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Municipal Water Supply Pumping Station Energy Efficiency Improvement Using Batteries

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Abstract **-** Electrical power distribution networks are inherently susceptible to service interruptions, such as those caused by grid faults. Maintaining the operational continuity of critical infrastructure, particularly isolated water supply pumping stations, requires robust backup power solutions. Uninterruptible Power Supply (UPS) systems commonly utilize Battery Energy Storage Systems (BESS), which, in addition to providing backup power, can facilitate energy arbitrage to reduce electricity costs. This study examines the feasibility of commercially available BESS for ensuring the autonomous operation of a water pumping station equipped with a main electric motor pump drive rated at 330 kW. Using historical municipal water consumption data for the Cres-Lošinj archipelago, obtained from publicly available sources, simulations were conducted to model the operation of pumping stations with and without BESS integration during continuous operation. The resulting data provides a comprehensive analysis of potential energy savings, cost reductions, and estimated return on investment (ROI).

Index Terms - Battery, Water pumping station, Simulation, Energy savings, Return-on-investment

I Introduction

Maintaining a continuous and reliable supply of potable water is paramount for public health, sanitation, and fire suppression in any municipality [1-3]. Water distribution systems rely on electrically powered pumping stations, which are crucial for ensuring a stable supply. However, electrical grids are vulnerable to disruptions caused by extreme weather events, equipment failures, and cyberattacks, posing a significant threat to these facilities [4-6]. Consequently, ensuring the resilience of water pumping stations against power outages is a critical aspect of urban infrastructure planning and management.

Traditionally, diesel generators have been the predominant backup power solution for water pumping stations [7, 8]. While effective, they present several drawbacks, including high operating and maintenance costs, noise pollution, greenhouse gas emissions, and logistical challenges related to fuel storage and replenishment. Additionally, diesel fuel spills pose an environmental risk [9, 10]. Reliance on fossil fuels for backup power undermines efforts toward sustainable and environmentally friendly urban infrastructure.

In recent years, battery energy storage systems (BESS) have emerged as a promising alternative to conventional backup power solutions [11-14]. BESS offers several advantages over diesel generators, including rapid response times, improved energy efficiency, reduced environmental impact, and the potential for grid ancillary services [15-17]. However, the adoption of BESS in municipal water pumping stations has been relatively slow due to factors such as high initial investment costs, perceived complexity, and concerns about long-term performance and reliability [18, 19].

This study investigates the feasibility and benefits of integrating BESS into municipal water supply pumping stations to enhance energy efficiency and resilience. The study considers factors such as electricity pricing, water demand patterns, and battery performance characteristics. By using historical water consumption data within different simulation scenarios, the aim is to quantify the potential for energy cost savings, return on investment, and improved operational reliability.

The structure of this paper is described in the following way. Section 2 provides a comprehensive overview of the municipal water supply system, detailing its key components and analyzing historical water consumption patterns alongside the corresponding electricity pricing framework utilized in this study. Section 3 introduces the proposed BESS solution, specifically focusing on lithium-iron- phosphate (LiFePO4) technology. This section also elaborates on the parameterization of the BESS based on the manufacturer data and an established battery power versus state-of-charge (SoC) model from [20]. Additionally, a battery aging model is presented, which estimates the equivalent number of charge/discharge cycles to assess the long-term viability of the proposed BESS implementation. Section 4 discusses the control strategies employed for pump system operation, ensuring optimal water distribution efficiency. Section 5 presents simulation results across multiple operational scenarios, ranging from daily functionality assessments to a long-term analysis aimed at identifying electricity pricing conditions and battery system costs under which the ROI remains feasible over the anticipated 16-year lifespan of the BESS. The findings derived from these simulations are critically analyzed and discussed in section 5, while section 6 provides concluding remarks, acknowledges study limitations, and outlines potential avenues for future research.

II Municipal Water Supply System Description

The water supply system of the islands of Cres and Lošinj is managed by the Water Supply and Drainage Company, Cres Mali Lošinj d.o.o., owned by the cities of Cres and Mali Lošinj.

The system supplies potable water to most of the population, with some settlements and small islands relying on water tankers [21]. The primary freshwater source is the Vrana Lake (Fig. 1), with absolute depth of 74.5 meters, average water level of about 13 meters above sea level, and the deepest part of the lakebed lying about 61.5 meters below sea level.

Figure 1. Photograph of Vrana Lake crypto-depression.

A water pumping station is stationed on the Vrana Lake, which pumps water from the lake and transports it to the Vrana 1 and Vrana 2 water reservoirs (with capacities V_1 = 1000 m^3 and V_2 = 2500 m^3, respectively, and total capacity V_{tot} = 3500 m^3) at the altitude of 220 meters above sea level, with water inlet level being about 10 meters above sea level, as shown by the schematic representation of the water pumping system in Fig. 2. From these two water reservoirs water is brought by gravity to all settlements on the northern and southern branches of the water supply pipelines. The pumping station is equipped with 330 kW variable-speed drives (VSDs) for powering the water pumps, with one of these VSDs assumed to be in use during operation.

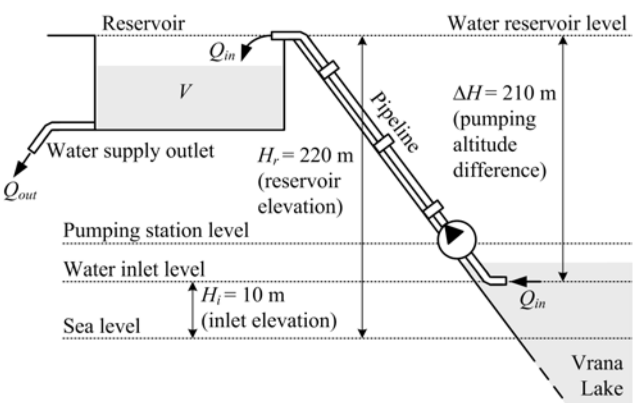

Figure 2. Schematic representation of water pumping system

Based on the schematic representation in Fig. 2, the reservoir filling (water accumulation) process model reads as follows:

$$dV/dt = \dot{V} = Q_{in} - Q_{out}, \quad (1)$$

where V is the reservoir water volume, and Q_{in} and Q_{out} are reservoir input and output water volume flow rates, respectively.

The pumping station input flow Q_{in} vs. pump power P_{pump} static relationship is determined based on the required flow rate for the altitude difference (pumping height) ΔH as follows:

$$Q_{in} = (\rho g \Delta H)^{-1} P_{pump} = K_{pump} P_{pump}, \quad (2)$$

where ρ is the water density (1000 kg/m^3), g = 9.81 m/s^2 is the free-fall acceleration due to gravity, while K_{pump} represents the proportionality factor between the flow rate and pump mechanical power supplied by the pump electrical drive (VSD).

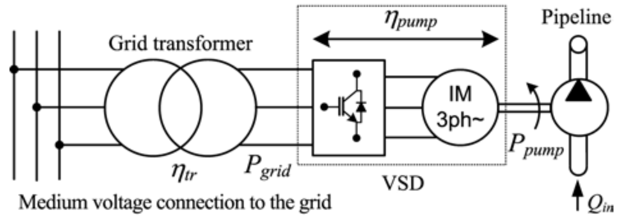

Figure 3. Pump electrical drive schematic representation.

Figure 3 shows the pump station electrical system connection with respect to the medium-voltage (11 kV) main grid and the connection of the pump electrical drive to the low-voltage 0.4 kV side. Based on the electrical system representation in Fig. 3, the relationship between the mechanical power of the pump electrical drive and the electrical power supply to the VSD is defined by the pump VSD efficiency η_{pump} as follows:

$$P_{pump} = \eta_{pump} P_{grid}, \quad (3)$$

which needs to account for the grid transformer efficiency η_{tr} to obtain the total power drawn from the medium-voltage grid P_{mv}:

$$P_{grid} = \eta_{tr} P_{mv}, \quad (4)$$

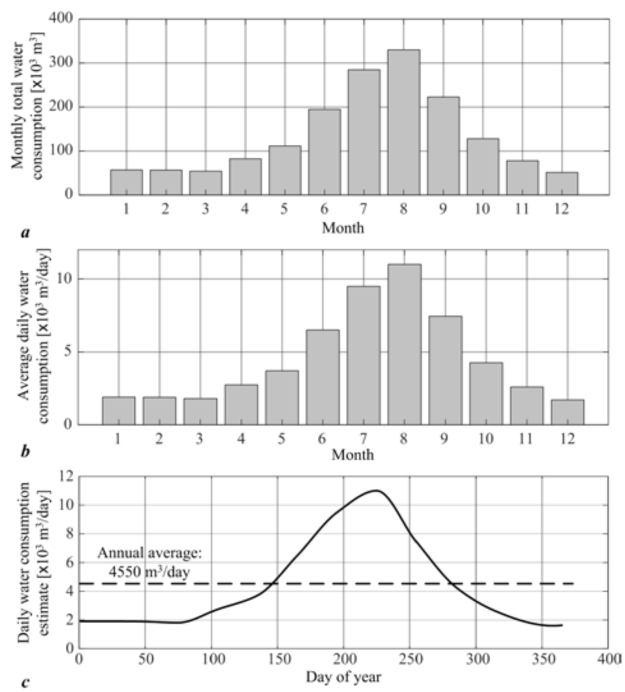

Figure 4. Cres-Lošinj water supply system aggregated monthly water consumption data (a), average daily consumption (b), and estimated daily water consumption throughout the year (c)

The aggregated water consumption data for the Cres-Lošinj water supply system from [22], representing the total water consumed per month for the year 2023, are shown in Fig. 4a. Based on the data in Fig. 3a, average daily water consumption data for each month are estimated as shown in Fig. 4b. Finally, by interpolating the data in Fig. 4b by means of cubic splines, the daily water consumption data for each day of the year is estimated, and the results are shown in Fig. 4c. These estimates are subsequently used for the analysis of the water supply system operation, including seasonal variability of water consumption.

On the other hand, municipal water consumption also exhibits daily fluctuations, initially increasing during the morning, and subsequently decreasing during the late afternoon and in the evening [23]. This daily variability of water consumption (flowrate) can be modeled by a simplified daily water consumption characteristic shown in Fig. 5. The characteristic is determined by only two parameters: average water flow rate Q_0, and the flowrate variation coefficient α_s (Fig. 5).

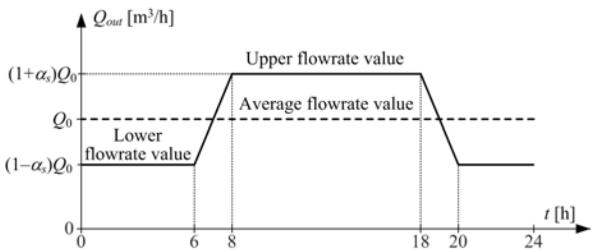

Figure 5. Model of daily water flowrate variations

III Battery Energy Storage System

A commercial 500 kWh BESS turnkey solution (Fig. 6) based on $LiFePO_4$ battery cell technology equipped with integrated grid inverter [24] is considered in this study due to the following inherent advantages:

- (i) *Compactness and portability* of a single BESS unit being encased in a standard 20 ft. (6 m) shipping container;
- (ii) *Integrated AC grid inverter* facilitating straightforward connection to the local three-phase 230V/400V AC grid;
- (iii) *Modularity*, i.e. easy augmentation of the BESS by simply connecting more than one containerized BESS system to the local AC grid;
- (iv) *Inherent operational safety* of the $LiFePO_4$ batteries, due to their wide operating temperature margins [25].

Figure 6. Considered $LiFePO_4$ BESS turnkey solution [24]

Since BESS manufacturer's technical data is not provided by the wholesaler (see [24]), the parameters of the BESS need to be determined using the existing experimental data for the standard 3.2V/100Ah $LiFePO_4$ battery cell [26], and upscaling the battery cell model to fit the declared energy storage capacity of the BESS turnkey solution from [24]. For that purpose, the battery cell is modeled by the so-called quasi-static Thevenin model, characterized by its open-circuit voltage and internal resistance:

$$u_{b,c} = U_{oc,c}(\xi_c) - i_{b,c}R_{s,c}(i_{b,c},\xi_c), \quad (5)$$

where $u_{b,c}$ is the battery cell terminal voltage, $U_{oc,c}$ is the cell open-circuit voltage (OCV), $R_{s,c}$ is the cell series resistance, $i_{b,c}$ is the battery cell current, with minus sign in the above equation denoting positive current direction ($i_{b,c}$ > 0) for discharging operation, and vice versa, and ξ_c is the cell state-of-charge (SoC):

$$\xi_c = -\frac{1}{Q_{b,c}}\int i_{b,c}dt, \quad (6)$$

where $Q_{b,c}$ is the battery cell charge capacity.

Figure 7 shows the static characteristics of the $LiFePO_4$ battery cell Thevenin model parameters with respect to cell state-of-charge, which have been previously recorded in [27]. While the Thevenin model parameters remain relatively constant-valued across a wide range of battery cell SoC, notable variations are observed at the extreme ends of the SoC range (i.e. when the cell is either deeply discharged or fully charged). The rather flat OCV vs. SoC characteristic and low internal resistance of the $LiFePO_4$ cell results in relatively small battery terminal voltage variations during its operation, which is beneficial from the standpoint of the integrated inverter voltage control with respect to the grid.

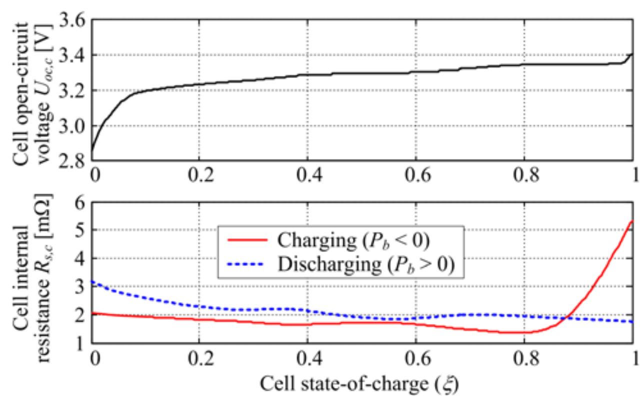

Figure 7. $LiFePO_4$ battery cell Thevenin model parameters [20]

Figure 8. shows the simplified BESS internal arrangement comprising of N_S series connections (stacks) of cells and N_P parallel branches, which is convenient from the standpoint of battery cell model up-scaling to the battery system level. The number of series-connected cells (series) stacks for the nominal cell voltage is given as follows:

$$N_S = \frac{U_{bn}}{U_{cn}}, \quad (7)$$

which yields N_S = 225 for the particular BESS with assumed nominal DC-link voltage U_{bn} = 720 V and the particular $LiFePO_4$ cell whose declared nominal voltage is U_{cn} = 3.2 V [26]

The number of parallel stacks is determined based on the single cell charge capacity, nominal battery voltage and energy storage capacity as follows:

$$N_P = \frac{W_{st}}{U_{bn}Q_{b,c}}, \quad (8)$$

which, after rounding, yields N_P = 7 parallel branches for the BESS with U_{bn} = 720 V, and individual cell charge capacity $Q_{b,c}$ = 100 Ah and overall energy storage capacity W_{st} = 500 kWh.

Using thus-obtained numbers of series stacks N_S and parallel branches N_P, the parameters of the $LiFePO_4$ battery cell Thevenin model are scaled up to the BESS level (Fig. 9) as follows:

$$U_{oc}(\xi) = N_S U_{oc,c}(\xi_c), \tag{9}$$

$$R_s(\xi) = \frac{N_S}{N_P} R_{s,c}(\xi_c), \tag{10}$$

$$Q_b = N_P Q_{b,c}, \tag{11}$$

wherein the BESS state-of-charge ξ is calculated according to the following first-order nonlinear model [20]:

$$\frac{d\xi}{dt} = \frac{\sqrt{U_{0c}^2(\xi) - 4R_s(\xi, P_b)P_b} - U_{oc}(\xi)}{2R_s(\xi, P_b)Q_b}. \tag{12}$$

where $P_b > 0$ represents the discharging power and vice versa.

Figure 9 shows the schematic representation of the pump electrical drive augmented with the BESS. In this configuration, BESS can be charged independently of the pump electrical drive operation, using grid electricity during lower electricity tariff intervals, and subsequently being used to supply the pump drive during lower electricity tariff intervals. Note that the utilization of BESS is also characterized by round-trip losses due to inherent losses within the battery (battery internal resistance losses), and the efficiency of the BESS inverter.

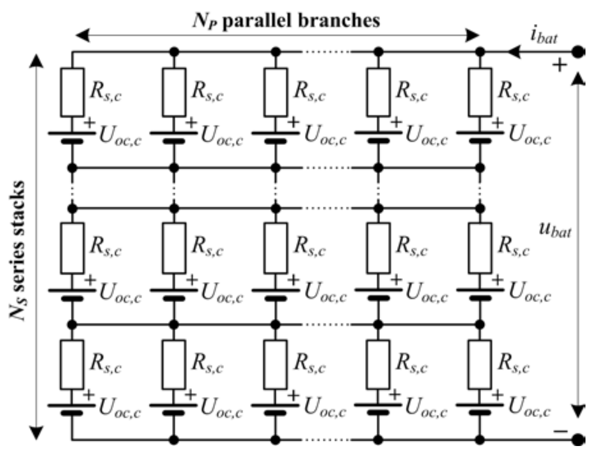

Figure 8. Simplified internal structure of $LiFePO_4$ battery, comprising N_S series stacks and N_P parallel branches

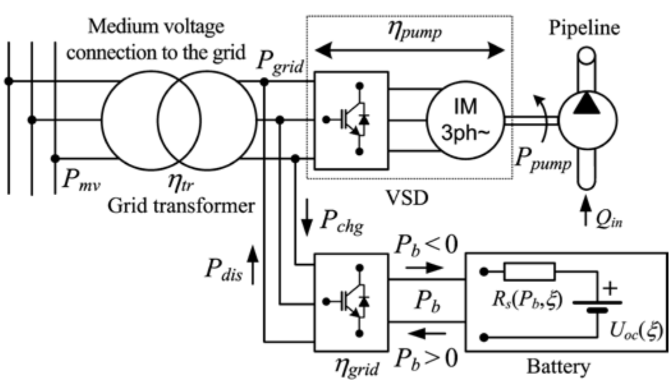

Figure 9. Schematic representation of pump electrical drive augmented with battery energy storage

Battery lifespan is also an important quantity because it determines whether return on investment (ROI) is feasible within the battery system lifetime. Assuming that the battery is fully charged and subsequently discharged to the specified depth-of-discharge (DoD) level (DoD = 80% is assumed herein) once every day, the considered battery, characterized by N_{cyc} = 6000 charge/discharge cycles [24] would be characterized by the lifespan of 16.43 years, which is rounded down to 16 years.

To quantify the BESS deterioration due to repeated charging and discharging cycles, battery state-of-health (SoH) is defined as follows [28]:

$$\mathrm{SoH} = 1 - \frac{\mathrm{DoD}}{2Q_b N_{cyc}} \int |i_b| dt, \tag{13}$$

which can be used to update the parameters of the BESS Thevenin model in the following way, thus signifying BESS series resistance increase and charge capacity decrease during the rather slow battery aging process:

$$R_s(\xi, \mathrm{SoH}) = R_s(\xi)(2 - \mathrm{SoH}), \tag{14}$$

$$Q_b(\mathrm{SOH}) = Q_b(0.8 + 0.2 \cdot \mathrm{SoH}). \tag{15}$$

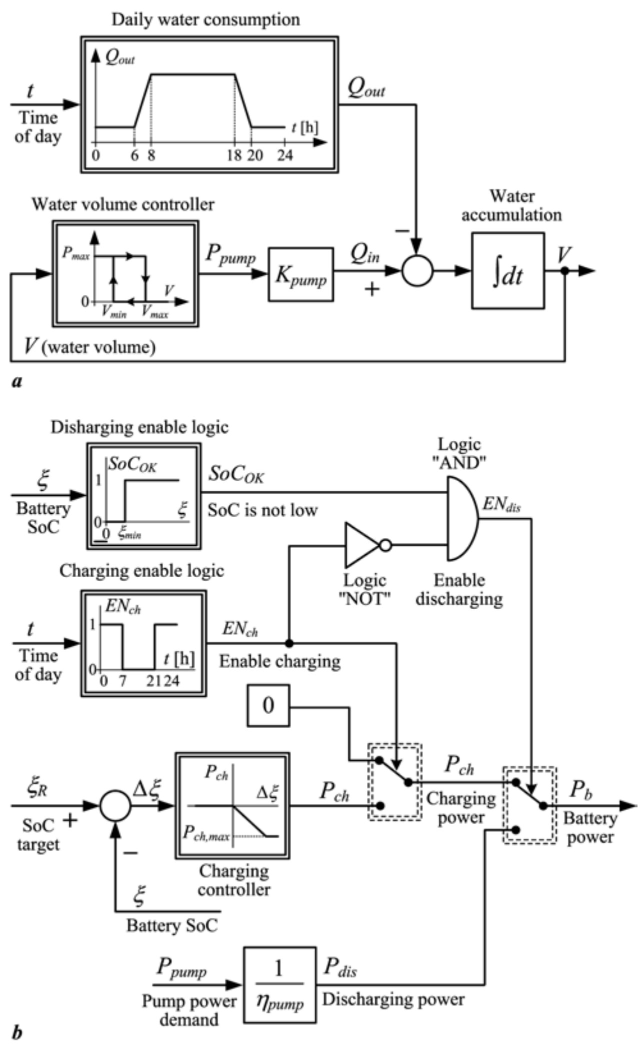

Figure 10. Schematic representations of water accumulation volume control system (a) and BESS charging and discharging control system (b)

IV Pump System Control Strategies

Figure 10 illustrates the control strategies of water accumulation volume control and the battery charging and discharging. The water accumulation volume V is controlled by a simple relay controller (Fig. 10a) which maintains the accumulated water volume between its maximum value (V_{max} = 0.95V_{tot}) and the minimum allowed water volume (V_{min} = 0.25V_{tot}). It turns on the main water pump and operates it at rated power (P_{max}) when the water volume falls below the lower threshold (V_{min}), with pumping being maintained until the water volume reaches the upper threshold (V_{max}). Figure 10b shows the control logic for the charging and discharging of the BESS, wherein battery charging is enabled only during the lower electricity tariff (which is set herein from 21h to 7h, Fig. 10b). Battery charging is based on a simplified proportional-type (P) SoC controller, whose characteristics and design have been adopted from [20]. Battery discharging is enabled when the battery SoC is above the lower SoC threshold ξ_{min} and during the higher electricity tariff (i.e. from 7h to 21h). In this way, load is shifted from the electricity grid to the battery, thus temporarily avoiding consumption of electrical power during higher tariff, at least until the battery SoC falls below the lower threshold ξ_{min}, after which grid electrical power needs to be used instead.

V Simulation Results

All simulations of the water pumping facility have been carried out for five characteristic scenarios that include operation without BESS, and operation with one, two, three and four 500 kWh BESS containers (that is, for 500 kWh, 1000 kWh, 1500 kWh and 2000 kWh storage capacity, respectively). Moreover, two characteristic cases have been considered in this study: (i) a single day of facility operation, and (ii) 16-year operation of the facility without and with BESS for energy price arbitrage, using the water consumption data from Figs. 4 and 5. Fixed efficiencies of the pump electrical drive and the grid inverter η_{pump} = 0.925 and η_{grid} = 0.95 have been used in all scenarios.

Figure 11 shows the simulation results for a single day of operation of the water pumping facility characterized by average water consumption rates (average output flowrates) of Q_0 = {150 m^3/h, 250 m^3/h, 350 m^3/h and 450 m^3/h} and flowrate variation factor α_s = 0.4 (see Fig. 5). All simulations have been run with water accumulation being near-full (i.e. at 95% of the maximum volume V_{max}). The results show that in all cases water accumulation is emptied faster during the daily (higher) tariff, which mandates the engagement of the BESS which provides power to the pumps and ensures pumping continuity until the BESS SoC reaches the lower threshold ξ_{min}. Once the battery is discharged to $\xi = \xi_{min}$, and high-tariff operation is still indicated, the power needs to be supplied from the utility grid. Obviously, higher water consumption rates tend to empty the water accumulation more quickly, and larger-capacity BESS tends to offset the grid power consumption during the high tariff operation for a longer period. However, even the highest-capacity BESS considered herein (2000 kWh) is unable to cover for the whole period of high-tariff operation, especially under increased water consumption conditions during the day hours (i.e. from 6h to 20h, see Fig 4c). Further increase in the BESS capacity (increase of the number of battery containers) could eventually resolve this issue, but it would also result in high initial investments (capital expenses, CapEx) and operational expenses (OpEx) of the BESS, as will be shown later.

Figures 12 and 13 show the results of simulations of the water pumping facility without and with BESS during the anticipated 16-year lifespan of the BESS [24], with the cumulative electricity cost calculated based on the fixed electricity costs during the higher and lower tariffs. According to [29, 30] the current total tariffs (including transmission and distribution costs) are valid for the commercial use in the Republic of Croatia for the case of medium voltage connection to the distribution grid:

- Higher tariff electricity cost C_{HT} = 0.166681 EUR/kWh.
- Lower tariff electricity cost C_{LT} = 0.096390 EUR/kWh.

Based on the results of energy consumption simulation analysis shown in Fig. 12a, the total electrical energy costs during 16-year operation have been estimated using the simple formula:

$$C_{tot} = C_{HT}E_{HT} + C_{LT}E_{LT}, \qquad (16)$$

where E_{HT} and E_{LT} are the pumping facility high-tariff and low-tariff electrical energy consumptions, respectively.

Based on thus-obtained total electricity cost, the electricity cost reduction in the case of BESS utilization is obtained by subtracting the total electricity cost in the case of BESS use from the electricity cost when BESS is not utilized:

$$\Delta C_E = C_{tot}(\text{w/o BESS}) - C_{tot}(\text{w/ BESS}). \qquad (17)$$

Figure 12 also shows that utilization of a BESS with higher storage capacity results in more substantial electricity cost reductions and vice versa, and the electricity cost reduction is proportional to the installed storage capacity of the BESS.

Figure 13 shows the simulation results of the battery SoH during the anticipated 16-year period of BESS operation. As expected, battery SoH deteriorates due to battery exploitation (according to equation (13)), because the battery is periodically charged and discharged during the facility operation. However, battery SoH at the end of the 16-year exploitation period is moderately lower compared to the initial SoH (by about 35%), which points out to under-utilization of the BESS under the considered scenario. More precisely, in the first 90 days and the last 30 days of a calendar year, the municipal water consumption is quite low (see Fig. 5), so it is expected that the water accumulation can be filled up to the maximum level during the lower tariff operation using electrical power from the grid, and it can supply the water demand without refilling during the day (consumption of about 2000 m^3/day is much less than the total water accumulation volume V_{tot} = 3500 m^3). In that case, BESS would be minimally utilized for water pumping during the daytime under the higher electricity tariffs. Consequently, the BESS would be under-utilized for about 1/3 of the year, which ultimately results in less SoH degradation. This also means that the battery could be used even beyond its estimated end-of-life date. However, such second-life usage of the BESS is beyond the scope of this work.

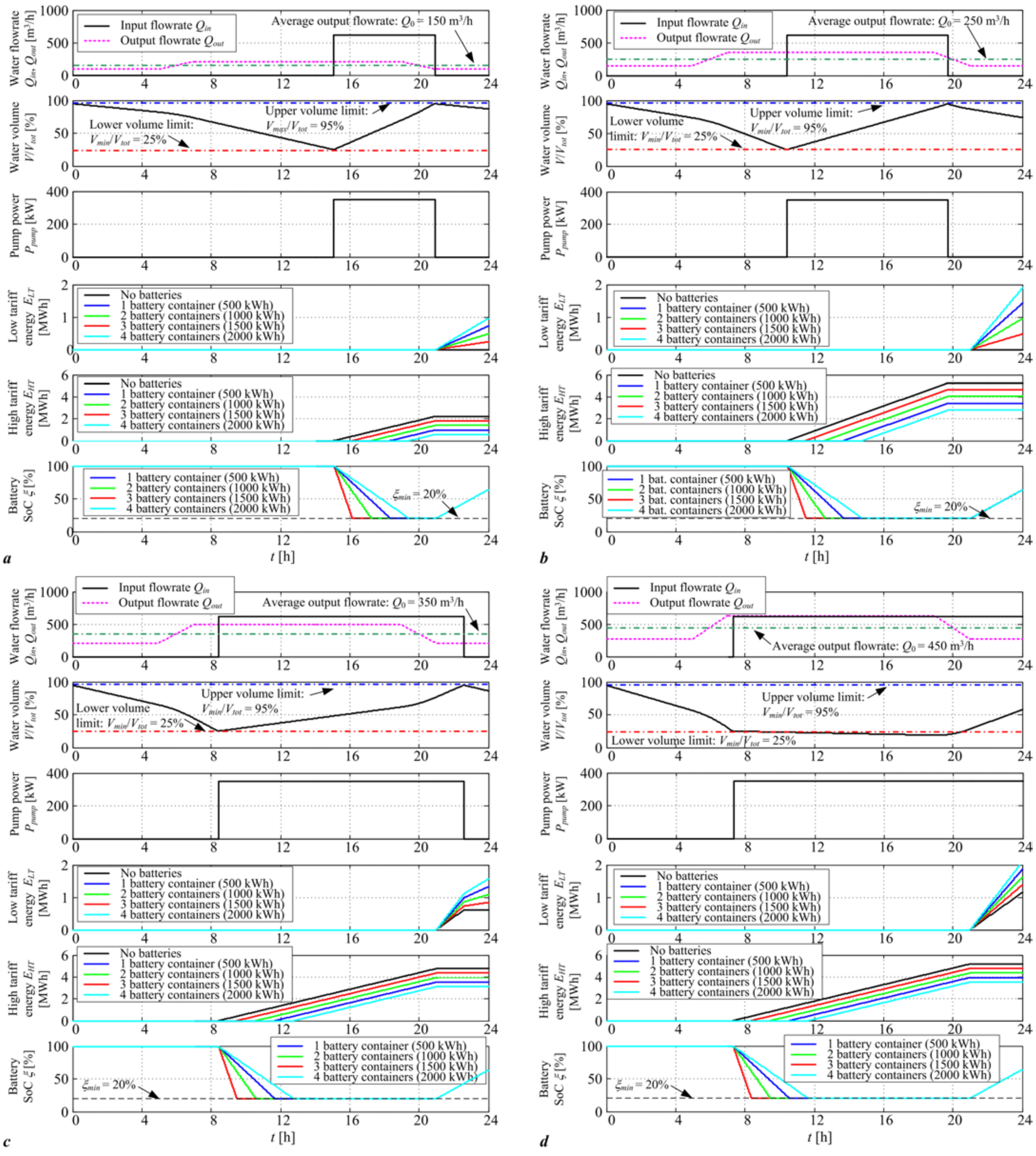

Figure 11. Results of simulations of single day water pumping facility operation without and with BESS for average water

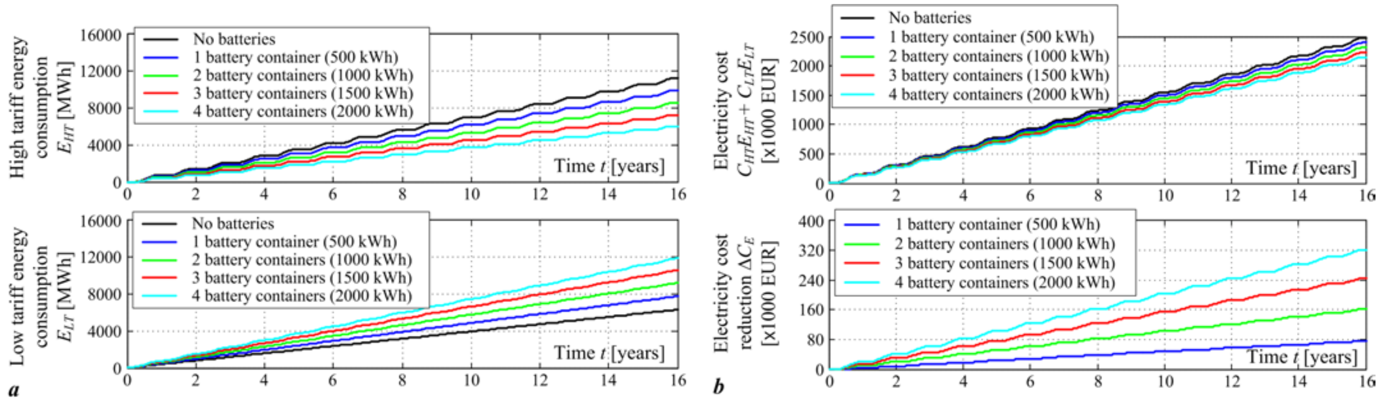

Figure 12. Results of water pumping facility energy consumption without and with BESS (a) and electricity costs and cost reductions for different BESS utilization scenarios (b)

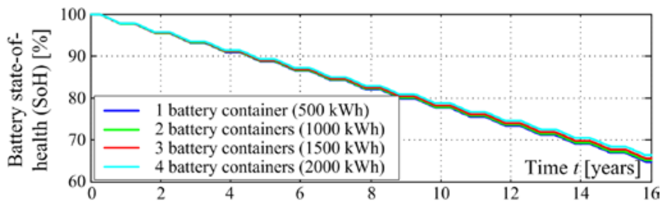

Figure 13. Battery state-of-health degradation for the 16-year BESS utilization scenario

Table 1. CapEx and OpEx for considered BESS configurations.

Number of containers	CapEx	OpEx (16 years)	Total cost of ownership
1	100000 EUR	40000 EUR	140000 EUR
2	200000 EUR	80000 EUR	280000 EUR
3	300000 EUR	120000 EUR	420000 EUR
4	400000 EUR	160000 EUR	560000 EUR

Finally, the estimated electricity reduction costs need to be leveraged against the BESS capital and operational expenses (CapEx and OpEx) using the available battery system cost data. According to [24], the wholesale cost of the grid-ready BESS in question is less than 80000 EUR per a single 500 kWh BESS. After adjusting this cost with respect to value-added tax (VAT) in Croatia (25% VAT rate applies herein), the overall cost of a single 500 kWh BESS container is estimated to 100000 EUR (it may also include shipping costs according to [24]), which represents the CapEx for a single-container 500 kWh BESS. This CapEx amounts to the specific cost of 200 EUR per kWh of energy storage, which agrees with the results presented in [31]. Annual operational costs for a commercial BESS are estimated at 2.5% of CapEx according to [31-33]. This results in the annual OpEx of 2500 EUR/year for a single 500 kWh BESS container, and the cumulative OpEx of 40000 EUR for the anticipated 16-year BESS exploitation period. Table 1 summarizes these results for the cases of one, two, three and four BESS considered herein. By comparing these results with the estimated electricity costs based on the BESS utilization and electricity tariffs (equations (16) and (17)), it is evident that under current tariffs none of the BESS configurations considered herein would break even at the end of the 16-year exploitation period considered herein. Therefore, additional analysis is carried out to find the range of high-tariff and low-tariff electricity costs and battery system costs, which would result in feasible return on investment period (ROI) that is less than the 16-year BESS exploitation period.

Figures 14 and 15 show the results of cost-benefit analysis for a wide range of higher and lower electricity tariff values and for three scenarios related to BESS costs, i.e. the nominal (current) BESS cost based on battery system prices obtained from [24] (Fig. 14), and for BESS costs reduced from nominal costs by 40% (Fig. 15). The latter scenario takes into account the realistic declining trend of battery storage system costs presented in [31-33], wherein 40% lower commercial and utility-scale battery system prices are anticipated in the next five to ten years. The results in Figs. 14 and 15 can be summarized as follows:

- For the nominal case of BESS purchase costs (Fig. 14), characterized by 100000 EUR per 500 kWh BESS container unit, it would only be possible to achieve ROI within very narrow high tariff vs. low tariff electricity cost margins. Namely, ROI periods between 10 and 16 years are theoretically achievable only if high tariffs are kept higher than the current rates (well above 0.16 EUR/kWh) while low electricity tariffs would be consistently below the current rates (i.e. well below 0.09 EUR/kWh). Consequently, the currently valid high-tariff and low-tariff electricity costs cannot yield ROI within the 16-year period for any of the considered BESS utilization scenarios (number of BESS units), as indicated earlier.
- In the case of 40% BESS cost reduction (Fig. 15), proportional reduction of both CapEx and OpEx, and ultimately lower total cost of ownership is achieved. Thus, the margin for achieving ROI within the 16-year BESS calendar life is significantly widened. Moreover, in that case even the current state of electricity tariffs can yield a ROI period of about 12 years. Since the margins for achieving ROI are now significantly widened, ROI periods may be as short as 6 years at the extremes of electrical energy costs (i.e. at 0.21 EUR/kWh for high tariff and 0.06 EUR/kWh for low tariff). However, it would be more realistic to estimate the ROI within the mid-ranges of electricity tariffs, which would yield ROI periods of about 10 years in that case.

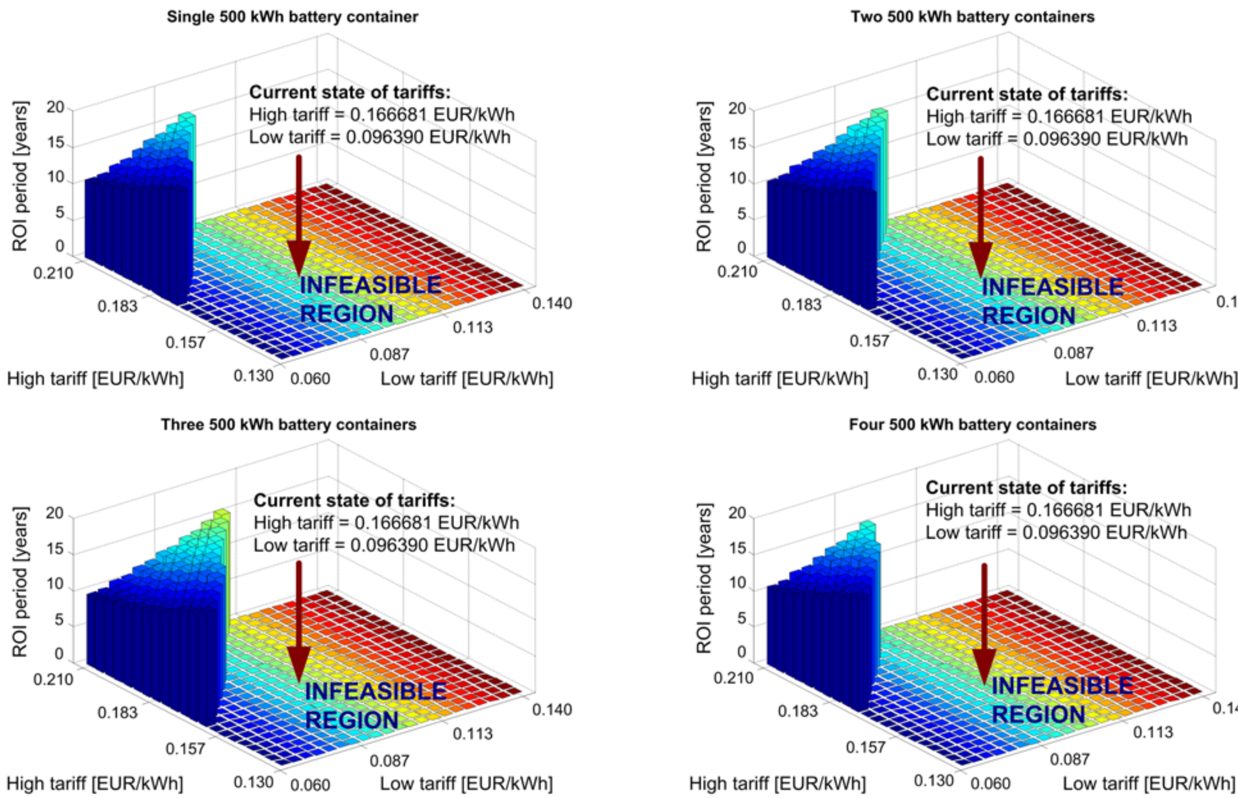

Figure 14. Results of estimation of ROI period for different BESS configurations (1-4 battery system containers) for nominal battery system container purchase cost of 100000 EUR per 500 kWh of battery energy storage (VAT included)

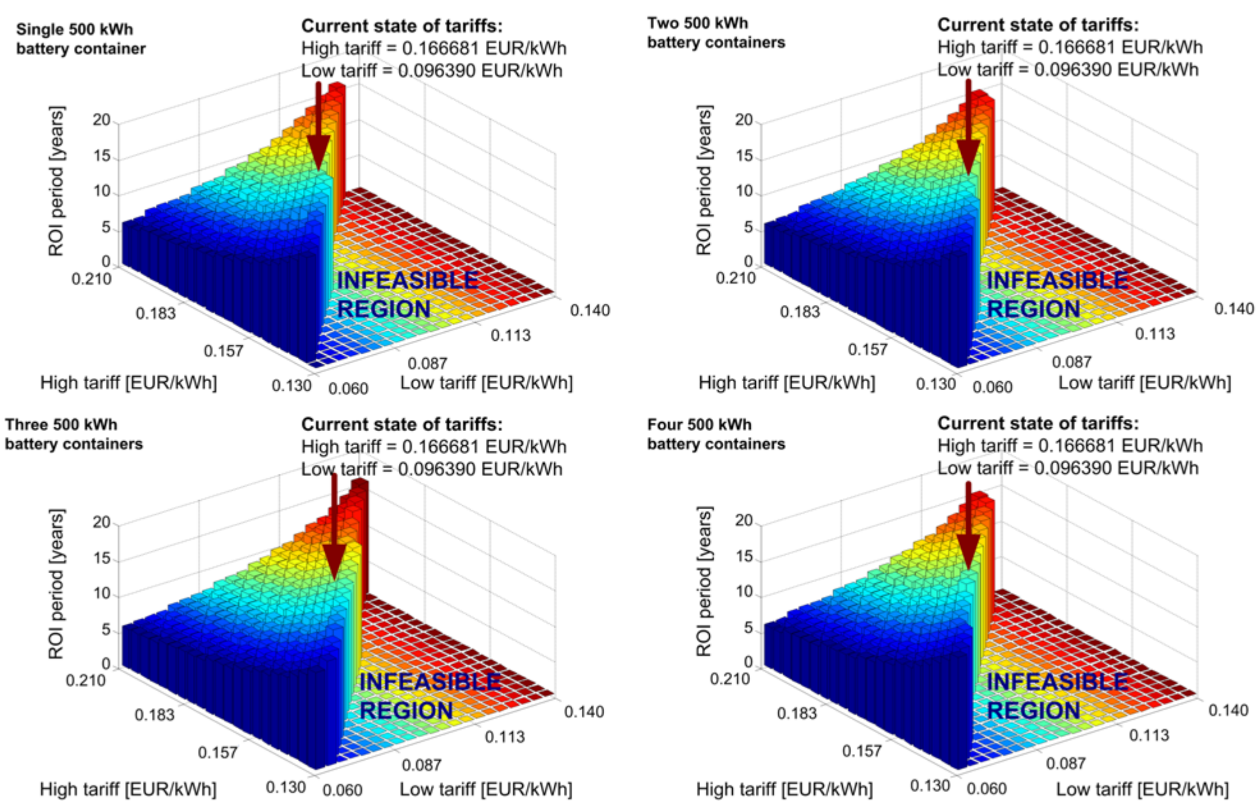

Figure 15. Results of estimation of ROI period for different BESS configurations (1-4 battery system containers) for reduced battery system container purchase cost of 60000 EUR per 500 kWh of battery energy storage (VAT included)

It should be noted herein that the above analysis is based on relatively simple electricity cost reduction vs. investment model, which does not account for electricity tariffs variability, effects of inflation, and various exigent costs such as those related to unscheduled maintenance and other unforeseen events. Even though these issues have not been addressed herein, they can be further researched in future work on this subject.

