valavi, 2018). Given the converter-interfaced operation, new SG design solutions lead to smaller volumes, reduced material costs, and enhanced efficiencies (Holzer, 2020). Moreover, due to their decoupled operation from the grid, converter-interfaced SGs can provide various services to the power grid, as required by EU Regulation 2016/63, including inertial frequency response, power oscillation damping, and fast-fault current injection. Thus, the controllability of such SGs is of the utmost importance.

This abstract presents the eigenvalue and controllability analyses of an electrically excited SG using a *d-q* axis model of the electromagnetic subsystem. Based on the obtained results, we can conclude the following: (1) Damper windings increase the damping of oscillatory modes, but reduce the overall controllability of the system; (2) A cylindrical rotor increases damping and provides better controllability;

(3) Increasing the angular speed reduces the controllability and decreases damping; (4) The resistances of the model windings are generally inversely related to controllability, except for the damper winding resistance in the *q*-axis.

Keywords: synchronous generator, variable speed, controllability, eigenvalues, stability.

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Thermal Modelling Methods for Optimal Monitoring and Analysis of Small Synchronous Machines

Željko Špoljarić, Vedrana Jerković Štil, Željko Hederić, Krešimir Miklošević
Josip Juraj Strossmayer University of Osijek, Faculty of Electrical Engineering, Computer Science and Information Technology Osijek, Osijek, Croatia
zeljko.spoljaric@ferit.hr, vedrana.jerkovic@ferit.hr, zeljko.hederic@ferit.hr, kresimir.miklosevic@ferit.hr

The paper presents methods for optimal thermal modelling, with the accent on lumped parameter thermal network modelling. The main research topic is the impact of synchronous machine thermal model simplification on the thermal behaviour prediction accuracy. The paper focuses on small synchronous machines (rated active power from 0,3 kW to 10 kW) with passive cooling. These machines are usually totally enclosed and fan cooled. Synchronous machine thermal models are given and discussed with equivalent electrical schemes. The synchronous machine stator consists of stator windings, a stator iron core made of laminated steel and a housing (which is usually made from aluminium alloys). The thermal model equivalent schemes consist of thermal resistance (*R* in K/W) and thermal capacitance (*C* in Ws/K). These parameters are used to represent the thermal behaviour of different machine parts such as: stator winding, rotor winding or permanent magnets, stator and rotor core, machine housing, as well as convective heat transfer to the air.

Modern permanent magnet synchronous machines have increased torque/power density, which leads to the problem of heat dissipation and cooling of the machine.

Sufficiently accurate thermal model is essential for machine design and the prediction of temperature distribution (Tang et al., 2023).

Advanced thermal management techniques (Liang et al., 2024) have become a great interest in the research of real-time thermal monitoring and predictive maintenance (Liang et al., 2025). Electrically excited synchronous machines have specific problems related to thermal presentation and cooling of the rotor winding, which are also discussed in this paper (Boscaglia et al., 2023).

Keywords: thermal modelling, synchronous machine, lumped parameter network, permanent magnet, electrical excitation.

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Application of Principal Component Analysis to Measurement Data in Electric Drives

LUKA ŽIVKOVIĆ,[1] TIN BENŠIĆ,[1] KRISTIAN KNOL,[1] MARKUS SIEVERS[2]
[1] Josip Juraj Strossmayer University of Osijek, Faculty of Electrical Engineering, Computer Science and Information Technology, Osijek, Croatia
luka.zivkovic@ferit.hr, tin.bensic@ferit.hr, kristian.knol@ferit.hr
[2] KAI Kompetenzzentrum Automobil- und Industrieelektronik GmbH, 9524 Villach, Austria
Markus.Sievers@k-ai.at

Modern electric drive test setups involve the acquisition of numerous electrical and mechanical signals, resulting in high-dimensional datasets with redundancy and strong interdependencies between the variables. In this work, measurement data were obtained from an experimental electric drive system consisting of an induction motor supplied by a frequency converter and coupled mechanically to a permanent magnet synchronous motor operating as a braking machine. The measured quantities include stator currents and voltages, rotational speed, and electromagnetic torque, recorded under steady-state conditions and processed in MATLAB.

Due to the high dimensionality and correlation of the measured variables, direct analysis of the raw data provides limited insight into the dominant system behavior. Not all the measured physical quantities contribute equally to the drive dynamics, and some variables may have a negligible influence. Identifying these contributions is therefore essential for reducing the number of variables, while preserving the relevant information.

To address this, Principal Component Analysis (PCA) was applied to the measurement dataset, to extract the dominant modes of variation and evaluate the relative importance of the individual variables. By transforming the correlated measurements into a reduced set of uncorrelated principal components, PCA enables dimensionality reduction and clearer interpretation of system behavior (Hadraoui et al, 2023). The results show that most of the variance is captured by a small number of components, yielding a compact and informative representation of the electric drive system suitable for further analysis.

Keywords: electric drive systems, measurement data analysis, principal component analysis, dimensionality reduction, pattern analysis

Reference

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HIL Approach for Drone Brushless Drive Testing and Analysis

TIN BENŠIĆ, DAMIR ŠOŠTARIĆ, ŽELJKO HEDERIĆ, MARINKO BARUKČIĆ
Josip Juraj Strossmayer University of Osijek, Faculty of Electrical Engineering, Computer Science and Information Technology, Osijek, Croatia
tin.bensic@ferit.hr, damir.sostaric@ferit.hr, zeljko.hederic@ferit.hr, marinko.barukcic@ferit.hr

This work focuses on developing an approach for testing the brushless electric motor drive system for drones using HIL systems. The problem of HIL testbed design and test automation is visible from literature like: (Wang et.al. 2024), (Teriya et.al. 2023), (Sputh et.al. 2021)

The drive system is composed of an electronic speed controller (ESC) board and a small permanent magnet synchronous motor working as a brushless DC drive.
The test goal is to determine the functionality of the ESC board, since no knowledge is available on the implemented algorithms. A Hardware-in-the-Loop (HIL) approach is used to ensure that the correct signals are passed to the ESC board. An OPAL-RT 5031 RT simulator is used as the master controller. Through the HIL interface the ESC is connected to the HIL system and exchanges PWM signals used for speed referencing of the brushless drive. The HIL system also measures the electric motor currents and voltages, DC link current and voltage, and uses these measurements to determine if the board is operating correctly.

The ESC requires specific sequences on the PWM line to start the motor. These sequences are developed in the HIL-System to test the functionality of the ESC preprogrammed algorithms. On higher layers a full testing sequence is developed in Python to handle the HIL-System operation, tests` starts and finishes, and data transfer. An HMI is developed in LabView to monitor the test procedure by an operator.

The tests are conducted on four ESC boards, and the results can be used to determine which boards are delivered faulty from the factory, with the type of fault isolated.

Keywords: HIL testing, BLDC motors, ESC Board analysis, motor control

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The Electronic Impact of a PWM-Generated Controlling Signal on an ESC Start with a Brushless Motor

Damir Šoštarić, Tin Benšić, Željko Hederić
Josip Juraj Strossmayer University of Osijek, Faculty of Electrical Engineering, Computer Science and Information Technology Osijek, Osijek, Croatia
damir.sostaric@ferit.hr, tin.bensic@ferit.hr, zeljko.hederic@ferit.hr

A testbed setup based on a Brushless ESC (*Electronic Speed Controller*) was designed for multipurpose testing of similar or identical ESC-controlled boards. The battery-powered DC link ensures an adequate voltage/current for the application, while the capacitors indicate they are not designed properly on the PCB (Printed Circuit Board) for the time constant in the charging circuitry. A quality prediction design with properly calculated values solves those issues during the soft start. Controlling the PWM (*Pulse Width Modulation*) signal, generated from the primary microcontroller, is defined as an Idle value, Minimum, and Maximum throttle thresholds. Those values specify the time interval for each impulse on the different controlling frequencies of the PWM necessary for calibration. During sequences of measurements, a range was used from 50Hz to 500Hz. It's defined by firmware in the primary microcontroller, and manifested as a constant in the macro library/compiler of the controlling firmware. The measured control voltage level was in the range 2,64V - 5V, which represents the capability of driving the ESC on 3,3V and 5V. The time interval was measured with a secondary microcontroller on the ESC by measuring the time from the generated signal to the presence of an interrupt. The measurement sequence was done to isolate the firmware issue vs MOSFET burnout in the bridge. Secondary microcontroller sensing pins were in the loop with voltage feedback on the microcontroller analog inputs. The primary microcontroller, based on an ARM STM32F4 core, works on 168MHz, and with timers/pre-scalers defines the PWM frequency of the controlling signal. The main goal is to move four slot Mikrobus PWM pins to dedicated hardware pins on the development board, and migrate to a HAL (*Hierarchical Architecture Layer*) dedicated development board for a multipurpose application for controlling and sensing data.

Keywords: ESC (*Electronic Speed Controller*), PWM (*Pulse Width Modulation*), Brushless Motor, Primary uC – ARM STM32F407VG/ZG, Secondary uC ATMega8A, MOSFET bridge.

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A Three-Phase Diode Bridge Rectifier Model for Continuous Conduction Mode

ERMIN BEGANOVIĆ,[1] HASEN ZEJĆIROVIĆ,[1] MENSUR KASUMOVIĆ,[1] MARINA PEJIĆ,[1] IVAN RAMLJAK,[2] AMIR TOKIĆ[1]
[1] University of Tuzla, Faculty of Electrical Engineering, Tuzla, Bosnia and Herzegovina
ermin.beganovic@fet.ba, hasen.zejcirovic@fet.ba, mensur.kasumovic@fet.ba, marina.pejic@fet.ba, amir.tokic@fet.ba
[2] University of Mostar, Faculty of Mechanical Engineering, Computing and Electrical Engineering, Mostar, Bosnia and Herzegovina
ivan.ramljak@fsre.sum.ba

The six-pulse three-phase rectifier represents a simple, relatively low-cost, and widely adopted solution for applications requiring a stable high-power DC output voltage (Bleijs, 2005). The main application areas of these rectifiers include industrial electronic equipment, electrical drives, battery charging stations for electric vehicles, telecommunication systems, and welding power supplies. The key advantages of three-phase rectifiers are their high efficiency at large power scales, reduced output voltage ripple compared to single-phase rectifiers - which minimizes filter size, and their robust and simple configuration.

However, due to the presence of diodes, these rectifiers act as typical nonlinear loads of relatively high power, inherently generating nonsinusoidal currents that degrade the power quality in distribution networks. Consequently, the development of a qualitative rectifier model is essential for understanding rectifier operation, predicting harmonic distortion, and assessing its impact on distribution systems. Depending on the rectifier`s parameters, operation can occur in two modes: discontinuous conduction mode (DCM) and continuous conduction mode (CCM). The CCM mode is considerably more complex to model, as within one fundamental period (20 ms) twelve conduction intervals occur, during which two or three diodes conduct simultaneously.

The rectifier configuration is well known: a three-phase voltage source, a series R, L impedance (representing the input filter and Thevenin equivalent network impedance), a six-pulse diode bridge, and a parallel connection of a smoothing capacitor (C) with an equivalent load resistance (R_l). Nevertheless, the values of these parameters (R, L, C, and R_l) are typically unknown, and cannot be measured or calculated directly, as the rectifier is usually enclosed hermetically. On the other hand, it is possible to measure the waveforms of the three input voltages and three input currents at the rectifier terminals. In this context, the central idea of this study is to develop an algorithm that determines the rectifier parameters in the more complex CCM mode, based on the recorded voltage and current waveforms. The proposed algorithm employs an objective function defined as the difference between the reference and simulated input currents. Minimization of this function is achieved using optimization methods such as Levenberg-Marquardt, Particle Swarm Optimization (PSO), or the Nelder-Mead simplex method. The algorithm begins by computing an initial vector from the space of admissible (nonnegative) solutions. The objective function is evaluated analytically in each conduction subinterval, depending on which two or three diodes are conducting.