VI CONCLUSION

This paper has presented the analysis of a BESS integrated with a municipal water supply pumping station to improve its energy efficiency and reduce its electric energy costs. The analysis focused on utilizing BESS for energy arbitrage and shifting energy consumption from high-tariff to low-tariff periods while ensuring continuous operation of the water pumping station. The study specifically examined the potential benefits of BESS integration for a pumping station serving the Cres-Lošinj archipelago in Croatia.

In order to evaluate the effectiveness of BESS integration, a straightforward simulation model comprising only two state variables (accumulated water volume and battery SoC) has been developed, which also incorporates historical water consumption data for the Cres-Lošinj archipelago, electricity pricing schemes, and a $LiFePO_4$ battery model with realistic aging characteristics. The model simulated the operation of the pumping station under various scenarios, including different BESS capacities and electricity tariff structures. Such an approach allowed for a comprehensive assessment of energy savings, cost reductions, and return on investment (ROI) over the anticipated 16-year lifespan of the BESS.

The simulation results have pointed out that BESS integration can indeed lead to significant reductions in electricity costs by enabling energy arbitrage. However, the economic viability of BESS deployment is highly sensitive to factors such as BESS capital and operational expenses, electricity tariff structures, and battery degradation. Under current market conditions and electricity tariffs, the analysis showed that achieving a reasonable ROI within the BESS lifespan requires about 40% reduction in BESS costs. Alternatively, a significant increase in the difference between high and low electricity tariffs may also produce very favorable results in terms of ROI, but these electricity pricing schemes are unlikely to occur in the current electricity markets.

Future research will focus on expanding the proposed model to include variable electricity tariffs and effects of inflation, as well as the potential of integrating renewable energy sources, such as solar photovoltaic systems. Further research into BESS second-life applications may also be considered in the future work.

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Poboljšanje energetske efikasnosti primenom baterija za komunalnu pumpnu stanicu za vodosnabdevanje

Rezime - *Elektrodistributivne mreže su inherentno podložne prekidima usluga, kao što su kvarovi na mreži. Održavanje kontinuiteta rada kritične infrastrukture, posebno izolovanih pumpnih stanica za vodosnabdevanje, zahteva robusna rešenja za rezervno napajanje. Sistemi za besprekidno napajanje (UPS) obično koriste sisteme za skladištenje energije baterija (BESS), koji pored obezbeđivanja rezervnog napajanja mogu omogućiti arbitražu energije radi smanjenja troškova električne energije. Ova studija istražuje izvodljivost komercijalno dostupnog BESS-a za obezbeđivanje autonomnog rada pumpne stanice za vodu, opremljene glavnim elektromotornim pogonom pumpe snage 330 kW. Koristeći istorijske podatke o komunalnoj potrošnji vode za Cresko-Lošinjski arhipelag, dobijene iz javno dostupnih izvora, sprovedene su simulacije za modeliranje rada pumpnih stanica sa i bez BESS integracije tokom kontinuiranog rada. Dobijeni podaci pružaju sveobuhvatnu analizu potencijalnih ušteda energije, smanjenja troškova i procenjenog povraćaja investicije (ROI).*

Ključne reči - *baterija, pumpna stanica, simulacija, ušteda energije, povrat investicije*

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Modeliranje i analiza uticaja magnetnog zasićenja na elektromagnetnu silu u vibracionim aktuatorima

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Rezime **-** Elektromagnetni vibracioni aktuatori imaju ključnu ulogu kao pogonski elementi industrijskih vibracionih transportera, koji se koriste za transport zrnastih i rasutih materijala u različitim procesnim industrijama, uključujući prehrambeni, farmaceutski i poljoprivredni sektor. Elektromagnetna sila generisana u ovim aktuatorima značajno zavisi od magnetnih osobina jezgra aktuatora. Magnetno kolo aktuatora sastoji se od vazdušnog zazora i feromagnetnog jezgra, koje je obično sastavljeno od gvozdenih limova sa nelinearnom magnetskom permeabilnošću, koja je u direktnoj zavisnosti od pobudne struje. Ovaj rad analizira dva karakteristična slučaja vezana za generisanje elektromagnetne pobudne sile: (1) kada se razmatra samo vazdušni zazor u magnetnom kolu i (2) kada se uzima u obzir kompletno magnetno kolo, uključujući i materijal sa nelinearnom magnetskom permeabilnošću. Uticaj magnetske nelinearnosti na pobudnu silu estimiran je primenom metode konačnih elemenata (MKE) u softverskom paketu *Maxwell*. U završnom delu rada prikazani su i analizirani ključni rezultati kompjuterskih simulacija za oba razmatrana slučaja.

Ključne reči - Elektromagnet, aktuator, vibracioni transporter, MKE simulacije

I UVOD

Vibracioni transporteri predstavljaju sofisticirane uređaje koji koriste oscilatorne pokrete za efikasan transport materijala duž definisanih putanja u okviru određenog radnog okruženja. Ovi sistemi nalaze primenu u različitim industrijskim sektorima, uključujući prehrambenu industriju, farmaceutsku, hemijsku industriju, rudarstvo itd. [1]. Na primer na slici 1 je prikazano kako je kompanija *KMG Systems* rešila problem unutrašnjeg transporta materijala i precizno doziranje istog na izlazu [2]. Posebno su pogodni za prenos finih, sitnozrnih ili praškastih materijala, jer njihove vibracije omogućavaju kontinuiran i homogen protok bez zastoja. Koriste se za različite industrijske procese kao što su doziranje, sortiranje, razdvajanje, hlađenje i sušenje materijala. Zahvaljujući svojoj jednostavnoj konstrukciji, visokoj pouzdanosti i sposobnosti da precizno obavljaju kompleksne zadatke uz minimalno održavanje, ovi sistemi su neizostavni u savremenim industrijskim pogonima.

Osnovni element jednog takvog vibracionog transportera čini njegov aktuator, koji može biti mehaničke prirode, a u poslednje vreme sve češća su izvođenja aktuatora sa elektromagnetom. Mehanički aktuatori su zastupljeniji u teškim industrijama, gde nije potrebno fino doziranje, već su zahtevane velike sile, uglavnom zbog mlevenja ili preturanja materijala (uglja, šljunka, pepela, itd.).

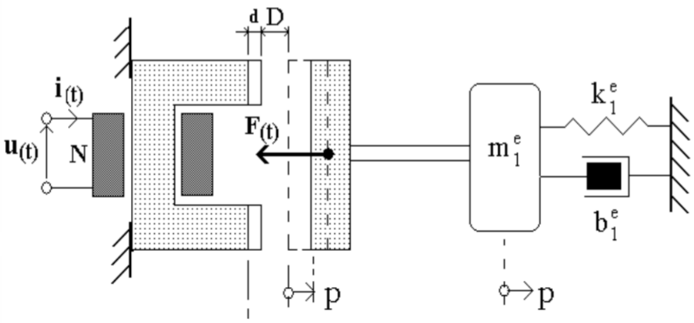
Slika 1. Primena vibracionih transportera u prehrambenoj industriji

II MOTIVACIJA I DEFINISANJE PROBLEMA

Elektromagnetni aktuatori imaju ključnu ulogu u funkcionisanju vibracionih transportera, jer generišu potrebne oscilacije za kretanje materijala. U poređenju sa mehaničkim aktuatorima, elektromagnetni aktuatori pružaju niz značajnih prednosti [3]:

- omogućavaju preciznu kontrolu frekvencije i amplitude vibracija, što rezultira većom preciznošću u transportu i obradi materijala,
- elektromagnetni aktuatori rade tiše i imaju smanjen nivo habanja, što produžava njihov radni vek i smanjuje troškove održavanja,
- njihova sposobnost brze reakcije na promene u opterećenju čini ih idealnim za dinamičke industrijske procese.

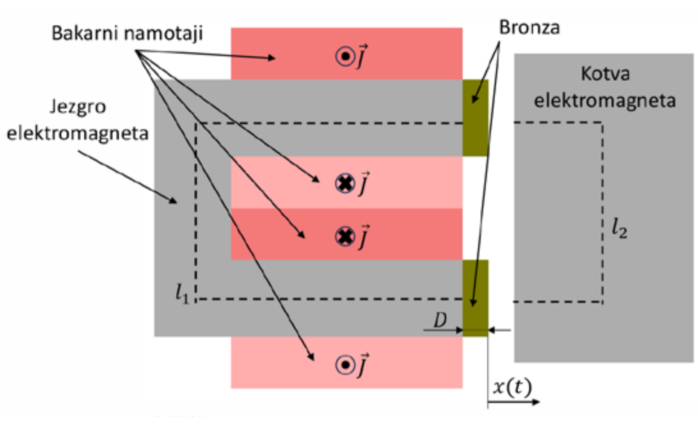
Elektromagnetna sila vibracionog aktuatora je u velikoj meri određena magnetnim svojstvima materijala od koga je sačinjen sam aktuator. Magnetno kolo vibracionog aktuatora se sastoji od vazdušnog procepa i ostatka kola koga čine gvozdeni limovi određene magnetne permeabilnosti, koja je nelinearna funkcija pobudne struje elektromagnetnog aktuatora. Na slici 2 prikazana je šema jednog elektromagnetnog aktuatora [4]. Namotaji su obmotani oko gvozdenih limova ukupno N puta i kroz njih protiče električna struja $i(t)$. Napon između krajeva provodnika $u(t)$ je takođe u funkciji vremena. Na jezgro elektromagneta je nalepljen nemagnetni materijal, da se ne bi zatvaralo magnetno kolo. Debljina bronze je definisana parametrom d, a početna vrednost zazora u magnetnom kolu je $2D$. Kotva je kruto vezana za vibraciono korito. U opštem slučaju, kompozitne elastične opruge su modelovane pomoću Kelvin-Voigtovog modela deformabilnog tela, s obzirom da su pomeraji elastičnih i viskoznih elemenata identični [5].



Slika 2. Šema elektromagnetnog vibracionog aktuatora sa mehaničkim opterećenjem

Tokom rada vibracionog transportera, odnosno elektromagnetnog vibracionog aktuatora, generiše se privlačna sila *F(t)*, koja je privlačnog karaktera. S obzirom da se većina magnetne energije nalazi unutar vazdušnog procepa, opšteprihvaćena je inženjerska praksa zanemarivanja dela konture magnetnog kola unutar magnetika. Drugim rečima, zanemaruje se uticaj magnetnog zasićenja u konačnom izrazu za elektromagnetnu silu *F*.

U ovom istraživanju izvršeno je modeliranje uticaja magnetnog zasićenja na pobudnu silu (*F*) za konkretan slučaj elektromagnetnog vibracionog aktuatora, slika 3. Magnetno kolo se sastoji od dva nelinearna magnetna materijala čije su srednje linije dužine l_1 i l_2, a magnetna indukcija je uneta u softver numerički pomoću krive magnetisanja koja je prikazana na slici 4. Oko magnetnog jezgra su obmotani bakarni namotaji, ukupno *N* puta i kroz njih protiče gustina električne struje *J*.



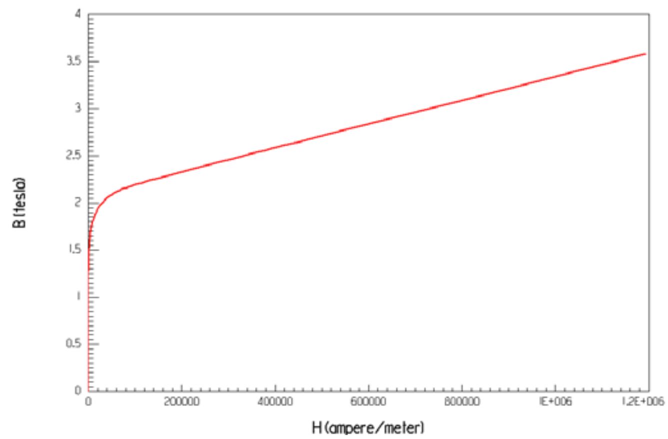
Slika 3. Model elektromagneta korišćen u okviru *Maxwell* softverskog paketa za MKE analize

Vazdušni procep, koji u posmatranom trenutku razdvaja kotvu od jezgra sa namotajima ima vrednost *D+x(t)*, pri čemu je *D* debljina bronzanog umetka, koji služi da spreči slepljivanje kotvu sa jezgrom elektromagneta. Poprečni presek bronzanog umetka i jezgra elektromagneta ima površinu jednaku *A*.

Kako je elektromagnetna sila u vazdušnom procepu data sa:

$$F = \frac{1}{2} B_0 \cdot H_0 \cdot 2A = \frac{H_0^2}{\mu_0} \cdot A \tag{1}$$

gde su B_0 intenzitet magnetne indukcije u vazdušnom procepu, H_0 intenzitet vektora jačine magnetnog polja i μ_0 magnetna permeabilnost vazduha. U daljem izlaganju posmatraće se da je prostor koji zauzima bronzini umetak ispunjen vazduhom, pa će i magnetna permeabilnost bronze u tom slučaju takođe iznositi μ_0. uticaj magnetnog zasićenja posmatraće se preko intenziteta vektora jačine magnetnog polja *H* unutar vazdušnog procepa.



Slika 4. Kriva magnetisanja za razmatrani magnetik

Polazeći od uopštenog Amperovog zakona $\oint H\,dl = \int J dS$ za konturu čiji je diferencijalni element dl sa vektorom jačine magnetnog polja *H*, koja opisuje površ *S* kroz koju protiče gustina električne struje data sa *J*, može se pisati sledeće:

$$2H_0\big(D + x(t)\big) + H_m(l_1 + l_2) = N \cdot i(t)$$

$$2\frac{B_0}{\mu_0}(D + x) + H_m(i, x) \cdot l_m = N \cdot i$$

$$B_0 = \frac{\mu_0[N \cdot i - H_m(i, x) \cdot l_m)]}{2(D + x)}$$

S obzirom da je pobudna sila u vazdušnom procepu data pomoću jednačine (1), dalje sledi:

$$F_0 = -\frac{\mu_0 A}{4(D + x)^2}[N \cdot i - H_m(i, x) \cdot l_m]^2$$

Nakon kvadriranja i zanemarivanja člana nižeg reda izraz za elektromagnetnu silu vibracionog aktuatora, prethodni izraz se svodi na:

$$F_0 = -\frac{\mu_0 A}{4(D+x)^2}[N^2 \cdot i^2 - 2H_m(i, x) \cdot l_m \cdot N \cdot i] \tag{2}$$

Zanemarivanjem drugog člana u zagradi u prethodnom izrazu, dobija se klasičan izraz za elektromagnetnu silu koji se koristi za proračun elektromagnetnih aktuatora u industriji:

$$F_0 = -\frac{\mu_0 A N^2 \cdot i^2}{4(D+x)^2} \tag{3}$$

Kako su promenjive veličine u datom sistemu pomeraj kotve $x(t)$ i vektor gustine električne struje $J(t) = N \cdot i(t)$, izvršene su MKE simulacije za različita moguća stanja sistema. U izrazu za elektromagnetnu silu pomeraj kotve ne figurše direktno na rezultat unutar zagrade, već se odražva preko intenziteta vektora jačine magnetnog polja u magnetiku, tj. $H_m(i, x)$. Ukoliko bi se ovaj problem rešavao grafičkom metodom nalaženjem radne tačke sistema, promena koordinate $x(t)$ odgovara promeni nagiba radne prave sistema. S obzirom da je ovaj uticaj mnogo manji od uticaja jačine struje, simulacije su vršene za konstantnu vrednost $\boldsymbol{x}$. Promena $i(t)$ odgovara paralelnom pomeraju radne prave na grafiku. Kako je promenjiva $i(t)$ periodičnog karaktera, uzima se njena najveća vrednost, tj. $I(t)$.

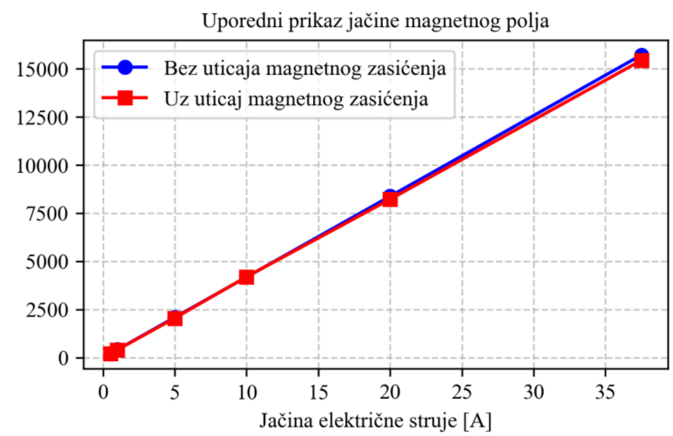
Uzevši u obzir da je u industrijskoj primeni intenzitet električne struje ide i do 37,5A [6], simulacije su izvršene za vrednosti električne struje od: 0,5, 1, 5, 10, 20 i 37,5A. Da se ne bi rad preterano opterećivao slikama, rezultati simulacije za krajnje slučajeve (0,5 A i 37,5 A) dati su pomoću slike iz simulacionog softvera i opisani u sledećem poglavlju, dok su rezultati svih dvanaest simulacija dati u okviru tabele 1. Dobijene vrednosti su maksimalne očitane vrednosti sa grafika u softverskom paketu za simulaciju elektromagetnih polja.

III MKE SIMULACIJE

MKE simulacije su izvršene pomoću softverskog paketa *Maxwell* za 2D analizu elektromagnetnih polja. Na slici 3. je prikazan presek elektromagneta u vertikalnoj ravni korišćen za potrebe simulacije. Nakon definisanja geometrije elektromagneta, neophodno je uneti i karakteristike materijala. Krivu magnetisanja je moguće uneti preko tabelarnih podataka u okviru *.txt* fajlova. Kako su od interesa vrednosti unutar vazdušnog procepa, gustina mreže (eng. "*mesh*") u tom delu data je gušće, dok je mreža elemenata najšira u delu koji predstavlja magnetik, odnosno u oblasti namotaja elektromagneta. Vektori gustine električne struje su uneti prema smerovima datim na slici 3. Olakšavajuća okolnost je što softver ima mogućnost unosa konačne vrednosti za jačinu električne struje po konačnoj površi provodnika, tj. kalema.

Ukupno je izvršeno dvanaest simulacija. U okviru prve grupe simulacija, za navedenih šest jačina električne struje, posmatran je isključivo uticaj magnetnog polja u vazdušnom procepu. Što se tiče simulacionog softvera, ovaj efekat je postignut zamenom stvarnih numeričkih vrednosti krive magnetisanja sa veoma visokim vrednostima. Matematički posmatrano, ovaj postupak identičan je izjednačavanjem sa nulom drugog sabirka u zagradi u okviru jednačine (2). Rezultati ovih šest simulacija dati su unutar druge kolone u okviru tabele 1.

Druga grupa simulacija predstavlja stvarnu vrednost vektora jačine magnetnog polja, gde je uzeto u obzir kompletno magnetno kolo, tj. srednja linija magnetnog jezgra, srednja linija kola kroz kotvu i dvostruka vrednost vazdušnog zazora. Vrednosti jačine magnetnog polja na ivicama magnetnog jezgra date su unutar treće kolone u okviru tabele 1. Može se uočiti blagi pad u odnosu na vrednosti iz druge kolone. Dodatno, izračunata je apsolutna razlika između ova dva slučaja, iako apsolutna razlika ima tendenciju rasta s porastom jačine električne struje, relativna razlika ostaje na približno identičnom nivou, ispod 2%. Radi preglednosti, uporedni prikaz maksimalnih jačina magnetnog polja dat je na slici broj 5. Može se uočiti linearna zavisnost intenziteta vektora jačine magnetnog polja od jačine električne struje koja protiče kroz namotaje. Sa porastom struje raste i apsolutna greška između ova dva slučaja, te postaje uočljiva na grafiku. Za veće vrednosti jačine električne struje, razlika između ova dva slučaja bila bi znatno veća, jer bi došlo do izraženijih posledica nelinearnosti krive magnetisanja date na slici 4. Sa grafika se može uočiti da već od 20 kA/m počinje opadanje intenziteta magnetne indukcije. Za te vrednosti neophodne su mnogo veće jačine električne struje koje se ne koriste u industriji za napajanje vibracionih elektromagnetnih aktuatora.



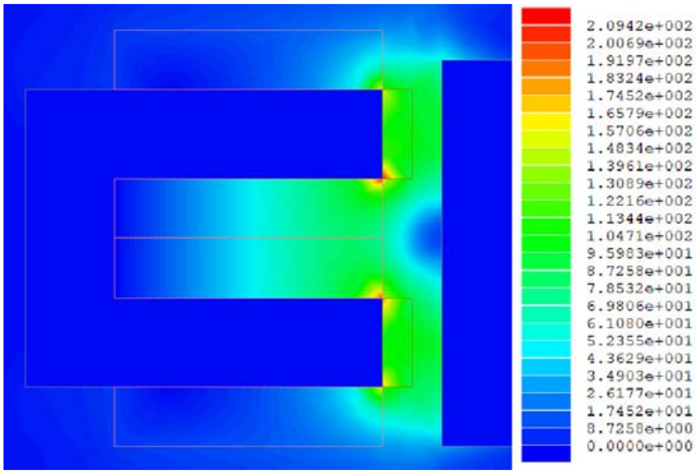
Slika 5. Uporedni prikaz maksimalnih jačina magnetnog polja

Na slici 6 je prikaz rezultata simulacije za slučaj jačine električne struje od 0,5 A pri čemu se uzima u obzir samo vazdušni procep. Desno od slike je data legenda jačine magnetne indukcije u A/m. Jasno je vidljivo da dolazi do velikog porasta intenziteta jačine magnetne indukcije na oštrim ivicama magnetnog jezgra. Maksimalna vrednost jačine magnetnog polja koja je dostignuta iznosi preko 200 A/m, dok je intenzitet jačine magnetnog polja unutar zazora znatno manja i iznosi oko 120 A/m. Takođe, usled

Tabela 1. Rezultati simulacije sa prikazanim apsolutnim i relativnim razlikama za odabrane jačine električnih struja

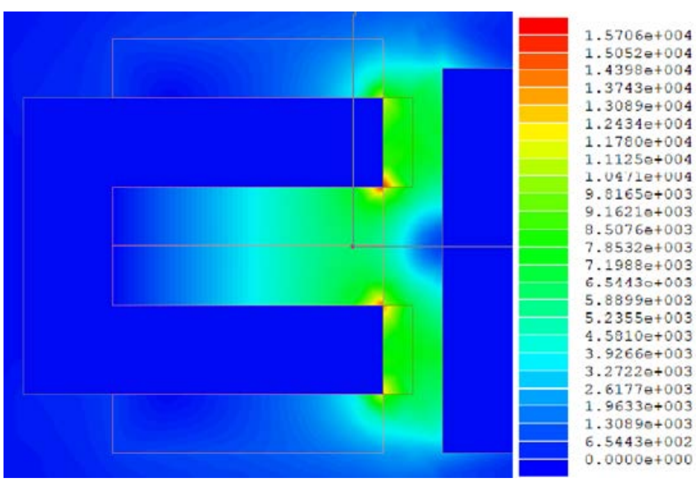
Jačina električne struje, I	Maksimalna jačina magnetnog polja		Apsolutna razlika [A/m] $\Delta = H_0 - H_M$	Relativna razlika [A/m] $\delta = \frac{H_0 - H_M}{H_0}$
	Bez uticaja magnetnog zasićenja, H_0 [A/m]	Uz uticaj magnetnog zasićenja, H_M[A/m]		
0,5 A	209,42	205,59	3,83	1,83%
1 A	418,84	411,19	7,65	1,83%
5 A	2.094,2	2.056	38,2	1,82%
10 A	4.188,4	4.199	69,4	1,66%
20 A	8.376,7	8.224	152,7	1,82%
37,5 A	15.706	15.429	286	1,82%

pojave rasipanja EM polja, na nekim mestima unutar bakarnog provodnika ostvaruje se jačina magnetnog polja i do čak 100 A/m.



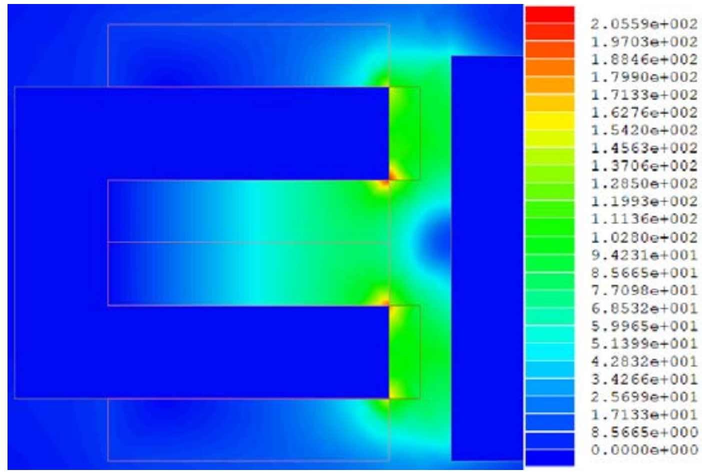
Slika 6. Rezultat MKE simulacije za jačinu struje od 0,5 A, pri čemu se uzima u obzir samo vazdušni procep

Na slici 7 je prikazan rezultat *Maxwell* simulacije za slučaj maksimalne jačine električne struje koja se nalazi u upotrebi u industriji. U pitanu je šesti slučaj iz tabele 1, tj. jačina struje od 37,5 A. Legenda sa jačinama magnetnog polja po rasteru MKE analize data je sa desne strane slike 6. Takođe, identično kao i u prethodnom slučaju, dolazi do porasta jačine magnetnog polja na ivicama magnetnog jezgra. Maksimalna vrednost jačine magnetnog polja u ovom slučaju iznosi čak preko 15,7 kA/m, dok je vrednost jačine magnetnog polja između magnetnog jezgra i kotve, tj. unutar vazdušnog procepa oko 9 kA/m. I u ovom slučaju ostvaruje se znatna vrednost jačine magnetnog polja unutar bakarnog provodnika i ona iznosi oko 7 kA/m, što je direktna posledica rasipanja elektromagnetnog polja.



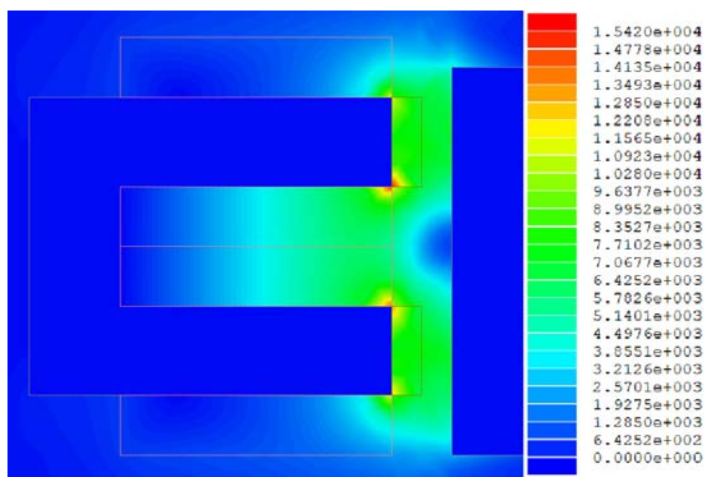
Slika 7. Rezultat MKE simulacije za jačinu struje od 37,5 A, pri čemu se uzima u obzir samo vazdušni procep

Na slici 8 je prikazana raspodela jačine magnetnog polja u prostoru oko elektromagneta, za jačinu struje od 0,5 A, pri čemu je uzet u obzir i magnetno zasićenje nelinearnog magnetika. Sa desne strane se nalazi legenda, gde su crvenom bojom označene maksimalne vrednosti intenziteta jačine magnetnog polja, koje se ostvaruju na ivicama magnetnog jezgra. Za ovaj slučaj maksimalna vrednost iznosi oko 205 A/m, što je neznatno manje u odnosu na slučaj prikazan na slici 5.



Slika 8. Rezultat MKE simulacije za jačinu električne struje od 0,5 A, gde je uzeto u obzir celo magnetno kolo

Poslednja simulacija je izvršena sa jačinom električne struje od 37,5A i uzeto je u obzir celo magnetno kolo, tj. i vazdušni procep i ostatak magnetnog kola (jezgro i kotva). Na slici 9 je prikazan rezultat pomenute simulacije. Maksimalna vrednost koju jačina magnetnog polja dostiže je, očekivano, na ivicama magnetnog jezgra i ona u ovom slučaju iznosi 15,42 kA/m, što jeste manje u odnosu na slučaj prikazan na slici 7.



Slika 9. Rezultati MKE simulacije za jačinu električne struje od 37,5 A, gde je uzeto u obzir celo magnetno kolo

V ZAKLJUČAK

Na osnovu izvedenih simulacija sledi da je posledica aproksimacije izraza za elektromagnetnu silu vibracionog aktuatora izostavljanjem uticaja magnetnog zasićenja odgovara relativnoj grešci ispod 2%. U zavisnosti od potreba i željenih rezultata, kao i povećanja brzine računanja, ovaj uticaj je moguće zanemariti za navedene slučajeve (x = 5mm; I = 0,5…37,5A). Sa prikazanih simulacija se može se uočiti da je najveća koncentracija gustine magnetne energije na oštrim ivicama magnetika. S obzirom da je tema rada uticaj magnetskog zasićenja, odnosno karakteristike materijala, sam oblik magnetika (tj. pojava šiljatih ivica) nije uzet u razmatranje. Slični zaključci važe i za pojavu rasipanja EM polja

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Modelling and Analysis of Magnetic Saturation Effects on the Electromagnetic Force in Vibratory Actuators

Abstract *– Electromagnetic vibration actuators play a crucial role as the drive elements of industrial vibration conveyors, which are used to transport granular and bulk materials in various process industries, including the food, pharmaceutical and agricultural sectors. The electromagnetic force generated in these actuators significantly depends on the magnetic properties of the actuator core. The magnetic circuit of the actuator consists of an air gap and a ferromagnetic core, which is usually composed of iron sheets with a non-linear magnetic permeability, which is directly dependent on the excitation current. This paper analyses two characteristic cases related to the generation of electromagnetic excitation force: (1) when considering only the air gap in the magnetic circuit and (2) when considering the complete magnetic circuit, including the material with nonlinear magnetic permeability. The influence of magnetic nonlinearity on the excitation force was estimated using the finite element method (FEM) in the Maxwell software package. In the final part of the paper, the key results of computer simulations for both considered cases are presented and analysed.*

Index terms *– Electromagnet, Actuator, Vibration transport, FEA simulations*

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UDK 620.9:33]:629.33

Tehno-ekonomska analiza rada elektroenergetskog sistema sa integracijom električnih vozila

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Rezime **-** Energetska tranzicija i povećana primena obnovljivih izvora energije u elektroenergetskim sistemima dovode do izazova u upravljanju mrežom. Jedan od značajnih faktora u ovom procesu je integracija električnih vozila (EV) i njihova mogućnost dvosmernog punjenja kroz *Vehicle-to-Grid* (V2G) tehnologiju, koja omogućava vraćanje energije iz baterija EV u mrežu. Ovaj rad analizira uticaj V2G tehnologije na stabilnost napona u distributivnoj mreži naponskog nivoa 35 kV, kao i njen ekonomski značaj za sistem. Pomoću PLEXOS i MATLAB softverskih paketa, modelovani su različiti scenariji punjenja i pražnjenja EV, uz solarne elektrane kao primarni obnovljivi izvor. Rezultati ukazuju na pozitivne efekte V2G tehnologije, uključujući poboljšanje naponskih prilika i smanjenje operativnih troškova. Ekonomska analiza pokazuje da V2G omogućava uštede potrošačima i smanjuje potrebu za konvencionalnim izvorima snabdevanja tokom vršnih opterećenja. Međutim, ubrzano trošenje baterija EV predstavlja značajan izazov, te se preporučuju dalja istraživanja radi unapređenja tehnologije i razvoja regulatornih okvira za široku primenu V2G u budućnosti.

Ključne reči - Energetska tranzicija, Električna vozila, Naponska stabilnost, Ekonomska analiza

I UVOD

Energetska tranzicija, usmerena na održiviju i ekološki prihvatljiviju budućnost, stavlja obnovljive izvore energije u centar savremenih elektroenergetskih sistema. Njihova primena doprinosi smanjenju emisije štetnih gasova, smanjuje zavisnost od fosilnih goriva i ublažava klimatske promene [1]. Ipak, integracija obnovljivih izvora u postojeće elektroenergetske mreže predstavlja značajne tehničke i ekonomske izazove [1].

Transformacija energetskog sektora podstiče upotrebu distribuiranih izvora energije, kao što su solarni paneli i vetroelektrane. Ovi izvori se najčešće priključuju na srednjenaponsku i niskonaponsku mrežu, unoseći dvosmerni tok snage koji utiče na naponske prilike, kvalitet energije i rad relejne zaštite u mreži [1]. U cilju stabilnosti mreže, planiranje distributivnog sistema mora da obezbedi da napon ostane u dozvoljenim granicama i da se kontrolišu naponske oscilacije usled varijabilnosti obnovljivih izvora [2].

Pored obnovljivih izvora, električna vozila dobijaju sve važniju ulogu u globalnoj energetskoj tranziciji. Prema podacima iz 2023. godine, na globalnom nivou je registrovano više od 40 miliona električnih vozila, što je porast od 54% u odnosu na prethodnu godinu [3]. Masovno usvajanje električnih vozila smanjuje emisiju CO_2 u transportu, ali zahteva razvoj infrastrukture i utiče na distributivne mreže [4]. Pravilno integrisana, ova vozila mogu biti značajan fleksibilni resurs za skladištenje energije i balansiranje mreže, posebno kroz koncept *Vehicle-to-Grid* (V2G) tehnologije [5].

Električna vozila se dele na baterijska (BEV), hibridna (HEV) i plug-in hibridna vozila (PHEV), sa značajnim rastom broja ovih vozila na globalnom nivou. Punjači se deče na tri nivoa: Nivo 1 (kućni punjači), Nivo 2 (brži punjači u javnim i poslovnim objektima) i Nivo 3 ili DC brzo punjenje. Ova infrastruktura je ključna za postizanje klimatskih ciljeva i omogućava pametno punjenje i V2G tehnologiju, koja doprinosi stabilizaciji mreže i podršci za obnovljive izvore energije [5]. Razvoj infrastrukture za punjenje električnih vozila je ključan za dalje širenje upotrebe električnih vozila. Prema Evropskoj komisiji, za postizanje klimatskih ciljeva do 2025. godine biće potrebno oko milion javnih punjačkih stanica u Evropi [6].

V2G omogućava dvosmerni protok energije između električnih vozila i mreže, čime vozila mogu doprineti balansiranju mreže u vršnim periodima. Prednosti V2G uključuju smanjenje zavisnosti od fosilnih goriva, finansijske koristi za vlasnike vozila i podršku stabilnosti mreže u uslovima povećane upotrebe obnovljivih izvora. Međutim, izazovi uključuju visoke troškove dvosmernih punjača, potencijalno smanjenje trajanja baterija i potrebu za jasnim regulatornim okvirom [5].

Softverski paket PLEXOS omogućava simulaciju i optimizaciju rada energetskih sistema na različitim vremenskim horizontima, od dugoročnog planiranja do kratkoročnih operacija. On integriše podatke, simulira realne uslove i procenjuje efekte različitih faktora na energetski sistem. Ovakve simulacije omogućavaju efikasnije upravljanje resursima i optimalno planiranje sistema [7].

II METODOLOGIJA

U pogledu uticaja na naponske prilike, ukoliko se posmatra distributivni vod nazivnog napona U_n, napon na mestu priključenja u jednom vremenskom intervalu, distribuiranog izvora (U), aktivne i reaktivne snage P_D i Q_D, iznosi:

$$U = \sqrt{U_{Re}^2 + U_{Im}^2}, \tag{1}$$

gde su U_{Re} i U_{Im} realna i imaginarna komponenta napona U, definisane sledećim jednačinama:

$$U_{Re} = A \pm \sqrt{A^2 - B - \left(R_V \cdot (P_P - P_D) + X_V \cdot (Q_P - Q_D)\right)} \quad (2)$$

$$A = \frac{U_1}{2}, \qquad B = \frac{\left(X_V \cdot (P_P - P_D) - R_V \cdot (Q_P - Q_D)\right)^2}{U_1^2},$$

$$U_{Im} = \frac{(X_V \cdot (P_P - P_D) - R_V \cdot (Q_P - Q_D))}{U_1} \quad (3)$$

u kojima su X_V i R_V reaktansa i rezistansa posmatranog distributivnog voda.

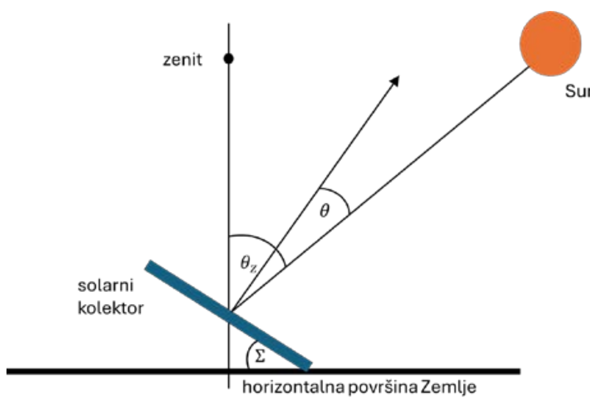
Iradijansa je gustina snage sunčevog zračenja po površini objekta u Zemljinoj atmosferi koji se posmatra. Maksimalna vrednost iradijanse na površi Zemlje postiže se pri čistoj atmosferi i vedrom danu i iznosi 1.000 W/m^2 [8]. Deli se na direktno i difuzno zračenje. Direktno zračenje je najveće pri vedrom danu i čistoj atmosferi i podrazumeva zračenje koje dolazi do tla direktno u liniji sa Suncem. Difuzno zračenje se javlja kao posledica rasejanja zračenja u atmosferi i najveće je kada je mutnost atmosfere najveća.

Ukupna iradijacija na solarni kolektor (I_C) je zbir direktne (I_{BC}), difuzne (I_{DC}) i reflektovane (I_{RC}) komponente zračenja. Reflektovana komponenta zračenja je posledica refleksije od horizontalne površine tla i najveća je u zimskom periodu [8].

$$I_C = I_{BC} + I_{DC} + I_{RC}. \quad (4)$$

Zenit je tačka na nebu neposredno iznad posmatrane površine, a zenitni ugao θ_z je ugao između prave koja povezuje zenit i posmatranu površinu i prave koja povezuje posmatranu površinu i Sunce. Incidentni ugao θ je ugao između normalne na solarni kolektor i Sunca, dok se nagib solarnog kolektora u odnosu na horizontalnu površinu tla često označava sa Σ. Na Slici 1 je dat prikaz solarnog kolektora pod nagibom sa relevantnim uglovima i može se uočiti da važi:

$$\theta = \theta_z - \Sigma. \quad (5)$$



Slika 1. Prikaz relevantnih uglova za proračun incidentnog ugla

Direktna iradijansa na solarni kolektor iznosi [8]:

$$I_{BC} = I_B \cdot \cos\theta. \quad (6)$$

Difuzna komponenta iradijanse na površinu kolektora iznosi [7]:

$$I_{DC} = I_{DH} \cdot \frac{3 + \cos 2\Sigma}{4}, \quad (7)$$

gde je I_{DH} difuzna horizontalna iradijansa.

Reflektovana komponenta iradijanse određuje se na osnovu jednačine [8]:

$$I_{RC} = \rho \cdot (I_{BH} + I_{DH}) \cdot \frac{1 - \cos 2\Sigma}{4}, \quad (8)$$

gde je $I_{BH} = I_B \cdot \cos\theta_z$ direktna horizontalna iradijansa, a ρ je koeficijent refleksije tla (površinski albedo).

Takođe, za solarni panel vezan na mrežu važi [8]:

$$t_{cell} = t + \frac{NOCT - 20\,°\mathrm{C}}{0{,}8} \cdot I_C, \quad (9)$$

$$P_{DC} = n \cdot \eta \cdot P_{DC,STC} \cdot \left(1 + \alpha_P \cdot (t_{cell} - 25\,°\mathrm{C})\right), \quad (10)$$

$$P_{AC} = P_{DC} \cdot \eta_{inv} \cdot (1 - \eta_s) \cdot (1 - \eta_m), \quad (11)$$

gde su t_{cell} – temperatura ćelije pri datim atmosferskim uslovima [°C], P_{DC} – izlazna DC snaga solarnog modula [W], P_{AC} – izlazna AC snaga solarnog modula [W].

Optimizacija je postupak pronalaženja najboljeg rešenja u datim uslovima, pri čemu se vrednosti upravljačkih promenljivih određuju tako da se optimizuje određena objektivna funkcija, uz zadovoljavanje ograničenja. U zavisnosti od prirode promenljivih i objektivne funkcije, optimizacija može biti linearna, nelinearna, sa kontinualnim ili diskretnim promenljivama. U okviru optimizacije, mešovito celobrojno programiranje (MCP) je metoda koja obuhvata diskretne i kontinualne promenljive, omogućavajući rešavanje kompleksnih problema koji uključuju binarne i celobrojne odluke, poput odluke o instalaciji novih resursa [9].

MCP se najčešće rešava *branch-and-bound* metodom, koja deli problem na manje podprobleme kroz razgranavanje na integralne i relaksirane promenljive [10]. Ovaj algoritam stvara stablo razgranavanja, gde se podproblemi rešavaju rekurzivno do pronalaženja optimalnog rešenja. U svakom čvoru stabla, problem se relaksira na LP (linearno programiranje) da bi se dobile granice rešenja. Ova metoda podržava i heurističke pristupe i napredne tehnike za optimizaciju izbora promenljivih i detekciju simetrije u stablu, čime se ubrzava proces [11].

U ovom radu za optimizaciju rasporeda punjenja i pražnjenja električnih vozila korišćen je Gurobi optimizator, koji je uključen u softverski paket PLEXOS. Gurobi optimizator je jedan od vodećih rešavača za složene MCP probleme, sa primenom u raznim industrijama, uključujući energetiku i finansije. On koristi multijezgarne procesore i paralelnu obradu za brže rešavanje velikih problema [12]. Gurobi podržava različite tipove optimizacije, uključujući linearno programiranje, MCP, kvadratno programiranje i stohastičko programiranje, čime je izuzetno fleksibilan i pouzdan za primenu u kritičnim zadacima kao što je planiranje proizvodnje ili optimizacija lanaca snabdevanja [11].

Analizirani elektroenergetski sistem je distributivna mreža naponskog nivoa 35 kV, prikazana na Slici 2. Ekvivalentni vod koji povezuje distributivnu mrežu i konzum ima reaktansu od 10,3 Ω i rezistansu od 4,16 Ω.

Definisano je četiri scenarija:

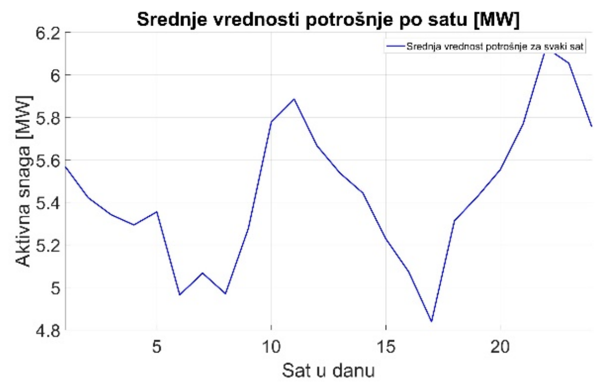
- „GODINA“: Godišnji model sa satnim intervalima bez V2G.
- „GODINA V2G“: Godišnji model sa satnim intervalima sa V2G.
- „DAN“: Dnevni model sa petnaestominutnim intervalima bez V2G.
- „DAN V2G“: Dnevni model sa petnaestominutnim intervalima sa V2G.

Za analizu naponskih prilika izabran je dan sa najvećom naponskom razlikom.

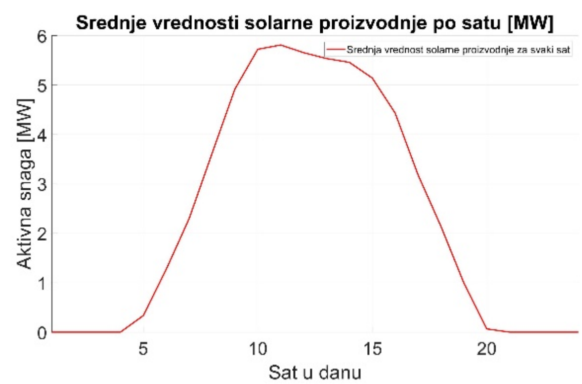
Pretpostavlja se da potrošački konzum čine pretežno domaćinstva sa konstantnim faktorom snage $\cos\varphi = 0{,}98$. Profil aktivne potrošnje na petnaestominutnim intervalima za jednu godinu za 1000 domaćinstava preuzet je iz [13]. Tarifni sistem ovih domaćinstava se deli na: nižu tarifu – u periodu od 00.00 do 09.30 časova i od 21.45 do 00.00 časova svakog dana i višu tarifu – u periodu od 9.45 do 21.30 časova svakog dana. U skladu sa podacima, pretpostavljene su: niža tarifa od 4,5 RSD/kWh, koja važi od 22.00 do 00.00 i od 00.00 do 9.00 časova svakog dana, i viša tarifa od 13 RSD/kWh, koja važi od 09.00 do 22.00 časova svakog dana. Ovi profili su sumirani za svaki interval na godišnjem nivou, zatim je tako dobijen profil skaliran (prema maksimalnom vršnom opterećenju) tako da napon u tački priključenja konzuma ostane u granicama ispod $1{,}05\ r.j.$ Maksimalna vršna aktivna snaga domaćinstava dobija se korišćenjem formula (1), (2) i (3), gde su $P_D = 0$ i $Q_D = 0$. Tako odabrana vršna aktivna snaga potrošača iznosi 8,828 MW.

Konzum se napaja i iz distribuiranih solarnih panela. Uz pretpostavku da se potrošačko područje ne prostire na dovoljno velikoj površini da postoje značajne razlike u insolaciji na pojedinačnim solarnim panelima na krovovima domaćinstava, usvojeno je pojednostavljenje da se proizvodnja solarnih panela može modelovati kao solarna elektrana sa istom tačkom priključenja na mrežu kao i sumirana potrošnja domaćinstava. Uvedene su sledeće pretpostavke o solarnom panelu: koristi se jedan inverter na dva solarna panela ($n = 2$), u skladu sa pretpostavkom da se solarni paneli nalaze na krovovima domaćinstava; nagib panela (Σ) jednak je uglu geografske širine (44,81 °, u skladu sa lokacijom merenja preuzetih podataka); panel je orijentisan ka jugu i fiksiran je; panel je snage $P_{DC,STC} = 1.000$ W pri standardnim uslovima ispitivanja (STC – eng. *Standard Test Conditions*); efikasnost panela je $\eta = 20\%$, pri temperaturnom koeficijentu od $\alpha_P = 0{,}4\ \%/°\mathrm{C}$; efikasnost invertora je $\eta_{inv} = 97\%$, koeficijent zaprljanja iznosi $\eta_s = 3\%$, a koeficijent neuparenosti je $\eta_m = 3\%$.

Godišnji profil proizvodnje solarne elektrane izračunat je na osnovu podataka o vremenu dobijenih iz [14] koji sadrže podatke (na petnaestominutnim intervalima) za 18 godina, od 2005. godine do 2022. godine, za područje Beograda. Podaci koji su korišćeni za izradu ovog rada su: datum i vreme, direktna normalna iradijacija (I_B [W/m^2]), horizontalna difuzna iradijacija (I_{DH} [W/m^2]), solarni zenitni ugao (θ_z [°]), površinski albedo (ρ) i temperatura ambijenta (t [°C]). Podaci su prvo usrednjeni za sve intervale u godinu dana. Ovi podaci su obrađeni u skladu sa jednačinama (4) do (8) redom na svakom intervalu na nivou od godinu dana, čime je dobijena ukupna iradijansa na solarni modul I_C [W/m^2]. Zatim su primenjene jednačine (9) do (11). Ovako dobijene vrednosti izlazne snage modula za date vremenske uslove su zatim skalirane, u odnosnu na godišnju maksimalnu vršnu izlaznu snagu, tako da odgovaraju maksimalno dozvoljenoj vrednosti, a da napon na priključcima ne opadne ispod granice od $0{,}95\ r.j.$ Maksimalna vršna snaga solarne elektrane dobija se korišćenjem formula (1), (2) i (3) za svaki sat u godini, gde su P_P i Q_P vrednosti dobijene za aktivnu i reaktivnu snagu konzuma. Tako izračunata maksimalna snaga solarne elektrane iznosi 23,022 MW.



Slika 2. Srednja satna potrošnja konzuma na nivou godine



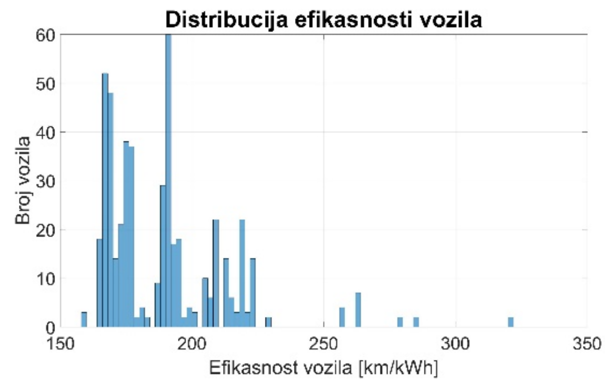
Slika 3. Srednja satna potencijalna proizvodnja solarne elektrane na nivou godine

Na Slici 3 dati su dobijeni profili potrošnje konzuma, a na Slici 4 potencijalne proizvodnje solarne elektrane za godinu dana usrednjeni na satnom nivou.

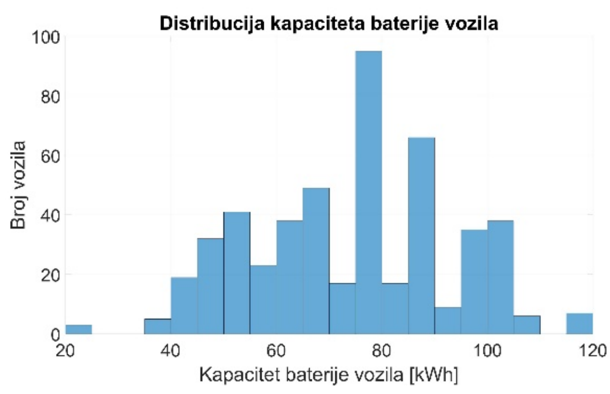
Vršna snaga stanice za punjenje električnih vozila izabrana je tako da napon ne prelazi dozvoljene granice od $0{,}9\ r.j.$ do $1{,}1\ r.j.$ Maksimalna vršna snaga stanice dobija se korišćenjem formula (1), (2) i (3) za svaki sat u godini, gde su P_P i Q_P vrednosti snage domaćinstava od kojih je oduzeta proizvodnja solarne elektrane. Ovako izabrana vršna snaga stanice iznosi 9,878 MW. Pretpostavljeno je da je vršna snaga jednog punjača u stanici 22 kW, efikasnost punjenja 95 %, a efikasnost pražnjenja 85 % u slučaju V2G mogućnosti. U skladu sa tim, izabrano je da će ukupno biti 500 vozila koji u toku godine redovno koriste tu stanicu za punjenje električnih vozila, a punjača je ukupno 449.

U radu [15] autori su obradili preko 860 repozitorijuma otvorenog pristupa (*open access*) i dobili više od 60 skupova podataka relevantnih za modelovanje punjenja električnih vozila.

Autori su zatim objavili skup podataka za šest lokacija koje prethodno u literaturi nisu obrađivane [16], koji su u ovom radu korišćeni. Za ovaj rad, odbacivanjem podataka koji sadrže nepotpune informacije, dobijen je skup od 138.328 podataka koji sadrži sledeće parametre: vreme prispeća električnog vozila na stanicu za punjenje, vreme koje je vozilo provelo na stanici, da li je u pitanju radni dan ili vikend. Na osnovu ovih podataka, klasterizacijom metodom K srednjih vrednosti (u daljem tekstu: K-klasterizacije) određeno je 50 klastera električnih vozila u koje je raspoređeno ukupno 500 električnih vozila. Posebno su obrađeni radni dani i vikendi. Dodatno, omogućeno je odstupanje od sat i po vremena za momenat dolaska na stanicu i sat vremena za vreme provedeno na stanici, u odnosu na ovako dobijeni profil korišćenja stanice za punjenje. Na ovaj način dobijen je profil za petnaestominutne intervale na nivou jedne godine sa vrednošću 100 % ukoliko se klaster vozila u tom intervalu nalazi na stanici za punjenje električnih vozila i vrednošću 0 % u suprotnom, u skladu sa zahtevanom formom unosa podataka u PLEXOS softverski paket.

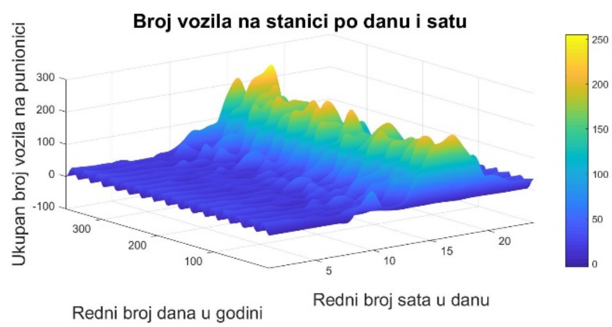


Slika 4. Distribucija efikasnosti vozila

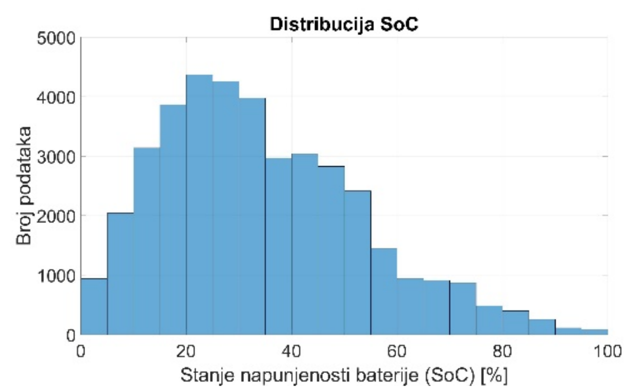


Slika 5. Distribucija kapaciteta baterije vozila

Na osnovu podataka o dostupnim modelima električnih vozila na tržištu u [17] i na osnovu podataka o zastupljenosti određenih vrsta električnih vozila na tržištu po realnoj maksimalnoj kilometraži pri punoj bateriji iz [18], formiran je skup podataka koji sadrži informacije o efikasnosti vozila i maksimalnom kapacitetu baterije vozila. Ovi podaci obrađeni su K – klasterizacijom i dodeljeni klasterima određenim u prethodnoj tački u skladu sa veličinom klastera iz obe tačke. Za sva vozila pretpostavljena je maksimalna snaga punjenja od 22 kW, a maksimalna snaga pražnjenja od 20 kW. Stanje napunjenosti baterije (SoC – eng. *state-of-charge*) se može kretati od 0% do 100%. Na osnovu podataka iz [19] određena je K-klasterizacija na 50 klastera električnih za SoC prilikom dolaska na stanicu za punjenje. Zatim su podaci o vremenu provedenom na stanici i podaci o SoC obrađeni, uz pretpostavku da je $SoC = 100\,\%$ u početnom trenutku simulacije, kako bi se dobila raspodela vožnje (u km) za svaki sat koji vozilo ne provodi na stanici. Pretpostavljeno je da za svaki klaster vozila pri odlasku sa stanice, baterija vozila mora da se napuni minimum koliko bi se napunila konstantnim (tokom vremena provedenog na stanici) korišćenjem punjača od 11 kW. Na ovaj način, u skladu sa zahtevanim načinom unosa podataka u PLEXOS softverski paket, „namešteno" je da dati klaster vozila u trenutku dolaska na stanicu za punjenje električnih vozila ima zahtevani SoC. Na Slikama 5, 6, 7 i 8 dat je prikaz distribucije ovako dobijenih ulaznih podataka električnih vozila.



Slika 6. Raspored dolaska vozila na stanicu



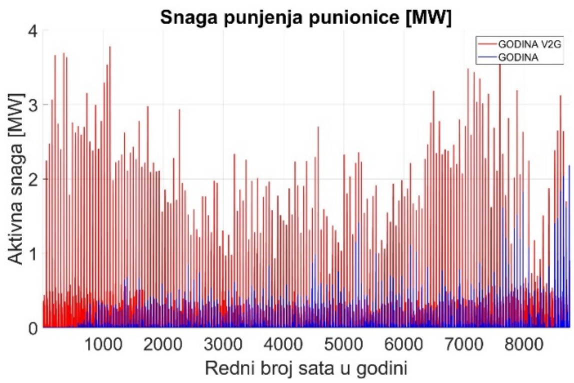
Slika 7. Distribucija SoC pri dolasku na stanicu

Za analizu naponskih prilika na godišnjem i dnevnom nivou koristi se softverski paket MATLAB. Naponske prilike određene su pomoću formula (1), (2) i (3) za svaki interval posmatranog scenarija.

III REZULTATI

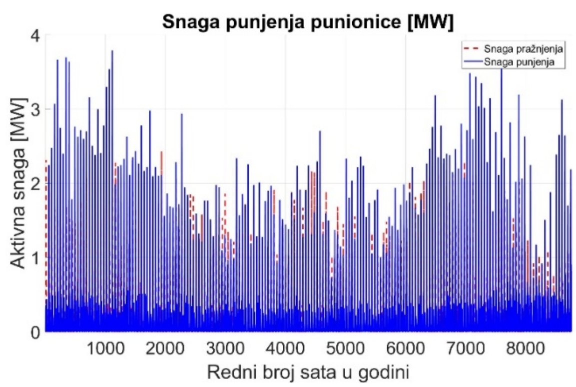
Optimalni raspored punjenja vozila koji je generisan pomoću PLEXOS softverskog paketa za scenarije „GODINA" i „GODINA V2G" dati su na Slici 8.

Na ovom grafiku može se uočiti znatno veća snaga punjenja vozila u slučaju mogućnosti V2G. Razlog ovome je potreba za većom energijom u skladištu baterije vozila, kako bi se ona mogla prazniti u trenucima kada je manja proizvodnja iz solarnih elektrana, kako bi se izbegla kupovina energije od distributivne mreže.

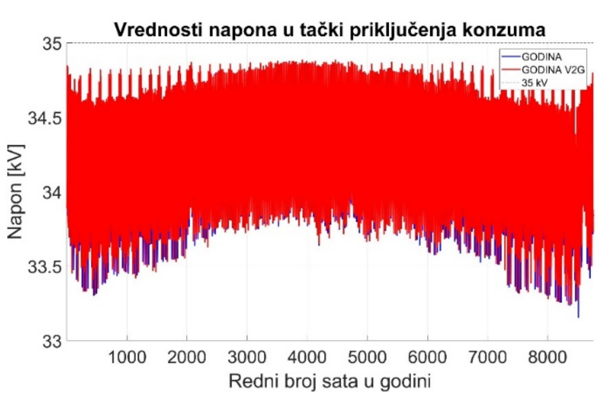


Slika 8. Snaga punjenja vozila stanice za punjenje na nivou godine u slučaju sa i bez mogućnosti V2G

Na Slici 9 dat je prikaz optimalnog rasporeda punjenja i pražnjenja vozila na nivou godine u ovom slučaju. Značajno veća snaga punjenja u odnosu na snagu pražnjenja objašnjava se manjom efikasnošću pražnjenja baterija u odnosu na punjenje.



Slika 9. Snage punjenja i pražnjenja punionice za scenario „GODINA V2G“



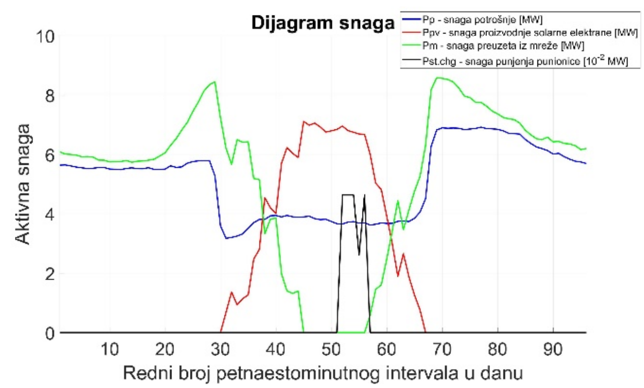
Slika 10. Napon na priključcima konzuma na nivou godine za dva posmatrana scenarija

Napon tačke priključenja konzuma na mrežu u skladu sa optimizovanim rasporedom punjenja i pražnjenja električnih vozila prikazan je na Slici 10.

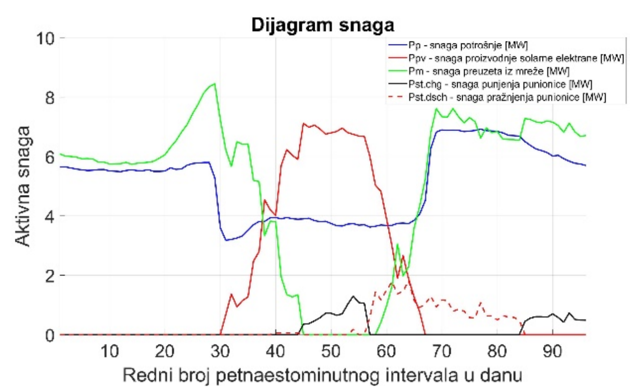
Sa ovog grafika može se uočiti da je napon na priključcima konzuma viši u slučaju V2G mogućnosti odnosu na slučaj gde ovo nije omogućeno, pogotovo u zimskim mesecima. U ovom periodu, poboljšanje naponskih prilika, odnosno povećanje napona, usled pražnjenja baterija vozila nazad u mrežu je najznačajnije. Ovo se objašnjava činjenicom da je potrošnja domaćinstava u ovom periodu godine viša, usled grejne sezone, pa je i napon na priključcima niži. Istovremeno, uz nižu iradijaciju Sunčevog zračenja tokom zimskih meseci, solarne elektrane proizvode manje energije, što takođe utiče na niži napon u tački priključenja.

Na nivou dana, sa petnaestominutnom rezolucijom, mnogo se lakše uočavaju razlike u naponskim prilikama u slučaju mogućnosti vraćanja energije nazad u mrežu iz baterija električnih vozila i bez.

Na Slici 11 prikazani su snaga proizvodnje iz solarne elektrane, snaga preuzeta iz mreže, snaga punjenja punionice i snaga potrošnje na nivou jednog dana, za scenario „DAN“. Za scenario „DAN V2G“ dijagram prethodno opisanih snaga, uz snagu pražnjenja punionice, prikazan je na Slici 12.

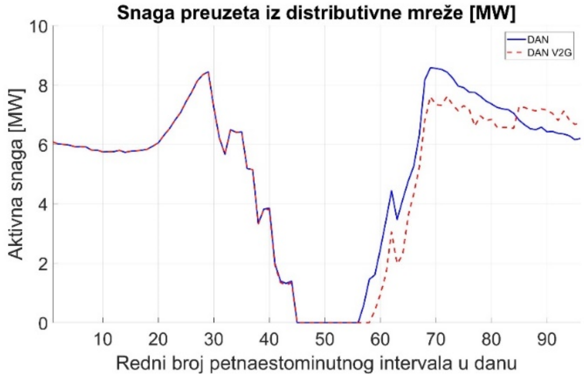


Slika 11. Dijagram snaga za posmatrani dan za scenario „DAN“



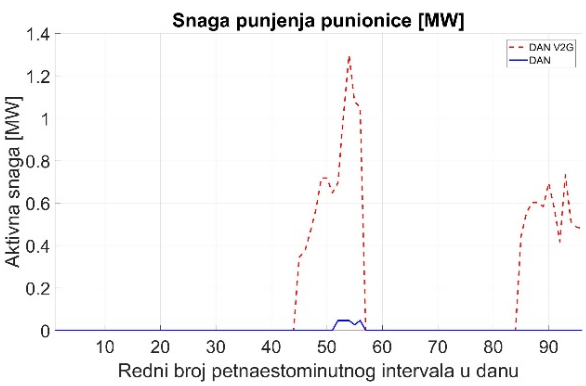
Slika 12. Dijagram snaga za posmatrani dan za scenario „DAN V2G“

Može se uočiti da se snaga preuzeta iz mreže u večernjim satima smanjuje u slučaju mogućnosti pražnjenja vozila u mrežu, usled pražnjenja baterija. Uporedni prikaz snage preuzete iz mreže prikazan je na Slici 13.

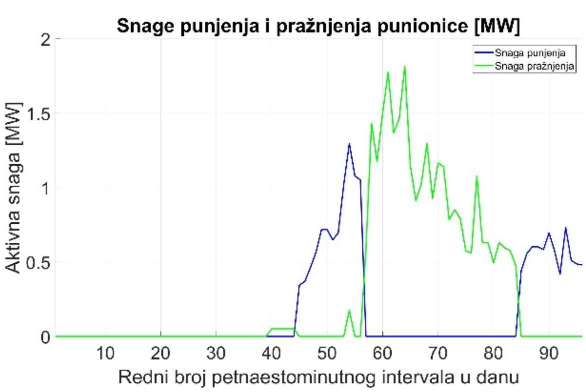


Slika 13. Snaga preuzeta iz distributivne mreže za posmatrane scenarije

Istovremeno, snaga punjenja baterija je povećana, ali na račun proizvodnje iz solarne elektrane. Snage punjenja baterija za posmatrane scenarije date su na Slici 14.



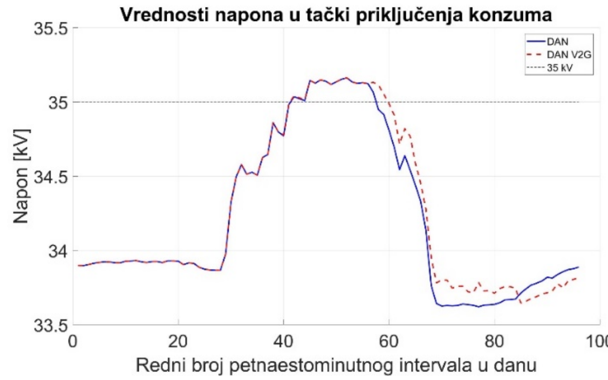
Slika 14. Snaga punjenja stanice za punjenje električnih vozila za posmatrane scenarije



Slika 15. Snage punjenja i pražnjenja punionice za scenario „DAN V2G"

Optimalni raspored punjenja i pražnjenja vozila za posmatrane scenarije dat je na Slici 15. Razlika u snazi je usled manje efikasnosti pražnjenja baterija u odnosu na punjenje.

Ovakav raspored punjenja i pražnjenja dovodi do promene naponskih prilika na priključcima konzuma. Na Slici 16 je prikazan nivo napona za scenarije „DAN V2G" i „DAN" na nivou posmatranog dana.



Slika 16. Naponi na priključcima mreže na nivou dana za dva posmatrana scenarija

Na ovom grafiku može se uočiti smanjenje napona u periodu kada je najviši, odnosno kada postoji proizvodnja iz solarnih elektrana. S druge strane, povećanje napona dešava se u večernjim satima kada baterije vraćaju energiju u mrežu, a kada je napon na znatno nižoj vrednosti od nominalne. U oba slučaja, naponske prilike su se poboljšale.

Rezultat optimizacije u softveru PLEXOS pruža podatke o ekonomskim parametrima relevantnim kako za vlasnike proizvodnih jedinica, tako i za operatore sistema i potrošače. Ekonomski parametri koji se u ovom radu analiziraju su: cena generisanja, cena energije, vremenski ponderisana cena, cena ponderisana po proizvodnji, troškovi opterećenja, prihodi generatora i suficit poravnanja. Svaki od ovih parametara je ključan za razumevanje ukupnog ekonomskog učinka elektroenergetskog sistema u okviru ova dva scenarija.

Napominje se da su varijabilni troškovi proizvodnje modelovani za objekat generatora, zapravo cene više i niže tarife posmatrane distributivne mreže. Na ovaj način, izlazni ekonomski parametri koji se tiču generatora, a koji su rezultat analize, zbog pretpostavke da su varijabilni troškovi proizvodnje i održavanja solarnih panela jednaki nuli, zapravo se odnose na telo koje upravlja distributivnom mrežom.

Analiza ekonomskih parametara će se vrši samo na nivou godinu dana, a rezultujuće vrednosti parametara za dva scenarija date su u Tabeli 1.

U scenariju sa V2G, primetno je smanjenje troškova generisanja energije (sa 202.375 hilj. RSD na 193.243 hilj. RSD), što se može pripisati funkciji baterija električnih vozila kao resursa za skladištenje, smanjujući potrebu za skupim vršnim generatorima. Ovo je rezultiralo i nižom cenom energije koju plaćaju potrošači (sa 4.137 na 4.081 RSD/MWh), jer se u periodu visokog opterećenja energija vraća u mrežu iz baterija, čime se smanjuje pritisak na tradicionalne generatore.

Prosečna vremenski ponderisana cena (3.966 RSD/MWh u V2G scenariju) je neznatno viša nego u scenariju bez V2G, što se objašnjava čestim pražnjenjem baterija tokom perioda nižeg opterećenja. Iako V2G snižava cene u vršnim periodima, njegova upotreba tokom manje potražnje blagom povećanju prosečne cene. Slično tome, cena ponderisana po proizvodnji je takođe nešto niža u V2G scenariju zbog porasta konkurencije sa alternativnim izvorom energije, što umanjuje prihode generatora.

Tabela 1. Uporedni prikaz ekonomskih parametara za dva posmatrana scenarija na nivou godine

Parametar	GODINA	GODINA V2G
Cena generisanja [hilj. RSD]	202.375,3	193.243,5
Cena energije [RSD/MWh]	4.136,6	4.080,8
Vremenski ponderisana cena [RSD/MWh]	3.966,0	3.981,4
Cena ponderisana po proizvodnji [RSD/MWh]	4.077,7	3.863,6
Troškovi opterećenja [hilj. RSD]	198.284,0	200.899,2
Prihodi generatora [hilj. RSD]	197.908,6	192.473,5
Suficit poravnanja [hilj. RSD]	375,460	8.425,668

Troškovi opterećenja su neznatno veći u V2G scenariju (200.899 hilj. RSD) zbog dinamike punjenja i pražnjenja baterija, što ukazuje na potrebu za pažljivijim planiranjem kako bi se maksimizovala ušteda. Prihodi generatora opadaju u V2G scenariju (na 192.474 hilj. RSD), budući da V2G obezbeđuje alternativu konvencionalnoj proizvodnji i stvara konkurenciju. Suficit poravnanja značajno raste u V2G scenariju (sa 376 na 8.426 hilj. RSD), što ukazuje na ekonomičnije funkcionisanje sistema i veći ekonomski potencijal za operatore.

Ovi parametri zajedno ukazuju na ekonomske benefite V2G sistema za operatore i potrošače, uz blagu redukciju prihoda za konvencionalne generatore. Time se podstiču investicije u obnovljive izvore i tehnologije za skladištenje, što je značajan korak ka zelenoj energetskoj tranziciji i smanjenju emisija.

IV Zaključak

Na osnovu analize sprovedene u ovom radu, može se zaključiti da tehnologija V2G pruža značajne prednosti u upravljanju elektroenergetskim sistemima sa visokim udelom obnovljivih izvora energije. V2G sistem omogućava da električna vozila ne budu samo potrošači energije, već i aktivni učesnici u balansiranju mreže, što doprinosi stabilizaciji naponskih prilika i smanjenju operativnih troškova. Ovaj pristup, u kombinaciji sa obnovljivim izvorima energije, potencijalno može značajno uticati na povećanje efikasnosti i održivosti elektroenergetskih sistema.

Rezultati pokazuju da korišćenje električnih vozila kao skladišta energije u V2G sistemu poboljšava stabilnost mreže i omogućava fleksibilnost koja je neophodna za integraciju velikih količina obnovljivih izvora energije. Ovo je posebno važno u slučaju varijabilnih izvora kao što su solarna energija i energija vetra, gde V2G sistemi mogu igrati ključnu ulogu u ublažavanju intermitentnosti i oscilacija proizvodnje i potrošnje.

Međutim, jedan od značajnih izazova koji se mora uzeti u obzir jeste uticaj V2G tehnologije na dugovečnost baterija električnih vozila. Ponovljeni ciklusi punjenja i pražnjenja, koji su neophodni za učešće u V2G sistemu, mogu dovesti do ubrzanog trošenja baterija, čime se smanjuje njihov životni vek i efikasnost. Ovaj problem otvara prostor za dalja istraživanja, posebno u pravcu razvoja baterijskih tehnologija koje bi bile otpornije na česte cikluse punjenja i pražnjenja, kao i planiranja optimalnog rasporeda punjenja i pražnjenja električnih vozila.

V2G tehnologija pokazuje veliki potencijal za poboljšanje upravljanja elektroenergetskim sistemima i podršku obnovljivim izvorima energije, ali su dalja istraživanja neophodna, kako u pogledu navika potrošača, uticaja na životni vek baterija, algoritama za optimalno punjenje i pražnjenje električnih vozila, tako i u pogledu razvoja infrastrukture za podršku masovnijoj integraciji električnih vozila u mrežu, kao i unapređenja regulatornih okvira koji bi omogućili efikasnu i sigurnu primenu V2G tehnologije na globalnom nivou.

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Techno-Economic Analysis of the Power System Operation with the Integration of Electric Vehicles

***Abstract* -** The energy transition and increased application of renewable energy sources in power systems pose challenges in electric grid management. One significant factor in this process is the integration of electric vehicles (EVs) and their capability for bidirectional charging through Vehicle-to-Grid (V2G) technology, enabling energy return from EV batteries to the grid. This paper analyses the impact of V2G technology on voltage stability in a 35 kV distribution network and its economic significance for the system. Using PLEXOS and MATLAB software packages, various EV charging and discharging scenarios were modelled, with solar power plants as the primary renewable energy source. The results indicate positive effects of V2G technology, including improved voltage conditions and reduced operational costs. Economic analysis shows that V2G enables consumer cost savings and reduces the need for conventional supply sources during peak loads. However, accelerated battery wear in EVs presents a significant challenge, and further research is recommended to enhance the technology and develop regulatory frameworks for the broader adoption of V2G in the future.
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Index Terms - Energy transition, Vehicle-to-Grid (V2G), Voltage stability, Economic analysis doi: 10.46793/EEE25-1.24H

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Numerical Simulations of Heat Transfer in Underground Thermal Energy Storage (UTES) System: CFD Approach

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Abstract – This study presents a numerical analysis of heat transfer phenomena within an underground thermal energy storage system using Computational Fluid Dynamics (CFD). Three scenarios were analysed to examine heat transfer mechanisms: (i) *Influx of hot water* – Hot water enters the chamber, displacing colder water and transferring heat to both the surrounding soil and the outgoing water. The soil, acting as a thermal reservoir, absorbs heat with minimal temperature variation, except in regions near the chamber; (ii) *Natural cooling* – With the chamber's inlets and outlets sealed, the water gradually cools through interaction with the colder surrounding soil. The focus is on the initial cooling rate, which determines how long the water remains above a certain temperature before reaching thermal equilibrium; (iii) *Heat extraction via a heat exchanger* – A submerged heat exchanger extracts heat from the chamber water while the surrounding soil compensates for the loss. The efficiency of this process depends on the dimensions and operational parameters of the heat exchanger.
The results indicate that in all scenarios, the system maintains stable thermal stratification, with warmer water staying in the upper layers while cooler water settles due to density differences. The interaction between water and soil plays a crucial role – acting as a heat source during extraction and as a reservoir during cooling.

Index Terms – Thermal energy storage, Heat transfer, Geothermal energy, Solid-fluid interaction, Aquifer, Computational Fluid Dynamics (CFD)

I Introduction

In the global effort to mitigate climate change and reduce greenhouse gas emissions, renewable energy sources play a crucial role. However, these sources often provide energy only intermittently, as is the case with photovoltaic systems, waste heat from industrial processes, and biofuels. To overcome this limitation, it is essential to store renewable energy when available and utilize it during periods of increased demand.

Underground thermal energy storage (UTES) is a technology that stores thermal energy by heating or cooling a storage medium, enabling its use for heating and cooling applications. Aquifer thermal energy storage (ATES) is a specific type of UTES that stores heat in underground water-bearing layers (aquifers). This method, which involves the injection and extraction of water at different temperatures depending on the season, has been the subject of numerous studies [1-6], offering a viable solution for balancing energy supply and demand.

A significant challenge in ATES systems lies in accurately assessing the heat transfer rates to and from the surrounding soil. Since thermal energy is stored over extended periods – such as when water is heated during the summer months and later used for district heating in the winter – the accurate estimation of heat losses and gains from the surrounding soil becomes crucial. These estimations are necessary for evaluating the system's overall efficiency and long-term viability.

Given the complexity of heat transfer interactions between fluids and solids, along with the transient nature of these processes, numerical simulations are indispensable for predicting heat transfer dynamics with high accuracy. In systems characterized by complex geometries, convection heat transfer, significant temperature gradients, and turbulent flows, simulations that effectively resolve fluid dynamics are essential for generating reliable predictions. Computational Fluid Dynamics (CFD) is a powerful tool that enables the investigation and optimization of thermal energy storage systems. Its advantages include the ability to evaluate temperature distribution, heat transfer rates, and fluid flow patterns in a transient manner, making it particularly well-suited for analyzing ATES systems [7-10].

This study employs the CFD methodology to evaluate the heat transfer processes in various scenarios of heat storage and extraction within an ATES system, providing insights into system performance and optimization strategies.

II Considered Scenarios

Three heat transfer scenarios were systematically analysed in this study to evaluate thermal dynamics within a thermal energy storage chamber.

Scenario A examines the introduction of hot water through a pipeline into a chamber initially filled with water at the ambient temperature of the surrounding soil. As the heated water enters, it displaces the pre-existing water, which exits through a corridor at the opposite end, potentially leading to an adjacent chamber. The primary mode of heat transfer is convective, wherein the inflowing hot fluid increases the chamber temperature while the cooler fluid is displaced. Thermal conduction within the water is considered negligible. Buoyancy-driven flow significantly influences the system, particularly in the initial stages, due to temperature gradients between the incoming and existing fluids. The soil in proximity to the chamber experiences localized heating, while the soil at greater distances remains thermally unaffected, effectively acting as a heat reservoir. Given the high thermal inertia of soil, it absorbs substantial heat without substantial temperature variations, except near the chamber boundary.

Scenario B commences from the steady-state condition achieved in Scenario A. At this stage, the chamber inlet and outlet are sealed, ceasing fluid exchange. In the absence of an external heat source, thermal dissipation occurs through conductive heat transfer to the surrounding soil, leading to a gradual decline in water temperature. Over time, thermal equilibrium is reached, where the water temperature asymptotically approaches that of the surrounding soil. The primary focus of this scenario is to quantify the transient cooling rate and assess the duration for which the water temperature remains above a prescribed threshold.

Scenario C investigates the thermal interaction between the chamber water and a submerged heat exchanger, whose external surface is maintained at a constant temperature lower than that of the surrounding water. This configuration simulates heat extraction through forced convection without direct fluid replacement. Unlike the previous scenarios, heat transfer occurs exclusively through conduction and convective exchange between the chamber water and the heat exchanger. The surrounding soil remains at an assumed fixed temperature, while the soil adjacent to the chamber undergoes thermal adjustments in response to the localized heat extraction. In this scenario, the soil functions as an effectively infinite thermal reservoir, with heat removal constrained solely by the heat exchanger's surface area and internal thermal conditions. Fluid motion is induced solely by buoyancy forces.

III METHODOLOGY

Heat transfer analysis in the chamber is conducted using the Computational Fluid Dynamics (CFD) methodology. This approach entails solving the full set of Navier-Stokes equations governing the three-dimensional motion of water, in conjunction with transport equations for energy (temperature) and turbulence properties. By employing numerical techniques, detailed distributions of velocity, pressure, temperature, and turbulent variables are obtained throughout the computational domain.

The simulations adopt a field-based approach, wherein water velocity and temperature are computed simultaneously and interactively within a time-dependent, three-dimensional framework. A computational mesh with appropriate spatial and temporal resolution is utilized to capture the time evolution of flow patterns and temperature distribution across the entire solution domain.

The numerical results enable the extraction of various averaged quantities, including time, field, and spatially averaged data. This flexibility facilitates the assessment of integral and statistical metrics such as local and average velocity, temperature, and heat flux.

The Navier-Stokes and the passive scalar transport equations in the RANS framework read:

$$\frac{\partial U_i}{\partial x_i} = 0,$$

$$\frac{DU_i}{Dt} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\nu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) - \overline{u_i u_j}\right) + g_i$$

$$\rho c_p \frac{DT}{Dt} = \frac{\partial}{\partial x_j}\left(\lambda \frac{\partial T}{\partial x_j} - \rho c_p \overline{\theta u_j}\right) + Q$$

where U_i is velocity vector, ρ is fluid density, g_i is gravity vector, ν is kinematic viscosity, T is temperature, λ is thermal conductivity, c_p is specific heat capacity, and Q is heat source.

The momentum and energy conservation equations are closed by the linear eddy-viscosity/diffusivity formulation:

$$\overline{u_i u_j} = -\nu_t S_{ij} + 2k\delta_{ij}/3, \qquad \overline{\theta u_j} = -\frac{\nu_t}{Pr_t}\frac{\partial T}{\partial x_j}$$

Where ν_t is turbulent (eddy) viscosity, and Pr_t turbulent Prandtl number set to its standard value of 0.9.

Turbulence modelling is based on the Reynolds-Averaged Navier-Stokes (RANS) approach, specifically employing the k-ε-ζ-f model by [11]. This turbulence model has been extensively validated against numerous benchmark cases, ensuring its reliability and predictive accuracy [12-17].