The proposed optimization algorithm is validated under several scenarios with different rectifier parameter sets. First, the algorithm is tested using numerical values of the input current waveforms for a reference rectifier (110 V). Subsequently, it is applied to the measured signals of the three input currents obtained from a laboratory-constructed (220 V) three-phase diode bridge rectifier. It should be noted that the available references estimate primarily the parameters of single-phase rectifiers (Tokić et al., 2016, 2023; Milcev et al., 2026). Therefore, this work represents a natural extension toward parameter estimation of three-phase rectifiers operating in CCM mode.

Keywords: three-phase rectifier model, continuous conductive mode, parameter calculations, optimization.

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Application and Simulation of SVPWM for a PMSM Drive

IZTOK BRINOVAR,[1] DENIS BATIUK,[1] MIRALEM HADŽISELIMOVIĆ, [1, 2]
BOJAN ŠTUMBERGER, [1, 2] AMOR CHOWDHURY [1, 3]
[1] University of Maribor, Faculty of Energy Technology, Krško, Slovenia
iztok.brinovar@um.si, denis.batiuk1@um.si, miralem.h@um.si, bojan.stumberger@um.si, amor.chowdhury@um.si
[2] University of Maribor, Faculty of Electrical Engineering and Computer Science, Maribor, Slovenia
miralem.h@um.si, bojan.stumberger@um.si
[3] University of Ljubljana, Faculty of Mechanical Engineering, Ljubljana, Slovenia
amor.chowdhury@um.si

Space vector pulse-width modulation (SVPWM) is a key modulation method for two-level voltage source inverters (VSIs) used in AC drives, including permanent magnet synchronous motor (PMSM) drives. Compared with conventional sinusoidal PWM, SVPWM generally provides better DC-link voltage utilization, a wider linear modulation range, and can contribute to lower harmonic distortion, reduced switching losses, and lower common-mode voltage. Both methods are based on voltage synthesis by time-weighting of the switching states.

This paper presents the implementation and simulation of an SVPWM algorithm for a PMSM drive, focusing on gate-signal generation for a two-level VSI. The algorithm uses the space-vector representation of stator voltages in the stationary αβ reference frame, and selects inverter switching states according to the sector of the reference voltage vector. Switching states are presented for active and zero voltage vectors in different sectors, together with the switching sequence and switching-time allocation

within one switching period. The simulation study focuses on the inverter output voltages obtained with the implemented SVPWM algorithm. A simplified VSI model is included, with switching delays and dead time effects considered. For experimental verification, the simulated output voltages are compared with measurements from a real two-level VSI operating with the implemented SVPWM algorithm. The agreement confirms the correctness of the implementation and the adequacy of the adopted model. The developed simulation framework provides a basis for further analysis of inverter-fed PMSM drives, including analysis of the output-voltage quality, harmonic distortion, and the effects of the switching frequency, dead time, and switching delays on the converter and drive performance.

Keywords: electric drive, permanent magnet synchronous motor (PMSM), simulation, space vector pulse width modulation (SVPWM), voltage source inverter (VSI).

Calculation of a BLDC Motor Back EMF by FEM Simulation and Python

Marinko Barukčić, Željko Hederić, Danijel Topić
Josip Juraj Strossmayer University of Osijek, Faculty of Electrical Engineering, Computer Science and Information Technology Osijek, Osijek, Croatia
marinko.barukcic@ferit.hr, zeljko.hederic@ferit.hr, danijel.topic@ferit.hr

Urban personal e-mobility has garnered significant interest in recent years. Key representatives include e-bikes and e-micromobility vehicles, which are powered frequently by brushless DC (BLDC) motors. Among the various performance parameters, the back electromotive force (back-EMF) is a critical characteristic. Multiple analytical and measurement methods exist for estimating and calculating back-EMF. This paper presents a finite element method (FEM) simulation approach using a Finite Eleements Method Magnetics (FEMM) simulation tool, coupled with an automated calculation procedure implemented in a Python environment. The back electromotive force (back-EMF) is a critical parameter in motor control applications, particularly in the implementation of sensorless control algorithms (Zicheng Li, 2008). Typically, practical estimations of back-EMF are conducted using analytical formulations that leverage the back-EMF constant provided in the motor's technical specification datasheet (Yedamale, 2003.). In this study, the back-EMF is evaluated quantitatively using a software tool for electromagnetic field simulation that integrates geometric modeling and numerical calculations through the Finite Element Method (FEM). This methodology involves the automation of sequential computations utilizing the FEMM simulation environment (Meeker, 2019), facilitated through a Python programming framework (see Fig. 1).

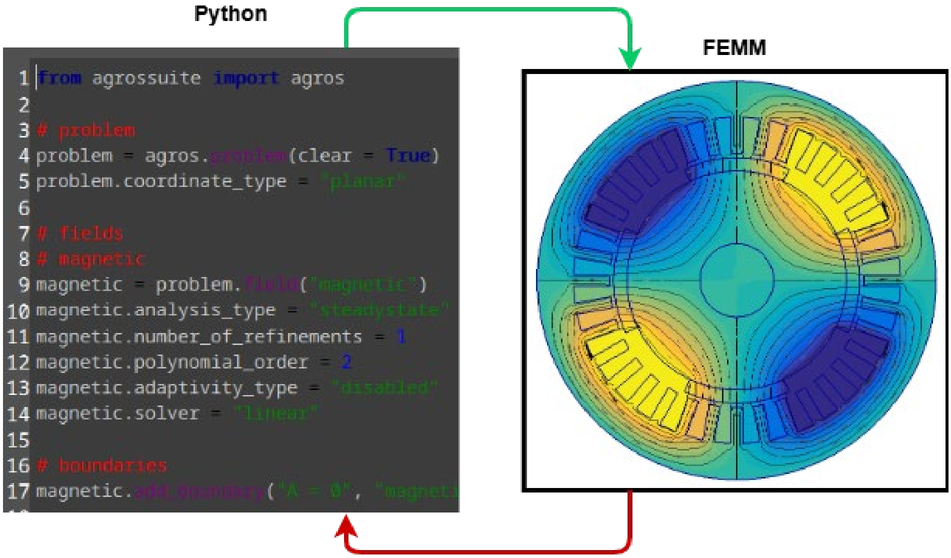

Figure 1: A frameeork used in the research
Source: own.

Keywords: back EMF, BLDC motor, FEMM, FEM simulation, Python.

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SESSION

2

Diagnostics, Measurements, Network & Storage


Renewable energy sources
Uranium - 235
Photovoltaics
Battery
e - mobility
Electrical energy
Hydrogen technologies
Innovative technologies

Overview of the Available Corona Discharge Detection Methods on Transmission Lines

HRVOJE GLAVAŠ, DINA JUKIĆ, ANITA KVAČEK BLAŽEVIĆ
Josip Juraj Strossmayer University of Osijek, Faculty of Electrical Engineering, Computer Science and Information Technology Osijek, Osijek, Croatia
hrvoje.glavas@ferit.hr, dina.jukic@ferit.hr, anita.kvacek@ferit.hr

A corona is a localized electric discharge in the air around a conductor or insulator, which occurs when the electric field exceeds a critical value, resulting in ionization of the air, glow, noise, and radio interference (Goldman et al., 1985). The causes of corona discharge can be geometric factors like sharp edges, an insufficient distance between the conductors, or contamination, (Hidayat & Abdul-Malek, 2025). HV transmission lines are particularly affected by corona, which causes premature aging of the insulators, power loss, and reduced energy efficiency (Zobaa et al., 2025). Corona losses can account for up to half a percent of the total transmision losses, but the effects of corona (ozone and nitrogen oxides) can halve the lifespan of the insulators (Qiao et al., 2019). Timely detection of corona is essential for responsible system management and predictive maintenance. In practice, a corona is detected acoustically (Egger et al., 2009), by ultrasound (Ivanov et al., 2025), visually in the ultraviolet (UV) spectrum (SONEL S.A., 2014), weakly in the visible part of the spectrum (Bruce et al., 2008), and in the infrared part of the spectrum (Stolper et al., 2007; Kumru et al., 2023).. The efficiency of corona detection is highest with a UV camera, estimated at around 90%, followed by ultrasound and acoustic cameras with approximately 70% detection efficiency. Infrared thermography is estimated to be 50% efficient, and visual inspection 25% (GNSS.AE, 2025). The goal of the research is to provide an example of the usage of a UV camera, an infrared thermal camera, and a sound camera for corona detection.

Keywords: corona, transmission, UV camera, IR thermography, acoustic imager.

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Data Driven Fault Diagnosis of Rotating Machines

NEJC FRIŠKOVEC,[1, 2] DALIBOR IGREC,[1] AMOR CHOWDHURY[1]
[1] University of Maribor, Faculty of Energy Technology, Krško, Slovenia
nejc.friskovec@student.um.si, dalibor.igrec@um.si, amor.chowdhury@um.si
[2] Elmont Krško d.o.o, Krško, Slovenia
nejc.friskovec@elmont-kk.si

This paper presents a model-based approach to fault detection in a medium-voltage electric motor using several linear regression techniques as a foundation for data-driven condition monitoring. Instead of relying only on conventional fixed alarm limits, a baseline linear regression model is trained on historical data representing healthy operation (Hastie, T et al., 2009). Deviations between the measured and predicted values, referred to as residuals, are used as indicators of potential degradation or emerging faults. Different linear regression models are tested, with the fault detection being performed by thresholding the absolute value of the residuals. The threshold is defined based on the statistical properties of the residuals during a healthy reference period, and selected to balance detection sensitivity against the false alarm rate (Allal & Khechekhouche, 2022). The results demonstrate that even relatively simple linear models can achieve high predictive accuracy and detect localized thermal anomalies reliably. A key advantage of the approach is its interpretability, as regression coefficients provide a direct insight into the influence of operational and environmental variables (Rosli et al., 2022). Limitations arise when inputs are correlated strongly, where a fault in one component may be partially explained by correlated variables, potentially masking anomalies in related channels.

Another limitation is the lack of real fault data, as true failure events are rare and unavailable, requiring synthetically generated fault scenarios for evaluation. In addition, limited physical information about the motor prevents the development of a high-fidelity digital twin capable of simulating fault mechanisms. Despite these constraints, regression-based monitoring remains a practical and interpretable framework for early fault detection, and supports data-informed maintenance strategies (De Angelo et al., 2009).

Keywords: linear regression, least squares method, rotating machines, predictive maintenance, early fault detection.

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Experimental Validation of a Simplified Model of a Current Transformer

JERNEJ ČERNELIČ,[1] ERMIN RAHMANOVIĆ,[1] BOŠTJAN POLAJŽER,[1]
GAŠPER HABJAN,[2] MATEJ PETEK,[2] DARINKO STICH[2]
[1] University of Maribor, Faculty of Electrical Engineering and Computer Science, Maribor, Slovenia
jernej.cernelic@um.si, ermin.rahmanovic@um.si, bostjan.polajzer@um.si
[2] Dravske elektrarne Maribor d.o.o., Maribor, Slovenia
gasper.habjan@dem.si, matej.petek@dem.si, darinko.stich@dem.si

Modeling of current transformers (CTs) is essential for understanding their behavior, especially during transient phenomena, when the non-linear magnetizing characteristic can lead to iron-core saturation (Stumberger et al., 2008). For this purpose, a simplified dynamic model of CT was used, which included only non-linear magnetizing characteristics, while the winding resistance and leakage inductance were neglected, as in (Martinez et al., 2005). The non-linear magnetizing characteristic was modeled using a look-up table.

A measurement-class CT, Circutor TA210, with a current ratio of 10 A to 5 A, was used to validate this simplified CT model. The magnetizing characteristic was measured using an Omicron CT Analyzer from the measured induced voltage and magnetizing current in accordance with the IEEE C57.13 Standard.

The considered simplified model of CT with measured magnetizing characteristic was validated in a transient condition, where it was supplied with a primary current with an aperiodic component (Zhang et al., 2013), which caused the saturation of the iron core after 3 periods. The simulated secondary current was then compared to the measured current using the range-normalized Root-Mean Square Error (NRMSE) method, calculated within a sliding window of 20 ms, the fundamental period, similar to (Stumberger et al., 2008). Even with the use of a simplified model, the maximum NRMSE was 3.66 %, while deviations exceeding 3 % occurred only during one fundamental period, when the saturation was the highest. This indicates a relatively high level of agreement between the simulated and measured secondary currents of CT.

Keywords: validation, current transformer, model, magnetizing characteristic, saturation

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Nonlinear Inductor Modeling of a Ferroresonant Circuit

PATRICIJA RONTA, TIN BENŠIĆ, ŽELJKO HEDERIĆ, MARINKO BARUKČIĆ
Josip Juraj Strassmayer University of Osijek, Faculty of Electrical Engineering, Computer Science and Information Technology Osijek, Osijek, Croatia
patricija.ronta@ferit.hr, tin.bensic@ferit.hr, zeljko.hederic@ferit.hr, marinko.barukcic@ferit.hr

This paper presents the modeling of a nonlinear coil, which represents the most challenging component in a ferroresonant circuit (Slow Transients Task Force, 2000), and the evaluation of its dynamic behavior through a simulation model validated by a real-time experiment. The primary object was to develop an accurate mathematical representation of the nonlinear inductor, and integrate it into a ferroresonant circuit model suitable for real-time simulation. To ensure a high level of fidelity between the simulated and physical systems, measurements of the winding resistance as well as the inductor voltage and current were performed on a representative nonlinear coil. The measured data were used to approximate hysteresis loops, based on which an algorithm was developed to detect the loop extrema, and estimate the parameters of an analytical magnetization curve. The nonlinear inductor was modeled using Chua's model (Chua, 1976.), where hysteresis losses were represented by a parallel resistance defined by the area of the major hysteresis loop. The approximated model of a nonlinear coil was incorporated into a ferroresonant circuit simulation framework structured to eliminate algebraic loops, enabling stable numerical integration and simulation. The complete simulation model was then deployed in a real-time environment, and tested alongside the physical ferroresonant circuit under identical voltage conditions and at the same

time. A comparative analysis of the time and frequency domain responses demonstrated a high level of agreement between the simulated and real systems, confirming that the developed simulation model captures the nonlinear dynamics of the ferroresonant circuit accurately, and represents a reliable digital replica of the physical system.

Keywords: ferroresonant circuit, magnetization curve, nonlinear coil, simulation model, real-time simulation

Acknowledgement

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Effect of Supraharmonics on Losses in Low-Voltage Cables

MISLAV TRBUŠIĆ, PRIMOŽ SUKIĆ, MARKO JESENIK
University of Maribor, Faculty of Electrical Engineering and Computer Science, Maribor, Slovenia
mislav.trbusic@um.si , p.sukic@um.si, marko.jesenik@um.si

Recent studies indicate that the presence of higher-harmonic components in the current of low-voltage and medium-voltage power grids has increased significantly in recent years. This rise is due primarily to the growing use of electronically driven converters, such as electric vehicle chargers, photovoltaic inverter systems, and industrial power units equipped with Power Factor Correction (PFC). Higher harmonics, also referred to as superharmonics, typically range from 2 kHz to 150 kHz, and can constitute several percent of the total current in certain parts of the network. These harmonics can lead to various detrimental effects, including interference among the power supply components, distortion of the fundamental voltage and current waveforms, and increased losses, which may result in excessive heating and reduced service life of the equipment. This article assesses the impact of superharmonics on cable losses and the associated heating issues. Numerical calculations on a low voltage cable indicate that a 20% share of the 15 kHz component in the nominal current can increase losses by 23% and cause a temperature rise of appx. 6°C. As superharmonics become more prevalent in power networks, it will be essential to consider their effects when terminating the permissible load for cables in the future.

Keywords: cable, eddy currents, FEM, losses, supraharmonics, temperature

Embedded Electrochemical Impedance Spectroscopy Using a Dedicated IC for SoX Estimation in Lithium-ion Cells

DENIS BATIUK,[1] IZTOK BRINOVAR,[1] IGOR MELE,[2] KLEMEN ZELIČ,[2] MARTIN PEC,[3,4] TOMAŽ KATRAŠNIK,[2] AMOR CHOWDHURY[1,2]

[1] University of Maribor, Faculty of Energy Technology, Krško, Slovenia
denis.batiuk1@um.si, iztok.brinovar1@um.si, amor.chowdhury@um.si
[2] University of Ljubljana, Faculty of Mechanical Engineering, Ljubljana, Slovenia
igor.mele@fs.uni-lj.si, klemen.zelic@fs.uni-lj.si, tomaz.katrasnik@fs.uni-lj.si, amor.chowdhury@um.si
[3] University of Maribor, Faculty of Electrical Engineering and Computer Science, Maribor, Slovenia
martin.pec@um.si
4 EMSISO d.o.o., Pesnica pri Mariboru, Slovenia
martin.pec@emsiso.com,

Lithium-ion batteries require accurate estimation of the SoC/SoH/SoP for safe and efficient BMS operation. This thesis examines whether a dedicated integrated circuit can implement electrochemical impedance spectroscopy (EIS) as an embedded diagnostic for SoX estimation. EIS measures small-signal, frequency-dependent impedance, allowing different electrochemical processes to be distinguished across frequency. A Samsung INR18650-25R cell was characterized at several SoC levels using three platforms: an Analog Devices AD5941 evaluation system, an AD5941-based EmStat instrument, and a laboratory Ivium XP40 reference. The cell specifications used in the study are based on the referenced INR18650-25R source. (Samsung SDI Co., Ltd. and Cell Business Division, n.n.) Each SoC point was measured three times, and relaxation was applied to reduce the voltage drift effects prior to EIS acquisition. (Deng, 2015) The spectra were exported to MATLAB for analysis and model fitting. A Thévenin equivalent circuit model with multiple RC elements was implemented in MATLAB/Simulink. The parameters were identified from the EIS data via optimization, and the resulting model was used for an observer-based SoC estimation. An extended Kalman filter (EKF) was applied as the primary estimator, following the established EKF-based workflows. (Shamarova, Komarnicki and Wenge, 2021) A proportional–integral observer was also considered. (Lin, , Tang and Wang, 2015) The AD5941-based platform reproduced the main impedance trends seen with Ivium, but showed higher noise and offsets, while EmStat produced smoother spectra. The current identification approach yielded nearly constant parameters across the SoC, limiting model fidelity and SoC estimation accuracy. Overall, chip-based EIS is promising for low-cost trend monitoring in BMS, but improved filtering, measurement setup, identification strategy, and/or richer models, are needed for reliable SoX estimation.

Keywords: lithium-ion batteries, electrochemical impedance spectroscopy, parameter identification, equivalent circuit model, EKF, state of charge.

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Stochastic Modelling of Low-Voltage Distribution Networks

MAREK HÖGER, PETER BRACINIK, MICHAL BAHERNIK
University of Zilina, Faculty of Electrical Engineering and Information Technology, Zilina, Slovakia
marek.hoger@uniza.sk, peter.bracinik@uniza.sk, michal.bahernik@uniza.sk

The rapid development of new technologies has driven significant changes in consumer behaviour and introduced new challenges for distribution system operators. The growing penetration of residential PV installations, the increasing use of air conditioning and heat pumps, and the expansion of residential EV charging infrastructure, are all transforming the operating conditions in low-voltage networks rapidly (Damianakis, 2025).

To address these challenges, distribution system operators must analyse network conditions carefully, identify potential weak points, and develop measures to mitigate the negative impacts of these emerging technologies. Accurate modelling of the operating conditions in low-voltage networks is a key component of such analyses.

However, modelling the operation of low-voltage networks remains a highly challenging task, due primarily to the strongly stochastic nature of consumer behaviour.

There are several approaches to the stochastic modelling of consumer behaviour, ranging from highly detailed simulations of appliance usage in individual households (Jang, 2016) to various regression-based methods (Fatma, 2024), neural networks (Martellotta, 2017), and advanced mathematical concepts such as copulas (Nelsen, 2006). This paper presents a relatively simple stochastic model based on real-world measurement data, using a system of histograms to describe the probability density of power or current loading during different time intervals throughout the day.

The proposed method is then applied to analyse changes in the operating conditions of a real rural low-voltage network, and to estimate the impact of the different penetration levels of the emerging technologies, such as heat pumps and residential EV charging, on the network's reliability and safety. The method identifies potential violations of operational limits and quantifies the probability of such events.

Keywords: stochastic modelling, low voltage networks, probability density, histogram

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Transient Events in Low Voltage Systems of Electric Vehicles

Kristian Knol, Tin Benšić, Luka Živković, Patricija Ronta
Josip Juraj Strassmayer University of Osijek, Faculty of Electrical Engineering, Computer Science and Information Technology Osijek, Osijek, Croatia
kristian.knol@ferit.hr, tin.bensic@ferit.hr, luka.zivkovic@ferit.hr, patricija.ronta@ferit.hr

Low voltage loads in electric vehicles are an important factor when estimating vehicle range. Due to its complexity and overall dependence on different factors such as weather conditions or driving route, most of the loads are neglected in the calculations (with the exception of HVAC) (Bosch, 2024). Modeling different loads requires knowledge of not only the weather conditions and route, but also the load parameters and working regime, which can be a difficult task.

During driving low voltage loads are being turned on and off according to various criteria, which causes transient events such as voltage drop or overshoot, and can cause disturbance in the entire low voltage network. Analysis of the transient events is needed, in order to make the low voltage network more resilient and reliable.

This paper analyzes transient events in a simulation model of a low voltage network made in the MATLAB/Simulink environment. According to (Kim et al., 2025), 48 VDC could be used in the future as an additional low voltage level (alongside 12 VDC) in electric vehicles, primarily for propulsive loads. The transient events` analysis includes transient time, voltage change (drop or shoot).

Keywords: electric vehicle, low voltage network, low voltage loads, load 44odelling, transient event

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SESSION

3

Renewable Energy Sources, Storage, and Multi-Energy Systems


Renewable energy sources
Uranium - 235
Photovoltaics
Battery
e - mobility
Electrical energy
Hydrogen technologies
Innovative technologies

Results of R&D Project HESS – Hybrid Energy Storage System in Post-Mining Infrastructure

SERGEJ JAMNIKAR, GREGOR JEROMEL, JANEZ ROŠER
Premogovnik Velenje, Velenje, Slovenija
sergej.jamnikar@rlv.si, gregor.jeromel@rlv.si, janez.roser@rlv.si

The project aim was to develop a Hybrid Energy Storage System (HESS) consisting of three different energy storage systems: the Pumped Storage Hydroelectricity (PSH), Compressed Gas – Air/CO_2 Energy Storage (CAES) and Thermal Energy Storage (TES) using post-mining infrastructure. The possibility of using geothermal energy and the use and potential storage of CO_2 were also included in research. The assumed total energy storage capacity in HESS project was in the range of 30 MWh.

On the basis of the energy demand of each HESS component, a method of thermal and mechanical integration of the entire system was investigated and developed, together with an algorithm for the mutual interaction between the elements of the energy storage system. Optimal cooperation of the various elements of the HESS was decided to be supervised by an energy router. The router also manages energy exchanges with the national power grid for the intake of low-cost green energy and peak energy production. The single HESS energy router system should take into account the possibility of cooperation of multiple HESS systems working in a distributed system.

Techno-economic analysis and environmental assessment of HESS, planned for the end of the project, will be the basis for further industrial implementation of the project results.

The project represents a groundbreaking approach to post-mining infrastructure revitalization, offering a sustainable alternative to costly decommissioning while addressing the growing need for energy storage solutions in the era of global decarbonization. By repurposing abandoned mining infrastructure, such as shafts and underground workings, the project not only reduces capital costs but also provides a strategic advantage by situating energy storage systems near major consumption hubs.