The ζ-f model in its original form consists of the following equations, applied also in the ensemble-averaged framework:

$$\frac{Dk}{Dt} = \mathcal{D}_k + P_k - \varepsilon$$

$$\frac{D\varepsilon}{Dt} = \mathcal{D}_\varepsilon + \frac{c_{\varepsilon 1}P_k - c_{\varepsilon 2}\varepsilon}{\tau}$$

$$\frac{D\zeta}{Dt} = \mathcal{D}_\zeta + f - \frac{\zeta}{k}P_k$$

$$L^2\nabla^2 f - f = \frac{1}{\tau}\left(c_1 + c_2'\frac{P_k}{\varepsilon}\right)\left(\zeta - \frac{2}{3}\right)$$

$$\tau = max\left[min\left(\frac{k}{\varepsilon}, \frac{0.6}{\sqrt{6}c_\mu^\nu |S|\zeta}\right), c_\tau\left(\frac{\nu}{\varepsilon}\right)^{1/2}\right]$$

$$L = C_L max\left[min\left(\frac{k^{\frac{3}{2}}}{\varepsilon}, \frac{k^{\frac{1}{2}}}{\sqrt{6}c_\mu^\nu |S|\zeta}\right), c_\eta\left(\frac{\nu^3}{\varepsilon}\right)^{\frac{1}{4}}\right]$$

$$\nu_t = c_\mu^\nu\, \zeta\, k\, \tau$$

where k is the RANS ensemble modelled turbulent kinetic energy, ε its dissipation rate, $P_k = \overline{u_i u_j}\frac{\partial U_i}{\partial x_j}$ is the production rate of turbulent kinetic energy, $\zeta = \overline{v^2}/k$ is the velocity scale ratio, f is an elliptic relaxation function and $\mathcal{D}$ denotes the total (molecular plus turbulent) diffusion:

$$\mathcal{D}_\phi = \frac{\partial}{\partial x_k}\left[\left(\frac{\nu}{\sigma_\phi} + \frac{\nu_t}{\sigma_t}\right)\frac{\partial \Phi}{\partial x_k}\right]$$

Wall boundary conditions for all variables are prescribed within the grid cells nearest to solid surfaces, positioned beyond the viscous sub-layer. This is achieved through the application of semi-empirical wall functions, which are derived by pre-integrating the governing equations over near-wall grid cells.

The influence of surface roughness is incorporated through a roughness model commonly employed to account for the effects of uneven surfaces or obstacles on the flow field [18].

A coupled fluid-solid simulation approach is adopted, wherein both the water and surrounding soil domains are solved simultaneously. This is facilitated through an interface that enables the exchange of heat transfer properties, such as temperature and heat flux, between the interacting domains.

The computations were conducted using the in-house finite-volume unstructured T-Flows CFD code (https://github.com/DelNov/T-Flows), developed at TU Delft by [19, 20]. T-Flows has been extensively tested and validated against multiple benchmark cases relevant to the present configurations by [12-17, 21-25].

IV Computational Details

Computational domain for Scenario A is illustrated in Figure 1. The chamber has dimensions of 200 m in length, 12 m in width, and 10 m in height. It is initially filled with 26 °C water (blue region in Figure 1) and encased by a 3 m thick soil layer. Hot water (red stream in Figure 1), with an inlet temperature of 70 °C and a velocity of 1 m/s, enters through a 0.3 m diameter opening located at the ceiling of the chamber's left end. This opening represents the exit of a pipe extending from the earth's surface. The centre of the inlet is positioned at the mid-width of the chamber and 6 m from the left wall. Under these conditions, the inlet water mass flow rate is 72.2 kg/s, equivalent to 254.3 m^3/h. The water exits the chamber through a 3 m × 3 m opening at the chamber's bottom, located diametrically opposite the inlet. The water is initially motionless. The chamber walls are assumed to be rough to replicate the natural unevenness of the surface, with a roughness coefficient of 0.05 m.

The nominal inlet power is determined based on the temperature difference between the incoming and initial water temperatures, calculated as follows:

$$\dot{Q}_{nom} = \dot{m} c_p \left(T_{in} - T_{ref} \right) = \text{ 12.7 MW}$$

where $\dot{Q}_{nom}$ is the power supplied, c_p is the specific heat for saline water, T_{in} is the inlet water temperature, T_{ref} is the initial temperature, and $\dot{m}$ is the incoming mass flow rate.

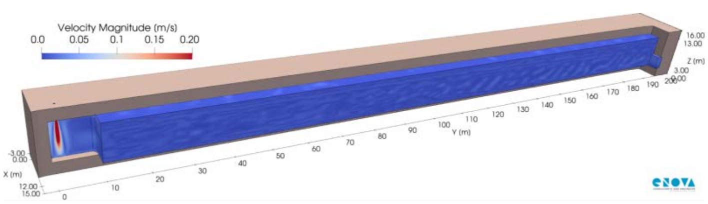

Figure 1. Cross-section of the computational domain for Scenario A

The computational domain for Scenario B is identical to that of Scenario A, except that no inlets or outlets are present, preventing any exchange of water with the surroundings.

The computational domain for Scenario C, illustrated in Figure 2, corresponds to those of Scenarios A and B. However, Scenario C also lacks any inlets or outlets for water flow, with the addition of a submerged heat exchanger within the chamber. The heat exchanger is modelled as a vertically oriented cylinder (yellow cylinder located in the middle of the chamber, Figure 2) with a diameter of 0.3 m, extending from the chamber's ceiling. Positioned 5 m below the chamber's mid-height, its centre is aligned with the chamber's midpoint. The surface area of the heat exchanger is 4.78 m², and its surface temperature is maintained at a constant value. Computations are conducted for five different heat exchanger wall temperatures, varying from 16°C to 24°C in increments of 2°C.

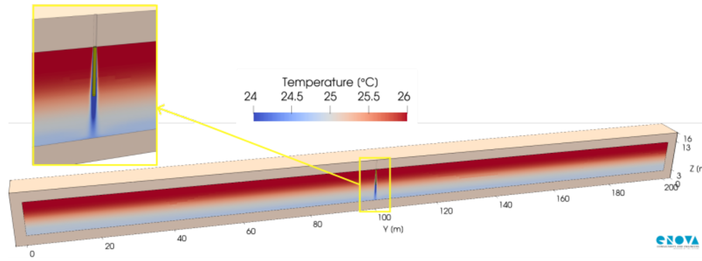

Figure 2. Cross-section of the computational domain for Scenario C

The computational mesh, illustrated in Figure 3, remains consistent across all scenarios. The blue grid covers the fluid domain, while the green grid covers the solid domain. The mesh comprises approximately 8×10^5 computational cells, with 5×10^5 cells allocated for discretizing the solid domain and the remaining cells used for fluid domain discretization. The average cell size within the fluid domain is 1 m × 1 m in the horizontal directions, while the maximum cell size in the vertical direction is 0.5 m. The mesh is refined near all walls, including the interface between the fluid and solid domains, ensuring that the distance between the wall/interface and the first cell centre is 0.004 m. The mesh consists exclusively of hexahedral cells, which are preferred due to their superior numerical accuracy and stability. The temporal resolution is set to two seconds.

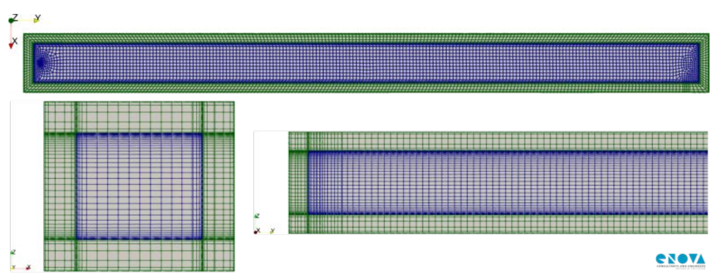

Figure 3. Top, front, and side views of the computational mesh used in simulations

V Results and Analysis

<u>Scenario A: Influx of hot water</u>

The heating of the water inside the chamber, initially at rest, is simulated over a period of 23 days, during which hot water enters through an opening at the chamber's ceiling. At the end of this period, both the mean water temperature within the chamber and the temperature of the exiting water converge to a common value, indicating that the statistically steady state has been reached.

Figure 4 presents the distribution of the velocity component in the Y direction, corresponding to the predominant horizontal velocity from the inlet to the outlet, in the mid-plane after 23 days of simulation. The results reveal the formation of distinct flow layers within the chamber. Near the ceiling, water exhibits rightward motion, whereas a counterflow to the left is observed in the layer beneath. Near the chamber floor, the flow direction again shifts to the right. The magnitude of the velocity component in the Y direction remains below 0.03 m/s throughout the chamber.

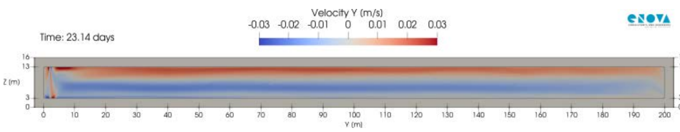

Figure 4. Velocity field of the Y-component in the mid-plane after 23 days of simulation for Scenario A. The positive Y direction is oriented to the right. Red shades indicate water motion to the right, while blue shades represent flow to the left

Figure 5 presents the temperature field in the mid-plane after 23 days of simulation. As hot water enters the chamber, it rises toward the ceiling, while cold water remains near the bottom due to buoyancy effects driven by density differences. This leads to a system exhibiting stable thermal stratification. In the upper portion of the chamber, the water shows weak stratification, approaching near-isothermal conditions, whereas strong stratification is observed near the bottom wall. This distinction is clearly reflected in the temperature profile along a vertical line through the chamber's midpoint, as shown in Figure 6, which illustrates the temperature variation from the bottom to the top of the chamber.

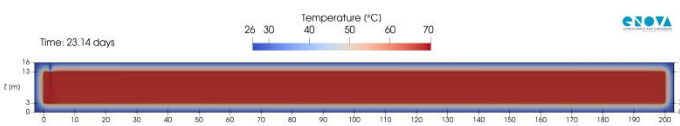

Figure 5. Temperature field after 23 days of simulation in mid-plane for scenario A

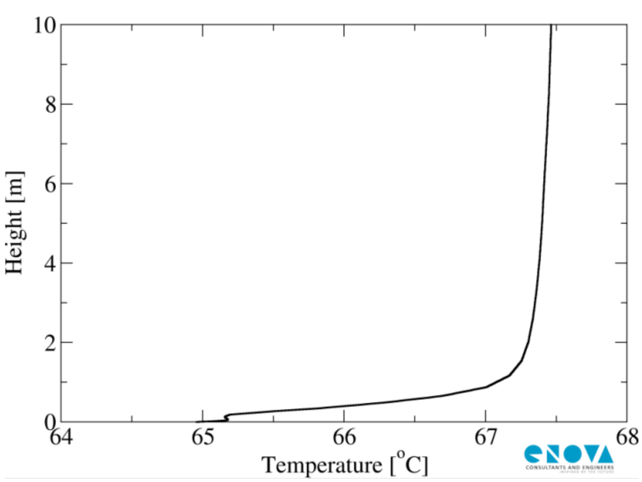

Figure 6. Temperature profile along a vertical line at the midpoint of the chamber

The water temperature exhibits spatial variations, and due to continuous cooling from the soil, the system never reaches an isothermal state. Thermal stratification persists as a result of buoyancy forces. However, the average water temperature within the chamber and the average temperature of the outflow can be determined. These profiles are presented in Figure 7 (left). Initially, during the first 3-4 days of hot water injection, the average water temperature increases rapidly in a linear manner. Thereafter, the rate of increase slows, following a logarithmic trend where temperature gains diminish over time. The profiles eventually converge at 67.4°C, which is reached after approximately 20 days.

The average heat flux at the water-soil interface is shown in Figure 7 (right). At the beginning, the heat flux rises as the temperature difference between water and soil increases due to the influx of hot water. However, after 3-4 days, as the rate of water temperature rise slows and the surrounding soil begins to warm, the temperature difference decreases, leading to a gradual decline in heat flux. After approximately 20 days, the heat flux stabilizes at around 65 W/m².

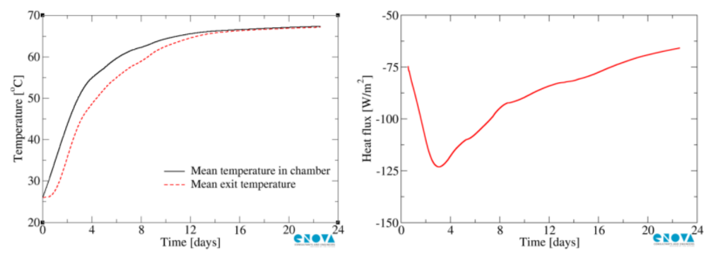

Figure 7. (Left) Time evolution of the average water temperature in the chamber and the exit water temperature (Right) Time evolution of the average heat flux at the water–soil interface

The relationship between the temperature difference (ΔT) and heat flux is well established, as heat flux is a direct function of ΔT. However, instead of relying solely on heat flux, a more insightful and universal approach is to estimate the heat transfer coefficient, *h*, as follows:

$$h = \frac{\dot{q}}{T_{in} - T_{wall}}$$

where $\dot{q}$ represents the heat flux, T_{in} is the inlet water temperature, and T_{wall} is the cavity wall temperature. From our simulations, the obtained heat transfer coefficient *h* is 1.48 W/m^2°C. This provides a straightforward method for calculating the heat flux for different inlet temperatures. For instance, with an inlet temperature of 80°C, the heat flux would be:

$$\dot{q} = h(T_{in} - T_{wall}) = 1.48 \cdot (80 - 26) = 79.9\, W/m^2$$

Unlike heat flux, which varies proportionally with ΔT, the coefficient h depends primarily on factors such as fluid velocity, surface geometry (e.g., flat, cylindrical, spherical, or curved), fluid properties, and surface roughness. Importantly, these parameters remain relatively constant within the dimensions of the cavity under consideration. Consequently, as long as the system involves a cavity with flat walls, fluid velocities on the order of 1 m/s (approximately 0.5–10 m/s), and temperatures ranging from 20°C to 90°C, the heat transfer coefficient can be considered universal. Furthermore, within this temperature range, the thermophysical properties of water do not change significantly enough to impact heat transfer behaviour. The obtained value of h remains consistent under these conditions, providing a reliable means to calculate heat flux for different inlet temperatures in a straightforward manner.

Scenario B: Natural cooling

This scenario, a continuation of Scenario A, involves sealing the chamber's inlet and outlet, preventing water exchange. Consequently, the hot water inside the chamber cools solely through heat transfer to the surrounding soil. The simulated cooling period in this scenario is approximately 41 days.

Figure 8 presents the temperature distribution after 41 days of simulation. Stable thermal stratification is observed, with cooled water accumulating at the bottom of the chamber. Initially, a temperature gradient is evident only within the lower 2 meters, while the remaining chamber remains nearly isothermal. Over time, colder water gradually infiltrates the isothermal region, leading to a more diffuse temperature gradient, as illustrated in Figure 9.

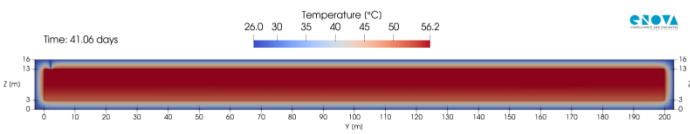

Figure 8. Temperature field after 41 days of simulation in mid-plane for scenario B

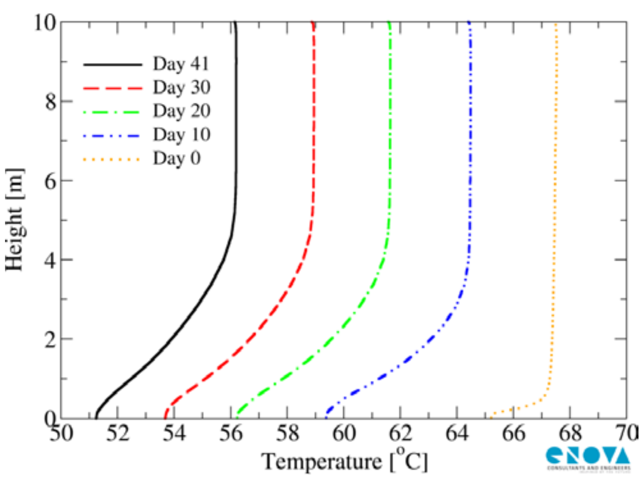

Figure 9. Temperature profiles along a vertical line at the chamber's center at different time instances

Figure 10 illustrates the average water temperature in the chamber during the natural cooling scenario. Over 41 days of simulation, the average temperature decreases from 67.4°C to 55.3°C, corresponding to an average cooling rate of 0.295°C per day. In a worst-case scenario, assuming a linear temperature decline, the water would reach 30°C in 127 days and 26°C in 140 days. However, due to the nonlinear nature of heat transfer, the actual cooling process deviates from a linear trend, resulting in prolonged heat retention. A more accurate prediction of the cooling rate can be obtained using an exponential function of the form:

$$T = Ae^{b \cdot t} + C$$

where T is the predicted water temperature in °C, t is time in days, and constants A, b and C are given in Table 1. According to the given exponential relation, the temperature of the water is expected to reach a value of 30 °C in approximately 274 days.

Table 1. Coefficients for exponential temperature prediction

A	b	C
41.17	-8.449×10^{-3}	26.00

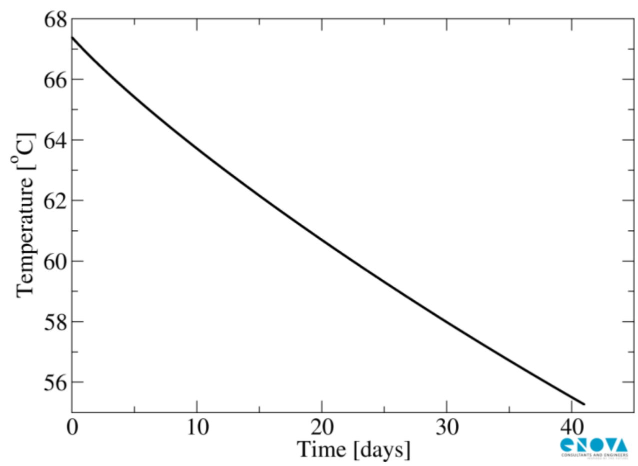

Figure 10. Time evolution of the average water temperature in the chamber during Scenario B

Scenario C: Heat exchanger

In the third scenario, heat extraction from the chamber is facilitated by a heat exchanger. The key parameter in this case is the amount of thermal energy that can be extracted, which is determined by the heat flux at the heat exchanger surface.

Figure 11 presents the velocity magnitude field in the mid-plane of the chamber after 5 days of computation, assuming a 10°C temperature difference between the heat exchanger surface and the chamber water. The highest velocity, 0.13 m/s, occurs beneath the heat exchanger. As water contacts the heat exchanger, it cools below the surrounding water temperature and descends toward the chamber bottom. Upon reaching the bottom surface, the cooled water spreads radially at a significantly lower velocity.

Figure 12 illustrates the temperature field in the mid-plane after 5 days of computation, considering the same 10°C temperature difference. A weak but stable thermal stratification is observed, with cooler water accumulating at the bottom and warmer water remaining at the top. As the cold water reaches the chamber's bottom, the surrounding soil acts as a heat source, transferring thermal energy back to the water.

Another computation was conducted for a scenario in which the temperature difference between the heat exchanger walls and the initial water temperature was set to 16°C. The water in the chamber was initially at 26°C, while the heat exchanger walls were maintained at 10°C. Over an extended period, the system evolved toward a steady-state equilibrium, where the final temperature of both the water and heat exchanger walls stabilized at 15°C. The initial heat flux at the heat exchanger surface was 120,000 W/m^2, but as equilibrium was approached, it gradually decreased to 28,000 W/m^2. Throughout this process, the surrounding soil acted as a thermal energy source, supplying heat to the water that was extracted by the heat exchanger. Once steady-state conditions were reached, the heat flux supplied by the soil to the water stabilized at 14 W/m^2. Additionally, the temperature of the chamber walls, which initially matched the water temperature at 26°C, gradually decreased to 16°C as thermal equilibrium was established.

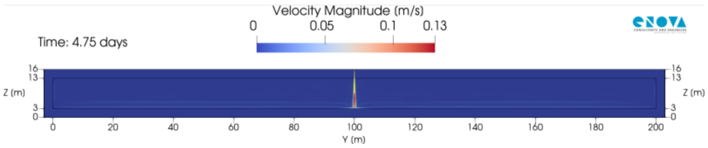

Figure 11. Velocity magnitude field after 5 days of computation in the mid-plane for Scenario C, with a 10°C temperature difference

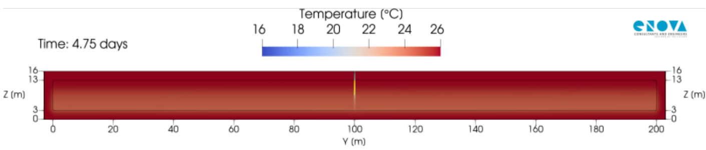

Figure 12. Temperature field after 5 days of computation in the mid-plane for Scenario C, with a 10°C temperature difference

Numerical computations have been performed for five different values of ΔT, representing the temperature difference between the heat exchanger surface and the water temperature in the chamber. Table 2 summarizes the heat flux values obtained numerically, along with their corresponding temperature differences.

Table 2. Heat flux at the heat exchanger surface for the corresponding temperature difference

ΔT [°C]	2	4	6	8	10
Heat flux q [kW/m^2]	1.921	9.231	27.611	43.784	62.126

As expected, the heat flux increases with the temperature difference, indicating that larger temperature differences facilitate the extraction of greater amounts of energy from the water in the chamber. However, this increase is not linear. The data suggests that the relationship follows power-law dependence. Based on the data in Table 2, the power law can be expressed as:

$$q = A \cdot \Delta T^B$$

where $q\ [kW/m^2]$ is the heat flux, $\Delta T\ [°C]$ is the temperature difference, $A = 0.43808$, and $B = 2.2087$. The power law approximation is plotted against numerical computations results in Figure 13.
Given the value of the heat exchanger's area, the amount of power that can be extracted using the heat exchanger can be calculated as follows:

$$Q = q \times A_{HE}$$

where $Q\ [kW]$ is total energy extracted, $q\ [kW/m^2]$ is heat flux at heat exchanger's surface, and $A_{HE}\ [m^2]$ is the area of the heat exchanger in contact with water.

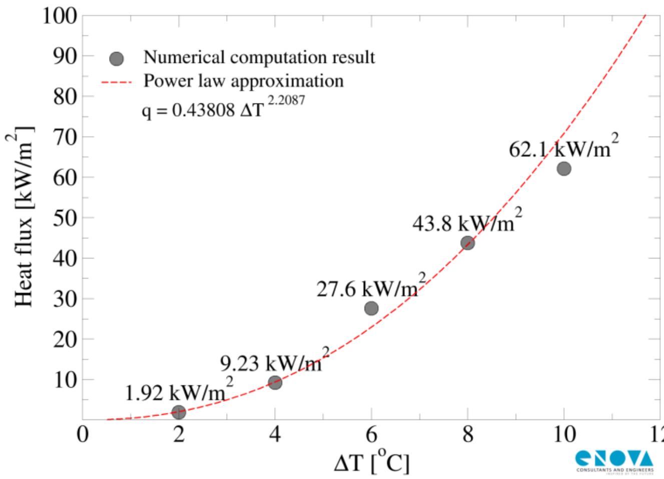

Figure 13. Average heat flux at the heat exchanger surface for different ΔT values after 5 days of computation, along with the power law approximation

VI Conclusion

This study presents a comprehensive analysis of heat transfer phenomena within an aquifer thermal energy storage chamber using Computational Fluid Dynamics (CFD) simulations. Three scenarios are explored: heat transfer due to hot water influx, natural cooling following the closure of inlets/outlets, and heat extraction via a heat exchanger.

Steady-state conditions and stable thermal stratification are observed in all scenarios, with temperature profiles varying depending on the presence of heat sources and sinks, as well as flow patterns. Buoyancy effects are crucial in determining these flow patterns and temperature distributions, especially in scenarios involving hot water influx and natural cooling.

In Scenario A, the average water temperature in the chamber stabilizes at 67.4°C after approximately 20 days. At this point, the heat flux reaches around 65 W/m². The total heat losses for the current chamber amount to 587.6 kW, or 4.8% of the power supplied to the chamber.

In Scenario B, which involves the natural cooling of the water in the chamber, the average temperature decreases from 67.4°C to 55.3°C over 41 days of computation, resulting in an average cooling rate of 0.295°C per day. However, the cooling rate is not linear due to the nature of the heat transfer process. An exponential function accurately predicts the cooling rate, suggesting that the water temperature will reach 30°C in approximately 274 days.

In Scenario C, which focuses on heat extraction using a heat exchanger, the efficiency of heat extraction is influenced by the temperature difference between the heat exchanger surface and the chamber water. Higher temperature differences result in greater heat flux values. Although larger temperature differences allow for more energy extraction, the relationship between temperature difference and extracted energy is nonlinear, following a power-law dependence rather than a linear trend.

Mathematical models, such as exponential functions and power laws, are proposed to predict temperature variations and heat flux values. These models provide valuable insights into long-term temperature trends and the efficiency of energy extraction.

Numerical simulations based on Computational Fluid Dynamics (CFD) are essential for the accurate prediction of flow and heat transfer phenomena in solid-fluid interactions. These simulations provide detailed insights into the complex behaviour of fluids and thermal fields that are difficult to capture through traditional analytical methods. CFD allows for the modelling of intricate flow patterns, temperature distributions, and the interaction between fluids and solid surfaces, enabling the precise calculation of critical parameters such as heat flux.

The ability to simulate various scenarios, including heat influx, natural cooling, and heat extraction, further highlights the importance of CFD in optimizing system design and improving energy efficiency. Accurate heat flux predictions, for example, are crucial for assessing energy extraction efficiency and ensuring effective thermal management in real-world applications such as aquifer, geothermal systems, and industrial heat exchangers. Therefore, CFD simulations serve as an invaluable tool for advancing the understanding and optimization of heat transfer processes in complex solid-fluid systems.

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Numeričke simulacije prenosa toplote u sistemu podzemnog skladištenja termalne energije (UTES): CFD pristup

***Rezime* -** Fenomen prenosa toplote unutar podzemnog skladišta toplotne energije analiziran je koristeći metodu računske dinamike fluida (CFD). Analizirana su tri scenarija kako bi se istražili mehanizmi prenosa toplote: (i) *Dotok tople vode* – Topla voda ulazi u komoru, potiskuje hladniju vodu i prenosi toplotu na okolno tlo i odlaznu vodu. Tlo, kao toplotni rezervoar, apsorbuje toplotu uz minimalne promjene temperature, osim u blizini komore; (ii) *Prirodno hlađenje* – Kada su ulazi i izlazi zatvoreni, voda se postepeno hladi kroz interakciju s hladnijim tlom. Posebno je analizirana početna brzina hlađenja, koja određuje koliko dugo voda ostaje iznad određene temperature prije nego što sistem dostigne termičku ravnotežu; (iii) *Ekstrakcija toplote izmjenjivačem* – Uronjeni izmjenjivač odvodi toplotu iz vode u komori, dok okolno tlo nadoknađuje gubitak. Efikasnost ovog procesa zavisi od dimenzija i radnih parametara izmjenjivača.
Rezultati pokazuju da sistem u svim scenarijima zadržava stabilnu termičku stratifikaciju, gdje toplija voda ostaje u gornjim slojevima, dok se hladnija spušta uslijed razlika u gustini. Interakcija vode i tla je ključna – tlo djeluje kao izvor toplote tokom ekstrakcije i kao rezervoar tokom hlađenja..

***Ključne reči* -** Skladištenje toplotne energije, prenos toplote, geotermalna energija, interakcija čvrstog tijela i fluida, akvifer, računska dinamika fluida (CFD)

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Izazovi održivog razvoja u energetskom sektoru

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Rezime **-** Primena principa održivog razvoja predstavlja jedan od osnovnih zahteva savremenog privređivanja. Ispunjavanje datih principa posebno je važno u privrednim granama koje predstavljaju najveće zagađivače životne sredine, kakva je i energetika. U ovom radu razmatraju se izazovi koji postoje u održivom razvoju energetskog sektora, s obzirom na njegovu specifičnost i značaj za celokupni privredni i društveni razvoj. U proučavanju predmetne problematike polazi se od razmatranja uloge i značaja održivog razvoja u savremenom privređivanju, zatim se pažnja usmerava na problematiku primene održivog razvoja u energetskom sektoru, dok se u završnom delu rada vrši komparativna analiza određenih pokazatelja poslovanja energetskog sektora u zemljama Evropske unije i Srbije, a koji se tiču njegove održivosti, kao što su energetska efikasnost, energetska sigurnost, korišćenje obnovljivih izvora i drugi. U radu se zaključuje da je preduslov održivog razvoja ovog sektora donošenje adekvatne energetske politike, budući da primena principa i različitih elemenata održivog razvoja podrazumeva odgovarajuća ulaganja, adekvatna tehnološka rešenja, ali i vreme da se ostvare željeni efekti. Zato zelena i održiva ekonomija podrazumevaju sprovođenje reformi koje bi omogućile energetsku tranziciju, a koja bi mogla da doprinese kako povećanju energetske efikasnosti, tako i većem korišćenju obnovljivih izvora energije i čistih energetskih tehnologija.

Ključne reči - energetika, održivi razvoj, zelena ekonomija, energetska tranzicija, energetska efikasnost.

I UVOD

Energetika, kao jedna od ključnih privrednih grana, sa ekonomijom je povezana mnogobrojnim, složenim i uzajamno uslovljenim vezama. Tokom čitave istorije društveno-ekonomskog razvoja energija je predstavljala ključni input za dati razvoj, a načini proizvodnje i korišćenja energije imali su izuzetno veliki uticaj i na privredne i na društvene tokove. Najznačajniji uticaji energetike u privrednim aktivnostima ispoljeni su posebno u sferi inputa u procesu proizvodnje, transporta, obavljanja poljoprivrednih delatnosti i vršenja različitih usluga. U industrijskom sektoru dostupnost i cena energije mogu bitno uticati kako na visinu troškova proizvodnje, tako i na konkurentsku prednost pojedinih industrijskih grana. Ovo se posebno odnosi na energetski intenzivne sektore, kao što je pre svega proizvodni sektor. Pored mnogobrojnih podstičućih uticaja, funkcionisanje energetskog sektora često dovodi i do negativnih posledica, posebno u sferi zagađenja i narušavanja životne sredine. Naime, intenzivno korišćenje neobnovljivih fosilnih goriva (kao što su nafta, ugalj i prirodni gas) dovodi do znatnog zagađenja vazduha i predstavlja jednu od najvećih prepreka zaustavljanju globalnog zagrevanja. Iako proizvodnja energije iz fosilnih goriva može znatno da doprinese ostvarenju ekonomskog rasta, na ovaj način dobijena energija često dovodi do bespovratnog zagađenja životne sredine.

Sa stanovišta veze koja postoji između energetike i ostvarenja globalnih ciljeva održivog razvoja može se reći da energetika ima jednu od najvažnijih uloga. To je posledica činjenice da sektor energetike oduvek ima značajan uticaj na ekonomski rast, na razvoj tehnoloških inovacija, kao i na ostvarivanje socijalne jednakosti i očuvanje životne sredine. Zato je neophodno da se u daljem toku razvoj energetike fokusira na proizvodnju i potrošnju energije u skladu s principima održivosti. Takođe je nužno naglasiti da obezbeđenje troškovno-efikasne i stabilne ponude energije predstavlja preduslov budućeg društveno-ekonomskog razvoja, kako razvijenih ekonomija, tako i ekonomija u razvoju, kao što je naša. Podsticanje primene održivih praksi u oblasti energetike naročito je značajno za realizaciju dva od ukupno sedamnaest ciljeva održivog razvoja, definisanih Agendom 2030, koju su usvojile zemlje Ujedinjenih nacija 2015. godine. Sedmi cilj održivog razvoja upravo je usmeren na povećanje energetske efikasnosti i učešće obnovljivih izvora energije. Ostvarenjem ovog cilja obezbedila bi se pristupačna, pouzdana i obnovljiva energija. S druge strane, trinaesti cilj odnosi se na borbu protiv klimatskih promena i na zaštitu vazduha. Postizanjem navedenih ciljeva energetski sektor bi mogao pozitivno da utiče na sve tri ključne dimenzije održivog razvoja - ekonomiju, društvo i životnu sredinu.

U skladu s iznetim, posle uvoda, u drugom delu rada, biće ukazano na izazove koji prate održivi razvoj energetskog sektora, kao i na ulogu i značaj zelene energetske tranzicije. U trećem delu rada biće prikazani najznačajniji pokazatelji održivog razvoja energetike. Rezultati analize uspešnosti primene koncepta održivog razvoja energetike u zemljama Evropske unije i Srbiji tokom perioda 2013-2023. godina biće predstavljeni u četvrtom delu rada, dok će u završnom delu rada biti izneta zaključna razmatranja.

II ZELENA ENERGETSKA TRANZICIJA

Ubrzan ekonomski rast u prošlosti za posledicu je imao veoma izraženo narušavanje životne sredine. Ovo se posebno odnosi na privredne grane koje su poznate kao veliki zagađivači, kakva je i energetika. Kao posledica toga, u razvojnim teorijama definisan je koncept održivog razvoja, s ciljem da njegova primena u praksi omogući pomirenje ekonomskih, ekoloških i socijalnih ciljeva. Primena datog koncepta znatno je uslovljena i održivošću funkcionisanja i poslovanja energetskog sektora, koji bi trebalo da obezbedi da se postigne ravnoteža između energetske sigurnosti, ekonomskog rasta i zaštite životne sredine. Negativni uticaj energetike na životnu sredinu svakako je posledica činjenice da su rezerve fosilnih goriva ograničene, kao i da je njihova ekstrakcija sve teža i sve skuplja, čime je i proces zagađenja životne sredine sve intenzivniji. Jedno od rešenja ovakve situacije je okretanje ka zelenim izvorima energije, koji, budući da su obnovljivi i čistiji, mogu smanjiti zagađenje i emisiju štetnih gasova u okruženje. Međutim, prelazak na održiviji energetski sistem predstavlja veliki izazov, kako sa stanovišta finansijskih, materijalnih, kadrovskih i drugih ulaganja, tako i sa stanovišta neophodnosti kreiranja odgovarajućih novih tehničko-tehnoloških rešenja za realizaciju datog procesa. Usled toga, nužno je izvršiti promenu energetskog miksa putem diversifikacije energetskih izvora, koja bi značila povećanje korišćenja obnovljivih izvora energije i smanjenje korišćenja fosilnih goriva. Sve to uticalo bi na jačanje energetske sigurnosti i smanjenje rizika od prekida u snabdevanju električnom energijom.

U literaturi koncept održivog razvoja posmatra se kao sistem koji se sastoji od četiri međusobno tesno povezana podsistema održivosti, a to su: *održivost energije i resursa*, *ekonomska održivost*, *ekološka održivost* i *društvena održivost* [1], [2]. Pri tome, poslovanje po principu dugoročne održivosti posebno je značajno za privredne subjekte energetskog sektora. Ovo stoga što proizvodnja i potrošnja energije može da prouzrokuje značajne ekološke probleme na globalnom, nacionalnom i na lokalnom nivou. Da bi razvoj energetike bio zaista održiv neophodno je da se više oslanja na alternativne izvore energije, koji se mogu pribaviti po prihvatljivoj ceni, a koji ili nemaju nikakav, ili ostvaruju minimalan negativan uticaj na društvo kao celinu. Termin održiva energija odnosi se na korišćenje energetskih resursa koji mogu da zadovolje sadašnje energetske potrebe bez ugrožavanja mogućnosti da buduće generacije zadovolje svoje potrebe za energijom [3]. Zato održivi razvoj energetskog sektora treba da doprinese povećanju energetske sigurnosti preko smanjenja oslanjanja na fosilna goriva i preko jačanja energetske nezavisnosti. Primena savremenih tehnologija u proizvodnji i primeni održivih energija može znatno da doprinese smanjenju troškova otklanjanja negativnih uticaja energetike na životnu sredinu (kao što su uništavanje zemljišta i emisije gasova staklene bašte), a koji su povezani sa korišćenjem konvencionalnih izvora energije. Sve to može da omogući izgradnju održivijeg i otpornijeg sektora energetike. Razvoj energetike na održiv način podrazumeva i veći doprinos ekonomskom rastu, uz istovremeno smanjenje siromaštva, očuvanje životne sredine i uz širenje primene zelene i cirkularne ekonomije u oblasti energetike [4], [5].

Zelena ekonomija je jedan od osnovnih elemenata koncepta održivog razvoja. Pojam zelena ekonomija, kao i njegovi različiti aspekti, predstavljen je 1989. godine u izveštaju „Nacrt plana za zelenu ekonomiju“. Od tada do danas navođene su različite definicije koncepta „ozelenjavanja“ modernih ekonomija na putu ka održivom razvoju, a koje u prvi plan ističu tehnološke inovacije, efikasnost upotrebe resursa, značaj očuvanja prirodnog kapitala, ekološke rizike razvoja, kao i razvoj društva [6].

U konceptu održivog razvoja široka primena zelene energije u procesu privrednog razvoja zauzima veoma značajno mesto. Koncept ekonomije zelene energije (*green energy economy* - *GEE*) zalaže se za postizanje ravnoteže između ekonomije, društva i životne sredine, preko istovremenog [3]:

- povećanja ulaganja u čistu energiju;
- stimulisanja inovacija u sektoru energetike i razvoju tržišta za tehnologije sa niskim sadržajem ugljenika;
- kreiranja novih „zelenih radnih mesta“;
- povećanja energetske sigurnosti i konkurentnosti nacionalne privrede;
- smanjenja emisije CO_2;
- smanjenja ekonomskih nejednakosti i siromaštva;
- promovisanja međugeneracijske jednakosti i
- stvaranja novih mogućnosti za ljudski razvoj.

Zeleni energetski resursi i tehnologije smatraju se ključnim komponentama održivog razvoja. Za to se navode tri razloga [1]:

1) ostvarivanje manjeg negativnog uticaja na životnu sredinu u odnosu na druge izvore energije;
2) nemogućnost iscrpljivanja ako se pažljivo koriste, pri čemu se obezbeđuje pouzdano i održivo snabdevanje energijom i
3) podrazumevanje decentralizacije sistema, čime se značajno povećava njegova fleksibilnost i pruža mogućnost za lokalna rešenja koja su nezavisna od nacionalne mreže i koja mogu da pruže ekonomsku korist maloj izolovanoj populaciji.

Različiti oblici energije, kao što su energija dobijena od sunca, vode, vetra, biomase i geotermalna energija, predstavljaju izvore energije koji su ekološki prihvatljiviji i održiviji. Sa stanovišta održivog razvoja korišćenje datih oblika energije smatra se zelenim jer može znatno da smanji negativan uticaj na kvalitet vazduha, vodnih resursa i zemljišta, a koji nastaje korišćenjem energije dobijene iz fosilnih goriva. Osim toga, proizvodnja zelene energije u skladu je s rastućom tražnjom za čistom energijom u industriji i domaćinstvima.

Da bi se uspešno izgradio sigurniji, održiviji i pristupačniji energetski sistem neophodno je konstantno smanjivanje ekoloških pretnji kao što su: klimatske promene, gubitak biodiverziteta, zagađenje i gomilanje otpada i slično. Navedenim procesima znatno može da doprinese primena principa cirkularne ekonomije u procesu proizvodnje i korišćenja energije. U literaturi cirkularna ekonomija smatra se stubom održivosti, sigurnosti i efikasnosti energetskog sektora, kao i efikasnim sredstvom za ubrzanje dekarbonizacije. Osnovu koncepta cirkularne ekonomije čini unapređenje ekonomskog rasta uz smanjenje i eliminisanje otpada, uz očuvanje prirodnog kapitala, sa racionalnim upravljanjem oskudnim resursima, uz maksimalnu energetsku efikasnosti, recikliranje materijala i njihovu ponovnu upotreba. Unapređenje i očuvanje prirodnih resursa pomoću efikasnog upravljanja prirodnim kapitalom, racionalno korišćenje materijala i resursa kako bi se maksimizirala njihova vrednost, kao i eliminisanje negativnih eksternalija, predstavljaju osnovne principi cirkularne ekonomije. U cilju povećanja energetske efikasnosti veoma je bitan prelazak preduzeća na poslovne modele u okviru cirkularne ekonomije [7]. Stvaranje resursa iz otpada i razvijanje tehnologija za proizvodnju energije iz otpada (*waste-to-energy*, *WtE*) u skladu s principima cirkularnosti jedan je od najefikasnijih načina da se ostvari cilj održive proizvodnje energije, tj. proizvodnje energije sa niskom emisijom ugljenika, uz smanjenje rizika po zdravlje i životnu sredinu koje prouzrokuje otpad. Cirkularna ekonomija predstavlja adekvatnu zamenu za linearnu ekonomiju zato što se njenom primenom eliminiše otpad, maksimizira efikasnost resursa, optimizuje potrošnja materijala, koriste prednosti obnovljivih resursa i kontinuirano dopunjuju prirodni resursi [8].

Jedan od velikih problema proizvodnje energije iz konvencionalnih izvora jeste emisija gasova staklene bašte. Dati problem moguće je rešiti primenom novih tehnologija, kao i efikasnijim korišćenjem otpadnih materijala, kao što su biogas i biomasa. Najveći proizvođači električne energije iz biogasa, bioenergije, obnovljivog komunalnog otpada i čvrstih biogoriva jesu Evropa, Azija i Severna Amerika. Iako se u svetu količina električne energije proizvedene iz otpada povećala od 2012. do 2021. godine, njeno učešće u ukupno proizvedenoj električnoj energiji 2021. godine iznosilo je samo 3 procenta. Trebalo bi istaći da proces primene koncepta cirkularne ekonomije nije nimalo lak ni jednostavan, što se posebno odnosi na energetski sektor. Naime, na putu ka većoj primeni ovog koncepta u energetskom sektoru postoje mnogobrojne prepreke, kao što su postojeće politike i propisi koji su zasnovani na linearnim ekonomskim modelima, nedovoljna informisanost šire javnosti o prednostima reciklaže i cirkularnih sistema, postojanje rizika po životnu sredinu i pored smanjene emisije štetnih materija (npr. proizvodnja biogoriva je povezana sa problemima sigurnog snabdevanja hranom, iscrpljivanja vode, kontaminacije zemljišta, krčenja šuma, zagađivača povezanih sa đubrivom itd.).