Keywords: energy storage, post-mining infrastructure, pumped storage hydroelectricity, compressed gas – air/CO_2 energy storage, thermal energy storage, RFCS Project HESS

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Concept of an Integrated Multi-Energy System with Hydrogen-Based Long-Term Energy Storage

EVA SIMONIČ,[1] SEBASTIJAN SEME,[1, 2] KLEMEN SREDENŠEK,[1, 2] AMOR CHOWDHURY[1]

[1] University of Maribor, Faculty of Energy Technology, Krško, Slovenia
eva.simonic@um.si, sebastijan.seme@um.si, klemen.sredensek@um.si, amor.chowdhury@um.si
[2] University of Maribor, Faculty of Electrical Engineering and Computer Science, Maribor, Slovenia
sebastijan.seme@um.si, klemen.sredensek@um.si

The increasing deployment of distributed renewable energy sources highlights the temporal mismatch between electrical energy production and user demand. While short-term balancing can be addressed through battery storage, long-term and seasonal energy imbalances remain a critical challenge, particularly in residential-scale systems.

This work presents a conceptual architecture of an integrated multi-energy system that combines electrical, chemical hydrogen-based, and thermal subsystems within a unified management framework. Excess electrical energy from renewable sources is converted into hydrogen and stored for extended periods, enabling long-term energy shifting beyond daily balancing cycles. Unlike conventional hybrid photovoltaic-hydrogen systems focused primarily on electrical stabilisation, the proposed concept considers hydrogen and thermal flows as active energy carriers within a broader multi-energy architecture.

A central information-processing unit coordinates the interaction between energy production, consumption, storage and conversion. The system enables dynamic and predictive management of energy flows based on internal system states and external signals, thereby supporting extended storage horizons and improved utilisation of renewable resources.

The integration of hydrogen storage and thermal management within a unified information-processing framework enables coordinated multi-energy operation beyond conventional electricity-focused approaches.

Keywords: multi-energy system, long-term energy storage, hydrogen storage, renewable energy integration, predictive energy management

AI-Assisted Modeling of a Photovoltaic System with Energy Balance and Battery Integration

DOMEN TOMŠE, AMOR CHOWDHURY
University of Maribor, Faculty of Energy Technology, Krško, Slovenia
domen.tomse1@student.um.si, amor.chowdhury@um.si

The increasing penetration of distributed photovoltaic (PV) systems requires transparent and physically consistent modeling approaches that link theory, measurement, and simulation. In this study, a PV prosumer system is modeled by combining real operational data, a weather-driven simulation, and AI-assisted time series processing. The system`s behavior is analyzed as a dynamic interaction between irradiance, temperature, installation geometry, load demand, and grid exchange. A rigorous distinction between irradiance G [W/m²] and irradiation H [Wh/m²] is fundamental for correct power-to-energy conversion and temporal aggregation (Duffie, J. A. and Beckman, 2013). The methodological core is an interval-based energy balance computed at a 15-minute resolution. At each time step, the PV production, load consumption, grid import/export, and optional battery flows are separated explicitly, ensuring mathematical consistency and physical plausibility. This framework enables calculation of the annual yield, self-consumption ratio (SCR), and self-sufficiency ratio (SSR). Sub-hourly PV modeling improves accuracy under rapidly changing irradiance compared to purely hourly approaches (Li, 2017). Module performance under varying environmental

conditions is described using validated empirical formulations, such as the Sandia Array Performance Model (SAPM), which is verified experimentally under both indoor and outdoor conditions (Peng, Harrington and Jiménez, 2015). Battery integration is implemented through a state-of-charge (SOC) update equation,that accounts for the charging/discharging efficiencies and operational constraints,enabling transparent scenario analysis of the storage sizing and control strategies.Recognized modeling tools, such as NREL's System Advisor Model (SAM), provide a validated technical foundation for the weather-based PV simulation workflows (Gilman et al., 2018). For the investigated case, the simulated annual PV production reached approximately15.28 MWh, while the annual grid import equals 10.48 MWh, emphasizing theimportance of temporal matching and storage optimization. AI accelerates pre-processing and documentation significantly, whereas expert validation remainsindispensable for ensuring physical credibility and the correct interpretation of the measurement data.

Keywords: photovoltaic system modeling, energy balance analysis, self-consumption, battery storage (SOC), AI-assisted data processing, time-series simulation.

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The Rise of Physics-Informed Neural Networks for Large-Scale Energy Resource Assessment

NIKO LUKAČ, MARKO BIZJAK
University of Maribor, Faculty of Electrical Engineering and Computer Science, Maribor, Slovenia
niko.lukac@um.si, m.bizjak@um.si

Over the past decade, the volume of microclimate data from heterogeneous sources has increased substantially, particularly from satellite-based observations, weather stations, and IoT devices (Heldens, 2017). Additionally, detailed 3D models of entire cities have been generated using LiDAR (Light Detection and Ranging) and aerial surveys (Bizjak, 2023). These advancements have facilitated the development of new simulation and modelling techniques to predict energy resources, especially from renewables, such as solar and wind. Most simulation algorithms are based on physical equations, which impose a high computational burden when predicting variables accurately over large-scale areas at a high resolution (1 m^2). Although the rise of High-Performance Computing (HPC) and General-Purpose Computing on Graphics Processing Units (GPGPU) has enabled efficient implementation of these algorithms (Lukač, 2024), near real-time estimation with high accuracy remains limited to smaller areas, provided that the data are complete. Real-time estimation of microclimate variables is critical, especially in the energy domain, as digital twins are integrated increasingly into decision support systems at a larger scale (Francisco, 2020). Recently, the emergence of deep learning algorithms has led to the development of Physics-Informed Neural Networks (PINNs) (Cuomo, 2022), which are constrained by physical equations to enhance accuracy, particularly in the presence of data gaps (e.g., sparse weather stations). This approach overcomes the inherent limitations of simulations and non-physics-based deep learning approaches (Žalik, 2024), while also enabling near real-time inference. In this work, we present the advantages of state-of-the-art PINNs, their compatibility with existing simulations, and their application for large-scale energy resource assessment.

Keywords: energy resource assessment, remote sensing data, simulations & modelling, physics-informed neural networks

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A Probabilistic Reliability Assessment of High-Voltage Substation Topologies Using a Monte Carlo Simulation

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

The increasing structural complexity of modern power systems, driven by renewable integration and higher operational demands, requires reliability assessment methods capable of capturing the stochastic component behaviour and topology-dependent fault propagation. This contribution presents a scalable probabilistic framework for comparative evaluation of high-voltage substation configurations using a large-scale Monte Carlo simulation. Unlike deterministic reliability studies, the proposed approach models device-level unavailability through statistically derived outage frequencies and durations, enabling the generation of millions of randomised operational states. Series-connected components are grouped into simulation fields, allowing efficient propagation of device failures through topology-specific switching logic. The framework distinguishes between full supply interruptions and partial outages, thereby providing a nuanced representation of operational resilience.

The methodology is applied to representative substation architectures, including single-busbar, double-busbar, auxiliary-supported, withdrawable circuit breaker, bypass-based and ring-type configurations. The results reveal pronounced reliability differences between the topologies. Non-redundant single-busbar systems exhibit the highest vulnerability to complete outages, whereas redundancy, combined with auxiliary or bypass mechanisms, reduces the full outage probability to near-negligible levels. Ring-based structures demonstrate strong inherent robustness due to bidirectional supply paths. A device-level hit analysis indicates further that outage duration has a stronger influence on contribution metrics than a mere device count, emphasising the importance of targeted maintenance of high-impact components such as disconnectors and transfer elements. The presented framework provides a computationally efficient and transparent tool for topology optimisation, investment planning and predictive maintenance strategy development. By quantifying how structural redundancy and switching flexibility shape outage behaviour, the study supports evidence-based decision-making for resilient substation design in the evolving power networks.

Keywords: probabilistic reliability assessment, substation topology optimisation, stochastic fault modelling, operational resilience of power systems, high-voltage switchgear analysis.

Interactive Tool for Analyzing Self-Sufficient Energy Systems with a Solar Power Plant, Electric Vehicle, and Battery Storage

KLEMEN SRPČIČ,[1] SEBASTIJAN SEME,[1,2] KLEMEN SREDENŠEK,[1,2] EVA SIMONIČ[1]

[1] University of Maribor, Faculty of Energy Technology, Krško, Slovenia
klemen.srpcic1@um.si, sebastijan.seme@um.si, klemen.sredensek@um.si, eva.simonic@um.si
[2] University of Maribor, Faculty of Electrical Engineering and Computer Science, Maribor, Slovenia
sebastijan.seme@um.si, klemen.sredensek@um.si

The increasing integration of solar power plants, battery storage systems, and electric vehicles is changing the electricity consumption profile of households significantly. This paper presents an interactive tool for sizing and analyzing the interactions between these systems, enabling the simulation of electricity production, consumption, and storage at the level of an individual metering point. The tool enables the import of one-year 15-minute measured data from the Moj Elektro portal, the use of monthly consumption data, or analysis without available data. The solar power plant production is calculated using a physical model that accounts for solar geometry, module orientation and tilt, and temperature-dependent efficiency. The meteorological data are incorporated according to the selected metering point location. Electric vehicle consumption is modeled using an annual charging profile based on user-defined parameters, including electric vehicle range, daily driving distance, and charging availability. The algorithm simulates the battery state of charge at 15-minute intervals, and adjusts the charging mode according to the battery state and available charging time. The operation of the battery storage system is modeled using a control algorithm that accounts for the instantaneous difference between production and consumption, while considering capacity limits, state-of-charge constraints, and rated power limits. The results are presented monthly, and provide an overview of production, consumption, and grid energy exchange at the metering point level. Developed in MATLAB App Designer, the interactive tool supports the planning and sizing of integrated self-sufficient energy systems by enabling the assessment of interactions between production, consumption, and storage.

Keywords: interactive tool, solar power plant, electric vehicle, battery storage, self-sufficiency

Photovoltaic/Thermal Potential for Fossil Fuel Reduction in District Heating

JERNEJ POČIVALNIK,[1] DOMEN KUHAR,[1] EVA SIMONIČ,[1]
SEBASTIJAN SEME,[1, 2] KLEMEN SREDENŠEK[1, 2]
[1] University of Maribor, Faculty of Energy Technology, Krško, Slovenia
jernej.pocivalnik@um.si, domen.kuhar@um.si, eva.simonic@um.si, sebastijan.seme@um.si, klemen.sredensek@um.si
[2] University of Maribor, Faculty of Electrical Engineering and Computer Science, Maribor, Slovenia
sebastijan.seme@um.si, klemen.sredensek@um.si

Hybrid photovoltaic/thermal (PV/T) systems have been recognized as an efficient technology for the simultaneous production of electrical and thermal energy. Performance limitations of conventional photovoltaic (PV) systems caused by elevated operating temperatures have led to the development of PV/T systems enabling active thermal energy recovery (Saxena et al., 2018; Zilli et al., 2018). Despite the growing technological maturity of PV/T systems, their practical integration into district heating applications remains insufficiently explored.

The objective of this paper is to present and evaluate the potential of PV/T systems as a thermal energy source for district heating networks based on the results obtained within the SolarHEAT project, where the integration feasibility was assessed of PV/T systems in the Šalek Valley district heating network. A PV/T system was evaluated, and the site-specific solar potential was determined using Light Detection

And Ranging (LiDAR) data. A system layout optimization was conducted to maximize the electrical and thermal energy production.

Thermal energy storage (TES) sizing was identified as a key factor influencing the temperature levels and usable thermal energy capacity. Smaller TES volumes enabled higher operating temperatures, whereas larger volumes increased the total stored thermal energy while reducing the average temperature. The results indicate that PV/T systems combined with properly dimensioned TES can reduce fossil fuel-based thermal energy production. However, as a relatively young technology, PV/T systems are currently more suitable as a complementary thermal energy source, particularly when integrated with heat pump systems.

Keywords: photovoltaic/thermal systems, thermal energy storage, district heating, alternative thermal energy source, light detection and ranging

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Estimation of Soil Model Parameters Using Different Evolutionary Optimization Methods

MARKO JESENIK, JAKOB VIZJAK, MISLAV TRBUŠIĆ
University of Maribor, Faculty of Electrical Engineering and Computer Science, Maribor, Slovenia
marko.jesenik@um.si, jakob.vizjak1@um.si, mislav.trbusic@um.si

Grounding systems are an important part of protection systems that protect equipment and people in the event of lightning strikes and faults in power systems. The design of grounding systems is a demanding task that can be carried out using a grounding system model developed with the finite element method (FEM). FEM analysis enables the calculation of the electric potential distribution in the vicinity of the grounding system. Based on this, the touch voltage and step voltage can be determined, which must not exceed the values specified by the Standards. Soil data are required in the case of an FEM model. These data can be acquired through measurements using the Wenner method, which serves as the basis for determining the parameters of the analytical soil models. Parameter determination is an inverse problem that is solved using a direct approach with evolutionary optimisation methods. The methods used are the Genetic Algorithm, Differential Evolution, Teaching–Learning-Based Optimization, Artificial Bee Colony, and Dynamic Self-Adaptive Differential Evolution. Two-layer and three-layer soil models are used. The tests are performed using three different sets of measured data. The presented work shows a comparison of the selected optimisation methods, in which different soil

models were tested with the aim of obtaining a general approach to the considered problem. The goal of the work is to determine which of the selected soil models is the most appropriate, and to identify the most suitable optimisation method for parameter estimation. An improved calculation approach is also presented, which is a combination of two methods.

Keywords: numerical methods, optimisation, evolutionary methods, soil models, grounding systems

SESSION

4

Thermal Energy Engineering and Hydropower Engineering

Renewable energy sources
Uranium - 235
Photovoltaics
Battery
e - mobility
Hydrogen technologies
Innovative technologies

The Influence of the Expansion Valve Opening Degree on the Operation of the Vapor-Compression System in a Heat Pump Dryer

MELDIN HUSEINOVIĆ,[1] JURIJ AVSEC,[1] ANŽE VOLK[2]
[1] University of Maribor, Faculty of Energy Technology, Velenje, Slovenija
meldin.huseinovic@student.um.si, jurij.avsec@um.si
[2] Gorenje, Velenje, Slovenija
anze.volk@gorenje.com

This research determined the influence of the opening degree of an electronic expansion valve (EEV) on the operation of a vapor-compression system in a heat pump tumble dryer. The study was conducted on a prototype tumble dryer using R290 refrigerant and an inverter compressor. The system, equipped with an EEV, is compared with a reference unit that utilizes a capillary tube as the throttling device.

The experimental investigation was carried out in accordance with the SIST EN 61121 Standard under controlled ambient conditions (climatic chamber) and at a nominal load. The pressures, refrigerant and process air temperatures, compressor electrical power, total electrical energy consumption, and drying time were monitored with different openings of the electronic valve.

The results show that the opening degree of the expansion valve affects the system pressure ratio, temperature distribution at various locations within the evaporator and condenser significantly, as well as the levels of refrigerant superheat and subcooling. Proper valve adjustment improves the system`s adaptability to varying operating conditions, and influences both the energy efficiency and drying cycle duration.

Comparison with the reference system shows that a controlled throttling device enables more precise regulation of the refrigerant mass flow. However, replacing a capillary tube with an electronic expansion valve alone does not necessarily result in improved energy efficiency. Without additional control equipment and comprehensive system optimization, the integration of an electronic valve represents only a limited step toward further efficiency enhancement. The findings provide a basis for future development of control devices and performance improvement of heat pump tumble dryers.

Keywords: vapor-compression system, heat pump, throttling element, expansion valve, capillary tube

Using a High-Temperature Heat Pump for Heating of Greenhouses

ALMINA SARAJLIĆ, JURIJ AVSEC, URŠKA NOVOSEL
University of Maribor, Faculty of Energy Technology, Velenje, Slovenija
almina.sarajlic@um.si, jurij.avsec@um.si, urska.novosel@um.si

Energy efficiency in greenhouse heating represents a major challenge in modern agriculture, as maintaining stable microclimatic conditions is associated with high energy consumption and environmental impacts. High-temperature heat pumps convert low-temperature heat sources into useful heat at elevated temperatures, improving energy efficiency and reducing greenhouse gas emissions (Cox et al., 2023; Sun et al., 2023). These systems are also suitable for utilizing waste heat in industrial and district heating applications (Sun et al., 2023).

This paper analyzes a case study of greenhouse heating in the vicinity of Maribor for rose cultivation. Based on the geometry of the structure, the total envelope surface area was determined to be 933 m² (Nemali, n.d.). Heat loss calculations were performed for a target indoor temperature of 16 °C, considering the lowest recorded outdoor temperatures between October 2023 and April 2024 (Agencija Republike Slovenije za okolje, 2024). The transmission heat losses through double-wall polycarbonate panels (U=2.5 W/m²K) were determined according to the manufacturer`s data (Akripol, 2014), while the ground losses (U=1.5 W/m²K) were estimated using published data (Engineering ToolBox, 2024).

The required design heating capacity during the coldest month was calculated at approximately 91.31 kW, exceeding the capacity of the existing 80 kW electric heater. A geothermal high-temperature heat pump, Thermeco2 HHR180 (130 kW, COP 4.78), was selected (ENGIE, 2024). The total investment is estimated at €190,000, with a payback period of 6.55 years and annual savings of €29,143.07 based on the 2024 electricity prices (Daibau International, 2024; GEN-I, 2023). The results confirm the technical and economic feasibility.

Keywords: high-temperature heat pump, greenhouse heating, greenhouse, heat losses, renewable energy sources

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Decoupling Heat Production and Demand: Long-Term Evaluation of Thermal Energy Storage in Residential Air-Source Heat Pump System

MATEJ ĐURANOVIĆ, VJENCESLAV DAMIČEVIĆ, MARIJA ŽIVIĆ
University of Slavonski Brod, Mechanical Engineering Faculty, Slavonski Brod, Croatia
mzivic@unisb.hr, mduranovic@unisb.hr, vdamicevic@unisb.hr

Air-source heat pumps (ASHPs) are deployed widely in residential buildings, due to their high seasonal efficiency and potential for heating decarbonization. However, their performance is strongly dependent on the outdoor temperature variations, particularly under the continental climatic conditions characterized by pronounced diurnal fluctuations. The integration of thermal energy storage has been discussed extensively as a means of improving operational flexibility and seasonal efficiency, as highlighted in the review studies by (Heier et al. 2015), (Osterman and Stritih 2021), and, more recently, (Zhou et al. 2026).

This study investigates the long-term impact of integrating a water-based thermal energy storage tank into a residential ASHP system using eight consecutive years (2018–2025) of measured hourly microclimatic data. A single-family house equipped with underfloor heating was modeled under identical building and system boundary conditions for three representative locations. Hourly simulations were performed, to compare a reference configuration without storage and a system incorporating a fully mixed thermal energy storage tank operated under a simple rule-based charging–discharging schedule. Storage volumes were evaluated between 50 L and 1500 L.

The results indicate consistent seasonal performance improvements across all the analyzed years and locations. The annual electricity consumption was reduced by 4.8–9.1%, with a multi-year average reduction of 7.02%, corresponding to an average increase in a seasonal coefficient of performance of approximately 7%. The highest relative gains were observed under less favorable nighttime temperature conditions, highlighting the importance of diurnal temperature distribution rather than seasonal averages.

The findings demonstrate that stable and reproducible seasonal efficiency improvements can be achieved through appropriately sized thermal energy storage using a simple, non-predictive operating strategy under real microclimatic variability.

Keywords: air-source heat pump; thermal energy storage; seasonal performance; microclimate; load shifting; residential buildings

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Measuring Boundary Layer Characteristics on a Rotating Disk using Laser Doppler Anemometry

MATEJ FIKE, ANDREJ PREDIN, ANDRAŽ ROGER
University of Maribor, Faculty of Energy Technology, Krško, Slovenia
matej.fike@um.si, andrej.predin@um.si, andraz.roger@um.si

The paper presents an experimental approach on studying the boundary layer on rotating glass disks in a water medium. The velocity was measured using 2-dimensional Laser Doppler Anemometry (LDA), measuring the velocities in the X, and, perpendicular to this axis, the Y direction.

For this purpose, an experimental setup was designed, taking into account all the limits and prerequisites for using the chosen measurement method, namely, low light attenuation (Opti-clear), no colour-stained glass tank container and glass disks were selected for the experiment.

The glass disks were driven using a squirrel cage electric motor, the speed was set using a frequency converter, and the power needed to rotate the disks was calculated from the measured torque.

The minimum distance from the disk, where the velocity can be measured, was derived from the LDA system, where the laser width defines the measurement volume of the finite thickness, as the upper thickness of the laser beam is therefore the minimum measurable boundary layer resolution. As tracer particles, 50 μm polyamide particles were used, and the use of isopropanol was induced to promote particle dispersion.

The results, shown graphically and in tabular form, show how the boundary layer changes with increasing the glass disks` rotational speed. Due to the viscous shear stresses and hydrodynamic resistance within the surrounding fluid, the greater the glass disks rotational speed in non-rotating medium water, the greater the power needed to rotate the disks.

Keywords: LDA, boundary layer, tracer particles, viscous shear, rotating disk, torque measurement

Cavitation Dynamics of an Ultrasonic Horn

MARKO PEZDEVŠEK, MATEJ FIKE, ANDRAŽ ROGER, GORAZD HREN
University of Maribor, Faculty of Energy Technology, Krško, Slovenia
marko.pezdevsek@um.si, matej.fike@um.si, andraz.roger@um.si, gorazd.hren@um.si

In this study numerical simulations were conducted to assess the cavitation dynamics of an ultrasonic horn and validate them against experimental results from the literature. The computations were performed in Ansys Fluent, employing only one quarter of the full computational domain, by exploiting the geometric symmetry in order to reduce the computational cost while maintaining adequate solution accuracy. The operating frequency of the ultrasonic horn was set to 20 kHz, and the oscillation amplitude was prescribed as 164 μm, corresponding to typical experimental operating conditions.

The cavitation dynamics were modelled using the Schnerr–Sauer cavitation model, with parameter values adopted according to standard recommendations reported in the literature. The sensitivity of the numerical solution to spatial resolution was examined through a detailed mesh convergence study, in which the temporal evolution of the total vapour volume and pressure fluctuations were tracked at a predefined reference location.

The analysis revealed a dominant shedding frequency of approximately 5 kHz, associated with the periodic formation and collapse of the cavitation structures. This value shows very good agreement with the available experimental measurements, providing strong validation of the adopted numerical methodology. The close correspondence between the numerical and experimental results confirms the capability of the employed modelling approach to capture the essential physical mechanisms governing cavitation behaviour accurately.

Keywords: Cavitation, ultrasonic horn, CFD, shedding frequency, Ansys Fluent

The Application of Statistical Thermomechanics in Energy Technology

JURIJ AVSEC, URŠKA NOVOSEL
University of Maribor, Faculty of Energy Technology, Krško, Slovenia
jurij.avsec@um.si; urska.novosel@um.si

Statistical thermomechanics provides a unified framework for describing the mechanical behaviour of energy systems under thermal loading, material heterogeneity and stochastic operating conditions. This paper presents a comprehensive overview of the application of statistical thermomechanics in energy technology, spanning historical developments, classical energy machinery, renewable energy systems, hydrogen technologies and digital twins. By linking microscopic material behaviour and thermal fluctuations with the macroscopic mechanical response, statistical thermomechanics enables a deeper understanding of the degradation, reliability and efficiency in modern energy systems. Practical engineering examples drawn from thermal power plants, renewable energy technologies and hydrogen infrastructure, demonstrate that statistical approaches are essential for predicting fatigue, failure probability and long-term performance in energy technologies undergoing the energy transition.

Keywords: statistical thermomechanics, energy technology, thermo-mechanical reliability, stochastic mechanics, renewable energy, hydrogen technologies, digital twin

About the authors

Prof. **Jurij Avsec** is employed at the Faculty of Energy. He heads the Laboratory for Thermomechanics, Applied Thermal Energy Technologies and Nanotechnologies.

Urška Novosel is employed at the Faculty of Energy as an assistant. She does research within the Laboratory for Thermomechanics, Applied Thermal Energy Technologies and Nanotechnologies.