Iako je korišćenje obnovljivih izvora energije sve veće, kao i uprkos činjenici da se prilikom proizvodnje električne energije primenjuju određeni oblici cirkularne ekonomije, primarni izvor energije i dalje je fosilno gorivo. U prilog tome govore i podaci da se oko 60% svetske električne energije proizvodi iz fosilnih goriva (ugalj, nafta, prirodni gas i dr.), oko 19% dobija se iz nuklearne energije, dok se samo oko 21% svetske električne energije dobija iz obnovljivih izvora [9].

III POKAZATELJI ODRŽIVOG RAZVOJA ENERGETIKE

Koncept održivog razvoja energetike je složen i višedimenzionalan. Može se definisati kao razvoj koji je kontinuiran i koji je podržan od strane ekonomski profitabilnog, društveno i ekološki odgovornog sektora energetike sa globalnom i dugoročnom vizijom [10]. Aktivnosti povezane sa ovim konceptom primarno su usmerene na veću upotrebu obnovljivih izvora energije (diversifikaciju energetskog miksa), poboljšanje energetske efikasnosti, smanjenje emisija gasova sa efektom staklene bašte i unapređenje kvaliteta života i smanjenje energetskog siromaštva stanovništva [11].

Tranzicija ka održivom razvoju sektora energetike donosi mnogobrojne ekonomske, ekološke i društvene koristi za nacionalne privrede. Jedna od datih prednosti jeste i činjenica da se diversifikacijom energetskih izvora smanjuje zavisnost ekonomija od raspoloživih rezervi fosilnih goriva, zatim povećava se energetska sigurnost i nezavisnost zemalja, a samim tim smanjuje se i rizik od pojave poremećaja u snabdevanju energijom. Tranzicija ka održivosti donosi povećanje energetske efikasnosti, a u dugom roku omogućava znatne uštede u troškovima, koje se ne odnose samo na snižavanje troškova proizvodnje energije, već i na snižavanje troškova saniranja zagađenja vazduha i klimatskih promena. Prednosti tranzicije ka održivom razvoju energetike ogledaju se i u mogućnosti otvaranja novih radnih mesta u sektoru obnovljive energije, u rastu investicija za projekte održive energije, kao i u otvaranju novih ekonomskih mogućnosti za razvoj ruralnih područja (kao što su obezbeđenje novih izvora prihoda za poljoprivrednike i zemljoposednike), što sve utiče na jačanje konkurentnosti i ubrzanje ekonomskog rasta jedne privrede.

Tabela 1. Pregled pokazatelja održivog razvoja energetike [11], [12], [13], [14]

Dimenzija	Pokazatelj	Uticaj
Energija	Ukupna ponuda primarne energije po stanovniku	pozitivan
	Potrošnja primarne energije po stanovniku	negativan
	Potrošnja finalne energije po stanovniku	negativan
	Učešće energije iz obnovljivih izvora energije u bruto finalnoj potrošnji energije	pozitivan
	Zavisnost od uvoza energije (neto-uvoz/ukupno raspoloživa energija)	negativan
	Gubici električne energije (proizvodnja - potrošnja + neto uvoz električne energije)	negativan
Životna sredina	Ukupne emisije fosilnog CO_2	negativan
	Intenzitet ugljenika (CO_2/BDP)	negativan
	Emisije gasova sa efektom staklene bašte po stanovniku u oblasti energetike	negativan
Ekonomija	BDP po stanovniku	pozitivan
	Energetska produktivnost (BDP/ukupno raspoloživa energija)	pozitivan
	Ukupna izdvajanja za istraživanje i razvoj	pozitivan
	Primarna energetska intenzivnost (ukupna primarna potrošnja energije/BDP)	negativan
	Finalna energetska intenzivnost (ukupna finalna potrošnja energije/BDP)	negativan
	Neto trgovinska razmena energenata sa inostranstvom ((izvoz-uvoz)/BDP)	pozitivan
Društvo	Cena električne energije za domaćinstva	negativan
	Stanovništvo koje nije u mogućnosti da adekvatno zagreje stambeni prostor	negativan

U zemljama Evropske unije energetska tranzicija ima za cilj stvaranje konkurentnog, sigurnog i održivog energetskog sektora putem razvoja obnovljivih izvora energije, odnosno većeg korišćenja zelene (obnovljive) energije. Agencija za statistiku Evropske unije (Eurostat) definisala je set pokazatelja za praćenje napretka u ostvarenju globalnih ciljeva održivog razvoja. Ostvarenje ciljeva održivog razvoja u oblasti energetike, obezbeđenje dostupne i obnovljive energije, prati se na osnovu sledećih sedam pokazatelja [12]: 1) potrošnja primarne energije; 2) potrošnja finalne energije; 3) potrošnja finalne energije u domaćinstvima po stanovniku; 4) energetska produktivnost; 5) učešće energije iz obnovljivih izvora u bruto finalnoj potrošnji energije; 6) zavisnost od uvoza energije i 7) stanovništvo koje nije u mogućnosti da adekvatno zagreje stambeni prostor. Rast energetske produktivnosti i povećanje električne energije proizvedene iz obnovljivih izvora ubrzava, dok povećanje potrošnja primarne i električne energije po stanovniku i veća zavisnost od uvoza energije usporava tranziciju energetskog sektora ka dostupnoj i obnovljivoj energiji.

U literaturi se za potrebe istraživanja o ostvarenim rezultatima u oblasti održivog razvoja energetike, pored navedenih, koriste i drugi pokazatelji energetskog sektora. U Tabeli 1. prikazani su najznačajniji pokazatelji održivog razvoja energetike u oblasti energetske sigurnosti, ekološke bezbednosti, ekonomske i socijalne sigurnosti, kao i njihov uticaj na energetsku tranziciju.

Analiza uspešnosti implementacije koncepta održivog razvoja energetike u jedanaest zemalja EU na području centralne i istočne Evrope ukazala je na postojanje značajnih razlika u razvoju energetskog sektora, čije postojanje zahteva primenu različitih pristupa u kreiranju energetske politike koja će podržati energetsku tranziciju u ovim zemljama. Za ovu analizu korišćen je 21 pokazatelj održivog razvoja energetike u oblasti energetske sigurnosti, ekološke bezbednosti, ekonomske i socijalne sigurnosti za 2008. i 2018. godinu. Najuspešnije u pogledu sprovođenja energetske tranzicije su Letonija i Hrvatska, dok su najlošije rangirane Poljska i Bugarska [11].

Prema rezultatima komparativne analize energetske efikasnosti zemalja Evropske unije i Zapadnog Balkana, dobijenih primenom DEA pristupa, osam zemalja Evropske unije (Irska, Luksemburg, Belgija, Holandija, Češka, Francuska, Kipar i Austrija) bile su relativno energetski efikasnije u odnosu na ostale posmatrane zemlje u 2021. godini [7].

Preduslov za ostvarivanje koristi koje donosi energetska tranzicija jeste otklanjanje velikog broja prepreka. Visoki investicioni troškovi za izgradnju infrastrukture koja je potrebna za proizvodnju obnovljive energije i dalje predstavljaju jednu od ključnih barijera njihovog šireg korišćenja i pored toga što je tokom poslednje decenije došlo do značajnog napretka u razvoju tehnologije za proizvodnju obnovljive energije (što je uticalo na veću efikasnost i na snižavanje troškova proizvodnje energije). Jedan od problema energetske tranzicije jeste i postojeća energetska struktura koja se oslanja na tradicionalne izvore energije, kao i sumnja koliko će projekti obnovljive energije potencijalno uticati na povećanje zagađenja, buke i na promenu pejzaža. Funkcionisanje tržišnog mehanizma uglavnom ne dovodi do optimalnog nivoa/obima korišćenja energije iz obnovljivih izvora, što je posledica različitih vidova nesavršenosti tržišta (nizak nivo i/ili prisustvo nelojalne konkurencije u odnosu na ostale vrste energenata, nepotpuna internalizacija eksternih troškova i rigidno projektovani elektroenergetski sistemi koji otežavaju/ograničavaju povećanje udela energije iz obnovljivih izvora) [15].

Da bi se izazovi adekvatno procenili i prepreke lakše prevazišle, važno je razmotriti izazove i mogućnosti prelaska na održive izvore energije i pažljivo proceniti troškove i koristi (finansijske koristi i pozitivne eksterne efekte) svakog izvora energije. Energetska tranzicija je povezana i sa promenama na tržištu rada. Za razvoj održive energetike neophodni su odgovarajući stručnjaci za pojedina polja, koji poseduju odgovarajuće, specifično, tehničko znanje i veštine. Većina radnika ne poseduje odgovarajuće veštine za obavljanje novih, zelenih poslova, s obzirom na to da ih nisu ni mogli steći jer se radi o novim poslovima. Zato se stvara raskorak u veštinama, koji se može prevazići samo odgovarajućom obukom kadra. Za kompanije dodatna obuka i priprema zaposlenih predstavlja dodatni trošak i zahteva dodatno vreme, što takođe može biti jedan od problema prilikom tranzicije energetike na održive uslove poslovanja. Zato su za podsticanje proizvodnje i korišćenja obnovljive energije neophodne i odgovarajuće reforme, pre svega u sferi promene energetske politike. Novim, adekvatnim energetskim politikama trebalo bi kreirati stimulativno okruženje za unapređenje tehnologija za proizvodnju i korišćenje obnovljivih izvora energije, kako bi se oni učinili više dostupnim i pristupačnim za potrošače. Takođe je neophodna kontinuirana saradnja između sektora obnovljivih izvora energije i obrazovnog sistema koja treba da bude usmerena ka usklađivanju tražnje za specifičnim veštinama sektora obnovljivih izvora energije i veštinama koje nude studijski programi na fakultetima [16].

IV Energetska tranzicija u zemljama EU i Srbiji

Predmet istraživanja u ovom delu rada jeste analiza uspešnosti implementacije koncepta održivog razvoja energetike u zemljama Evropske unije i Srbiji. Analiza ima za cilj da se sagledaju razlike između posmatranih zemalja, da se sagledaju uzroci datih razlika, kao i da se predlože budući pravci akcija.

Na osnovu pregleda najznačajnih pokazatelja održivog razvoja energetike koji su predstavljeni u trećem delu rada i po ugledu na 3E&S model (*energy, environment, economy, and society model*) izabrano je dvanaest pokazatelja koji obuhvataju četiri dimenzije održivog razvoja energetike, a to su [11], [17]:

- *energija* (potrošnja primarne energije po stanovniku, potrošnja finalne energije po stanovniku, udeo obnovljivh izvora energije u bruto finalnoj potrošnji energije i zavisnost od uvoza energije),
- *životna sredina* (ukupne emisije CO_2 i intenzitet ugljenika),
- *ekonomija* (BDP po stanovniku, energetska produktivnost, ukupna izdvajanja za istraživanje i razvoj i primarni energetski intenzitet) i
- *društvo* (cena električne energije za krajnje potrošače i stanovništvo koje nije u mogućnosti da adekvatno zagreje stambeni prostor).

Podaci za izabrane pokazatelje odnose se na 2013. i 2023. godinu, a preuzeti su iz baza podataka Agencije za statistiku Evropske unije (Eurostat), Uprave za energetske informacije (EIA) američkog Ministarstva energetike i Svetske banke [12], [18], [19]. Kako bi se sagledala promena vrednosti pokazatelja tokom posmatranog vremenskog perioda izračunata je procentualna promena njihove vrednosti u odnosu na 2013. godinu. U Tabeli 2 prikazana je procentualna promena vrednosti izabranih pokazatelja održivog razvoja energetike za zemlje Evropske unije i Srbiju između 2013. i 2023. godine, dok je u Tabeli 3 prikazana vrednost pokazatelja u 2023. godini.

Tabela 2. Procentualna promena vrednosti pokazatelja održivog razvoja energetike za zemlje EU i Srbiju između 2013. i 2023. godine

Zemlja	Potrošnja primarne energije po stanovniku	Potrošnja finalne energije po stanovniku	Udeo OIE u bruto finalnoj potrošnji energije	Zavisnost od uvoza energije	Ukupne emisije CO_2	Intenzitet ugljenika	BDP po stanovniku	Energetska produktivnost	Ukupna izdvajanja za istraživanje i razvoj*	Primarna energetska intenzivnost	Cena električne energije za krajnje potrošače	Stanovništvo koje nije u mogućnosti da adekvatno zagreje stambeni prostor
Austrija	-14,95	-14,23	25,04	-0,34	-13,56	-27,94	11,39	22,81	8,29	-23,64	27,43	44,44
Belgija	-17,99	-16,06	92,17	-2,26	-18,87	-34,05	16,47	31,99	45,88	-29,59	100,18	3,45
Bugarska	13,38	22,94	19,32	3,67	-15,54	-53,94	106,64	28,95	21,39	-45,13	23,16	-53,90
Češka	-15,58	-6,13	33,45	51,11	-19,77	-50,20	55,92	40,97	6,43	-45,86	89,77	-1,61
Danska	-18,31	-10,27	63,38	215,69	-34,72	-44,74	11,53	42,18	-2,37	-26,76	27,03	81,58
Estonija	-30,81	-13,77	61,50	-76,10	-48,96	-68,54	56,05	74,44	4,40	-55,66	59,88	41,38
Finska	-4,73	-10,65	38,55	-40,44	-38,86	-44,09	6,51	9,52	-8.30	-10,55	62,04	116,67
Francuska	-19,13	-18,04	60,54	-6,49	-24,04	-29,90	4,74	33,03	-1,66	-22,79	50,92	83,33
Grčka	-10,38	8,13	64,88	22,43	-32,44	-34,37	8,47	29,75	84,10	-17,38	48,88	-34,92
Holandija	-23,61	-23,38	271,35	196,77	-27,97	-44,85	22,76	49,00	6,68	-37,77	99,95	144,83
Hrvatska	16,55	18,01	0,04	17,47	-4,83	-32,51	54,67	27,48	55,36	-24,65	7,87	-37,37
Irska	-5,51	-4,09	102,81	-14,87	-7,64	-59,25	97,43	103,11	-36,21	-52,14	19,17	-28,00
Italija	-9,51	-5,22	17,04	-2,51	-15,16	-20,61	9,11	22,28	-0,08	-17,06	65,01	-49,47
Kipar	0,03	4,53	139,83	-4,02	8,97	-22,96	31,49	31,30	71,09	-19,65	35,47	-44,59
Letonija	4,76	7,20	16,70	-41,44	-11,67	-39,05	55,36	34,12	30,46	-32,57	121,63	-68,72
Litvanija	11,88	13,73	40,71	-9,94	-5,46	-45,14	77,49	33,78	5,41	-36,97	105,84	-31,51
Luksemburg	-29,84	-30,40	310,85	-6,68	-32,33	-48,55	7,23	45,70	-18,95	-34,58	20,60	31,25
Mađarska	1,76	5,65	5,63	23,83	-7,59	-40,96	61,44	33,26	1,15	-36,97	-17,18	-50,68
Malta	-22,94	7,89	300,98	-6,32	-25,10	-63,78	59,37	21,83	-9,87	-51,65	-24,22	-71,55
Nemačka	-24,96	-16,01	56,63	6,36	-28,33	-39,69	15,09	44,04	9,31	-34,80	41,32	54,72
Poljska	3,91	15,78	44,64	82,92	-10,14	-42,46	61,92	44,42	69,52	-35,83	19,53	-58,77
Portugalija	-2,55	7,62	36,83	-8,84	-22,68	-39,38	26,09	23,18	30,43	-22,72	-0,48	-25,45
Rumunija	3,47	12,06	7,83	52,12	-13,18	-53,02	93,78	48,02	20,44	-46,60	43,01	-14,97
Slovačka	-5,72	-9,05	67,67	-1,14	-13,70	-35,63	33,74	32,69	21,94	-29,50	11,43	50,00
Slovenija	-14,45	-8,93	8,23	3,77	-25,12	-48,16	40,34	51,08	-18,12	-39,04	19,07	-26,53
Španija	-8,24	-2,48	64,79	-2,26	-12,03	-26,04	14,68	24,09	4,28	-19,99	10,14	160,00
Švedska	-18,70	-12,08	32,38	-19,55	-19,12	-19,23	-8,76	34,09	9,82	-10,90	26,70	555,56
Srbija	8,20	18,68	20,54	86,36	-4,96	-41,05	74,44	15,00	41,46	-37,97	70,92	-48,09

* Period posmatranja 2013. i 2022. godina

Tabela 3. Pokazatelji održivog razvoja energetike za zemlje EU i Srbiju, 2023. godina

Zemlja	Potrošnja primarne energije po stanovniku (toe)	Potrošnja finalne energije po stanovniku (toe)	Udeo OIE u bruto finalnoj potrošnji energije (%)	Zavisnost od uvoza energije (%)	Ukupne emisije CO_2 (mil. tona)	Intenzitet ugljenika ($kgCO_2/USD$)	BDP po stanovniku (tekući USD)	Energetska produktivnost (EUR/kgoe)	Ukupna izdvajanja za istraživanje i razvoj (% BDP)*	Primarna energetska intenzivnost (kgoe/USD)	Cena električne energije za krajnje potrošače (EUR/kWh)	Stanovništvo koje nije u mogućnosti da adekvatno zagreje stambeni prostor (%)
Austrija	3,22	2,65	40,84	61,05	58,58	0,11	56033,57	10,93	3,20	0,057	0,27	3,90
Belgija	3,57	2,66	14,74	76,10	83,37	0,13	54700,91	7,84	3,40	0,065	0,44	6,00
Bugarska	2,58	1,49	22,55	39,72	36,09	0,35	15885,54	2,94	0,77	0,162	0,11	20,70
Češka	3,27	2,08	18,59	41,68	85,62	0,25	31591,18	5,23	2,00	0,103	0,32	6,10
Danska	2,59	2,25	44,40	38,87	27,26	0,07	68453,88	18,81	2,90	0,038	0,38	6,90
Estonija	2,99	1,90	40,95	3,47	10,02	0,24	30133,30	4,64	1,80	0,099	0,22	4,10
Finska	5,61	3,98	50,75	29,57	31,62	0,11	52925,69	6,10	3,00	0,106	0,26	2,60
Francuska	3,07	1,90	22,28	44,87	272,48	0,09	44690,93	10,23	2,20	0,069	0,23	12,10
Grčka	1,91	1,51	25,27	75,60	55,20	0,23	23400,73	8,94	1,50	0,082	0,23	19,20
Holandija	3,01	2,29	17,42	70,45	118,67	0,10	64572,01	10,46	2,30	0,047	0,38	7,10
Hrvatska	2,20	1,84	28,05	55,72	17,52	0,21	21865,46	6,68	1,24	0,101	0,15	6,20
Irska	2,66	2,26	15,25	77,90	34,43	0,06	103887,80	26,16	1,00	0,026	0,27	7,20
Italija	2,28	1,84	19,59	74,81	313,46	0,14	39003,32	11,80	1,30	0,059	0,38	9,50
Kipar	1,86	1,41	20,21	92,21	7,17	0,21	36551,42	9,48	0,83	0,074	0,37	16,90
Letonija	2,29	2,08	43,22	32,73	6,51	0,15	22502,84	5,66	0,80	0,102	0,31	6,60
Litvanija	2,19	1,85	31,93	68,04	12,46	0,16	27786,01	6,02	1,00	0,079	0,28	20,00
Luksemburg	5,55	5,25	14,36	90,62	6,99	0,08	128678,19	15,08	1,00	0,043	0,20	2,10
Mađarska	2,30	1,75	17,12	62,06	40,19	0,19	22141,87	5,69	1,40	0,104	0,12	7,20
Malta	1,63	1,27	15,08	97,55	1,82	0,08	40395,77	4,52	0,67	0,040	0,13	6,80
Nemačka	2,87	2,25	21,55	66,38	596,15	0,13	54343,23	11,84	3,10	0,053	0,41	8,20
Poljska	2,55	1,91	16,56	48,02	289,28	0,36	22056,67	5,69	1,50	0,116	0,18	4,70
Portugalija	1,96	1,63	35,16	66,87	37,23	0,13	27331,21	8,98	1,73	0,072	0,21	20,80
Rumunija	1,57	1,22	25,76	27,86	68,24	0,19	18404,27	6,35	0,47	0,086	0,19	12,5

Slovačka	2,86	1,71	16,99	57,73	30,74	0,23	24491,38	5,48	1,00	0,117	0,19	8,10
Slovenija	2,78	2,12	25,07	49,27	11,33	0,16	32610,11	7,72	2,10	0,085	0,19	3,60
Španija	2,28	1,67	24,85	68,42	221,62	0,14	33509,01	9,94	3,40	0,068	0,25	20,80
Švedska	3,93	2,88	66,39	26,39	36,56	0,06	55516,84	10,07	1,40	0,071	0,27	5,90
Srbija	2,26	1,55	25,43	44,90	42,36	0,52	12281,51	2,53	0,97	0,184	0,10	9,50

* Podaci za 2022. godinu .

Na osnovu analize podataka prikazanih u Tabeli 2 i Tabeli 3 može se zaključiti da postoje određene sličnosti, ali i značajne razlike između posmatranih zemalja. Šesnaest zemalja povećalo je energetsku efikasnost zahvaljujući smanjenju potrošnje i primarne i finalne energije po stanovniku. Sve posmatrane zemlje povećale su udeo obnovljivih izvora energije u bruto finalnoj potrošnji energije. Najveći rast su imale Luksemburg, Malta, Holandija, Kipar i Irska. U 2023. godini udeo obnovljivih izvora energije u bruto finalnoj potrošnji energije od preko 50% imale su Švedska (66,39%) i Finska (50,75%). Najmanje dati udeo imale su Luksemburg i Belgija (oko 14%). Sa stanovišta uticaja na životnu sredinu, sve posmatrane zemlje uspele su da smanje intenzitet ugljenika (emisiju CO_2 po jedinici BDP-a) tokom posmatranog perioda.

Kada je u pitanju Republika Srbija, udeo obnovljivih izvora energije u bruto finalnoj potrošnji energije u periodu 2013-2023. godina povećan je relativno malo, sa 21,10% u 2013. na 25,43% u 2023. godini. Prema Integrisanom nacionalnom energetskom i klimatskom planu Republike Srbije (INEKP), koji predstavlja strateški dokument o obnovljivim izvorima energije, energetske efikasnosti i smanjenja emisija gasova sa efektom staklene bašte, očekuje se da će udeo obnovljivih izvora energije u bruto finalnoj potrošnji energije 2030. godine iznositi 27%, dok će udeo obnovljivih izvora energije u ukupnoj proizvodnji električne energije 2030. godine iznositi 29%, a 2050. godine 38% [20]. Ostvarenje planiranog trebalo bi da doprinese nastavku smanjenja ukupne emisije CO_2 i energetskog intenziteta.

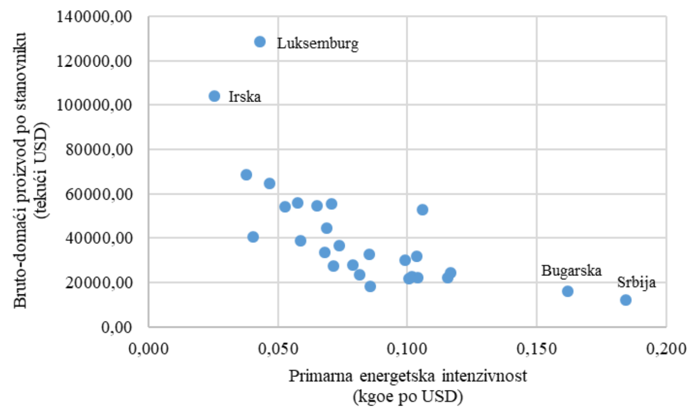
Najveće smanjenje zavisnosti od uvoza energije postigle su Estonija (76,10%), Letonija (41,44%) i Finska (40,44%). Za razliku od ovih zemalja, Danska i Holandija znatno su povećale svoju zavisnost od uvoza energije tokom posmatranog perioda. U 2023. godini najmanju zavisnost od uvoza energije imala je Estonija (3,47%), a najveću Malta, Kipar i Luksemburg (preko 90%).

Najlošija situacija u pogledu energetskog siromaštva, posmatrana na osnovu udela stanovništva koje nije u mogućnosti da adekvatno zagreje stambeni prostor, jeste u Španiji, Portugaliji, Bugarskoj, Litvaniji i Grčkoj. Procenat stanovništva koje nije u mogućnosti da adekvatno zagreje stambeni prostor u navedenim zemljama iznosio je oko 20%.

Energetska produktivnost, kao mera efikasnosti korišćenja energije, najveća je bila u Irskoj, Danskoj i Luksemburgu (26,16, 18,81 i 15,08 EUR/kg ekvivalentne nafte respektivno). Srbija i Švedska imale su najmanju energetsku produktivnost, manje od 3 EUR/kg ekvivalentne nafte. Sve zemlje zabeležile su rast energetske produktivnosti tokom posmatranog perioda.

U 2023. godini učešće izdvajanja za istraživanje i razvoj u BDP-u kretalo se od 3,40% u Belgiji i Sloveniji, do 0,47% u Rumuniji.

Koeficijent korelacije primarne energetske intenzivnosti i BDP-a po stanovniku je negativan i visok, a iznosi -0,68. Dve zemlje koje imaju najveći BDP po stanovniku, Luksemburg i Malta (preko 100.000 USD), imaju i najniži primarni energetski intenzitet. Važi i obrnuto, dve zemlje koje imaju najniži BDP po stanovniku, Bugarska i Srbija, imaju i najviši primarni energetski intenzitet u 2023. godini (Slika 1).



Slika 1. Primarni energetski intenzitet i bruto-domaći proizvod po stanovniku, 2023. godina

Kritična pitanja koja oblikuju odnos između energetskog sektora i održivosti jesu održivo upravljanje, regulatorni okvir i tehnološke inovacije [21]. Prognoze pokazuju da će fosilna goriva i dalje biti izvor najvećeg dela svetske potrošnje ukoliko ne dođe do promene propisa i regulative kojima bi se ograničila njihova upotreba [22]. Prvi uslov za početak tranzicije ka ekonomiji zelene energije zahteva definisanje troškovno efikasnih energetskih politika (politike koje promovišu prakse i tehnologije održive energije, poreski podsticaji, direktne subvencije i dr.) i strategija čija primena će obezbediti veću proizvodnju i potrošnju energije iz obnovljivih izvora. Tranzicija ka ekonomiji zelene energije zahteva veća ulaganja u energetske sisteme sa niskim sadržajem ugljenika i definisanje strategija za veću primenu zelene energije i kreiranje održivih energetskih sistema. Date strategije treba da ukažu na moguće načine rešavanja ekoloških i socijalnih problema koji su povezani sa proizvodnjom i korišćenjem energije iz fosilnih goriva. Njihova primena ima za cilj maksimiziranje koristi od zelenih izvora energije. Uz odgovarajuću politiku i ekonomsku podršku obnovljiva energija ima potencijal da nadmaši fosilna goriva u pogledu konkurentnosti [3]. Bitno je napomenuti da je neophodno i da se preduzmu odgovarajuće mere kako bi se podigla svest stanovništva o tome kakve negativne posledice po životnu sredinu mogu nastati usled neadekvatne potrošnje energije.

VIII Zaključak

Primena koncepta održivog razvoja znatno je uslovljena i održivošću energetskog sektora, koji bi trebalo da obezbedi da se postigne ravnoteža između energetske sigurnosti, ekonomskog rasta i zaštite životne sredine. Zeleni energetski resursi i tehnologije predstavljaju ključne komponente ovog koncepta. Održivi razvoj energetskog sektora treba da doprinese povećanju energetske sigurnosti i jačanju energetske nezavisnosti smanjenjem oslanjanja na fosilna goriva, uz značajnije korišćenje alternativnih zelenih izvora energije.

Može se zaključiti da tranzicija ka održivom razvoju energetskog sektora donosi mnogobrojne ekonomske, ekološke i društvene koristi, kako za razvijene ekonomije, tako i za zemlje u razvoju, među kojima je i Srbija. Kao najznačajnije koristi mogu se navesti sledeće: smanjenje zavisnosti nacionalnih ekonomija od raspoloživih rezervi fosilnih goriva, povećanje energetske sigurnosti i nezavisnosti zemalja, povećanje energetske efikasnosti zahvaljujući značajnim uštedama u troškovima u dugom roku, kreiranje novih radnih mesta, otvaranje ekonomskih mogućnosti za razvoj nedovoljno razvijenih područja i smanjenje emisije CO_2. Preduslov za ostvarivanje navedenih koristi zelene energetske tranzicije jeste otklanjanje određenih prepreka, od kojih su najizraženije: veliki investicioni troškovi za izgradnju infrastrukture potrebne za proizvodnju obnovljive energije, postojeća energetska struktura koja se oslanja na tradicionalne izvore energije, prisustvo raskoraka u veštinama (neposedovanje odgovarajućih veština za obavljanje zelenih poslova) i neefikasno funkcionisanje tržišnog mehanizma.

U radu je izvršena analiza najznačajnijih pokazatelje uspešnosti ostvarivanja ciljeva održivog razvoja energetike, odnosno stvaranja konkurentnog, sigurnog i održivog energetskog sektora. Takođe je izvršena analiza dvanaest pokazatelja održivog razvoja energetika u oblasti energetske sigurnosti, ekološke bezbednosti, ekonomske i socijalne sigurnosti. Uzorak su činile zemlje članice Evropske unije i Srbija, a analiza pokazatelja vršena je za period 2013-2023. godina. Rezultati analize ukazuju na postojanje određenih sličnosti, ali i značajnih razlika između posmatranih zemalja. Tokom posmatranog perioda sve zemlje uspele su, u odnosu na 2013. godinu da povećaju energetsku produktivnost i smanje primarnu energetsku intenzivnost, ukupne emisije CO_2 i intenzitet ugljenika. Navedeni rezultati ukazuju na povoljna kretanja u pogledu ostvarenja ciljeva energetske tranzicije. Pored sličnosti, rezultati ukazuju i na postojanje značajnih razlika između analiziranih zemalja, pre svega u sferi potrošnje primarne i finalne energije po stanovniku, zatim u zavisnosti od uvoza energije, izdvajanja za istraživanje i razvoj i u udelu stanovništva koje nije u mogućnosti da adekvatno zagreje stambeni prostor. Rezultati analize takođe su potvrdili da zemlje koje su ekonomski najrazvijenije (imaju najveći BDP po stanovniku) karakteriše i najniži primarni energetski intenzitet i obrnuto.

U radu se takođe zaključuje da donošenje adekvatne energetske politike predstavlja jedan od preduslova održivog razvoja u energetskom sektoru. Primena principa i različitih elemenata održivog razvoja u ovom sektoru zahteva odgovarajuća ulaganja, primenu adekvatnih tehnoloških rešenja, ali i neophodno vreme za postizanje željenih efekata. Može se takođe zaključiti da samo energetske politike koje podržavaju zelenu energetsku tranziciju mogu da obezbede troškovno-efikasnu i stabilnu ponudu energije uz istovremeno obezbeđenje socijalne jednakosti i očuvanje životne sredine.

ZAHVALNICA

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Challenges of Sustainable Development in the Energy Sector

Abstract *– The application of the principles of sustainable development is one of the basic requirements of the modern economy. Fulfilment of the given principles is especially important in the branches of economy which are the biggest polluters of the environment, such as the energy sector. This paper discusses the challenges that arise in the sustainable development of the energy sector, considering its specificity and importance for the overall economic and social development. In studying this subject matter, we start from the consideration of the role and importance of sustainable development in the joint economy; then, we focus on the problems of the application of sustainable development in the energy sector, while in the final part of the paper, we conduct a comparative analysis of certain indicators of the energy sector in the EU countries and Serbia which concern its sustainability, such as energy efficiency, energy security, use of renewable sources and others. We conclude that a prerequisite for the sustainable development of this sector is the adoption of an adequate energy policy, since the application of the principles and various elements of sustainable development implies appropriate investments, adequate technological solutions, as well as a certain amount of time to achieve the desired effects. That is why a green and sustainable economy implies the implementation of the reforms that would enable energy transition, which would, in turn, contribute both to an increase in energy efficiency and to greater use of renewable energy sources and clean energy technologies.*

Index Terms *– Energy, Sustainable development, Green economy, Energy transition, Energy efficiency* doi: 10.46793/EEE25-1.40V

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Matematički modeli sistema za hlađenje pokretanih energijom sunčevog zračenja

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Rezime **-** S obzirom na sve intenzivnije i očiglednije promene klime i porast globalne temperature, a istovremeno i na rast svetske populacije i ubrzane procese migracije stanovništva iz ruralnih u urbane sredine, potrošnja energije za hlađenje stambenog i poslovnog prostora je u stalnom porastu, sa tendencijom da će se i dalje ubrzano uvećavati. Sa druge strane, s obzirom na danas opšteprihvaćenu teoriju da je porast globalne temperature prouzrokovan povećanim antropogenim emisijama gasova sa efektom staklene bašte, kao jedan od ključnih načina za usporavanje njenog porasta ustanovljen je princip neophodnosti prelaska sa fosilnih goriva na korišćenje obnovljivih izvora energije (OIE). U tom smislu, povezujući porast potreba za energijom za hlađenje i prelazak na korišćenje OIE, kao optimalno rešenje nameće se korišćenje sunčeve energije za potrebe hlađenja. U prilog tome idu činjenice da je, među svim vrstama OIE, korišćenje sunčeve energije najperspektivnije jer je neiscrpno, svuda dostupno i gotovo bez efekata zagađivanja okoline. Pored toga, potrebe za hlađenjem su najveće upravo kada i sunčevo zračenje dostiže svoj maksimum, a i potreba za hlađenjem je veća u oblastima sa toplijom klimom. Jedna od mogućih tehnologija koje omogućavaju ostvarivanje procesa hlađenja pomoću sunčeve energije predstavljaju apsorpcioni rashladni sistemi. Usled razvijanja sve efikasnijih sistema za prikupljanje i skladištenje sunčeve energije, postoji mnogo razloga za sve veće istraživanje u oblasti apsorpcionih rashladnih sistema. Pored objašnjenja principa rada i sagledavanja energetskih tokova, te određivanja energetskih stepena korisnosti ovih sistema u ovom radu su predstavljeni do sada razvijeni matematički modeli sistema za hlađenje pokretanih energijom sunčevog zračenja i izvršena njihova termodinamička analiza.

Ključne reči - solarno hlađenje, apsorpcioni rashladni sistemi, matematički modeli

I UVOD

Porast globalne temperature, zajedno sa porastom broja i veličinom urbanih termičkih ostrva, u kojima je još više izražen porast lokalne temperature vazduha, za posledicu ima sve veću potrošnju energije za potrebe hlađenja stambenog i poslovnog prostora. Budući da se predviđa da će do 2050. godine 68% svetske populacije živeti u urbanim sredinama, što zajedno sa ukupnim rastom svetske populacije znači da će još dodatnih 2,5 milijardi ljudi živeti u urbanim sredinama [1, 2]. Kako će oni živeti u objektima dominatno izgrađenim od betona i okruženi površinama prekrivenim asfaltom, dakle u okruženju koje će stvarati termička ostrva, to će dodatno uticati na dalji i sve brži rast potrošnje energije, pre svega električne energije za potrebe hlađenja prostora. Pored povećane potrošnje električne energije, koja će još zasigurno dugi niz godina u većoj meri biti proizvođena iz fosilnih goriva, poseban problem predstavljaće i potreba zamene preopterećene postojeće distributivne mreže, kako bi joj se povećao kapacitet i omogućilo zadovoljenje povećanih potreba za njenom potrošnjom.

Kao jedan od mogućih načina, kojim bi bar u domenu potreba za hlađenjem mogli da se prevaziđu ovi problemi, očekuje se da će biti korišćenje potpuno autonomnih i održivih tehnologija koje omogućavaju solarno hlađenje. Trenutno postoje dve izvedbe ovih sistema: kompresorski rashladni sistemi koji se pogone električnom energijom proizvedenom preko fotonaponskih panela i sorpcioni rashladni sistemi, koji se pogone toplotom dobijenom iz termosolarnih panela.

Sorpcioni rashladni sistemi se u zavisnosti od procesa mogu podeliti u adsorpcione i apsorpcione rashladne sisteme. Proces adsorpcije je proces adhezije atoma, jona i molekula gasa ili tečnosti na neku površinu na čijoj se površini zadržavaju i ne prodiru je. Proces apsorpcije je fizičko-hemijski proces rastvaranja atoma, molekula ili jona jedne materije u odgovarajući gas ili tečnost. U poređenju sa apsorpcionim, adsorpcioni rashladni sistemi imaju manju vrednost koeficijenta hlađenja (*EER - Energy Efficiency Ratio*) [3].

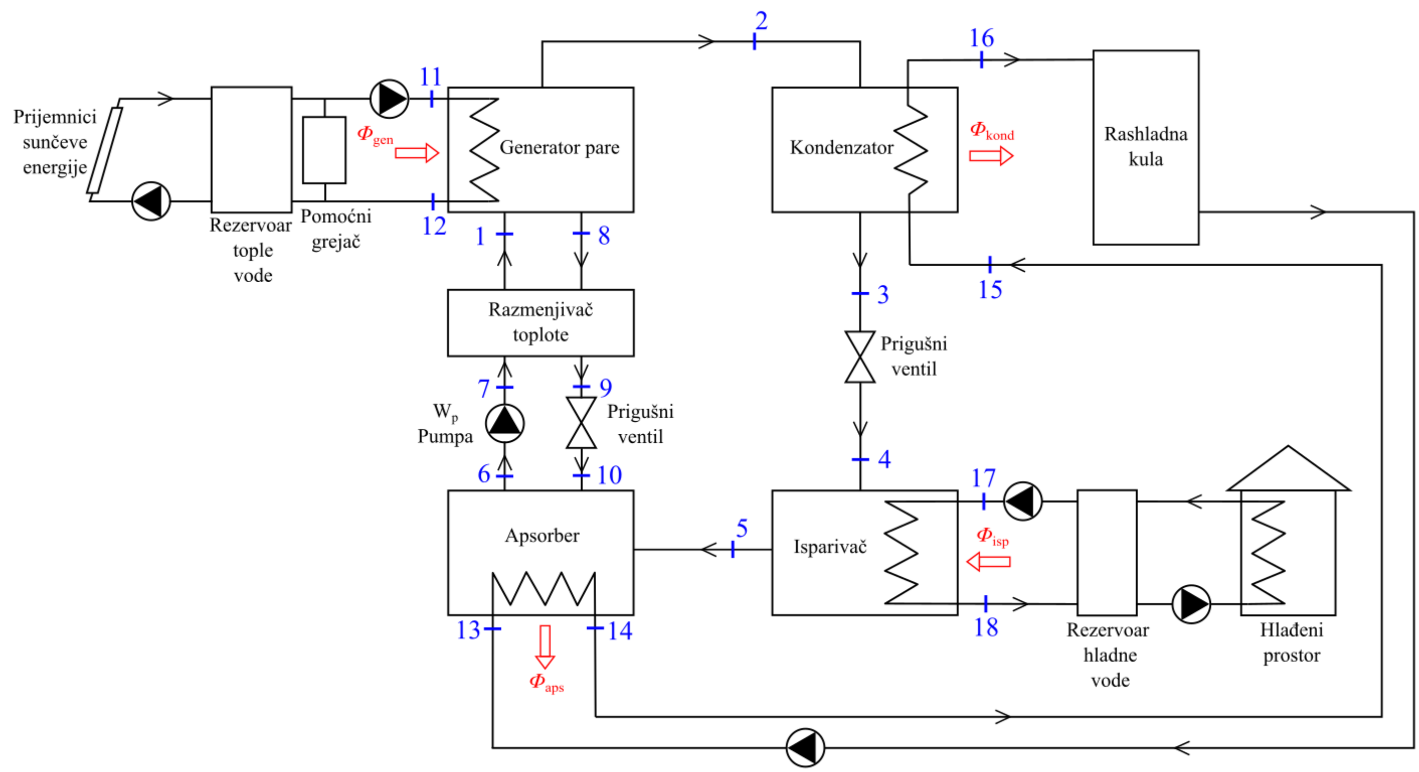
Apsorpcioni rashladni sistemi se prema tipu mogu podeliti na otvorene i zatvorene. U sistemima otvorenog tipa, lakše isparljiva komponenta rastvora umesto u kondenzator odlazi u atmosferski vazduh, dok se kod zatvorenog tipa ona kondenzuje u kondezatoru [4]. Pored toga, sistemi zatvorenog tipa, mogu se podeliti na one koje rade kontinualno i one koji rade sa prekidima [5]. Prema broju stepeni u kojima se ostvaruje proces apsorpcije, razlikuju se jednostepeni, dvostepeni i višestepeni solarni apsorpcioni rashladni sistemi [3].

Radni fluidi zatvorenih apsorpcionih rashladnih sistema koji rade kontinualno su najčešće dvokomponentni radni fluidi, odnosno binarne smeše. Binarnu smešu (rastvor) čine lakše isparljiva komponenta i teže isparljiva komponenta (apsorbent). Najčešće korišćene kombinacije radnih fluida u apsorpcionim rashladnim sistemima su litijum bromid-voda ($LiBr$-H_2O) i amonijak-voda (NH_3-H_2O) [6, 7]. U prvom slučaju lakše isparljiva komponenta je voda, a u drugom amonijak. Pored toga, kao radni fluidi mogu se koristiti i drugi fluidi kao što su: $LiNO_3$-NH_3, $LiCl$-H_2O, glicerol-voda itd. [8].

Koeficijenti hlađenja (*EER*) apsorpcionih sistema pogonjenih sunčevom energijom imaju jako malu vrednost: jednostepeni svega 0,6-0,8 [9], dvostepeni 1,4 i trostepeni 1,8 [10]. Mala efikasnost, tj. niske vrednosti *EER* posledica su relativno niske vrednosti temperature izvora toplote. Dvostepeni i trostepeni apsorpcioni sistemi imaju veću vrednost *EER* jer se primenjuju pri većim razlikama između temperatura kondenzacije i isparavanja. Takođe, *EER* sistema koji rade sa LiBr-H_2O kao radnim fluidom su veći od sistema koji rade sa drugim radnim fluidima [11].

Od svih vrsta obnovljivih izvora energije (OIE), korišćenje sunčeve energije je najperspektivnije jer je sunčeva energija neiscrpna, svuda dostupna i gotovo bez efekata zagađivanja okoline. Istovremeno, budući da su potrebe za hlađenjem najveće upravo kada i sunčevo zračenje dostiže svoj maksimum, to čini apsorpcione rashladne sisteme pogonjene sunčevom energijom perspektivnim. Rad solarnih rashladnih sistema izložen je brojnim ograničenjima, poput neprekidnosti snabdevanja energijom, niske koncentracije energije i složenosti u regulaciji i sl. [12]. Zbog toga, kako bi se postigla što veća efikasnost, solarni rashladni sistemi moraju biti pažljivo projektovani u skladu sa specifičnostima radnih uslova, rada prijemnika sunčeve energije itd. Kako su eksperimentalna ispitivanja radnih parametara složena i finansijski i tehnički veoma zahtevna [11], uobičajeno je njihovo ponašanje pratiti preko odgovarajućih matematičkih modela.

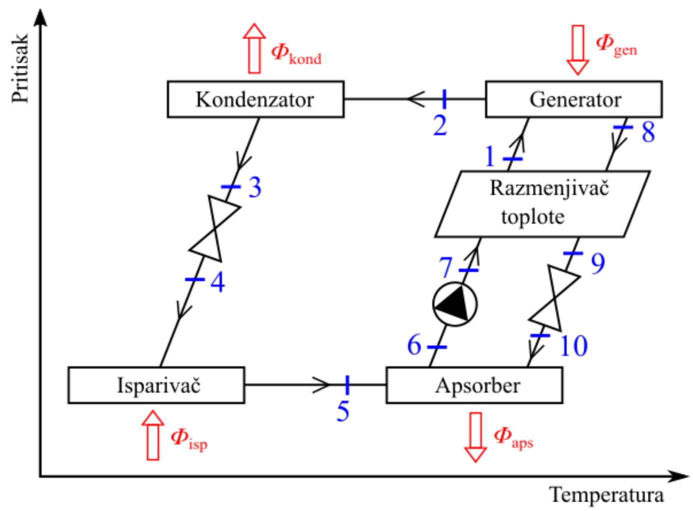
S obzirom da su u primeni najčešće jednostepeni apsorpcioni rashladni sistemi [9], kao i da je njihovo ponašanje nešto jednostavnije, u ovom radu su prikazani do sad razvijeni matematički modeli upravo ovih sistema za hlađenje i sprovedena je njihova termodinamička analiza.



Slika 1. Šema jednostepenog zatvorenog solarnog apsorpcionog rashladnog sistema sa kontinualnim radom

II Opis rada sistema

Šema jednostepenog zatvorenog solarnog apsorpcionog rashladnog sistema sa kontinualnim radom je prikazana na Slici 1. Sistem sačinjavaju prijemnici sunčeve energije (PSE), apsorpcioni rashladni uređaj (generator, kondenzator, isparivač, apsorber, prigušni ventili, pumpa, razmenjivač toplote), akumulacioni rezervoar toplote, pomoćni grejač i rashladna kula. PSE primaju toplotu sunčevog zračenja i zagreva se voda u akumulacionom rezervoaru tople vode. Kada ne postoji potreba za hlađenjem prostora, sunčeva energija se akumuliše u rezervoaru. Međutim, kada sunčeva energija nije dovoljna da zagreje vodu do nivoa potrebne temperature na ulazu u generator, uključuje se pomoćni grejač kao pomoćni izvor toplote kako bi se radnom fluidu na ulazu u generator obezbedila dovoljno visoka temperatura. U generatoru dvokomponentnom radnom fluidu (stanje 1) (Slika 3) predaje se toplotni protok Φ_{gen} pri čemu samo lakše isparljiva komponenta smeše isparava (stanje 2), a u generatoru ostaje slabi rastvor dvokomponentnog radnog fluida (stanje 8). Isparela, lakše isparljiva komponenta stanja 2 se odvodi u kondenzator gde se predajući toplotni protok toplotnom ponoru Φ_{kond} u rashladnoj kuli najpre hladi, a potom potpuno kondenzuje (stanje 3). Nastali kondenzat lakše isparljive komponente se u prigušnom ventilu adijabatski prigušuje na pritisak isparavanja (stanje 4). U prigušnom ventilu se istovremeno sa procesom snižavanja pritiska lakše isparljive komponente ostvaruje i proces snižavanja njegove temperature. Lakše isparljiva komponenta stanja 4, u stanju vlažne pare, odvodi se u isparivač gde joj fluid, kojim se ostvaruje hlađenje prostora predaje toplotni protok Φ_{isp}. Fluid, kojim se ostvaruje hlađenje prostora odvodi se najpre do rezervoara hladne vode, a odatle koristi za hlađenje prostora. Ovaj fluid predstavlja niskotemperaturni toplotni izvor apsorpcionog uređaja. U slučaju da nema pregrevanja, lakše isparljiva komponenta stanja 5 nalazi se u stanju suvozasićene pare. Ova para se odvodi u apsorber gde je apsorbuje slabi rastvor, doveden iz generatora. Slabi rastvor iz generatora, stanja 8, pre uvođenja u aspsorber, hladi se u rekuperativnom razmenjivaču toplote, a zatim u prigušnom ventilu prigušuje se na pritisak apsorpcije (stanje 9). Obogaćeni rastvor nastao mešanjem lakše isparljive komponente i slabog rastvora u apsorberu, dodatno se hladi, što mu omogućava da dodatno apsorbuje lakše isparljivu komponentu i pređe u stanje obogaćenog rastvora (stanje 6). Obogaćeni rastvor se odvodi u pumpu gde mu se povećava pritisak (stanje 7), a potom prolazi kroz rekuperativni razmenjivač toplote gde se zagreva na račun hlađenja oslabljenog rastvora. Ovim zagrevanjem obogaćeni rastvor prevodi se u polazno stanje 1.



Slika 2. *p-T* dijagram jednostepenog apsorpcionog rashladnog ciklusa [9]

III MATEMATIČKI MODELI

Modeliranje rada ovog sistema zasniva sa na formiranju bilansa energije za svaki podsistem, odnosno komponentu, pri čemu se svaka komponenta sistema tretira kao pojedinačna kontrolna zapremina.

Prijemnik sunčeve energije (PSE)

Pod pretpostavkom da se toplota sunčevog zračenja u sistem uvodi preko prijemnika sunčeve energije (PSE), bilans energije za ovu komponentu sistema može se napisati u obliku:

$$\frac{\mathrm{d}E_{\mathrm{PSE}}}{\mathrm{d}t} = \Phi_{\mathrm{PSE,prim}} - \left|\Phi_{\mathrm{PSE,gub}}\right| - \left|\Phi_{\mathrm{PSE,pred}}\right| \tag{1}$$

Prvi član sa leve strane jednačine (1) predstavlja ukupnu energiju koja se u jedinici vremena uskladišti u PSE, dok su članovi sa desne strane jednačine redom: dozračeni toplotni protok PSE-u, toplotni protok sa PSE na okolinu, tzv. toplotni protok u okolinu (gubici) i toplotni protok koji se preda radnom fluidu koji protiče kroz PSE.

Jednačina (1) može se predstaviti u razvijenom obliku:

$$m_{\mathrm{p}} c_{p,\mathrm{p}} \frac{\mathrm{d}T_{\mathrm{m}}}{\mathrm{d}t} = \\ = A_{\mathrm{PSE}} G(\tau\alpha) - U_L A_{\mathrm{PSE}} \left(T_{\mathrm{m}} - T_{\mathrm{amb}}\right) - q_{m,\mathrm{f,PSE}} c_{p,\mathrm{f,PSE}} \left(T_{\mathrm{f,iz}} - T_{\mathrm{f,ul}}\right) \tag{2}$$

gde su: m_p masa ploče PSE [kg], $c_{p,\mathrm{p}}$ specifični toplotni kapacitet ploče PSE [J/(kgK)], T_m srednja temperatura ploče PSE [K], A_{PSE} površina PSE [m^2], G globalno sunčevo zračenje [W/m^2], τ i α koeficijenti transmisije i apsorpcije PSE [-], U_L ukupni koeficijent toplotnih gubitaka (kondukcijom, konvekcijom i toplotnim zračenjem) [W/(m^{2}K)], T_{amb} temperatura okolnog vazduha solarnog kolektora [K], $q_{m,\mathrm{f,PSE}}$ maseni protok radnog fluida koji protiče kroz PSE [kg/s], $c_{p,\mathrm{f,PSE}}$ specifični toplotni kapacitet radnog fluida koji protiče kroz PSE [J/(kgK)], $T_{\mathrm{f,iz}}$ temperatura radnog fluida na izlazu iz PSE [K] i $T_{\mathrm{f,ul}}$ temperatura fluida na ulazu u PSE [K].

Prvi član sa leve strane jednačine (2) je posebno važan u trenucima izlaska i zalaska Sunca jer se tada temperatura ploče kolektora brzo menja, kao i ukoliko se menja maseni protok radnog fluida i kada se PSE modelira kao dinamički sistem.

U slučaju ustaljenih uslova, prvi član jednačina (1) i (2) se zanemaruje, a toplotni protok koji se preda fluidu u PSE u tom slučaju glasi:

$$\left|\Phi_{\mathrm{PSE,pred}}\right| = q_{m,\mathrm{f,PSE}} c_{p,\mathrm{f,PSE}} \left(T_{\mathrm{f,iz}} - T_{\mathrm{f,ul}}\right) = \\ = A_{\mathrm{PSE}} G(\tau\alpha) - U_L A_{\mathrm{PSE}} \left(T_{\mathrm{m}} - T_{\mathrm{amb}}\right) \tag{3}$$

pri čemu se razlika poslednja dva člana u jednačini (3) naziva iskorišćeni deo dozračenog toplotnog protoka sunčevog zračenja. Uvođenjem stepena korisnosti PSE η_{PSE}, prethodni izraz se svodi na oblik [13]:

$$\Phi_{\mathrm{PSE,doz}} = A_{\mathrm{PSE}} G(\tau\alpha) - U_L A_{\mathrm{PSE}} \left(T_{\mathrm{m}} - T_{\mathrm{amb}}\right) = A_{\mathrm{PSE}} G \eta_{\mathrm{PSE}} \tag{4}$$

U izrazima (5, 7-10), prikazani su različiti izrazi za izračunavanje stepena korisnosti PSE sa ravnim pločama i sa vakuumskim cevima.

Stepen korisnosti PSE se prema [13] može odrediti pomoću:

$$\eta_{\mathrm{PSE}} = F_R \left[(\tau\alpha) - U_L \frac{\vartheta_{\mathrm{f,ul}} - \vartheta_{\mathrm{amb}}}{G} \right] \tag{5}$$

gde su: F_R faktor odvođenja toplote [-], a $\vartheta_{\mathrm{f,ul}}$ temperatura fluida na ulazu u PSE [°C]. S obzirom na to da T_m nije moguće direktno izmeriti, uvođenjem faktora odvođenja toplote se ova temperatura zamenjuje temperaturom fluida na ulazu u PSE $\vartheta_{\mathrm{f,ul}}$, što je mnogo praktičniji pristup.

Faktor odvođenja toplote može se odrediti pomoću izraza [13]:

$$F_R = \frac{q_{m,\mathrm{f,PSE}} c_{p,\mathrm{f,PSE}} \left(\vartheta_{\mathrm{f,iz}} - \vartheta_{\mathrm{f,ul}}\right)}{A_{\mathrm{PSE}} \left((\tau\alpha G) - U_L \left(\vartheta_{\mathrm{f,ul}} - \vartheta_{\mathrm{amb}}\right) \right)} \tag{6}$$

Stepen korisnosti PSE se može odrediti pomoću izraza [14]:

$$\eta_{\mathrm{PSE}} = M - N \frac{\left(\vartheta_{\mathrm{f,ul}} - \vartheta_{\mathrm{amb}}\right)}{G} \tag{7}$$

gde su M i N odgovarajuće karakteristike kolektora.

Najčešće, stepen korisnosti PSE se izračunava prema ISO test metodi [15, 16] i to pomoću sledeće kvadratne jednačine:

$$\eta_{\text{PSE}} = a_0 - a_1 \frac{\left(\vartheta_{\text{sr}} - \vartheta_{\text{amb}}\right)}{G} - a_2 \frac{\left(\vartheta_{\text{sr}} - \vartheta_{\text{amb}}\right)^2}{G} \quad (8)$$

pri čemu su: a_0 stepen korisnosti računat bez gubitaka toplote [-], a_1 i a_2 koeficijenti gubitaka toplote koje daje proizvođač [-] i ϑ_{sr} srednja temperatura radnog fluida na ulazu i izlazu iz PSE [°C]. Glavno ograničenje ovog modela jeste odsustvo korekcionog člana za difuzno zračenje, što je neophodno u mnogim softverima za proračune za dugoročni vremenski period [16].

Kada je reč o PSE sa vakuumskim cevnim, stepen korisnosti se može odrediti pomoću izrazu [17]:

$$\eta_{\text{PSE}} = 0,418 - 1,17 \frac{\left(\vartheta_{\text{ul}} - \vartheta_{\text{amb}}\right)}{G} \quad (9)$$

a može i pomoću izraza [18]:

$$\eta_{\text{PSE}} = 0,45 - 1,10\left(\vartheta_{\text{rez}} - \vartheta_{\text{amb}}\right) \quad (10)$$

gde je ϑ_{rez} temperatura tople vode u rezervoaru koja je izmerena senzorom temperature [°C].

Rezervoar tople vode

Količina toplote koju može uskladišti rezervoar vode pod pretpostavkom uniformne raspodele temperature vode, određena je relacijom [13]:

$$Q_{\text{rez}} = \left(mc_p\right)_{\text{rez}} \Delta T_{\text{rez}} \quad (11)$$

gde su: m_{rez} masa tople vode u rezervoaru [kg], $c_{p,\text{rez}}$ specifični toplotni kapacitet tople vode u rezervoaru [J/(kgK)] i ΔT_{rez} razlika temperature vode na ulazu i izlazu iz rezervoara [K].

Bilans energije ove komponente sistema, pri prethodno navedenim uslovom uniformne raspodele temperature vode u rezervoaru, može se napisati kao:

$$\frac{\mathrm{d}E_{\text{rez}}}{\mathrm{d}t} = \Phi_{\text{rez,prim}} - \left|\Phi_{\text{rez,pred}}\right| - \left|\Phi_{\text{rez,gub}}\right| \quad (12)$$

Prvi član sa leve strane jednačine (12) predstavlja ukupnu energiju koja se u jedinci vremena uskladišti u rezervoaru, dok su članovi sa desne strane redom: toplotni protok koji primi voda u rezervoaru ($\Phi_{\text{rez,prim}}=|\Phi_{\text{PSE,pred}}|=\Phi_{\text{PSE,doz}}$), toplotni protok koji se odvede iz rezervoara za zadovoljavanje potreba i toplotni protok na okolinu (gubici toplote) koji se ostvaruje usled razlike temperature vode u rezervoaru i temperature okolnog vazduha.

U razvijenom obliku, jednačina (12) može se napisati kao [13]:

$$\left(mc_p\right)_{\text{rez}} \frac{\mathrm{d}T_{\text{rez}}}{\mathrm{d}t} = \Phi_{\text{PSE,doz}} - \left|\Phi_{\text{rez,pred}}\right| - (UA)_{\text{rez}}\left(T_{\text{rez}} - T_{\text{amb,rez}}\right) \quad (13)$$

gde je t vreme [s], U_{rez} koeficijent prelaženja toplote sa površine rezervoara na okolinu [W/(m^{2}K)], A_{rez} površina rezervoara za razmenu toplote sa okolinom [m^2], T_{rez} srednja temperatura vode u rezervoaru [K] i $T_{\text{amb,rez}}$ temperatura okolnog vazduha (koja može da se razlikuje od temperature okolnog vazduha solarnog kolektora) [K].

Integraljenjem jednačine (13), dobija se izraz za temperaturu vode u rezervoaru nakon posmatranog vremenskog perioda Δt:

$$T_{\text{rez,kr}} = T_{\text{rez}} + \frac{\Delta t}{\left(mc_p\right)_{\text{rez}}}\left[\Phi_{\text{PSE,doz}} - \left|\Phi_{\text{rez,pred}}\right| - (UA)_{\text{rez}}\left(T_{\text{rez}} - T_{\text{amb,rez}}\right)\right] \quad (14)$$

Pomoćni grejač

Referentna temperatura tople vode ϑ_{ref} [°C] na ulazu u generator je minimalno dozvoljena, odnosno potrebna temperatura koju je potrebno da dostigne voda u rezervoaru. Ukoliko to nije slučaj, uključuje se pomoćni grejač koji podiže temperaturu tople vode iz rezervoara do referentne temperature.

Teorijski toplotni protok koji se pomoćnim grejačem treba predati toploj vodi iz rezervoara može se odrediti iz izraza:

$$\Phi_{\text{pg}} = q_{m,\text{f,gen}} c_{p,\text{f,gen}} \left(\vartheta_{\text{ref}} - \vartheta_{\text{rez}}\right) \quad (15)$$

gde su $q_{m,\text{f,gen}}$ maseni protok [kg/s], a $c_{m,\text{f,gen}}$ specifični toplotni protok vode koja struji kroz generator [J/(kgK)].

Za određivanje stvarnog toplotnog protoka kojeg je u pomoćnom grejaču potrebno predati toploj vodi iz rezervoara, uključujući i gubitke toplote u okolinu, kao i efikasnost pomoćnog grejača, može se koristiti sledeći izraz [19]:

$$\Phi_{\text{pg}} = \frac{q_{m,\text{f,gen}} c_{p,\text{f,gen}} \left(\vartheta_{\text{ref}} - \vartheta_{\text{rez}}\right) + U_{\text{A}}\left(\overline{\vartheta} - \vartheta_{\text{amb,pg}}\right)}{\eta_{\text{pg}}} \quad (16)$$

gde su: U_{A} ukupni koeficijent gubitaka toplote u okolinu [W/(m^{2}K)], $\overline{\vartheta} = 0,5(\vartheta_{\text{ref}} + \vartheta_{\text{rez}})$ srednja temperatura [°C], $\vartheta_{\text{amb,pg}}$ temperatura okoline pomoćnog grejača [°C] i η_{pg} stepen korisnosti pomoćnog grejača [-].

Apsorpcioni rashladni uređaj

Šema jednostepenog apsorpcionog rashladnog uređaja prikazana je na Slici 1. Pri modeliranju rada ovog uređaja, obično se uzimaju u obzir sledeće pretpostavke:

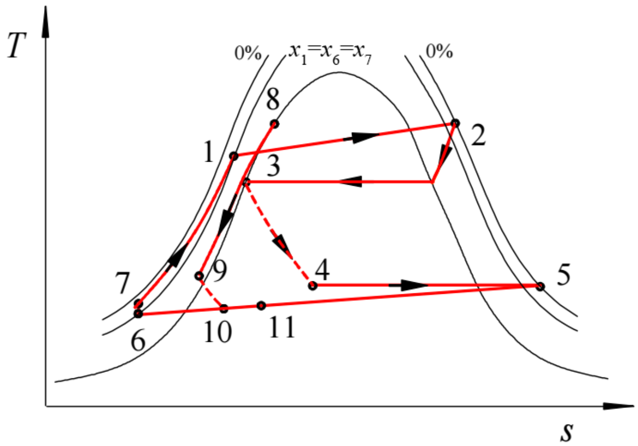
- promene potencijalne i kinetičke energije radnog fluida su zanemarljive,
- pad pritiska radnog fluida kroz komponente sistema i cevi su zanemarljivi,
- raspodela pritiska, temperature i koncentracije fluida unutar svake komponente je homogena,
- pritisci pare radnog fluida u generatoru pare i kondenzatoru su jednaki,
- pritisci radnog fluida u isparivaču i apsorberu su jednaki,
- povišenje pritiska radnog fluida u pumpi je adijabatsko,
- procesi prigušenja radnog fluida u prigušnim ventilima su adijabatski,
- lakše isparljiva komponenata rastvora u kondenzatoru i isparivaču je čista supstanca,
- radni fluid u stanju 2 je pregrejana para,
- radni fluid u stanjima 3 i 8 je zasićena tečnost,
- radni fluid u stanju 5 je suvozasićena para.

Pod navedenim pretpostavkama u skladu sa šemom prikazanoj na Slici 1, na Slici 3 je prikazan ciklus jednostepenog apsorpcionog rashladnog uređaja u *T-s* koordinatnom sistemu.

Bilans mase i bilans energije se u opštem obliku, pod navedenim pretpostavkama, za svaku komponentu *i* sistema (Slika 1) mogu opisati opštim izrazima (17) i (18):

$$\sum\left(q_m\right)_{\text{ul}} = \frac{\mathrm{d}\left(m_i\right)}{\mathrm{d}t} + \sum\left(q_m\right)_{\text{iz}} \quad (17)$$

$$\pm\Phi_i + P_{\text{teh}} + \sum\left(q_m h\right)_{\text{ul}} = \frac{\mathrm{d}\left(m_i c_{p,i} T_i\right)}{\mathrm{d}t} + \sum\left(q_m h\right)_{\text{iz}} \quad (18)$$



Slika 3. Prikaz promene stanja radnog fluida u *T*-*s* koordinatnom sistemu pri radu jednostepenog apsorpcionog rashladnog uređaja

Generator pare

U generatoru pare bilans mase definiše se za rastvor i posebno za pojedine komponente rastvora. U skladu sa izrazom (17), bilans mase za rastvor može se predstaviti kao:

$$q_{m,1} = \frac{\mathrm{d}\left(m_{\text{r,gen}}\right)}{\mathrm{d}t} + q_{m,2} + q_{m,8} \quad (19)$$

gde su q_m maseni protoci radnog fluida u određenim stanjima [kg/s], a $m_{\text{r,gen}}$ masa rastvora u generatoru [kg].

Bilans mase za apsorbent, oblika je:

$$x_1 q_{m,1} = \frac{\mathrm{d}\left(x_{\text{gen}} m_{\text{r,gen}}\right)}{\mathrm{d}t} + x_8 q_{m,8} \quad (20)$$

odnosno:

$$x_1 q_{m,1} - x_8 q_{m,8} = m_{\text{r,gen}} \frac{\mathrm{d}\left(x_{\text{gen}}\right)}{\mathrm{d}t} + x_{\text{gen}} \frac{\mathrm{d}\left(m_{\text{r,gen}}\right)}{\mathrm{d}t} \quad (21)$$

pri čemu su sa *x* označeni maseni udeli apsorbenta u ukupnoj masi rastvora (apsorbent + lakše isparljiva komponenata rastvora) u odgovarajućim stanjima [kg/kg].

Bilans energije za rastvor može se predstaviti izrazom:

$$\Phi_{\text{gen}} - \left|\Phi_{\text{gub,gen}}\right| + q_{m,1} h_1 = \frac{\mathrm{d}\left(m_{\text{r,gen}} c_{p,\text{r,gen}} T_{\text{r,gen}}\right)}{\mathrm{d}t} + q_{m,2} h_2 + q_{m,8} h_8 \quad (22)$$

odnosno:

$$\Phi_{\text{gen}} - \left|\Phi_{\text{gub,gen}}\right| + q_{m,1} h_1 = m_{\text{r,gen}} c_{p,\text{r,gen}} \frac{\mathrm{d}\left(T_{\text{r,gen}}\right)}{\mathrm{d}t} + c_{p,\text{r,gen}} T_{\text{r,gen}} \frac{\mathrm{d}\left(m_{\text{r,gen}}\right)}{\mathrm{d}t} + q_{m,2} h_2 + q_{m,8} h_8 \quad (23)$$

gde su: Φ_{gen} toplotni protok koji topla voda koja dolazi iz rezervoara preda radnom fluidu u generatoru [W], $|\Phi_{\text{gub,gen}}|$ toplotni protok sa generatora u okolinu (gubici toplote) [W], *h* specifična entalpija radnog fluida u odgovarajućem stanju [kJ/kg], $c_{\text{p,r,gen}}$ specifični toplotni kapacitet rastvora [J/kgK] i $T_{\text{r,gen}}$ temperatura rastvora [K].

Ukoliko se pretpostavi da je proces isparavanja u generatoru ustaljen, kao i da nema gubitaka toplote u okolinu, bilansi mase i energije prelaze u značajno jednostavniji oblik:

$$q_{m,1} = q_{m,2} + q_{m,8} \quad (24)$$

$$x_1 q_{m,1} = x_8 q_{m,8} \quad (25)$$

odnosno:

$$\Phi_{\text{gen}} = q_{m,2} h_2 + q_{m,8} h_8 - q_{m,1} h_1 \quad (26)$$

S obzirom na pretpostavku da se gubici toplote sa generatora u okolinu zanemaruju, toplotni protok koji se preda radnom fluidu u generatoru zapravo je jednak toplotnom protoku koji preda topla voda:

$$\Phi_{\text{gen}} = q_{m,\text{f,gen}} c_{p,\text{f,gen}} \left(\vartheta_{11} - \vartheta_{12}\right) \quad (27)$$

gde su: $q_{m,\text{f,gen}}$ maseni protok vode koja predaje toplotu rastvoru u generatoru [kg/s], $c_{m,\text{f,gen}}$ specifični toplotni kapacitet vode [J/kgK], a ϑ_{11} i ϑ_{12} temperatura tople vode na ulazu i izlazu iz generatora [°C].

Kondenzator

Bilans mase radnog fluida za procese u kondenzatoru može se predstaviti izrazom:

$$q_{m,2} = \frac{\mathrm{d}\left(m_{\text{t,kond}} + m_{\text{p,kond}}\right)}{\mathrm{d}t} + q_{m,3} \quad (28)$$

gde su $m_{\text{t,kond}}$ masa tečne i $m_{\text{p,kond}}$ masa parne faze lakše isparljive komponente rastvora koja protiče kroz kondenzator [kg].

Bilans energije kondenzatora može se predstaviti izrazom:

$$-\left|\Phi_{\text{kond}}\right| - \left|\Phi_{\text{gub,kond}}\right| + q_{m,2} h_2 = \frac{\mathrm{d}\left(m_{\text{p,kond}} c_{p,\text{p,kond}} T_{\text{p,kond}}\right)}{\mathrm{d}t} + q_{m,3} h_3 \quad (29)$$

odnosno:

$$-\left|\Phi_{\text{kond}}\right| - \left|\Phi_{\text{gub,kond}}\right| + q_{m,2} h_2 = m_{\text{p,kond}} c_{p,\text{p,kond}} \frac{\mathrm{d}\left(T_{\text{p,kond}}\right)}{\mathrm{d}t} + c_{p,\text{p,kond}} T_{\text{p,kond}} \frac{\mathrm{d}\left(m_{\text{p,kond}}\right)}{\mathrm{d}t} + q_{m,3} h_3 \quad (30)$$

gde su: $|\Phi_{\text{kond}}|$ toplotni protok koji radni fluid preda fluidu za hlađenje (ponoru toplote) koji se odvodi u kulu za hlađenje [W], $|\Phi_{\text{gub,kond}}|$ toplotni protok sa kondenzatora na okolni vazduh (gubici toplote) [W], $c_{p,\text{p,kond}}$ specifični toplotni kapacitet pare lakše isparljive komponente rastvora [J/kgK] i $T_{\text{p,kond}}$ temperatura pare lakše isparljive komponente rastvora [K].

Pod pretpostavkom da je proces kondenzacije lakše isparljive komponente rastvora u kondenzatoru ustaljen, bilans mase prelazi u oblik:

$$q_{m,2} = q_{m,3} \quad (31)$$

jer se u stanjima 2 i 3 nalazi samo lakše isparljiva komponenata rastvora.

Uz pretpostavku da kondenzator radi bez gubitaka toplote u okolinu, bilans energije prelazi u oblik:

$$\left|\Phi_{\text{kond}}\right| = q_{m,2}\left(h_2 - h_3\right) \quad (32)$$

odnosno:

$$\Phi_{\text{kond}} = q_{m,\text{f,kond}} c_{p,\text{f}} \left(\vartheta_{16} - \vartheta_{15} \right) \quad (33)$$

gde su: $q_{m,\text{f,kond}}$ maseni protok fluida za hlađenje, kome radni fluid predaje toplotu [kg/s] i $c_{p,\text{f,kond}}$ njegov specifični toplotni kapacitet [J/kgK], a ϑ_{13} i ϑ_{16} temperature tog fluida na ulazu i na izlazu iz kondenzatora [°C].

Isparivač

Bilans mase radnog fluida u isparivaču može se predstaviti izrazom:

$$q_{m,4} = \frac{\mathrm{d}\left(m_{\text{t,isp}} + m_{\text{p,isp}} \right)}{\mathrm{d}t} + q_{m,5} \quad (34)$$

gde su $m_{\text{t,isp}}$ i $m_{\text{p,isp}}$ mase tečne i masa parne faze lakše isparljive komponente rastvora koja protiče kroz isparivač [kg].

Bilans energije za isparivač može se predstaviti izrazom:

$$\Phi_{\text{isp}} - \left| \Phi_{\text{gub,isp}} \right| + q_{m,4} h_4 = \frac{\mathrm{d}\left(m_{\text{t,isp}} c_{p,\text{t,isp}} T_{\text{t,isp}} \right)}{\mathrm{d}t} + q_{m,5} h_5 \quad (35)$$

odnosno:

$$= m_{\text{t,isp}} c_{p,\text{t,isp}} \frac{\mathrm{d}\left(T_{\text{t,isp}} \right)}{\mathrm{d}t} + c_{p,\text{t,isp}} T_{\text{t,isp}} \frac{\mathrm{d}\left(m_{\text{t,isp}} \right)}{\mathrm{d}t} + q_{m,5} h_5 \quad (36)$$

gde su: Φ_{isp} toplotni protok sa fluida kojim se ostvaruje hlađenje prostora na radni fluid u isparivaču [W], $|\Phi_{\text{gub,isp}}|$ toplotni protok sa isparivača u okolinu (gubici toplote) [W], $c_{p,\text{t,isp}}$ specifični toplotni kapacitet radnog fluida u tečnom stanju u isparivaču [J/kgK] i $T_{\text{t,isp}}$ temperatura radnog fluida u tečnom stanju u isparivaču [K].

Pod pretpostavkom da je proces isparavanja u isparivaču ustaljen, bilans mase dobija sledeći oblik:

$$q_{m,4} = q_{m,5} \quad (37)$$

jer se u stanjima 4 i 5 nalazi samo lakše isparljiva komponenta rastvora.

Ako se zanemare gubici toplote isparivača u okolinu, bilans energije prelazi u sledeći oblik:

$$\Phi_{\text{isp}} = q_{m,4} \left(h_5 - h_4 \right) \quad (38)$$

odnosno:

$$\Phi_{\text{isp}} = q_{m,\text{f,isp}} c_{p,\text{f}} \left(\vartheta_{17} - \vartheta_{18} \right) \quad (39)$$

gde su $q_{m,\text{f,isp}}$ maseni protok fluida kojim se ostvaruje hlađenje prostora, a koji predaje toplotu radnom fluidu u isparivaču [kg/s] i $c_{p,\text{f,isp}}$ [J/kgK] specifični toplotni kapacitet fluida kojim se ostvaruje hlađenje prostora, a ϑ_{17} i ϑ_{18} temperature tog fluida na ulazu i izlazu iz isparivača [°C]. Fluid kojim se hladi prostor se iz isparivača odvodi u rezervoar hladne vode.

Apsorber

U apsorberu bilans mase definiše se posebno za rastvor i posebno za apsorbent. Bilans mase za rastvor može se predstaviti izrazom:

$$q_{m,5} + q_{m,10} = \frac{\mathrm{d}\left(m_{\text{r,aps}} \right)}{\mathrm{d}t} + q_{m,6} \quad (40)$$

gde je $m_{\text{r,aps}}$ masa rastvora u apsorberu [kg].

$$x_{10} q_{m,10} = \frac{\mathrm{d}\left(x_{\text{aps}} m_{\text{r,aps}} \right)}{\mathrm{d}t} + x_6 q_{m,6} \quad (41)$$

odnosno:

$$x_{10} q_{m,10} - x_6 q_{m,6} = m_{\text{r,aps}} \frac{\mathrm{d}\left(x_{\text{aps}} \right)}{\mathrm{d}t} + x_{\text{aps}} \frac{\mathrm{d}\left(m_{\text{r,aps}} \right)}{\mathrm{d}t} \quad (42)$$

pri čemu važi da su maseni udeli: x_5=x_4=x_3=0, x_{10}=x_9=x_8 i x_6=x_7=x_1.

Bilans energije za rastvor u apsorberu može se opisati izrazom:

$$-\left| \Phi_{\text{aps}} \right| - \left| \Phi_{\text{gub,aps}} \right| + q_{m,5} h_5 + q_{m,10} h_{10} = \frac{\mathrm{d}\left(m_{\text{r,aps}} c_{p,\text{r,aps}} T_{\text{r,aps}} \right)}{\mathrm{d}t} + q_{m,6} h_6 \quad (43)$$

odnosno:

$$\begin{aligned} -\left| \Phi_{\text{aps}} \right| - \left| \Phi_{\text{gub,aps}} \right| + q_{m,5} h_5 + q_{m,10} h_{10} = \\ = m_{\text{r,aps}} c_{p,\text{r,aps}} \frac{\mathrm{d}\left(T_{\text{r,aps}} \right)}{\mathrm{d}t} + c_{p,\text{r,aps}} T_{\text{r,aps}} \frac{\mathrm{d}\left(m_{\text{r,aps}} \right)}{\mathrm{d}t} + q_{m,6} h_6 \end{aligned} \quad (44)$$

gde su: $|\Phi_{\text{aps}}|$ toplotni protok koji se odvede rastvoru u apsorberu prilikom apsorpcije lakše isparljive komponente rastvora u slabi rastvor, a dovede fluidu koji predstavlja toplotni ponor koji se zagreva i odvodi prvo u kondenzator, a potom u rashladnu kulu [W], $|\Phi_{\text{gub,aps}}|$ gubici toplote u okolinu apsorbera [W], $c_{p,\text{r,aps}}$ specifični toplotni kapacitet rastvora u apsorberu [J/kgK] i $T_{r,\text{aps}}$ temperatura rastvora u apsorberu [K].

Pod pretpostavkom da se proces u apsorberu ostvaruje pri ustaljenim uslovima, izraz za bilans mase prelazi u oblik:

$$q_{m,5} + q_{m,10} = q_{m,6} \quad (45)$$

odnosno:

$$x_{10} q_{m,10} = x_6 q_{m,6} \quad (46)$$

Ako se zanemare gubici toplote sa apsorbera u okolinu, bilans energije za apsorber dobija sledeći oblik:

$$\left| \Phi_{\text{aps}} \right| = q_{m,5} h_5 + q_{m,10} h_{10} - q_{m,6} h_6 . \quad (47)$$

Istovremeno, ovaj toplotni protok može da se predstavi i preko izraza:

$$\Phi_{\text{aps}} = q_{m,\text{f,aps}} c_{p,\text{f}} \left(\vartheta_{14} - \vartheta_{13} \right) \quad (48)$$

gde su $q_{m,\text{f,aps}}$ maseni protok fluida kome radni fluid u apsorberu predaje toplotu [kg/s], njegov specifični toplotni kapacitet $c_{p,\text{f,aps}}$ [J/kgK], a ϑ_{13} i ϑ_{14} temperature ovog fluida na ulazu i na izlazu iz apsorbera [°C].

Razmenjivač toplote

Bilans energije za radni fluid koji se u razmenjivač toplote uvodi sa višom temperaturom (slabi rastvor) može se predstaviti izrazom:

$$-\left| \Phi_{\text{tf}} \right| - \left| \Phi_{\text{gub,tf}} \right| + q_{m,\text{tf}} h_{\text{tf,ul}} = m_{\text{tf}} c_{p,\text{tf}} \frac{\mathrm{d}T_{\text{tf}}}{\mathrm{d}t} + q_{m,\text{tf}} h_{\text{tf,iz}} \quad (49)$$

dok za radni fluid koji se u razmenjivač toplote uvodi sa nižom temperaturom (jaki rastvor) bilans energije može se predstaviti izrazom:

$$-\left|\Phi_{\mathrm{hf}}\right|-\left|\Phi_{\mathrm{gub,hf}}\right|+q_{m,\mathrm{hf}}h_{\mathrm{hf,ul}}=m_{\mathrm{hf}}c_{p,\mathrm{hf}}\frac{\mathrm{d}T_{\mathrm{hf}}}{\mathrm{d}t}+q_{m,\mathrm{hf}}h_{\mathrm{hf,iz}} \quad (50)$$

Pod pretpostavkom da razmenjivač toplote radi pri ustaljenim uslovima, bilans mase može se napisati u obliku:

$$x_7q_{m,7}+x_8q_{m,8}=x_1q_{m,1}+x_9q_{m,9} \quad (51)$$

odnosno:

$$q_{m,1}=q_{m,7}\,,\quad x_1=x_7\,,\quad q_{m,8}=q_{m,9}\,,\quad x_8=x_9 \quad (52)$$

Pod pretpostavkom da se predaja toplote u razmenjivaču toplote ostvaruje bez tzv. gubitka toplote u okolinu, bilans energije prelazi u oblik:

$$q_{m,1}\left(h_1-h_7\right)=q_{m,8}\left(h_8-h_9\right) \quad (53)$$

Pumpa

Pod pretpostavkom da je proces povišenja pritiska radnog fluida u pumpi ustaljen, bilans mase pumpe se može predstaviti jednostavnim izrazom:

$$q_{m,6}=q_{m,7} \quad (54)$$

Uz pretpostavku da je taj proces i adijabatski, energetski bilans je oblika:

$$P_{\mathrm{pum}}+q_{m,6}h_6=q_{m,7}h_7 \quad (55)$$

odnosno prema [20, 21]:

$$P_{\mathrm{pum}}=q_{m,6}\left(h_7-h_6\right)=q_{m,6}v_6\left(p_7-p_6\right)/\eta_{\mathrm{pum}} \quad (56)$$

gde su: P_{pum} snaga pumpe [W], v_6 specifična zapremina jakog rastvora [m^3/kg], p_7 pritisak radnog fluida u generatoru pare i kondenzatoru [Pa], p_6 pritisak radnog fluida u isparivaču i apsorberu [Pa], η_{pum} stepen korisnosti pumpe [-].

Prigušni ventili

Pod pretpostavkom da je proces prigušenja radnog fluida u prigušnim ventilima ustaljen, bilansi mase za prigušne ventile radnog fluida i slabog rastvora imaju oblik:

$$q_{m,3}=q_{m,4}\,,\quad x_3=x_4 \quad (57)$$

i

$$q_{m,9}=q_{m,10}\,,\quad x_9=x_{10} \quad (58)$$

S obzirom na male dimenzije i relativno veliku brzinu ostvarivanja, procesi prigušivanja u ventilu se mogu smatrati adijabatskim, pa bilans energije za prigušene ventile rashladnog fluida i slabog rastvora ima trivijalan oblik:

$$h_3=h_4 \text{ i } h_9=h_{10} \quad (59)$$

gde su sa h_3 i h_4 označene specifične entalpije lakše isparljive komponente rastvora pre i nakon procesa prigušenja, a sa h_9 i h_{10} su označene specifične entalpije slabog rastvora pre i nakon procesa prigušenja, redom.

IV ZAKLJUČAK

Zbog zanemarljivo male potrošnje električne energije i gotovo nepostojeće emisije gasova sa efektom staklene bašte, apsorpcioni solarni rashladni uređaji predstavljaju perspektivno rešenje za ostvarivanje rastućih potreba za hlađenjem. Visoka investiciona cena i relativno mala energetska efikasnost, a time i ekonomska isplativost zahtevaju dalji rad na unapređenju ovih sistema.

Predstavljeni matematički modeli, odnosno jednačine bilansa mase i energije svakog elementa koji čini sistem apsorpcionog solarnog rashladnog sistema, omogućavaju osnove praćenja ponašanja rada svake komponente ili grupe komponenti ovog sistema i određivanje njihovih pojedinačnih ili zbirnih performansi. U jednostavnijim analizama, dovoljno je koristiti izraze izvedene pod pretpostavkom da se svi procesi ostvaruju pri ustaljenim uslovima, dok je za kvalitetnije analize potrebno koristiti njihove opšte oblike izvedene za nestacionarne uslove. Sprezanje svih prikazanih jednačina u jedinstven matematički model, uz sprovođenje tek po nekog eksperimenta, omogućava predviđanje ponašanja i izučavanje rada celog sistema, optimizaciju njihovog rada, a time i približavanje komercijalnoj upotrebi.