Experimental Analysis of Materials in Energy Engineering Using Portable X-Ray Fluorescence Spectroscopy

BOJAN STERGAR,[1] KLEMEN SREDENŠEK[1, 2] ZDRAVKO PRAUNSEIS[1]
[1] University of Maribor, Faculty of Energy Technology, Krško, Slovenia
bojan.stergar@um.si, klemen.sredensek@um.si , zdravko.praunseis@um.si
[2] University of Maribor, Faculty of Electrical Engineering and Computer Science, Maribor, Slovenia
klemen.sredensek@um.si

The reliable operation of modern energy systems depends not only on the mechanical and electrical properties of the materials, but also on their chemical composition. This paper presents an experimental analysis of materials used in energy engineering employing portable X-ray fluorescence (XRF) spectroscopy, with particular emphasis on the influence of sample preparation on the measurement accuracy and repeatability. The experimental investigations were carried out using the portable Niton XL3t GOLDD+ analyser. Metallic materials, PVC cable insulation, and mineral samples were examined. Special attention was paid to the influence of elevated temperature on the chemical composition of the PVC insulation, with measurements performed at different temperatures to monitor changes in the chlorine content as an indicator of the dehydrochlorination process. Furthermore, samples of galena (PbS) and sphalerite (ZnS) were analysed in raw, polished, ground, and homogenised forms, to evaluate the effect of surface treatment and material homogeneity on the reliability of the analytical results. The results confirmed that appropriate sample preparation—such as grinding, homogenisation, surface polishing and pellet formation—improves the measurement quality and reduces the matrix effects significantly. It was demonstrated that even minor variations in the chemical composition can influence the material properties essential to the long-term reliability and safe operation of energy systems. The study confirms that portable XRF spectroscopy represents a fast, non-destructive and effective tool for material control in energy engineering, providing valuable support in material selection, maintenance procedures and quality assurance.

Keywords: X-ray fluorescence spectroscopy (XRF), chemical analysis, materials in energy engineering, sample preparation, PVC insulation, minerals.

SESSION

5

Ecology, LCA, Spatial Planning, and Biodiversity


Renewable energy sources
Uranium - 235
Photovoltaics
Battery
e - mobility
Electrical energy
Hydrogen technologies
Innovative technologies

Life Cycle Assessment of an Average Slovenian Solar Power Plant

GAŠPER GANTAR[1, 2]

[1] Faculty of Environmental Protection, Velenje, Slovenia
gasper.gantar@fvo.si
[2] College of Industrial Engineering, Celje, Slovenia
gasper.gantar@fvo.si

Electricity generation from non-renewable sources represents an environmental challenge, as it pollutes primarily air and water bodies and contributes to climate change. A key solution is electricity generation from renewable sources, including solar energy.

Solar panels are used most commonly to generate electricity from solar energy. Solar power plants are sometimes referred to as emission-free, because they do not impose environmental burdens during the use phase.

However, the question arises as to what the actual environmental impacts of solar power plants are across their entire life cycle. This includes the extraction of raw materials used in the plant, construction and installation maintenance during operation, and end-of-life management.

The purpose of the study was to assess the environmental impact of a solar power plant throughout its entire life cycle and to determine how "green" the electricity generated from such plants truly is compared with electricity produced from

conventional sources. The method used to analyse environmental impacts over the full life cycle is known as a Life Cycle Assessment (LCA). In our LCA model, we used input data relevant to Slovenia, referring to the average installed capacity of a self-sufficient solar power plant.

The LCA results showed that the greatest environmental impact occurs during the extraction of raw materials and manufacturing of components, while the lowest impact occurs during the use and maintenance phase. The calculated Global Warming Potential (GWP) was 40.4 g CO_2-eq per kWh of generated electricity. This value is significantly lower than that of electricity generated from coal, but slightly higher than electricity produced from some other renewable sources.

Keywords: solar power plant, life cycle assessment, environmental impacts

From Data to Decisions: LCA as a Key Tool for Identifying Energy System Bottlenecks

TANJA TAJNIK
Faculty of Environmental Protection, Velenje, Slovenia
tanjatajnik@gmail.com

The transition to low-carbon energy systems requires decisions based on robust, transparent, and systematic data. A Life Cycle Assessment (LCA) provides a comprehensive methodological framework to evaluate environmental impacts across the entire life cycle of energy technologies–from raw material extraction, distribution, and manufacturing, to operation and end-of-life treatment. However, the true strategic value of an LCA lies not only in impact quantification, but in its capacity to reveal bottlenecks within complex energy systems.

This contribution shows how an LCA can move beyond the static comparison of technologies, and serve as a decision-support tool for identifying critical bottlenecks in energy production and supply chains. By linking inventory data with impact categories such as climate change, resource depletion, and energy demand systematically, an LCA enables the detection of stages, materials, or processes that contribute disproportionately to the overall environmental burdens.

Rather than focusing on individual case studies, the paper adopts a methodological perspective to demonstrate how hotspot analysis within an LCA supports prioritization of mitigation measures, optimization of design parameters, and strategic planning. By mapping the environmental impacts across life cycle stages, the approach enables the identification of bottlenecks.

The analysis highlights further that environmental bottlenecks are not static; they shift along the value chain as technologies evolve, production scales increase, and background systems decarbonize. This dynamic perspective shows that assessments must consider both specific context and future changes when guiding energy transition strategies. By integrating hotspot identification into decision-making frameworks, an LCA becomes not only an analytical tool, but a strategic instrument for sustainable energy development.

Keywords: Life Cycle Assessment (LCA), energy systems, hotspot analysis, environmental bottlenecks, decision-support.

The Environmental Impacts of Photovoltaic and Wind Power Systems: A Pro and Contra Evaluation

KATJA ČRNEC, BORUT VRŠČAJ
Faculty of Environmental Protection, Velenje, Slovenia
katja.crnec@fvo.si, borut.vrscaj@fvo.si

The rapid expansion of large-scale renewable energy systems highlights the need to assess their environmental interactions (Hernandez et al., 2014; Turkovska et al., 2023). International policy frameworks have promoted renewable deployment increasingly, to reduce greenhouse gas emissions and enhance energy security (Intergovernmental Panel on Climate Change (IPCC), 2023). Nevertheless, the environmental impacts of photovoltaic (PV) and wind energy (WE) systems remain complex and context dependent (Gasparatos et al., 2017), requiring balanced evaluation.

This paper presents a structured review of peer-reviewed literature on PV and WE impacts on key environmental segments: air, water, soil, biota, and the main ecosystem services they provide, using a pro–contra evaluation framework.

The findings confirm substantial reductions in greenhouse gas emissions and air pollutants during operation compared with fossil-based systems (Intergovernmental Panel on Climate Change (IPCC), 2023; Nugent & Sovacool, 2014). However, the site-specific adverse effects include land-use change and habitat fragmentation (Hernandez et al., 2014; Turkovska et al., 2023), avian and bat mortality at wind turbines (Baerwald et al., 2014; Drewitt & Langston, 2006; Millon et al., 2018; Thaxter et al., 2017), soil sealing and compaction (Turney & Fthenakis, 2011), and localised hydrological changes (Fthenakis & Kim, 2010). The ecosystem service impacts range from climate regulation benefits to trade-offs in biodiversity and landscape values (Gasparatos et al., 2017; Moore-O'Leary et al., 2017). Health effects include improved air quality (Intergovernmental Panel on Climate Change (IPCC), 2023) and concerns related to noise and visual exposure near wind installations (Pedersen & Persson Waye, 2007).

The main outcome of the paper is a comparative matrix of positive and negative effects across environmental compartments, supporting informed spatial and environmental decision-making.

Keywords: photovoltaic systems; wind energy; environmental impacts; environmental segments; pro–contra evaluation; renewable energy

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The Environmental Impacts of Soil Remediation With Metal-to Char Encapsulation

BOŠTJAN DROBNIČ, MITJA MORI, DOMEN HOJKAR, ROK STROPNIK, MAJ RUDOLF VAHTAR, ANDREJ SENEGAČNIK, MIHAEL SEKAVČNIK
University of Ljubljana, Faculty of Mechanical Engineering, Ljubljana, Slovenia
bostjan.drobnic@fs.uni-lj.si, mitja.mori@fs.uni-lj.si, domen.hojkar@fs.uni-lj.si, rok.stropnik@fs.uni-lj.si, maj.rudolfvahtar@fs.uni-lj.si, andrej.senegacnik@fs.uni-lj.si, mihael.sekavcnik@fs.uni-lj.si

Soil remediation is an increasingly important process required to prevent contaminants from entering the human food chain. Heavy metals such as lead and zinc –introduced frequently through industrial discharge, mining operations, and the historical use of metal-heavy pesticides – pose severe health risks. To tackle this, a process called phytoremediation can be employed where specialized plants are used to absorb the toxic metals directly from the soil. The plants with increased heavy-metal content must be treated further, in order to retain the contaminants and to store the final product in an environmentally acceptable way.

The project PROMETHEIA – The process for metal-to-char encapsulation focuses on novel technologies for encapsulating heavy metals from biomass within the biomass char, and passivating the activated biochar with tars produced during pyrolysis of the contaminated biomass. The contaminated biomass treatment consists of three basic phases, pyrolysis, which results in char and pyrolysis gas

containing tars; gasification, which activates the char while heavy metal compounds stay in the solid phase, and passivation, where coking of the tar compounds at the surface of the activated char results in an inert final product.

The entire process is energy intensive, thus having notable environmental impacts. However, the passivated biochar can be treated as carbon sink, and, furthermore, the removal of heavy metals from the soil and revitalization of the soil has a positive impact for the local environment. A step-by-step analysis of the processes for the treatment of contaminated biomass is presented in this paper with a focus on environmental impacts.

Keywords: soil remediation, heavy metals, phytoremediation, pyrolysis, gasification, passivation, environmental impacts, life cycle assessment.

The Impacts of Wind and Solar Power Plants on Wildlife

KATARINA FLAJŠMAN,[1] AMANDA POPLAS,[1] ZARJA PLATOVŠEK,[2]
BOŠTJAN POKORNY[1, 2]
[1] Slovenian Forestry Institute, Ljubljana, Slovenia
katarina.flajsman@gozdis.si, amanda.poplas@gmail.com, bostjan.pokorny@fvo.si
[2] Faculty of Environmental Protection, Velenje, Slovenia
zarja.platovsek@fvo.si, bostjan.pokorny@fvo.si

The area occupied by wind and solar power plants is increasing rapidly, as policies around the world encourage the transition to renewable energy sources. However, such a scale of infrastructural interventions can affect biodiversity significantly at both the local and regional levels. Therefore, to support this development while also protecting wildlife, we need to understand what these impacts are and how to mitigate them. In this presentation, we provide a review of studies examining the various impacts of wind and solar power plants on wildlife.

The negative impacts of wind power plants can be direct (e.g. habitat destruction and fragmentation), or indirect (e.g. changes in interspecific relationships). They cause various types of disturbances that can lead to changes in behaviour, physiology, or space use in some species. A review of the existing literature shows that the responses of individual species vary, depending on their ecological niche and level of adaptability (e.g. Skarin et al. 2015; Bounas et al. 2025).

Solar power plants alter habitats through loss and fragmentation, changes in the microclimate, and the creation of new structures in the landscape. In connection with solar power plants, the so-called "lake effect" is also discussed often, as solar panels resemble and give a similar impression to calm water visually, which can, for example, confuse birds or bats in their perception and attract them as potential water surfaces, thereby increasing the risk of collisions and mortality (Fleming 2025).

The impacts on wildlife are multifaceted, species-specific and dependent on various factors.

Keywords: wind power plants, solar power plants, renewable resources, wildlife, disturbance

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The Impact of Power Lines on Wildlife – A Literature Review and Experiences From the Field

AMANDA POPLAS, KATARINA FLAJŠMAN
Slovenian Forestry Institute, Ljubljana, Slovenia
amanda.poplas@gmail.com, katarina.flajsman@gozdis.com

Power lines can have a significant impact on the environment, both during construction as well as during operation. Their greatest impact is in the so-called Right-of-Way (RoW) - area of regularly cleared and managed vegetation that runs under the power lines, and the width of which depends on various factors, including the voltage of the power lines themselves (Ituen and Sohn, 2010; Right of Way, n. d.).