ZAHVALNICA

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Mathematical Models of Solar Driven Cooling Systems

Abstract – *Considering the increasingly intense and obvious climate change and the increase in global temperature, as well as the growth of the world population and the accelerated process of population migration from rural to urban areas, the energy consumption for cooling residential and commercial spaces is constantly increasing, with a tendency to continue to increase rapidly. On the other hand, given the widely accepted theory that the increase in global temperature is caused by increased anthropogenic emissions of greenhouse gases, transitioning from fossil fuels to renewable energy sources (RES) has been established as a key strategy for slowing this temperature rise. In this sense, linking the growing demand for cooling energy and the transition to the use of RES, the use of solar energy for cooling purposes is imposed as an optimal solution. This is supported by the fact that, among all types of RES, the use of solar energy is the most promising because it is inexhaustible, available everywhere and almost without the effects of environmental pollution. In addition, the demand for cooling is greatest precisely when solar radiation reaches its maximum, and the need for cooling is greater in areas with a warm climate. One of the possible technologies that enable the realization of the cooling process using solar energy is absorption refrigeration systems. Due to the development of increasingly efficient systems for collecting and storing solar energy, there are many reasons for increasing research in the field of absorption refrigeration systems. In addition to explaining the working principles and observing energy flows, and determining the energy efficiency of these systems, this paper presents the mathematical models of cooling systems powered by solar radiation that have been developed so far and their thermodynamic analysis has been performed.*

Index Terms – *Solar cooling, Absorption refrigeration systems, Mathematical models* doi: 10.46793/EEE25-1.48N

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Energy Communities in Serbia and Europe: A Comparative Analysis of Regulatory Frameworks

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Abstract – The energy transition involves a careful shift away from conventional energy production, guided by principles of equity and fairness. In this context, energy communities have emerged as a new model, enabling citizens and local communities to play a crucial role in driving energy change. This paper analyses the regulatory frameworks that govern the functioning of energy communities in Denmark, the Netherlands, and Serbia. The goal is to identify key similarities and differences in the legislative approaches of these countries, highlighting factors that encourage or hinder the development of energy communities. The paper examines how European regulations are adapted into national frameworks, with a particular focus on aligning Serbia's legal system with European practices. Also, based on examples of best practices, the paper offers recommendations to enhance citizen participation in the energy transition process.

Index Terms – Energy community, Energy transition, Just energy transition, Energy policy

I INTRODUCTION

The transition to low-carbon technologies represents one of the key challenges today, grounded not only in changes to energy production and conversion methods but also in evolving societal perceptions of energy systems. Consequently, the shift from fossil fuels to renewable energy sources (RES) is a comprehensive and long-term process that entails both social and political transformations. The active involvement of citizens and local communities in the energy system, particularly through participation in the production of energy from RES, constitutes a pathway toward a sustainable energy transition [1], and as such, can foster societal acceptance of energy-related changes [2]. Energy communities (ECs) contribute not only to the expansion of RES capacities but also to the shaping of the energy system by educating citizens and establishing a foundation for long-term RES project planning [3]. Through this approach, citizens united around RES projects can reduce energy inequality, support energy-vulnerable consumers [4], and assist rural communities by promoting social values such as solidarity, empowerment, local engagement, and the creation of local jobs [5]. Thus, the growing popularity of the EC concept is rooted in the principles of a just energy transition, emphasizing the decentralization and democratization of the energy system [6].

Due to their numerous advantages, ECs have become a focal point of energy policy at various governance levels. The European Green Deal [7], developed as the European Union's (EU) response to climate change with the goal of establishing the first climate-neutral continent by 2050, ensuring that no one is left behind, emphasizes that "*consumers should be at the heart of the energy transition*". Simultaneously, the Clean Energy for All Europeans package [8] introduced directives regulating ECs, among which the most significant are the Renewable Energy Directive (EU 2018/2001) [9], the Directive on Common Rules for the Internal Market for Electricity (EU 2019/944) [10], and the Energy Efficiency Directive (EU 2023/955) [11].

Within this legislative package, ECs were formally defined for the first time through two legal categories: Citizen Energy Communities (CECs)[1] and Renewable Energy Communities (RECs)[2]. Although both concepts are grounded in the active involvement of citizens in the energy transition process, their primary distinction lies in ownership structures and operational approaches. In both cases, financial profit is not the principal objective; rather, the focus is on achieving economic, environmental, and social benefits. Energy communities may engage in the production, distribution, or consumption of locally generated energy. It is important to note that citizens can come together not only to participate in the electricity sector but also in the domains of thermal energy and energy efficiency**.**

In September 2024, the European Commission published a guidance document to support Member States and relevant stakeholders in implementing the revised Renewable Energy and Energy Efficiency Directives [12]. Among various recommendations, the guidelines in Article 20a on sectorial integration of renewable energy [13] emphasize the importance of ECs for enhancing the flexibility of the energy system through

[1] A Citizen Energy Community (CEC) is a legal entity based on voluntary and open participation, and is effectively controlled by its members or shareholders, who may be natural persons, local authorities—including municipalities—or small enterprises (Directive (EU) 2019/944).

[2] A Renewable Energy Community (REC) is a legal entity established in accordance with applicable national law, based on open and voluntary participation. It operates independently and is effectively controlled by shareholders or members who may be natural persons, small and medium-sized enterprises, or local authorities, including municipalities (Directive (EU) 2018/2001).

the active engagement of members as energy consumers. Additionally, distribution system operators (DSOs) are required to provide (anonymized) data on the potential use of electricity supplied to the grid by ECs, thereby improving the position and economic viability of citizen-led renewable energy projects.

The empowerment of citizens to unite around joint energy initiatives has led to the establishment of more than 7,700 ECs across Europe by 2021, with a total installed capacity of 6.3 GW from RES [14]. Projections suggest that by 2050, citizens could contribute to the production of up to 45% of renewable energy in the EU [15]. In this context, the establishment of clear legal frameworks is of critical importance, and EU Member States as well as candidate countries are obliged to align the directives with their national legal systems.

The aim of this paper is to provide a comparative overview and analysis of the adapted regulatory frameworks of leading EU countries in the field of citizen energy production, alongside Serbia, with a focus on identifying barriers and opportunities for the implementation of this concept. Furthermore, based on the experiences of Denmark and the Netherlands, the paper proposes potential improvements to Serbia's existing regulatory framework that would facilitate greater citizen participation in the energy transition process.

II Energy Communities in Denmark

Denmark has a long-standing tradition of civic cooperation and is one of the EU countries with the highest share of citizen ownership in energy investments, with more than 633 established energy cooperatives. Members of cooperatives have most commonly organized around heating projects or the production of energy from RES. It is estimated that 52% of the total installed wind power capacity in Denmark is under some form of citizen ownership, as well as 64% of district heating [16], with more than 320 registered cooperatives [17]. However, the sharing of electricity produced among citizens was not permitted until 2019[3], when the Danish Energy Agency (DEA) introduced a new energy community concept in response to proposed European regulations. According to Denmark's National Energy and Climate Plan (NECP) [18], the term "energy community" serves as an umbrella designation for both CECs and RECs. In the case of RECs, members must reside near the renewable energy project, whereas no such geographic restrictions apply to CECs [19].

In order to implement the principles of Directive (EU) 2018/2001 and to develop a legal framework for energy communities in Denmark, the *Executive Order on Renewable Energy Communities, Citizen Energy Communities, Electricity Trading Companies, and Collective Electricity Supply Companies*[4] stipulates that ECs may participate in energy production, supply, consumption, aggregation, and storage, as well as in energy efficiency services, electric vehicle charging, or the provision of other energy-related services. However, they are not permitted to own, establish, purchase, or lease distribution networks [20]. According to the Order, ECs must be treated in a non-discriminatory manner compared to other companies or consumers operating in the same sector. In this regard, Ecs are granted access to the electricity market, may engage in energy trading, or operate as electricity aggregators. They are expected to function under transparent and straightforward procedures, while also assuming financial responsibility for any potential disruptions they may cause to the distribution energy system [20].

These legislative changes have resulted in a clear distinction between energy communities and energy cooperatives. Unlike cooperatives, members of energy communities are allowed to share the electricity they produce via a collective network, which subjects them to grid tariffs and taxes. One way to mitigate the full cost of electricity sharing is through the so-called *local collective tariff for ECs*. By introducing a reduced tariff for energy used within 15 minutes of its production, Ecs can help alleviate grid congestion. This approach encourages the participation of multiple stakeholders with diverse consumption patterns, thereby maximizing benefits, reducing costs, and enhancing the positive impact of energy communities on the electricity distribution system [21]. Figure 1 illustrates the energy communities in Denmark where electricity sharing among members is permitted [22].

With regard to thermal energy, the Danish Heat Supply Act [23] aims to promote socio-economically and environmentally sustainable solutions for consumers. Similarly, the Act encourages the use of RES in the heating sector and ensures equal treatment of all stakeholders. District heating companies are required to have district heating as their core business activity, which implies that a district heating system can be operated as an activity of an EC only if it is owned by individuals or municipalities. In the case of district heating energy communities, all energy produced may be used and distributed solely within the community, but not beyond its boundaries. At the same time, district heating companies may also be members of ECs.

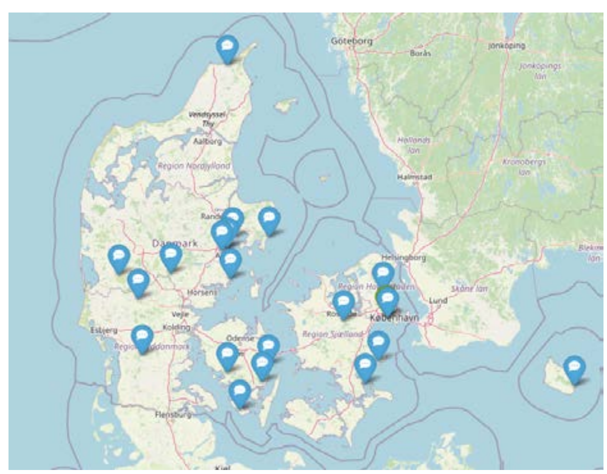

Figure 1. Map of (New) Energy Communities in Denmark Where Energy Sharing Is Permitted [22]

[3] With the exception of housing associations acting as prosumers, as well as behind-the-meter arrangements (the most well-known example being Hvide Sande).

[4] Bekendtgørelse om VE-fællesskaber og borgerenergifællesskaber og forholdet mellem VE-fællesskaber og borgerenergifællesskaber og elhandelsvirksomheder og kollektive elforsyningsvirksomheder

III Energy Communities in The Netherlands

Until 2024, the concept of energy communities in the Netherlands most commonly referred to energy cooperatives, but also included foundations, associations, or companies operating in the fields of energy efficiency, district heating, or the production of electricity from renewable energy sources (RES) [24]. As energy cooperatives are defined as private companies, their members face barriers when entering the electricity market. Specifically, in the event of any changes or the addition of new infrastructure, energy cooperatives are required to participate in tendering procedures alongside private companies, resulting in unequal market competition. The government addressed this issue by introducing a subsidized support scheme for cooperative energy production, with a total budget of €100 million [25]. Nevertheless, despite existing obstacles,such as complex bureaucratic frameworks-by 2023, the Netherlands had 714 energy cooperatives (Figure 2), including 301 focused on energy savings, 70 involved in cooperative district heating projects, and 243 engaged in RES-based energy production projects [26].

Figure 2. Map of Energy Cooperatives in the Netherlands [26]

The number of energy cooperatives involved in heat supply is increasing, with nearly 30 new district heating projects underway in 2024[5]. This shift emerged in response to the need to reduce dependence on imported gas. To promote the establishment of new energy cooperatives in district heating, Danish company EBO Consult A/S and the Dutch umbrella organization for energy cooperatives, Energi Samen, received financial support for the implementation of a project under Denmark's *Energy Export Initiative Support Program* [17]. The funded project will focus on establishing a foundational framework for cooperative support to facilitate the implementation and development of local district heating initiatives.

Under the previously applicable Electricity and Gas Acts, electricity sharing among cooperative members was practically impossible [24]. To overcome this regulatory barrier, energy cooperatives would first sell the energy produced in their own facilities to a supplier and then repurchase it for their own use. The only exceptions were experimental schemes under the *Stimulation of Sustainable Energy Production (SDE+) Program: the new experimental scheme of the Electricity Act and the Dutch Green Deal* [24]. In addition, a national program for regional energy strategies was developed [27], aiming for 50% of wind and solar projects to be citizen-owned. Furthermore, under the leadership of Energi Samen, pilot projects were launched to enable energy sharing among community members, under the name Local4Local. These projects include energy-sharing initiatives, typically in the form of virtual energy sharing, involving both citizens and small and medium-sized enterprises [28].

However, in order to align with EU regulations, on December 10, 2024, the Senate approved a new Energy Act[6], which, for the first time in Dutch legislation, defines the term "energy community." ECs are recognized as legal entities operating in the energy market, established with the aim of achieving environmental, economic, and social benefits, without the intention of generating profit [30].

According to Article 2.4 of the Energy Act, energy communities must meet the following conditions:

- Participation in the EC must be open and voluntary;
- Members, owners, or shareholders of the EC must have the right to leave the community;
- Decision-making must be based on the input of members, owners, or shareholders of the EC, who may include natural persons, small and micro enterprises, municipalities, regional authorities, or provinces, with all parties having equal voting rights.

In the case of energy communities developing renewable energy projects, the Energy Act stipulates that members, owners, or shareholders must reside in proximity to the projects.

Article 2.30 of the Energy Act provides that citizens, businesses, and/or local governments are permitted to share energy produced within the community. Every active energy consumer in the community must hold a consumption and production contract with an energy distribution company that enables energy sharing (Art. 2.30, sub a/b), and must use a metering device (Art. 2.30, sub c). Additionally, energy sharing must occur within a 15-minute time frame and within geographically defined areas, which may be specified according to local jurisdiction (Art. 2.30.2). The promotion of energy communities and their positive impact were also discussed and presented during the introduction of the draft Energy Act in the Dutch Senate [31].

IV Energy Communities in Serbia

The energy transition process in Serbia significantly lags behind that of EU countries, with evident inconsistencies in conceptual alignment and a lack of structural energy reforms introduced in a socially acceptable manner [32]. In this context, the absence of clear legal frameworks is also apparent, as is the lack of harmonization and adoption of new sector-specific secondary legislation that would enable the smooth operation of energy communities (ECs) [33]. Before ECs were legally recognized as

[5] The umbrella organization for energy cooperatives in the Netherlands, Energi Samen, oral statement

[6] „Energija Mokri", The new Energy Act, which consolidates the Electricity Act of 1998 and the Gas Act [29].

actors in the energy market, two energy cooperatives, Elektropionir [34] and Sunčani krovovi [35], were established in Serbia in 2019. Due to the absence of appropriate legal frameworks, these cooperatives were not founded under any energy sector legislation, but rather under the Law on Cooperatives [36]. Operating in this manner was the only available option for initiating active citizen participation in the energy sector. The establishment of energy cooperatives in Serbia was driven by the goal of achieving a just energy transition and reducing the injustices caused by the current centralized energy system [6], with four projects implemented to date (Figure 3).

Two years after the first energy cooperatives were founded, the term REC was introduced into the legal system of the Republic of Serbia through the adoption of the Law on the Use of Renewable Energy Sources. RECs are defined as "*a legal entity established on the principle of open and voluntary participation of its members in accordance with this law, and controlled by members whose residence or registered office is located near the renewable energy facility owned or developed by that legal entity*" [37]. Members of RECs may include natural or legal persons, as well as units of local and municipal self-government, with all members retaining the status of final electricity customers. Business entities or entrepreneurs may also be members of RECs, provided that the production of electricity from RES is not their primary commercial activity. As in the EU Directives, the main purpose of establishing RECs is to use RES to meet the energy needs of community members, while also generating social and economic benefits and contributing to environmental protection.

RECs have the right to produce, use, and store energy from RES and to access the energy market on a non-discriminatory basis. The Distribution System Operator (DSO) is obligated to maintain and regularly update an electronic register of all connected power plants, as well as a publicly available list of all pending connection requests (Art. 67). Since no REC has yet been established in Serbia, the issue of the permissible distance between community members and the shared RES project remains an open question.

On the other hand CECs were officially recognized as actors in the energy market with the adoption of the Energy Act [38], and are defined as "*a legal entity established on the basis of voluntary and open participation, under the effective control of community members, who may be natural persons, local self-government units, or small enterprises, with the aim of providing economic, environmental, or social benefits to its members, shareholders, or the local communities in which it operates, rather than generating financial profit. Such entities may engage in electricity production, including from renewable sources, supply, consumption, aggregation, energy storage services, energy efficiency, electric vehicle charging, or the provision of other services to their members*".

To be registered in the Distribution System Operator's (DSO) records within 30 days of submitting an application (Art. 210đ), a CEC must specify in its founding act the activities it intends to carry out and must meet the other conditions required for supplying final customers. Similarly, if a CEC ceases to meet any of the prescribed conditions, the DSO is obliged to remove it from the register. As the law enables energy sharing, the DSO must maintain records of community members and their metering points. Additionally, the DSO is required to ensure electricity delivery to CEC members and, with the approval of the Energy Agency of the Republic of Serbia, is entitled to a special financial compensation for energy sharing among community members, as a form of non-standard service.

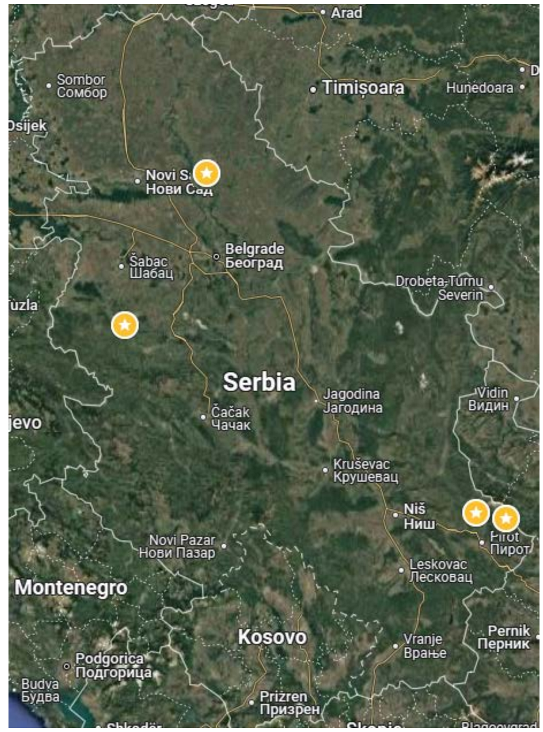

Figure 3. Map of projects of existing energy cooperatives in Serbia

The law stipulates that CECs are responsible for balancing obligations. According to Articles 171 and 210e, a supplier may assume balancing responsibility, but only if the energy produced within the community is used solely to meet the energy needs of its members.

Article 57 of the Energy Act establishes that non-discriminatory access is ensured through the work of the Energy Agency of the Republic of Serbia, which monitors unjustified barriers and restrictions affecting the production and use of electricity for community members. However, the law does not specify how the Agency may act to eliminate identified shortcomings.

The Law on Energy Efficiency [39] also defines the existence of Local Energy Communities (LECs), described as "*a legal entity based on voluntary and open participation, under the effective control of community members or shareholders who may be natural persons, local authorities including municipalities, or small enterprises. Its primary purpose is to provide economic, environmental, or social benefits to its members or the local areas in which it operates, rather than generating financial profit. LECs may engage in electricity production, including from renewable sources, distribution, supply, consumption, aggregation, energy storage services, energy efficiency, electric* *vehicle charging, or the provision of other services to their members or shareholders*".

It can be observed that there is virtually no distinction between LECs and CECs. However, the Energy Efficiency Law specifies that if an LEC operates in the field of high-efficiency cogeneration, the DSO must ensure equal and non-discriminatory participation in the balancing market and the provision of ancillary services. Furthermore, an LEC operating within these parameters is entitled to incentives (Art. 81).

According to the Law on the Use of Renewable Energy Sources, the DSO has the right to postpone the connection procedure for a RES power plant if there is insufficient balancing reserve to ensure the safe and uninterrupted operation of the power system (Art. 67a). This postponement does not apply to power plants that provide new energy storage capacities (at least 0.4 MWh per MW of installed system capacity) or contribute to the secure operation of the system.

V Comparative Overview of the Status of Energy Communities in the Analysed Countries

A comparison of the barriers and opportunities for establishing ECs in the analysed countries is presented in Table 1. The clearest definitions of ECs are found in Denmark's legislative framework. In this country, the definitions encompass all requirements set forth by EU Directives and include additional details aimed at ensuring equal status for ECs alongside other market participants.

Table 1. Comparison of the Status of Energy Communities in the Analysed Countries

DENMARK	
MEMBERS	Citizens, small and medium-sized enterprises, municipalities, district heating companies
BARRIERS	1. EC cannot operate or own the distribution network 2. General tariffs and taxes shall apply to electricity shared through the collective network 3. The availability of information and assistance by DSOs depends on their relationship with the EC
INCENTIVES	1. Clear technical procedures 2. Electricity sharing is possible 3. The EC is seen as an opportunity for innovation 4. Uncomplicated and clear solution for thermal energy 5. Advisory support
THE NETHERLANDS	
MEMBERS	Citizens, businesses and/or local governments
BARRIERS	1. There are still new and unclear definitions of EC 2. The EC shall have the same conditions for participation in the energy market as other actors 3. Financial barriers and high investments 4. Dependence on other actors (DSOs, municipalities, companies) 5. Energy sharing is not yet fully possible due to (sub)legal restrictions
INCENTIVES	1. The business model for electricity supply is more attractive due to the high cost of electricity 2. The EC have a strong and very active representative (Energy Samen) 3. Cooperation between local self-government and organizations 4. The DSO supports the development of the EC
SERBIA	
MEMBERS	Citizens, small and medium-sized enterprises, Municipalities and local communities
BARRIERS	1. There is still no example in practice 2. Waiting to connect 3. Suspension of the connection of RES projects 4. New and unclear definitions of EC 5. Lack of consulting support 6. Inconsistency of by-laws
INCENTIVES	1. New legislative frameworks that (on paper) enable the existence of the EC, as well as the sharing of energy 2. Existence of examples of good practice in cooperation between energy cooperatives and local self-governments (project „Solara Stara“ [34])

Although the Netherlands is an EU member state, it only adopted a new Energy Act at the end of 2024, which defines ECs and mentions the possibility of energy sharing. Until then, there were no clear legal definitions of ECs in the Netherlands, and citizens were actively engaged through energy cooperatives. While ECs are now legally defined, further clarification of their rights and obligations is expected through the adoption of future energy legislation and the development of a new draft National Energy and Climate Plan (NECP).

In Serbia, ECs remain a concept that exists only on paper. Although the legal framework defines the rights and responsibilities of ECs, further harmonization of legislation, the introduction of incentive measures, and the development of pilot projects are necessary to empower citizens for future engagement.

IV Conclusion

All analysed countries have adapted the EU directives on energy communities and aligned them with their specific legal and regulatory frameworks. Nevertheless, energy communities face several common challenges, including high initial investment costs and complex bureaucratic procedures. Moreover, the involvement of diverse stakeholders remains limited, resulting in restricted access for industry, except for small and medium-sized enterprises. This limitation is significant, as the industrial sector has the potential to contribute to alleviating grid congestion due to its distinctive energy consumption patterns.

The comparative analysis of regulatory frameworks for ECs in Denmark, the Netherlands, and Serbia reveals differences in legislative approaches. While Serbia is making progress in adopting new legal frameworks, it continues to face challenges in the implementation of regulations and in ensuring the long-term sustainability of energy communities. The experiences of Denmark and the Netherlands may serve as valuable guidance for further regulatory improvements in Serbia, particularly in terms of incentivizing benefits for community members and strengthening their role in the energy sector.

To foster and accelerate a just energy transition, it is essential to clarify and simplify administrative procedures and enable the digitalization of the application process. The introduction of dedicated programs, both financial and procedural, is necessary, especially for the initial citizen energy-sharing projects. Furthermore, the adoption of new secondary legislation for ECs should facilitate a simplified and expedited procedure for connecting citizen energy projects and registering them with the DSO.

It is evident that, despite numerous uncertainties and complex procedures, civic energy and the democratization of energy production are becoming increasingly significant developments in the energy sector, even in countries where traditional structures still prevail and the concept of energy communities is still evolving. In this regard, for citizens to become prominent drivers of the energy transition, it is necessary to remove existing barriers and transform them into opportunities.

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Energetske zajednice u Srbiji i Evropi: komparativna analiza regulatornih okvira

Rezime *- Energetska tranzicija, koja podrazumeva napuštanje konvencionalih oblika proizvodnje energije treba da bude sprovedena u skladu sa načelima pravednosti. U ovom procesu, energetske zajednice prepoznate su kao novi koncept koji omogućava građanima i lokalnim zajednicama da budu nosioci energetskih promena. U ovom radu analizirani su regulatorni okviri koji definišu funkcionisanje energetskih zajednica u Danskoj, Nizozemskoj, kao i u Srbiji. Cilj rada je sistematizacija ključnih sličnosti i razlika u zakonodavnim pristupima pomenutih zemalja, sa naglaskom na uticaje koji podstiču ili ograničavaju razvoj energetskih zajednica. Analizirano je prilagođavanje evropskih regulativa u nacionalne okvire, uz poseban osvrt na prilagođavanje pravnog sistema Srbije evropskim praksama. Takodje, na osnovu primera dobre prakse, prikazane su preporuke kojima bi se omogućilo olakšano delovanje građana u procesu energetske tranzicije.*

Ključne reči *- energetske zajednice, energetska tranzicija, pravedna energetska tranzicija, energetske politike*

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Possibilities of Cement Industry Decarbonisation Using Biomass

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Abstract – The integration of renewable energy sources in the final energy mix has become a narrative due to current environmental problems, such as global warming, air pollution, dependence on fossil fuels, and others. It is also known that the industry had a significant impact on the emergence, development, and maintenance of these problems. Accordingly, a large number of researchers have contributed to the field of application of renewable energy sources in industry. The diversity of renewable energy sources that can be used in industry is conditioned by the operating temperature, which in most cases reaches values of 1000 °C. One of the renewable energy sources that can achieve these operating temperatures is biomass. This paper provides an overview of the current technologies of biomass application in the cement industry, considers the possibilities of their application in the Republic of Serbia, and analyses the benefits that are achieved by them.

Index Terms – Decarbonisation, Biomass, Cement industry

I Introduction

Transition from fossil fuels to renewable energy sources (RES) became a necessity due to the current environmental and climate problems [1]. Besides that, the European Commission published the REPowerEU plan in 2022 as an answer to current geopolitical happenings, which strives toward energy security and renewable electricity production to reduce the dependence on imported fossil fuels [2]. These aspirations should be present in all branches of human activities, including industry, which was responsible for 20% of global greenhouse gas (GHG) emissions in 2022 [3]. Guided by the Paris Agreement directions, industrial emissions of developed countries should be equal to zero until 2050, and reduced to 75% by 2030 [4]. Taking into account the high temperature requirements of the industry (working temperatures around 1000°C), among all RES, biomass represents one of the best choices for its decarbonisation. Additionally, there are a lot of recent studies that have shown the potential of biomass from the aspect of industrial decarbonisation [5–9].

It is known that industry has an average share of 27% in final energy consumption in the European Union [10]. Analogously, the industry in the Republic of Serbia has a significant share in final energy consumption and GHG emissions. A review of the GHG emissions by industry sectors in Serbia is shown in Table 1. It is noticeable that the cement industry is the second most GHG-intensive industry sector, right after the steel and iron industry.

Cement is one of the basic materials whose use has increased over time, from 100 million tons in 1950 to 4.1 billion tons in 2023 [11,12]. The cement industry represents one of the most energy-intensive industries, responsible for 10.1% of final electricity consumption in China [13], 15% in Iran [14], and 18.5% in Turkey. From the technological aspect, cement production includes three phases: preparation of raw materials, clinker production, and clinker grinding. The cement production process is illustrated in Figure 1. The process starts with the collection of raw materials (lime, sand, and clay), their grinding, and combining into a homogeneous powder, which is later sent into high-temperature furnaces where the clinker is produced. During this process, the most CO_2 emissions occur, part of them are caused by the fuel combustion (30-40%), while the other part comes from the process of chemical transformation of lime into calcium oxide (60-70%). Finally, the clinker is ground and mixed with gypsum to produce cement [16].

Table 1. Review of the GHG emissions by industry sectors in Serbia

Industry sector	***GHG emissions [Gg CO_2 eq]***
A: Mineral industry	***1371.58***
A1: Cement industry	1167.81
A2: Lime industry	139.54
A3: Glass industry	6.12
A4: Other process uses of carbonates	58.11
A5: Other	0
B: Chemical industry	***300.49***
B1: Ammonia industry	0
B2: Production of nitric acid	0
B3: Petrochemical industry	294.39
B4: Other	0
C: Metal industry	***2660.19***
C1: Steel and iron industry	2623.34
C2: Production of magnesium	36.85
C3: Other	0
D: Electronic industry	***0***
E: Other	***0***

This study analyses the possibility of biomass implementation in the cement industry of Serbia with the goal of its decarbonisation. The Republic of Serbia has 3 cement plants presented in Table 2.

Table 2. Review of cement plants in Serbia

Ref.	**Plant**	**Technology**	**Capacity [t]**
[17]	1	Dry process	1.5×10^6
[18]	2	Dry process	1.35×10^6
[19]	3	Dry process	0.75×10^6

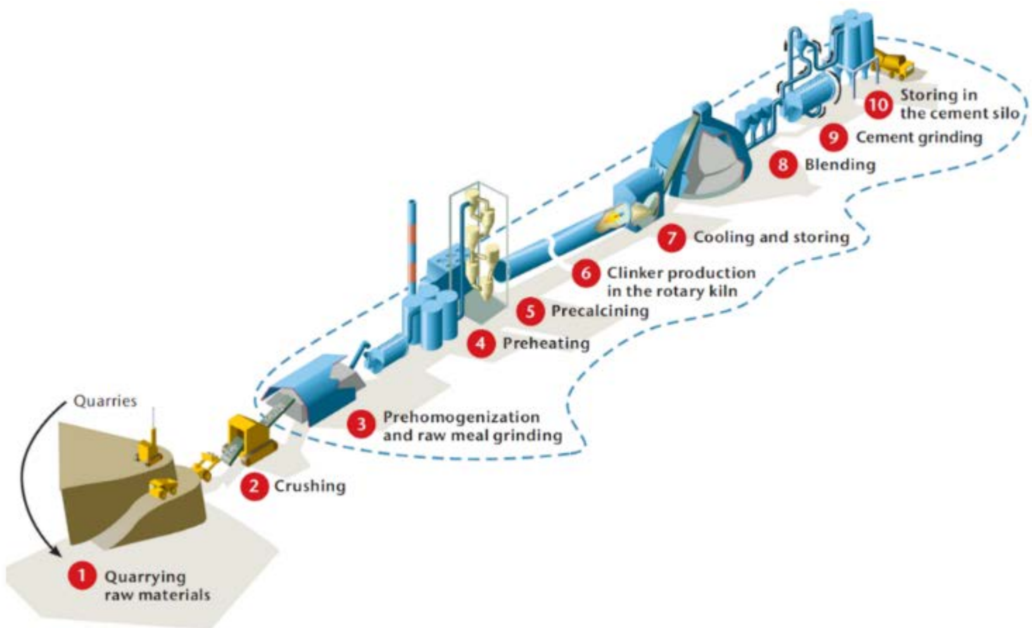

Figure 1. Illustration of the cement production process [16]

II Cement Industry Decarbonisation Possibilities

Taking into account that clinker production is responsible for more than 50% of total GHG emissions, its substitution is the crucial step toward cement industry decarbonisation. Cementitious materials, which can replace clinker, can be classified as hydraulic and pozzolanic materials. Hydraulic materials harden in contact with water, while pozzolanic materials harden only in the presence of dissolved calcium hydroxide [20]. Table 3 gives the systematization of cementitious materials.

Table 3. Cementitious materials

Hydraulic materials	Pozzolanic materials
• Blast furnace slag • Burned oil shales	• Fly ash • Silica dust • Calcined clay • Burnt rice husk • Natural pozzolans

Fly ash represents the most common cementitious material [21] produced during the coal combustion process. However, its availability will be reduced due to the current aspirations toward energy transition. Amran et al. [22] showed that the composition of biomass fly ash is competent to replace coal ash. Olatoyan et al. [23] analysed the potential of biomass ash as a cementitious material. They showed that the addition of biomass ash to concrete increases its mechanical characteristics, durability, and usability, while reducing its negative impact on the environment. Additionally, other research came to similar conclusions [24–28]. Table 4 gives a review of studies that analysed the potential of biomass ash as a cementitious material. These studies concluded that:

- Biomass ash is a good alternative for coal fly ash;
- Substitution of clinker with biomass fly ash reduces the negative impact of cement production on the environment;
- One of the studies showed that the addition of biomass ash to concrete reduces the emission factor from 0.772 to 0.338 kg CO_2 per kg of concrete;
- Substitution of clinker with biomass fly ash can simultaneously improve or worsen concrete's mechanical characteristics and functionality depending on the substitution rate;
- Mechanical characteristics of the concrete enhanced with biomass ash can be improved with ash pretreatment (sifting, washing, and grinding);
- Addition of biomass fly ash can delay the setting time of the concrete;
- Cementitious composites enhanced with biomass ash showed worsened characteristics in the first 3 to 7 days of curing, afterwards, they improved significantly due to pozzolanic activities.

Table 5 gives a review of studies that analysed the implementation of alternative fuels in the cement industry. Specifically, biomass such as wood and wood products [29–32], forest residues [29,33,34], agricultural residues [34–38], animal residues [29,38–42], and municipal solid waste [34,38,43–46]. These studies showed significant environmental and economic benefits, however followed by significant challenges. To ensure the performance of biomass as an alternative fuel, it has to be preprocessed and improved by applying conversion technologies. Additionally, the choice of the biomass and the substitution rate has to be carefully defined, taking into account its availability, the energy requirements of the industry, and its physical and chemical characteristics.

Table 4. Review of studies on biomass ash potential as a cementitious material

Reference	***Summary***	***Conclusions***
[23]	This work examines the advantages of replacing coal fly ash with biomass fly ash in cement production.	• The addition of biomass fly ash into concrete enhanced its mechanical properties, durability, and workability. • The addition of biomass fly ash into concrete mitigated its impact on the environment.
[24]	This study analyses wood ash as a cement replacement and as an alkali-activated material.	• Wood ash has larger, more porous, and more irregular particles compared to Portland cement, causing a decrease in the workability of the concrete. • The wood ash-based concrete workability can be enhanced by pre-treatment methods (sieving, washing, and grinding). • With an increase in wood ash share the setting time usually delays. • Cement with a partition of wood ash can show slightly worse or better mechanical properties than Portland cement-based concrete. • The optimum wood ash participation is between 10 and 20 wt%. • Water absorption increased with the levels of wood ash. • The addition of wood ash improves cement shrinkage. • The addition of wood ash increases the chloride permeability of the cement.
[25]	This research analyses geopolymer concrete and compares it with conventional concrete from the aspect of carbon and cost impact.	• Geopolymers based on biomass fly ash showed enhanced mechanical strength, acid resistance, sulphate degradation, and reduced shrinkage. • Geopolymer concrete has significantly decreased environmental impact compared to conventional concrete. The emission factor decreased from 0.772 kg of CO_2 per kg of concrete to 0.338.
[26]	This study evaluates the functional aspects of biomass fly ash as an alternative to coal fly ash in blended cements.	• Biomass fly ash contains significantly lower concentrations of hazardous elements. • The addition of biomass fly ash decreases the hydration heat evolution. • Replacement of 30 wt% of Portland cement with biomass fly ash resulted in minor changes in functional properties.
[48]	This work examines the impact of biomass ashes (from five available agricultural wastes) on the performance of cementitious composites.	• Large, irregularly shaped, highly porous, and rough on surfaces, untreated biomass ash particles significantly degrade the qualities of cementitious composites. • Biomass ash-enriched cementitious composites showed reduced mechanical properties in the first 3 to 7 days of curing, however, with the increased curing time, mechanical properties are significantly improved due to improved pozzolanic activity.
[49]	This research evaluates the influence of biomass feedstock and thermal conversion technology on ash properties.	• Generally, using biomass ash as supplementary cementitious material is a good approach to reduce CO_2 emissions and the volume of landfilled biomass ash. • Biomass ash quality can be influenced either positively or negatively by the thermal conversion technology. Two combinations of fuel/technology were recognized as most promising: i) a combination of wood biomass with low exogenous inclusion and high bark content combusted in a pulverized fuel installation, and ii) paper sludge and wood/bark combusted in a fluidized bed.

Table 5. Review of studies on the potential of biomass as an alternative fuel

Reference	***Summary***	***Conclusions***
[50]	This study analyses the impact of alternative fuels on production cost, environment, operation, and maintenance of Indian cement plants.	• Utilization of alternative fuels brings substantial savings in cement production. • Alternative fuels carry the potential to reduce greenhouse gas emissions. • The main issue with alternative fuel utilization is the jamming of the transfer and alternative fuel feeding chute to the calciner. • Another problem with alternative fuel utilization is economic demand, which could be recovered in 2 to 3 years.
[51]	This research evaluates the utilization of alternative fuels in the cement factory in Ethiopia.	• Caloric values of Prosopis juliflora (P. j.) wood, P. j. leaf, P. j. charcoal, used tires, and optimized fuels ranged between 14.37 and 33 MJ, meeting the minimum international standard of 14 MJ/kg. • Replacing 40% of coal with alternative fuels such as P. j. wood, P. j. leaf, P. j. charcoal, used tires, and optimized fuels can reduce CO_2 emissions by 2%, 9%, 9%, 21%, and 17% respectively. • Additionally, these alternative fuels carry the potential to reduce SO_2 emissions by 75%, 85%, 92%, 95%, and 17% respectively. • The problem with the utilization of alternative fuels is the NO_x emissions, but overall, all alternative fuels except P. j. charcoal and P. j. wood meet the emission standards. Still, P. j. charcoal and P. j. wood can be used as alternative fuels, but the replacement rate should not exceed 35% and 20%, respectively. • The alternative fuel utilization affects the quality of cement negatively, but the quality still meets international standards.

[43]	This paper analyses the status of alternative fuels and their usage in the cement industry.	• Used tires and biomass are the most attractive alternative fuels for the cement industry due to their low operational cost and high substitution rates. • Meat and bone meal, municipal solid waste, and sewage sludge need to be preprocessed before usage in the cement kiln. • Tire-derived fuel substitution rate above 30% is negatively affecting the chemistry of the cement and its hardening process. • Agricultural biomass is the best option from the environmental aspect, but its availability is a barrier toward its utilization. • Meat and bone meal and municipal solid waste are highly available, and have low environmental impact, but are economically expensive to use.
[44]	This paper compares six fuel alternatives using economic and environmental criteria.	• Municipal solid waste also showed a significant decrease in cumulative combustion and indirect GHG emissions reduction compared to reference from 2020 to 2050 (9%) with the most profitable marginal abatement cost in most regions (-54 – -170 CAD/tonne of CO_2e). • Hydrogen and electrification at full deployment offer the largest 2050 GHG emissions reduction of 98% and 89% respectively, compared to 76% and 52% reductions offered by the biomass and hythane, and municipal solid waste and hythane fuel mix. However, marginal abatement costs of hydrogen and electrification are not attractive as those of biomass and municipal solid waste.

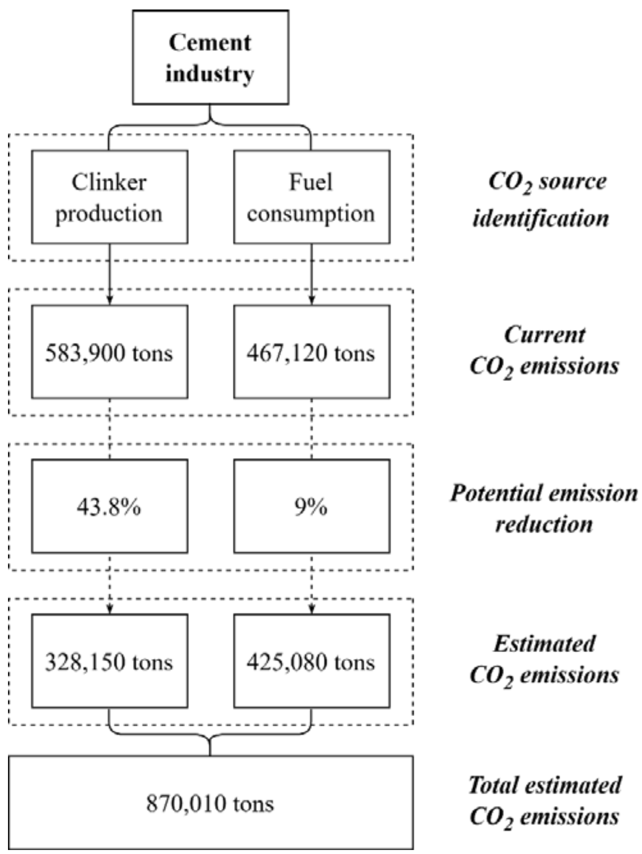

Figure 2. Estimation of CO_2 emission reduction of the cement industry in the Republic of Serbia

III CO_2 Reduction Estimation

As already mentioned, the cement production in the Republic of Serbia emitted around 1,167,810 tons of GHG in CO_2 eq. in 2020. To estimate the CO_2 emission reduction, firstly, it is necessary to define the sources of the emissions. According to Benhelal et al. [52] clinker production, fuel consumption, and transport and electricity consumption are responsible for 50%, 40%, and 10% of CO_2 emissions, respectively. Literature review showed that the potential reduction of CO_2 emissions in the case of clinker production is 43.8% [25] and 9% in the case of using biomass as an alternative fuel. The estimation (Figure 2) showed that by using biomass in the cement industry, the emissions can be reduced by 15.5% (181,010 tons of CO_2 eq).

IV Conclusion

Guided by the temperature requirements of the industry, economical costs, and implementation simplicity, biomass represents one of the best choices among RES for its decarbonisation. A hefty number of studies analyzed the biomass use in the cement industry, which represents the second most GHG-intensive industry sector in Serbia. Those studies showed that biomass can be used in the cement industry in two ways: 1) biomass fly ash can be used as a cementitious material, 2) biomass can be used as an alternative fuel.

Taking into account the quality of the produced cement, which depends on the substitution rate of clinker with biomass ash and on the amount of biomass used as alternative fuel, the CO_2 emission reduction estimation was done. It is concluded that by using biomass in the cement industry, the CO_2 emissions can be reduced from 1,167,810 to 986,800 tons CO_2 eq, which represents a reduction of 15.5%.