We reviewed recently published studies on the impact of power lines from initial installation to active operation on various game species and other wild animals, as well as on the original environment. In addition to reviewing the research, we also studied some practical examples in Slovenia.

Power lines can have both negative and positive effects on the environment and animals, depending on the species involved. The main negative effects mentioned are their barrier and corridor effect, as well as habitat degradation and fragmentation (Bartzke et al., 2014; European Commission, 2018). Some studies have found that proper management of vegetation under power lines can provide an attractive habitat for wild ungulates and many other animal species, therefore, power lines can also have a positive impact on the environment (e.g., Wagner et al., 2019; Hrouda and Brlík, 2021). We were able to confirm the latter when we surveyed selected locations in Slovenia – there were different signs of animal presence in the areas under the power lines which indicates that wildlife can also benefit from these sites.

Keywords: power lines, wildlife, habitat, environmental impacts

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The Impact of Hydroelectric Power Plants on Biodiversity, With an Emphasis on Fish Species

AMANDA POPLAS, KATARINA FLAJŠMAN
Slovenian Forestry Institute, Ljubljana, Slovenia
amanda.poplas@gmail.com, katarina.flajsman@gozdis.com

Among the known sources of renewable energy, hydroelectric power plants (HPPs) are often promoted as low-carbon energy sources, but, in practice, their ecological impact on the biodiversity of freshwater ecosystems is considerable and well researched (e.g., Luangphon et al., 2025).

With dam construction it comes to river fragmentation, which changes the natural flow regimes of watercourses, interferes with the longitudinal connection, and impacts sediment transport–all of which are critical for preserving the ecosystem function, as well as the diversity of aquatic and riparian species (e.g. Ding et al., 2026).

These barriers interfere seriously with fishes' essential migratory pathways for feeding and spawning. By isolating individual populations, they decrease the genetic diversity of species and make them more vulnerable to predators. (Consuegra et al., 2021). There are also direct affects, like sublethal injury and mortality, that result from turbine passage (Algera et al., 2020).

According to various studies, further dam constructions may hasten endangerment and the extinction rate of freshwater species, especially in waterflows that are considered biodiversity hotspots (ex. Amazon Basin) (Zarfl et al., 2019; Keijzer et al., 2024). Slovenia is no exception regarding the impact of HPPs on ecosystems and biodiversity.

Although hydropower plants will continue to have a huge, mostly negative impact on the environment and local biodiversity, this can be mitigated to some extent, or even turned into something positive, by following certain guidelines for ecosystem welfare during construction and operation (Nielsen and Szabo-Meszaros, 2022).

Keywords: hydropower, fish; biodiversity, habitat, environmental impacts

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New Legislation on the Siting and Permitting of Renewable Energy Installations, with a Focus on Wind and Solar Power Plants

TANJA PUCELJ VIDOVIĆ
New University, European Faculty of Law, Nova Gorica, Slovenia
tanja.pvidovic@gmail.com

The presentation addresses the background and content of the provisions of the *Act on the Deployment of Installations for the Generation of Electricity from Renewable Energy Sources (ZUNPEOVE)*, which has already undergone three amendments since 2023.

Although electricity generation from wind and solar energy is recognised as one of the pillars of the green transition, Slovenia continues to face lengthy procedures and negative reactions from parts of civil society. ZUNPEOVE attempts to address some of these challenges.

It focuses on the specific features of the legal framework regarding spatial planning and permitting of photovoltaic and wind power generation installations (i.e., solar and wind power plants).

Given that the Act affects numerous other regulations directly and indirectly, the contribution also discusses several challenges and systemic aspects related to the complexity and lengthy procedures. Specific features introduced by the Act range from the fact that the Act imposes an obligation on the state to take an active role in spatial planning and to adopt a so-called "*thematic action programme*", which will define potential priority areas, priority areas and accelerated siting areas, to the concept of "accompanying energy activities" or dual-purpose land use. It envisages the prescribed priority areas and other examples of planning based on an expert study. It also highlights the specific features of the legal mechanism establishing the predominance of the public interest, which the Act introduces in accordance with relevant EU Directive. Furthermore, it presents the particularities of the permitting procedures for photovoltaic and wind power generation installations.

Keywords: wind power plants, solar power plants, siting, spatial planning, permitting, public interest

Energy, Financial and Environmental Savings Achieved Through the Use of the ISO 9001, 14001 and 50001 Standards

DRAGO PAPLER
Biotechnical Center Naklo, Naklo, Slovenija
drago.papler@guest.arnes.si

1 Updates to ISO Standards with sustainability and digital aspects

The update to the ISO standards in 2026 will represent an important milestone in the context of climate change, digital transformation, and sustainable development.

The published draft of the international Standard ISO/DIS 9001:2026 for quality management systems highlights key changes in the role of culture and ethics, exposure to risk and opportunity management, and the integration of sustainability and climate aspects in the context of the organization (9001, 2025).

Topics related to climate, digitalization, and sustainability are highlighted particularly in the revision of the ISO 14001:2026 (SGS, 2024), which will include requirements for incorporating climate risks into the assessment of the organization's context, setting greenhouse gas emission reduction targets, considering the life cycle of products or LCA (Life Cycle Analysis) and the circular economy, monitoring impacts on biodiversity and ecosystems, and integration with other management systems, such as ISO 9001 for quality management systems and ISO 50001 for energy management.

With the restructuring of the organization to achieve greater efficiency, the development shift was the integration of the quality management system and the ISO 50001:2018 Standard for energy management. The decision to implement an energy management system was made with the aim of establishing the systems and procedures necessary to improve energy efficiency, energy consumption, and cost optimization.

2 Methodology for energy management analysis

The methodology harmonized the contact and control points that define energy accounting, verification, and the analysis of measurement data with evaluation, through which energy performance is monitored. Additional tools are used for the measurements, analyses, and improvements to the energy management system. Surveys with data processing and multivariate statistical analyses are used to monitor the satisfaction of electricity and service customers.

An application for targeted monitoring of energy use is used to identify deviations and potential improvements, and justify sensible investments. The aim of the system is to help organizations establish the systems and procedures necessary to improve energy efficiency. It was found that savings were achieved during the monitored consumption period, but, during the unmonitored period, there was an excess of heat consumption in the following periodic period, which meant a reduction in savings. This was due to an incorrect setting of the regulator.

3 Empirical results

Key energy indicators were developed based on parameters such as energy consumption and costs, energy prices, and usable floor space. The results over three years show the efficiency of specific energy consumption, namely, a reduction in energy consumption per unit of usable floor space (kWh/m^2) by 15.4%, a 29.2% reduction in electricity consumption per unit of usable floor space (kWh/m2), a

13.3% reduction in heat consumption per unit of usable floor space (kWh/m2), and an 18.8% reduction in CO2 emissions per unit of usable floor space (kg/m2).

We used the data obtained for processing with the statistical computer program SPSS (Kachigan, 1991, Norušis, 2002) for further analysis of the energy consumption using descriptive statistics and regression analysis.

Using regression analysis, which is basically used for forecasting, we developed a statistical model for predicting the value of a dependent variable based on at least one independent or explanatory variable (Šuster Erjavec, Južnik Rotar, 2013).

The empirical data from the regression analysis show that a one percent increase in the independent variable of outside temperature reduces the dependent variable of target heating cost by 1.13%. The independent variable external temperature is correlated negatively with the target value of heating costs, and is statistically significant.

Systematic energy management reduces greenhouse gas emissions, environmental impacts, and energy costs.

Keywords: quality management systems, energy management, consumption, energy efficiency, savings, CO_2 emissions, statistical analysis, regression analysis

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SESSION

6

Energy Transition, Transport, Statistics, and Communications


Renewable energy sources
Uranium - 235
Photovoltaics
Battery
e - mobility
Electrical energy
Hydrogen technologies
Innovative technologies

Enhancing Energy Efficiency in Transport Systems: The REDU-CE-D Project

DOMEN KUHAR,[1] JERNEJ POČIVALNIK,[1] EVA SIMONIČ,[1] SEBASTIJAN SEME,[1, 2] KLEMEN SREDENŠEK,[1, 2] KATJA HANZIC,[3] NINAPAVLETIĆ,[3] MARŠENKA MARKSEL,[3] TOMISLAV LETNIK[3]

[1] University of Maribor, Faculty of Energy Technology, Krško, Slovenia
domen.kuhar@um.si, jernej.pocivalnik@um.si, eva.simonic@um.si, sebastijan.seme@um.si, klemen.sredensek@um.si
[2] University of Maribor, Faculty of Electrical Engineering and Computer Science, Maribor, Slovenia
sebastijan.seme@um.si, klemen.sredensek@um.si
[3] University of Maribor, Faculty of Civil Engineering, Transportation Engineering and Architecture, Maribor, Slovenia
katja.hanzic@um.si, nina.pavletic@um.si, marsenka.marksel@um.si, tomislav.letnik@um.si

Transport remains one of the largest energy-consuming sectors worldwide, is heavily dependent on fossil fuels, and is a major source of greenhouse gas emissions. Empirical research has shown that transport energy consumption influences CO_2 emissions significantly, with higher energy intensity associated with greater environmental impact in regional economies (Shabir et al., 2022). Likewise, evaluations of transportation systems highlight the persistent inefficiencies and opportunities for substantial energy savings (Jiao et al., 2022). Bibliometric analyses demonstrate further the growing academic focus on sustainable transport and energy efficiency as critical research domains (Asha'ari et al., 2024). The REDU-CE-D project addresses these challenges by developing and testing a customized Environmental Management System (EMS) aligned with the European Energy Efficiency Directive (EED) within a joint transnational strategic framework. The project focuses on four transport domains: water, urban, air, and rail transport. The EMS was developed based on comprehensive local assessment reports that examined the existing partner measures to enhance energy performance. Through Transnational Working Group (TWG) activities, the partners exchanged best practices and analyzed the assessment data jointly, leading to the formulation of the REDU-CE-D strategy. This process identified applicable solutions and systems capable of monitoring and controlling energy consumption and environmental impacts. Each partner defined key performance indicators (KPIs) to be monitored through pilot implementations. The evaluation of the pilot results will assess the effectiveness of the EMS in improving energy efficiency and reducing greenhouse gas emissions. Beyond the consortium, the strategy and results will be disseminated to promote uptake by other transport organizations.

Keywords: energy efficiency, environmental management system, KPIs, strategy, transport

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Design and Economic Assessment of a 19-Seat Hydrogen Fuel Cell Aircraft for Regional Aviation

ANITA PRAPOTNIK BRDNIK, MARŠENKA MARKSEL
University of Maribor, Faculty of Civil Engineering, Transportation Engineering and Architecture, Maribor, Slovenia
anita.prapotnik@um.si, marsenka.marksel@um.si

The transition toward low-emission regional aviation requires the evaluation of alternative propulsion concepts that can meet both the technical and economic feasibility criteria. This study addresses the design implications and operational performance of a 19-seat regional aircraft powered by hydrogen fuel cells using liquid hydrogen storage. The analysis focuses on the aircraft`s mass characteristics and direct operating costs as key drivers influencing the viability of such configurations.

A conceptual aircraft sizing approach is applied to estimate the maximum take-off mass (MTOM) of a hydrogen fuel cell aircraft, and to identify the dominant parameters affecting mass growth relative to a conventional reference aircraft. Particular emphasis is placed on the influence of the fuel cell power-to-weight ratio, hydrogen storage system mass, and propulsion efficiency. The results indicate that the current technology levels lead to an increased MTOM compared to conventional aircraft; however, foreseeable improvements in fuel cell technology reduce this penalty significantly, enabling competitive mass characteristics (Marksel & Prapotnik Brdnik, 2022).

Building upon the technical assessment, a comparative economic analysis evaluates the direct operating costs under different fuel price and technology development scenarios over the 2030–2050 timeframe. The cost model incorporates real operational data, and demonstrates that hydrogen fuel cell aircraft can achieve cost competitiveness with conventional counterparts, particularly under favorable hydrogen pricing and continued technological progress (Marksel & Prapotnik Brdnik, 2023). The findings highlight hydrogen fuel cell propulsion as a promising solution for short-range regional aviation, provided that parallel advances are realized in the technology and energy infrastructure.

Keywords: fuel cell aircraft, hydrogen aircraft, regional aviation, MTOM estimation, direct operating costs, 19-seat aircraft

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Presenting Low-Carbon Energy Technologies: The ENVIRO project

Manja Obreza,[1] Almina Sarajlić,[1] Eva Simonič,[1] Klemen Srpčič,[1] Klemen Sredenšek,[1, 2] Sebastijan Seme,[1, 2] Matejka Gerjevič,[3] Boštjan Pišotek[4]

[1] University of Maribor, Faculty of Energy Technology, Krško, Slovenia
manja.obreza@um.si, almina.sarajlic@um.si, eva.simonic@um.si, klemen.srpcic1@um.si, sebastijan.seme@um.si, klemen.sredensek@um.si
[2] University of Maribor, Faculty of Electrical Engineering and Computer Science, Maribor, Slovenia
sebastijan.seme@um.si, klemen.sredensek@um.si
[3] Municipality of Brežice, Brežice, Slovenia
matejka.gerjevic@brezice.si
[4] HESS d.o.o., Brežice, Slovenia
bostjan.pisotek@he-ss.si

The paper presents the development of energy-focused interpretive materials within the ENVIRO project for Vila Envira in Brežice, aimed at strengthening public understanding of the energy transition. The objective of the paper is to define the conceptual structure and educational rationale of the interpretive content, and to evaluate its role in improving energy literacy through informal learning environments. Core topics are introduced through a comparative and system-oriented framework, covering nuclear energy, hydropower, pumped storage, geothermal energy, biomass, solar power, wind power, as well as storage technologies and system flexibility in a reliable electricity system. The content is structured to connect the fundamental operating principles of individual technologies with broader aspects, such as the environmental impact, resource availability and integration within the energy system. In this way, low-carbon technologies are presented not as isolated solutions, but as interdependent components of a coherent, balanced energy system.

The interpretive-centre format is grounded in established research on informal science learning, which shows that museum and science-centre environments support the understanding of complex scientific and technological concepts through contextualised and interactive experiences (Falk & Dierking, 2016). Furthermore, a scholarship on public engagement with science emphasises that societal challenges related to energy and climate require informed dialogue and inclusive participation (Stilgoe et al., 2014). Empirical evidence from a recent science-museum exhibition focused on the energy transition indicates measurable improvements in critical energy literacy, with conceptual knowledge identified as a key enabling factor (Kellberg et al., 2025).

Keywords: ENVIRO project, low-carbon energy sources, interpretive centre, knowledge exchange, cross-border cooperation, environmental awareness

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Gradual Closure of the Velenje Coal Mine 2026–2045 as Part of the Just Transition of the SAŠA Region

JANEZ ROŠER
Velenje Coal Mine, Velenje, Slovenia
janez.roser@rlv.si

The Velenje Coal Mine is entering a structured phase-out aligned with Slovenia's coal-exit commitments (latest by 2033) and the national energy-climate framework, while ensuring the continued supply of coal to maintain a reliable district heat supply during the transition period and enabling a just transformation of the SAŠA region. The Programme for the Gradual Closure of PV 2026–2045 sets out an integrated approach that links: (i) technical and technological closure solutions, (ii) environmental rehabilitation and long-term monitoring, and (iii) workforce and financial measures, under a dedicated legislative and governance framework.

Technically, the closure is organised in two phases: progressive closure (2026–2033) carried out in parallel with declining coal production, followed by final closure (2034–2045), which includes the remaining underground works, surface rehabilitation, reclamation and monitoring. The planned closure works cover more than 50 km of underground infrastructure, multiple shafts and key facilities, and approximately 660 ha of surface areas affected within the mining concession.

From a social perspective, the programme addresses the transition of a workforce of approximately 1,700 employees (PV group), relying primarily on natural attrition, targeted retention of critical competences for closure works, reskilling, and specific measures for vulnerable groups.

Financially, the programme establishes a multi-source funding model anchored in a dedicated closure-law mechanism and multi-year public budgeting, complemented by de-investment of non-core assets and other earmarked sources where applicable. It foresees phased financing consistent with the closure timeline, defined cost categorisation and governance safeguards, such as external review, periodic reporting, auditing and state-aid compliance procedures.

Keywords: Velenje coal mine, gradual mine closure, just transition, workforce reskilling, environmental rehabilitation.

Indigenous Production of Hydrogen as Part of the Annual Hydrogen Statistics

KLEMEN DEŽELAK
Statistical Office of the Republic of Slovenia, Ljubljana, Slovenia
klemen.dezelak@gov.si

Traditionally, energy statistics focused primarily on the conventional energy supply, nuclear energy, and fossil fuels; however, recent developments have shifted attention toward improving knowledge and the monitoring of final energy consumption and the renewable energy sector. The European Commission (EC) Regulation on energy statistics (European Commission, 2008) establishes a common framework for the production, transmission, and dissemination of comparable energy data across the European Union. On the other hand, because of the rapid pace of technological advancement, energy statistics must evolve continuously to remain relevant. Recently, the EC adopted the most comprehensive revisions of the energy statistics regulation to date. (European Commission, 2022 and 2024)

Related to the changed Act (European Commission, 2024), within the products section (item 3), all the nhydrogen must be reported used as a feedstock, fuel, or energy carrier/storage. Reporting is required, even when the hydrogen is produced and consumed within the same facility.

Hydrogen production, as part of the annual hydrogen statistics, is based mainly on fossil fuels, with smaller contributions from renewables and wastes. The major production routes include steam methane reforming from natural gas, hydrogen recovery from refinery gases using water-shift reactions and separation, biomass gasification, pyrolysis of solid fossil fuels, and production from non-renewable waste. Production may occur with or without carbon capture and storage. A relatively small percent of hydrogen is produced via electrolysis, including proton exchange membrane and alkaline electrolysis, using electricity from the grid or direct transmission lines supplied by renewable, nuclear, or fossil sources. (Gunathilake, 2024 and Accardo, 2025)

Keywords: hydrogen, annual statistics, hydrogen production, energy policies, electrolysis

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Bridging the Generalization Gaps in Deep Learning-Based Crack Detection Through Structured Synthetic Variability

TADEJ PAVLIN, KLEMEN SREDENŠEK, ZDRAVKO PRAUNSEIS
University of Maribor, Faculty of Energy Technology, Krško, Slovenia
pavlin_tadej@yahoo.com, klemen.sredensek@um.si, zdravko.praunseis@um.si

Structural crack detection plays an important role in monitoring the condition of the infrastructure associated with energy production and distribution systems. In digitalized energy environments, artificial intelligence (AI)-based inspection tools are applied increasingly to support automated condition assessment and predictive maintenance. However, model performance often depends strongly on dataset-specific characteristics, and the variability in imaging conditions can limit the generalization robustness significantly (Wu et al., 2025).

This study presents a conceptual framework that addresses the generalization challenges in deep learning-based crack detection through structured synthetic variability. Drawing on the principles of domain randomization (Tremblay et al., 2018), the framework proposes controlled variation of the environmental and structural parameters during synthetic data generation in order to expand the effective training distribution. Rather than aiming for a photorealistic simulation, the approach emphasizes variability as a mechanism for improving robustness under a distribution shift.

The framework integrates three elements: (1) a documented dataset and environmental variability in crack detection research, (2) domain randomization as a methodological strategy for controlled distribution expansion, and (3) sim-to-real validation as a necessary evaluation step. Within the context of energy infrastructure digitalization, improving generalization robustness may support more reliable automated inspection systems, and contribute to long-term infrastructure resilience.

Keywords: crack detection, energy infrastructure, artificial intelligence, domain randomization, generalization robustness, digitalization

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The Role of EIA and SEA in the Spatial Integration of Renewable Energy Sources

KLEMEN KOTNIK
Faculty of Environmental Protection, Velenje, Slovenia
klemen.kotnik@fvo.si.

Environmental impact assessment (EIA) and strategic environmental assessment (SEA) are key instruments of environmental protection, grounded in both Slovenian and European environmental legislation, whose main purpose is to prevent and reduce the negative effects of planned interventions and planning decisions before their implementation. In this way, they contribute directly to the application of the precautionary principle and the principle of sustainable development. An EIA is generally related to specific projects or spatial interventions, and assesses their direct and indirect impacts on individual environmental components, including air, water, soil, climate, nature, landscape, human health, cultural heritage and biodiversity. An SEA, by contrast, operates at the strategic planning level, accompanying the preparation of spatial plans, development programmes, and other planning documents, and ensuring that environmental considerations are already incorporated in the early stages of decision-making.

In the context of integrating renewable energy sources into space, both procedures are of particular importance. Although renewable energy sources make a major contribution to the decarbonisation of the energy sector, their spatial implementation may also generate environmental and land-use conflicts related to land occupation, impacts on the landscape, biodiversity, water regimes and the quality of the living environment. The SEA therefore enables the strategic identification of more suitable areas for the development of renewable energy sources, while the EIA provides a detailed assessment of the acceptability of individual projects. An important component of both procedures is also public participation and the involvement of the relevant planning authorities, which strengthens the transparency, professional soundness and social legitimacy of the adopted decisions.

Keywords: environmental impact assessment, strategic environmental assessment, sustainable development, renewable energy sources, spatial planning

Sustainable Management of the Gradual Closure of the Velenje Coal Mine

IRENA PODGORŠEK, SIMON KLINC, JANEZ ROŠER
Velenje Coal Mine, Velenje, Slovenia
irena.podgorsek@rlv.si, simon.klinc@rlv.si, janez.roser@rlv.si

As part of the gradual coal phase-out at the Velenje Coal Mine (Premogovnik Velenje, PV), sustainability management is becoming both a requirement for regulatory compliance and a strategic tool for the systematic closure of the mine and for supporting the just transition of the SAŠA region. This paper presents a practical sustainability management framework tailored to a mining company in the closure phase, with particular emphasis on: (i) preparedness for the requirements of the CSRD and ESRS (EU Parliament and Council, 2022; European Commission, 2023), (ii) double materiality as a decision-support tool, and (iii) the management of environmental and social impacts throughout the entire closure period.

The proposed approach connects the historical impacts of mining with future transition objectives within a comprehensive ESG management framework. Its key elements include a double materiality matrix linking physical and transition risks with stakeholder impacts, a set of key performance indicators (KPIs) aligned with the ESRS Standards (climate, pollution, water, biodiversity, workforce, and communities), and a data governance model defining the responsibilities, control mechanisms, and procedures for the verification of sustainability data. Particular emphasis is placed on the operational environmental issues relevant to coal mining and mine closure, such as emissions management, water protection, land rehabilitation and reclamation, long-term monitoring, as well as social measures including workforce transition, reskilling, and engagement with the local community (Premogovnik Velenje, 2025a; Premogovnik Velenje, 2025b).

The paper emphasises that ESG systems must be designed to remain effective even after production has ceased, as they enable transparent reporting, verifiable monitoring of rehabilitation progress, and credible transition planning.

Keywords: Velenje coal mine, gradual mine closure, sustainability, ESG, CSRD/ESRS

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7[TH] INTERNATIONAL CONFERENCE ENRE-ENERGY & RESPONSIBILITY: BOOK OF EXTENDED ABSTRACTS

SEBASTIJAN SEME, KLEMEN SREDENŠEK (EDS.)
University of Maribor, Faculty of Energy, Velenje, Krško, Slovenia
Sebastijan.seme@um.si, Klemen.sredensek@um.si

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In a time of intensive energy transitions and climate challenges, the year 2035 is recognized as a key milestone for achieving climate neutrality and sustainable development goals. The EnRe – Energy & Responsibility conference focuses on the vision of the future of energy in Slovenia and beyond, the restructuring of coal regions, the development of hydrogen technologies, digitalization and cybersecurity in the energy sector, as well as the strengthening of energy communities and local initiatives. The event brings together researchers, experts, policymakers, and industry representatives who will present their contributions, projects, and strategies for a sustainable energy future. The conference will be held in the form of round tables, thematic sessions, and interactive discussions.

Keywords:
district heating,
energy transition,
renewable energy sources,
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sustainable development,
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