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Mogućnosti za dekarbonizaciju cementne industrije primenom biomase

Rezime *- Integracija obnovljivih izvora energije u finalnom energetskom miksu je postao narativ usled aktuelnih ekoloških problema, kao što su globalno zagrevanje, zagađenje vazduha, zavisnost od fosilnih goriva i drugi. Takođe je poznato da je industrija, zbog dosadašnjeg intenzivnog korišćenja fosilnih goriva, imala značajan uticaj na nastanak, razvoj i održanje ovih problema. Shodno tome, veliki broj istraživača je dalo svoj doprinos u oblasti primene obnovljivih izvora energije u industriji. Diverzitet obnovljivih izvora energije koji se mogu koristiti u industriji uslovljen je radnom temperaturom koja u najvećem broju slučajeva dostiže i vrednosti od 1000°C. Jedan on obnovljivih izvora energije koji može postići ove radne temperature je biomasa. Ovaj rad pruža pregled trenutnih tehnologija primene biomase u cementnoj industriji, razmatra mogućnosti njihove primene u Republici Srbiji i analizira benefite koji se njima postižu.*

Ključne reči *- dekarbonizacija, biomasa, cementna industrija*

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The Importance of Small Hydro Power Plant Development in Advancing Sustainable Energy Solutions: Methodology and Case Study of Bistrica Majstorovina SHPP

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Abstract – Small hydropower plants (SHPPs) have evolved in a sustainable way, providing clean, renewable and reliable electricity with minimal impact on the environment. This paper looks at the methodology for planning SHPPs, with a detailed case study of the Bistrica Majstorovina SHPP. The study outlines the technical, environmental and economic aspects of SHPP development, including site selection, design optimization and integration into local energy grids. It also examines the socio-economic benefits of SHPPs, such as improving the living conditions of the local population and promoting local economic growth. The Bistrica Majstorovina SHPP case study demonstrates the practical implementation of sustainable energy solutions and highlights best practices and lessons learned from project implementation. This paper provides a comprehensive framework for future SHPP projects, contributing to the wider adoption of sustainable energy practices.

Index Terms – Small hydropower plant, Design flow, Methodology, Case study

I Introduction

As global energy demand rises and environmental concerns become more pressing, the development of renewable energy sources has become a key priority [1]. Among these, small hydropower plants (SHPPs) stand out as a sustainable and efficient solution for electricity generation. According to the internationally accepted convention, small hydropower in continental waters includes plants up to 10 MW. The convention is not binding, so each country, depending on its natural (climatic, hydrometeorological, topographic and other) specifics, level of technological development and economic standard, defines the limit values for SHPPs, but also changes them as necessary [2]. SHPPs minimize their ecological footprint while offering reliable power supply and economic benefits to local communities [3]. The successful implementation of SHPPs requires a well-structured methodology that accounts for technical, economic, and environmental factors [4-9]. Key considerations include site selection, design flow optimization, and financial feasibility, all of which influence the overall efficiency and sustainability of a project [10]. This paper explores the significance of SHPPs in advancing sustainable energy solutions, with a particular focus on the Bistrica Majstorovina SHPP as a case study. It provides an in-depth analysis of the planning and implementation process, highlighting best practices and challenges encountered. By examining the methodology used to determine optimal design parameters, this study aims to contribute valuable insights for future SHPP projects, ensuring their viability and long-term success in the global shift toward renewable energy. In addition to the scientifically based methodology, which takes into account all the energy-economic and ecological conditions of the design, construction and exploitation of the SHPP in question, special attention is devoted to the improvement of the living conditions of the local community.

II Methodology for SHPP Development

The successful development of SHPPs involves several critical stages, including site selection, feasibility studies, design optimization, environmental impact assessment, and project implementation. Each phase ensures that the project is technically, economically, and environmentally viable. Since the design flow rate is one of the most important parameters in the planning of SHPP, a methodology was developed to determine it as accurately as possible [9,11]. The methodology is based on technical and economic parameters. Technical parameters are the installed capacity and the annual electricity production, and economic parameters are the annual revenue, the net present value (NPV), the internal rate of return (IRR) and the payback period (PB). The term SHPP installed parameter (Ki) is also introduced, which represents the ratio between the design flow and the average perennial flow obtained from the flow duration curve at the location of the planned water intake. The methodology varies the value of Ki in the range from 1.0 to 2.5. with the step $\Delta Ki = 0.1$. For any given value of the design flow rate, the developed in-house software performs an optimization procedure, the results of which is the design flow rate that gives the highest electricity production, the highest gross income and the best economic parameters. In some cases, a unique solution is obtained, and in some cases, several solutions for the SHPP installed parameter are obtained. A detailed analysis of the built and planned small hydro power plants in Montenegro showed that the economic parameters NPV and IRR are the most influential parameters when choosing a SHPP installed parameter, and that for designing you should choose a SHPP installed parameter that is optimal from the aspect of NPV and IRR [12]. For all considered SHPPs, there were hydrological data obtained from the Registry of Small Rivers and Potential Locations of SHPPs in Montenegro [13,14] and Institute of

Hydrometeorology and Seismology of Montenegro [15]. The annual electricity production is calculated based on the hydrological data and the annual revenue is determined with the help of the incentive tariff, Table 1.

Table 1. Electricity prices depending on the capacity of the power plant [16]

Hydro power plant capacity [MW]	Incentive price [c€/kWh]
$P_{SHPP} < 1$ MW	10.44
$1 \leq P_{SHPP} < 3$ MW	$10.44 - 0.7 \cdot P_{SHPP}$
$3 \leq P_{SHPP} < 5$ MW	$8.87 - 0.24 \cdot P_{SHPP}$
$5 \leq P_{SHPP} < 8$ MW	$8.35 - 0.18 \cdot P_{SHPP}$
$8 \leq P_{SHPP} \leq 10$ MW	6.8

In the previous decade, 31 (thirty-one) small hydropower plants have been built and commissioned in Montenegro. A comparison was made between the built state of each of them and the results of the methodology. The following diagrams show some examples, one with equal methodology and constructed solution (Šeremet SHPP - Figures 1 and 2), one with different methodology and constructed solution (Temnjačka SHPP - Figures 3 and 4) and so-called No Name SHPP (Figures 5 and 6) with negative NPV value.

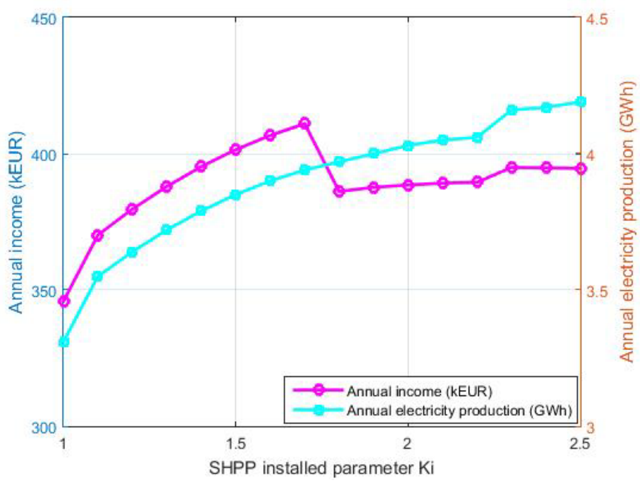

Figure 1. Annual electricity production and income – Šeremet SHPP

The maximum electricity production of 4.19 GWh is achieved at Ki = 2.5. Annual revenue increases up to Ki = 1.7, where it reaches its peak value of 411 kEUR, before declining at Ki = 1.8 due to the installed capacity exceeding 1 MW, which leads to a reduction in the incentive tariff. On the other hand, the maximum values for NPV (2605.95 kEUR) and IRR (22.54%) are obtained at Ki = 1.7 and Ki = 1.5, respectively. The total investment required for achieving the maximum NPV is 1458.2 kEUR, while for the maximum IRR, it stands at 1415.83 kEUR, with corresponding payback periods of 4.21 years and 4.19 years, respectively. The difference in revenue compared to the maximum NPV scenario is 9.52 kEUR, whereas the investment gap between the highest revenue scenario and the maximum IRR scenario is 42.37 kEUR. The optimal solution for the Šeremet SHPP is determined to be Ki = 1.7. The designed Ki value for the constructed Šeremet SHPP is 1.7. A comparison of the results obtained through the developed methodology with the designed parameters confirms that the same parameter values are achieved. From an economic perspective, this designed solution appears to be well-chosen.

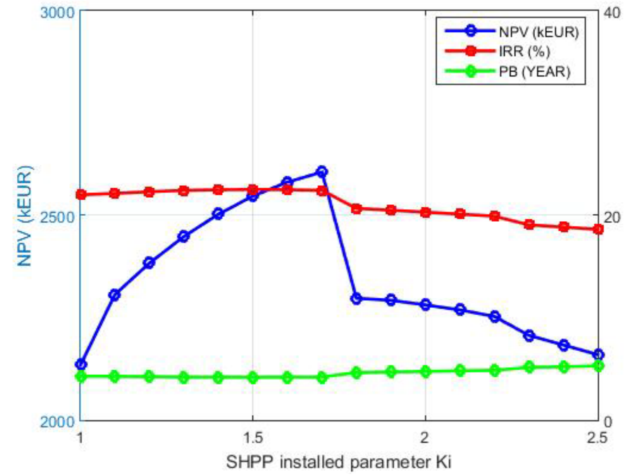

Figure 2. Annual electricity production and income – Šeremet SHPP

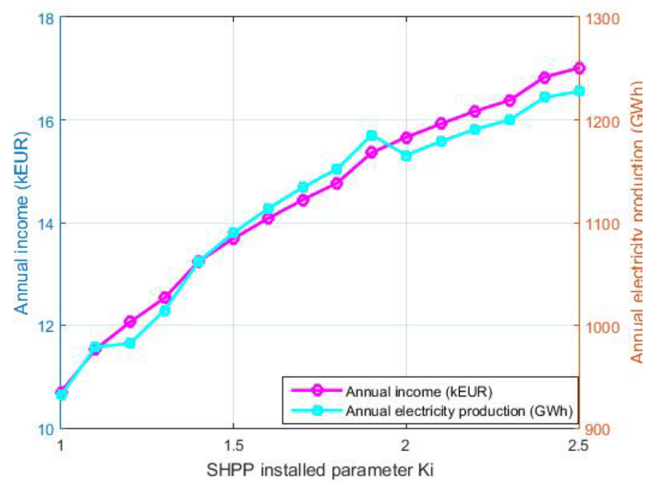

Figure 3. Annual electricity production and income – Temnjačka SHPP

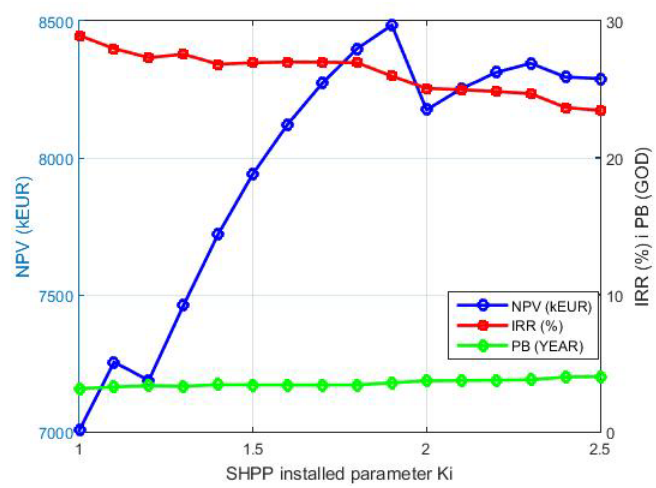

Figure 4. NPV, IRR and PB – Temnjačka SHPP

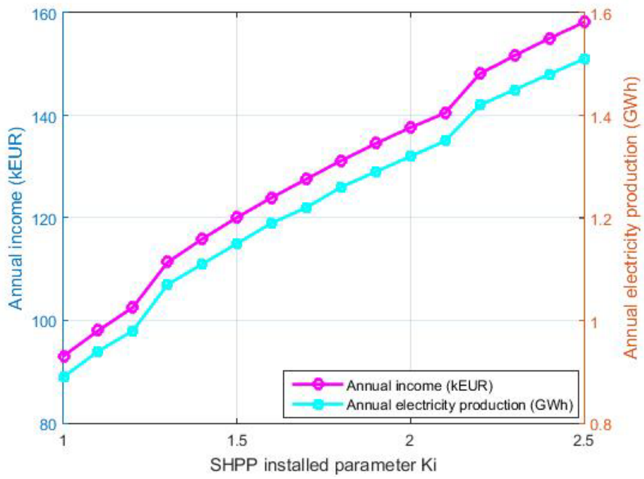

Figure 5. Annual electricity production and income - No Name SHPP

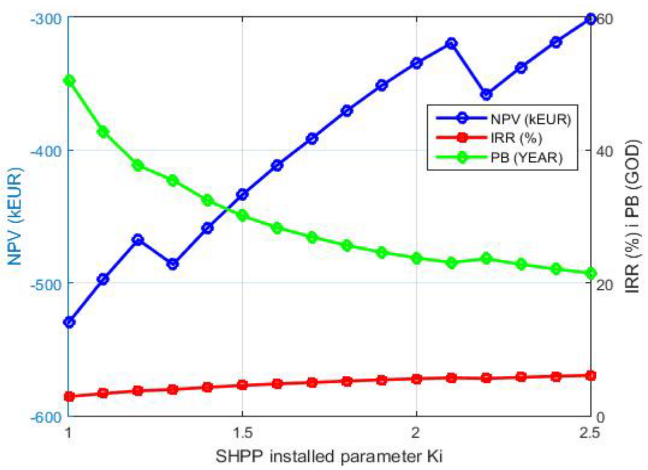

Figure 6. NPV, IRR and PB - No Name SHPP

The maximum electricity production and revenue is achieved at Ki = 2.5. On the other hand, the highest values for NPV (8,484.88 kEUR) and IRR (28.94%) are obtained at Ki = 1.9 and Ki = 1.0, respectively. As the pipeline diameter increases from DN800 to DN900, the NPV value experiences a slight decline up to Ki = 1.1, after which it steadily rises until Ki = 1.9. Beyond this point, due to exceeding the 5 MW threshold, NPV shows a slight decrease and remains nearly constant throughout the remaining range. The total investment required for achieving the maximum NPV is 3,784.95 kEUR, while for the maximum IRR, it stands at 2,651.96 kEUR, with corresponding payback periods of 3.14 years and 4.03 years, respectively. The revenue difference compared to the maximum NPV scenario is 42.32 kEUR, while the difference in revenue relative to the maximum IRR scenario amounts to 296 kEUR. Additionally, the investment gap between the highest revenue scenario and the maximum IRR scenario is 1,691.3 kEUR, whereas the difference compared to the maximum NPV scenario is 558.31 kEUR. Based on this findings the optimal solution for the Temnjačka SHPP is determined to be Ki = 1.9. The actual installed parameter for Temnjačka SHPP is Ki = 1.3. At this installed parameter, the total production is 12.53 GWh, annual revenue is 1,014.57 kEUR, NPV is 7,461.46 kEUR, IRR stands at 27.57%, and the payback period (PB) is 3.32 years. By comparing these two installed parameters, it can be observed that the optimal solution yields slightly better results in terms of higher annual revenue, total production, and NPV.

For No Name SHPP, the maximum value of annual production 1.51 GWh and the maximum value of annual income 158.15 kEUR is obtained for K_i = 2.5. The maximum values for NPV (-301.11 kEUR) and IRR (6.08%) i.e. the corresponding PB (21.48 years) were obtained also for K_i = 2.5. Designed value of K_i on constructed No Name SHPP is 1.8. For this value, annual electricity production is 1.26 GWh, annual income is 131.16 kEUR, NPV is -370.25 kEUR, IRR is 5.22% and PB is 25.65 years. Based on the obtained results, it can be noted that the NPV has a negative value for the entire K_i range, which indicates that this SHPP was not designed properly or was designed with wrong input data. Also, the maximum IRR value of 6.08% is lower than the adopted discount rate of 8%, which means that the project is not feasible.

The normalized values of NPV and IRR are used for a precise comparison of the results obtained by the methodology and the constructed SHPP solution. Normalized values were obtained by dividing calculated values with optimal ones given with chosen K_i for every plant. With relative values, we are able to check results on the same level and compare different plants. Vertical lines mean constructed K_i and cross points with NPV or IRR lines give constructed NPVs or IRRs. Figure 7 shows the criteria for evaluating the validity of the constructed solution.

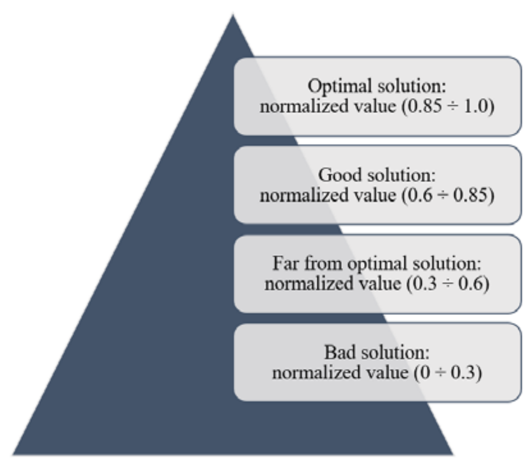

Figure 7. Criteria for evaluating the validity of the constructed solution (normalized values of NPV i IRR)

For Šeremet SHPP (Figure 8), the solution obtained by the methodology is the same as the constructed solution. Considering the above, the constructed SHPP installed parameter (NPV=1) is the optimal solution.

Figure 9 shows normalized values of NPV for Temnjačka SHPP. Comparing the constructed, SHPP installed parameter and the SHPP installed parameter obtained by the methodology; it can be observed that better results of all considered parameters are provided by the optimal solution. Based on this comparison, the normalized value accounts for 88% (NPV = 0.88) of the optimal solution, indicating that the constructed SHPP installed parameter represents a well-balanced alternative in the range of the optimal solution near the lower limit of 0.85.

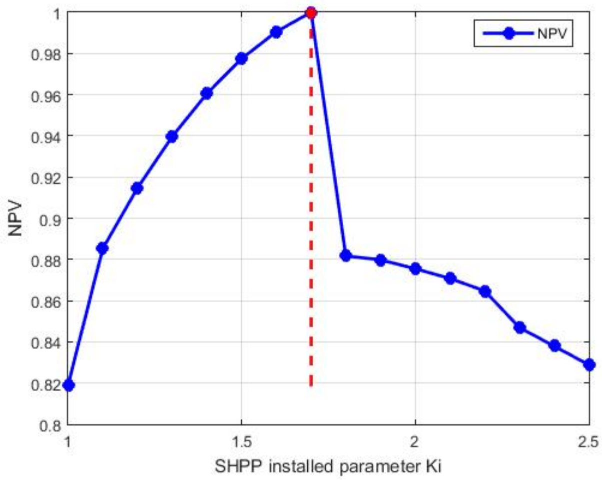

Figure 8. Normalized values of NPV –Šeremet SHPP

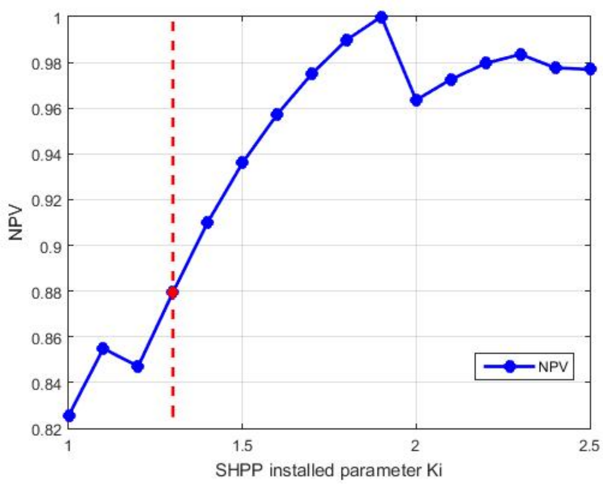

Figure 9. Normalized values of NPV –Temnjačka SHPP

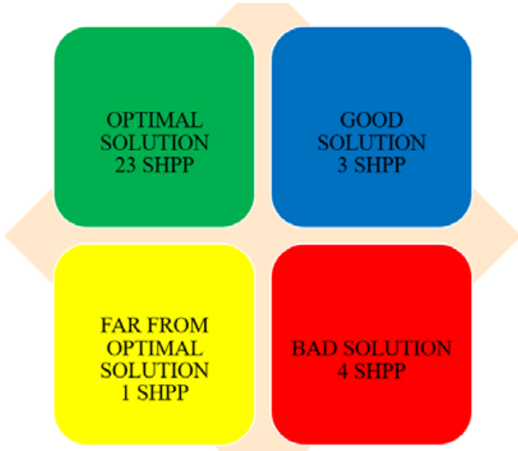

Figure 10. Evaluation of the validity of the implemented solutions

Considering that the net present value (NPV) for the No Name SHPP, has a negative value and the maximum IRR value is below the assumed discount rate, one can conclude that this power plant was built as a bad solution. Fig.10 shows results for all 31 newly-built SHPPs in Montenegro.

It can be concluded that out of 31 newly built SHPP in Montenegro, even 23 were made as an optimal solution, which is a very high 74%. Three can be considered as a good solution, one as far from optimal and four SHPPs were built as a bad solution.

III Case Study: Bistrica Majstorovina SHPP

The Bistrica Majstorovina SHPP, located in Bijelo Polje, Montenegro, serves as an exemplary model for small-scale hydropower development. This section provides an overview of its development process and outcomes. In November 2011, a limnigraph for measuring the water level was installed on the watercourse at the position of the planned water intake, Figure 11, and continuous measurements were carried out for two full years. The flow was measured several times every month using a flow-tracer, a device that measures the change in the concentration of the solution in the watercourse, Figure12. A hydrological study was performed and a flow duration curve (FDC) was obtained, Figure 13, which during design was used to estimate annual electricity production and determine ecological flow.

Figure 11. Limnigraph at the location of the water intake

Figure 12. Flow measurement using a flow-tracer

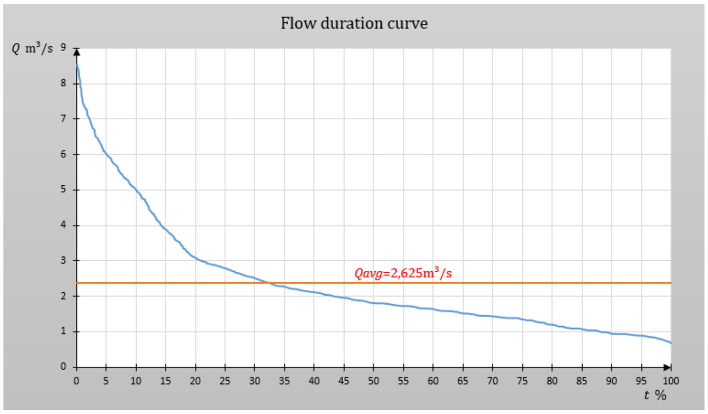

Figure 13. Flow measurement using a flow-tracer

Bistrica Majstorovina SHPP was commissioned at the end of 2017 and has been in commercial operation since January 2018. Its basic characteristics are given in Table 2.

Table 2. Main technical characteristics of the Bistrica Majstorovina SHPP

Gross head:	H_b = 102.00 m
Average perennial flow at the water intake:	Q_{avg} = 2.625 m^3/s
Ecological flow	Q_{DEF} = 0.260 m^3/s
Design discharge:	Q_D = 4.20 m^3/s
SHPP installed parameter	K_i = 1.6
Net head:	H_n = 95.5 m
Pipeline diameter:	D = 1600 mm
Pipeline length:	L = 3723 m
Two equal Francis turbines:	P_F = 1800 kW
Total capacity	P = 3600 kW
Designed annual electricity production:	E_{DEP} = 11.7 GWh

The anticipated investment in the Bistrica Majstorovina SHPP project was about 7260 kEUR with a specific investment of 2016 EUR/kW and 0.62 cEUR/kWh. After the project completion, the total costs were exceeded by about 7% and amounted to about 7785 kEUR with a specific investment of 2162 EUR/kW and 0.66 cEUR/kWh. Figure 14 shows the cost structure.

The most, 50%, was the cost of civil works which is construction of a power house, water intake and procurement and installation of pipeline. Electro-mechanical and hydro-mechanical equipment cost is 22%, while design and infrastructure cost 5% each. The infrastructure costs include the installation of an underground energy cable to connect the power plant to the grid on 10 kV level and the construction and asphalting of the access road to the power house. Other costs, which account for 18%, include management and supervision of the project, settlement of property-legal relations, preparatory works and implementation of multi-purpose solutions for the needs of the local community. It should be emphasized that only electro-mechanical and hydro-mechanical equipment was purchased abroad, and that the rest of the invested money remained in Montenegro and partly in Serbia, where the pipeline was purchased. The following pictures show the main parts of the Bistrica Majstorovina SHPP.

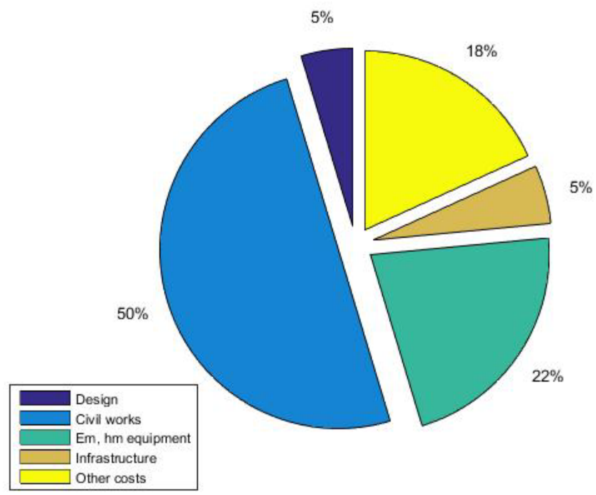

Figure 14. Cost structure of the Bistrica Majstorovina SHPP

Figure 15. Water intake of the Bistrica Majstorovina SHPP

Bistrica Majstorovina SHPP (Figures 15-17) has been in operation for seven years. Table 3 shows the costs of its work in this period as well as the amount of energy produced. Table 4 shows the difference between the foreseen and actually produced amount of electricity, from which it can be seen that in seven years of operation, the Bistrica Majstorovina SHPP produced 648 MWh less electricity than was designed.

Figure 16. Bistrica Majstorovina SHPP pipeline

Figure 17. Bistrica Majstorovina SHPP power house

Table 3. Energy production, income and costs of the Bistrica Majstorovina SHPP

Year	Electricity production MWh	Income EUR	Loan EUR	OM costs EUR	Concession fee EUR	Operator fee EUR
2018	9.525	852.451,59	675.963,37	103.124,92	51.688,28	6.667,18
2019	10.236,32	875.102,95	474.518,97	117.102,72	56.881,69	7.165,42
2020	10.352,05	888.516,59	476.783,40	175.888,39	57.753,58	7.297,28
2021	12.336,98	1.055.675,71	481.030,87	134.837,02	68.618,92	9.400,78
2022	12.854,80	1.126.337,26	485.074,17	140.280,48	73.211,92	9.024,07
2023	17.170,64	1.700.065,08	551.990,85	142.184,26	110.504,23	11.160,92
2024	8.777,80	943.788,64	1.920.755,41	252.110,38	61.346,26	6.755,39
SUM:	**81.253,13**	**7.441.937,83**	**5.066.117,04**	**1.065.528,17**	**480.004,88**	**57.471,04**

Table 4. Difference between designed and actual energy production

Year	2018	2019	2020	2021	2022	2023	2024	SUM
$E_{DEP} – E_{AEP}$ MWh	- 2175	-1464	-1348	637	1154	5470	-2922	-648

Table 5. Difference between designed and average ecological flow

Year	2018	2019	2020	2021	2022	2023	2024
Average ecological flow (Q_{AEF}) l/s	840	770	1650	1050	744	1650	550
Q_{AEF} / Q_{DEF}	3.2	3.0	6.3	4.0	2.9	6.3	2.1

Designed ecological flow (DEF) for Bistrica Majstorovina is $Q_{DEF} = 0.1Q_{AVG} = 0.260$ m^3/s according to the law valid in 2015. In order to monitor the ecological flow downstream of the water intake, a limnigraph was installed, Figure 18.

Every year, a hydrological study of the watercourse downstream of the water intake was carried out and a FDC as well as a value of the average ecological flow was determined, Figure 19. Table 5 shows that the average ecological flow is always higher than the designed ecological flow, at least 2.1 times in 2024 and at most 6.3 times in 2020 and 2023.

Figure 18. Limnigraph downstream of the intake

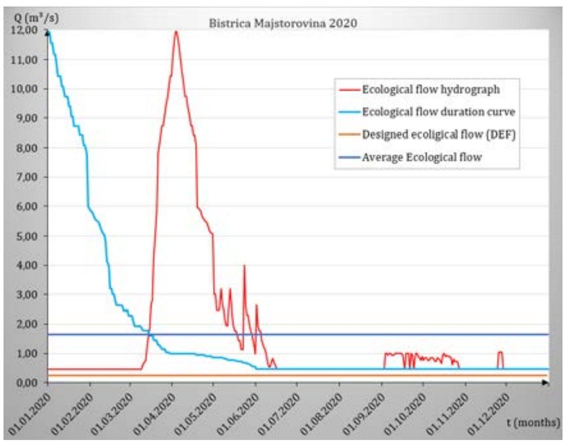

Figure 19. Ecological flow, example from 2020 year

The local community also had and has numerous benefits from the construction of a SHPP. A significant amount of money was set aside for the settlement of property-legal relations. For several households, drinking water was brought from the water intake. Several kilometres of the local road and the plateau in front of the elementary school were paved. Although the power plant works in automatic mode, eight young people got permanent employment, formed families and stayed to live in their native hearths. In cooperation with the local community, the most socially vulnerable families are provided with firewood and assisted in various ways. Downstream from the water intake of the SHPP and the limnigraph for measuring ecological flow, and for the needs of Ravna Rijeka monastery, three large-scale fishponds are constructed, which are producing trouts for commercial use. Off-grid solar systems have been installed on 15 katuns, which significantly improved the living conditions of people who go up to the mountain with their cattle during the summer.

Applying the developed methodology to the case of Bistrica Majstorovina SHPP gives the result shown in Figure 20. The normalized value of IRR = 0.82 means that constructed solution with K_i = 1.6 belong to group of good solution close to upper limit of 0.85. It is also can be seen that decreasing SHPP installed parameter to K_i = 1.4 will bring solution to the group of optimal and the best results will be obtained for K_i = 1.0.

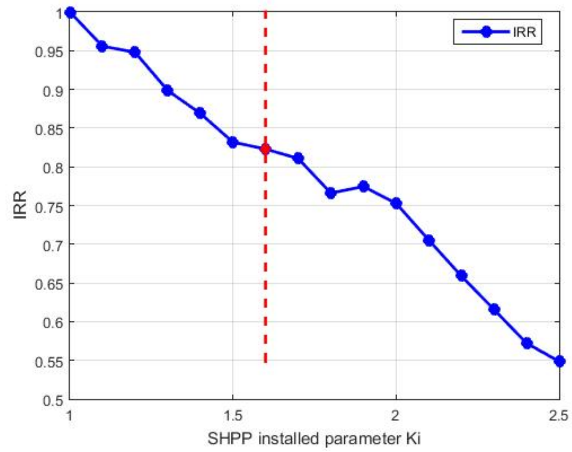

Figure 20. Normalized values of IRR –Bistrica Majstorovina SHPP

IV Conclusion

The development of small hydropower plants (SHPPs) plays a crucial role in advancing sustainable energy solutions by providing clean, renewable, and reliable electricity with minimal environmental impact. This study has explored the methodology for SHPP planning and design, emphasizing the importance of technical, economic, and environmental parameters in optimizing performance. Through an in-depth analysis of various SHPPs in Montenegro and a detailed case study of the Bistrica Majstorovina SHPP, the practical application of the proposed methodology has been validated. In the case of Bistrica Majstorovina SHPP, the selected parameter (Ki = 1.6) resulted in a well-balanced solution, as confirmed by the normalized value of IRR. This demonstrates that the developed methodology provides a robust framework for selecting optimal design parameters, ensuring maximum efficiency and economic return. Furthermore, the evaluation of 31 newly constructed SHPPs in Montenegro revealed that 74% were designed optimally, with an additional 10% classified as good solutions. However, the study also identified cases where suboptimal design choices led to reduced financial feasibility, highlighting the importance of rigorous methodological application. Beyond economic and technical aspects, SHPP development has contributed to local socio-economic growth and infrastructure improvements. The Bistrica Majstorovina SHPP, in particular, has provided employment opportunities, enhanced local infrastructure, and supported ecological initiatives, such as off-grid solar systems and fish farming projects. Overall, the research underscores the significance of a systematic approach to SHPP development, ensuring that future projects are both economically viable and environmentally sustainable. The proposed methodology serves as a valuable tool for decision makers, engineers, and investors aiming to implement small hydropower solutions that align with global energy sustainability goals. At the same time, the presented SHPP is an example of good practice showing that goals can only be achieved with respect and constant verification of all standards-defined, legally prescribed, socially and environmentally acceptable, technically feasible and economically rational conditions for the construction and operation of a conteprorary SHPP.

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Značaj razvoja malih hidroelektrana u unapređenju održivih energetskih rešenja: metodologija i studija slučaja MHE Bistrica Majstorovina

Rezime *- Male hidroelektrane (MHE) su se razvijale na održiv način, obezbeđujući čistu, obnovljivu i pouzdanu električnu energiju sa minimalnim uticajem na životnu sredinu. Ovaj rad razmatra metodologiju za planiranje MHE, sa detaljnom studijom slučaja MHE Bistrica Majstorovina. Studija opisuje tehničke, ekološke i ekonomske aspekte razvoja MHE, uključujući izbor lokacije, optimizaciju projektovanja i integraciju u lokalne energetske mreže. Takođe, ispituje društveno-ekonomske koristi MHE, kao što su poboljšanje životnih uslova lokalnog stanovništva i podsticanje lokalnog ekonomskog rasta. Studija slučaja MHE Bistrica Majstorovina demonstrira praktičnu primenu rešenja za održivu energiju i ističe najbolje prakse i lekcije naučene iz implementacije projekta. Ovaj rad pruža sveobuhvatan okvir za buduće projekte MHE, doprinoseći širem usvajanju praksi korišćenja održive energije.*

Ključne reči *- mala hidroelektrana, projektni protok, metodologija, studija slučaja*

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Analiza isplativosti primene solarnih sistema kod kupaca-proizvođača koji su domaćinstva

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Rezime **-** U radu će biti analiziran uticaj ugradnje solarnih sistema kao primene novih tehnologija u domaćinstvima, kroz procenu troškova, ušteda na računima za električnu energiju i perioda povraćaja investicije. Na početku će biti prikazan uporedni pregled stavki računa za električnu energiju između potrošača koji nisu kupci-proizvođači i onih koji to jesu. Nakon toga, analiza će obuhvatiti primenu solarnih sistema u domaćinstvima kategorije kupaca-proizvođača sa različitim nivoima godišnje potrošnje električne energije i različitim odnosima potrošnje u višoj i nižoj tarifi. Biće razmatrano šest grupa potrošača koje se razlikuju po prosečnoj godišnjoj potrošnji, dok će za svaku grupu biti analizirana dva slučaja odnosa potrošnje u višoj i nižoj tarifi. Na osnovu podataka o potrošnji električne energije, usvojene godišnje raspodele potrošnje po mesecima i modela proizvodnje solarnih sistema dobijenih korišćenjem PVGIS Online Tool-a, biće određene optimalne instalisane snage solarnih sistema za analizirane grupe potrošača. Analiza će obuhvatiti procenu potrebnih investicionih sredstava, očekivane uštede na računima za električnu energiju i vreme povraćaja investicije. Posebna pažnja biće posvećena uticaju odnosa potrošnje u višoj i nižoj tarifi na izbor optimalne snage solarnog sistema, kao i mogućnostima korišćenja viškova proizvedene energije. Očekuje se da će rezultati ukazati na isplativost i opravdanost investicije u zavisnosti od vrednosti godišnje potrošnje električne energije domaćinstva.

Ključne reči - kupac-proizvođač, solarni sistem, optimalna instalisana snaga, ekonomski uticaj, domaćinstva

I Uvod

Poslednjih godina, globalno tržište električne energije beleži značajan rast primene obnovljivih izvora energije (OIE), uz istovremeni porast broja kupaca-proizvođača. Upoređujući države članice Evropske unije [1-3] sa državama Zapadnog Balkana [4-7], evidentno je da region Zapadnog Balkana značajno zaostaje u razvoju kupaca-proizvođača. Razlog tome leži u istorijskom kašnjenju uvođenja OIE na Zapadnom Balkanu, što je dodatno uticalo na sporiji razvoj kupaca-proizvođača u elektroenergetskom sistemu ovih zemalja.

Osnovni faktori koji utiču na sporiji napredak u ovom segmentu su regulatorni okvir i strategije razvoja energetike, koje se u državama Zapadnog Balkana i dalje nalaze u fazi postepenog usklađivanja i implementacije [5]. U mnogim slučajevima, energetska politika u regionu oslanja se na kratkoročne mere, što usporava ulaganja u modernizaciju elektroenergetskog sistema. Dodatni izazov predstavlja dugotrajan proces smanjenja oslanjanja na termoelektrane na ugalj, što usporava tranziciju ka čistijim izvorima energije.

U Srbiji primena OIE obuhvata više modela, definisanih važećom regulativom. Među njima se izdvajaju: proizvođač [8-10], kupac-proizvođač [8-11], aktivni kupac [8], zajednica OIE [8,10,12] i energetska zajednica građana [8]. U Srbiji su kupci-proizvođači podeljeni u tri kategorije: domaćinstva, stambene zajednice i ostali [10,11].

Iako Srbija zaostaje u primeni koncepta kupaca-proizvođača u odnosu na razvijene zemlje sveta, kontinuirano se kroz analize i predloge za unapređenje regulative i strategija razmatraju mere koje mogu doprineti lakšoj, efikasnijoj i bržoj integraciji većeg broja kupaca-proizvođača u elektroenergetski sistem [4-7,12-17].

Na sajtu Elektrodistribucije Srbije (EDS) dostupni su registri kupaca-proizvođača [18]. Prvi kupac-proizvođač iz kategorije domaćinstava u Srbiji registrovan je 29. aprila 2022. godine. Prema podacima preuzetim sa sajta EDS, 7. marta 2025. godine, u ovoj kategoriji registrovano je 3229 kupaca-proizvođača, sa ukupnom instalisanom snagom od 26.418,99 kW. Svi proizvodni objekti su solarne elektrane, što potvrđuje da je solarna energija dominantan izbor za kupce-proizvođače u Srbiji. Iako postojeći zakonski okvir ne ograničava kupce-proizvođače na upotrebu samo solarne energije, nekoliko ključnih faktora doprinosi njenoj širokoj primeni. U poređenju sa drugim obnovljivim izvorima energije, solarni sistemi se ističu kao tehnički jednostavnije i ekonomski isplativije rešenje, posebno kada se instaliraju na krovovima domaćinstava.

Cilj ovog rada je da analizira isplativost primene solarnih sistema kod kupaca-proizvođača koji su domaćinstva i da ukaže na značaj izbora optimalne instalisane snage solarne elektrane. U radu će biti dat uvid u ključne ekonomske faktore koji utiču na odluku o investiranju, uključujući procenu troškova instalacije, očekivane uštede na računima za električnu energiju i vremenski okvir povraćaja ulaganja.

II Ekonomski uticaj

Kroz analizu početnih investicija, troškova održavanja i perioda otplate u odnosu na uštede u troškovima električne energije, može se sagledati isplativost solarnih sistema za kupce-proizvođače.

2.1. Početni investicioni troškovi kupaca-proizvođača

Početni investicioni troškovi za kupce-proizvođače variraju u zavisnosti od instalisane snage male elektrane, korišćene tehnologije, kao i od uslova i finansijskog okvira u zemlji. Može se primetiti da početni investicioni troškovi opadaju iz godine u godinu.

U Srbiji, u 2021. godini, troškovi instalacije, u okviru kompletne usluge instalacije za krajnje korisnike, kretali su se od 1000 do 1200 EUR po kW. U narednoj, 2022. godini, primetno je smanjenje troškova, koje je dodatno potpomognuto državnim podsticajima, pri čemu su prosečni troškovi instalacije bez državnih podsticaja bili između 900 i 1100 EUR po kW. Tokom 2023. i 2024. godine, troškovi instalacije smanjeni su na raspon od 800 do 1000 EUR po kW, uz dodatnu mogućnost korišćenja subvencija.

Formula za procenu vrednosti početnih investicija (C_{invest}), koja je korišćena u ovom radu, dobijena je od kompanije specijalizovane za projektovanje i izvođenje solarnih sistema:

$$C_{invest}\left[EUR\right] = 2000 + 500 \cdot \mathrm{P}_{inst}\left[kW\right] \ , \qquad (1)$$

gde je P_{inst} - instalisana snaga male solarne elektrane u [kW].

Formula (1) podrazumeva troškove instalacije po sistemu "ključ u ruke" za krajnjeg korisnika.

U Tabeli 1 prema formuli (1) je dat prikaz procene potrebnih početnih sredstava za instalaciju male solarne elektrane, u zavisnosti od njihove snage, kao i odnos potrebnih početnih sredstava i instalisane snage male solarne elektrane. Može se uočiti da cena po instalisanom kW opada sa porastom instalisane snage.

Tabela 1. Prikaz procene potrebnih početnih sredstava za instalaciju male solarne elektrane

P_{inst} [kW]	2	4	6	8	10	10.8
C_{invest} [EUR]	3000	4000	5000	6000	7000	7400
P_{inst} / C_{invest} [EUR/kW]	1500	1000	833.37	750	700	685.2

U Srbiji, subvencije i poreske olakšice mogu pokriti do 50% početnih investicionih troškova, za elektrane do 6 kW za domaćinstva, što ovu investiciju čini privlačnijom za prosečnog potrošača. Ministarstvo rudarstva i energetike pokrenulo je 2021. godine program subvencionisanja ugradnje solarnih panela u saradnji sa 37 opština. Opštine su finansirale do 50% troškova instalacije, sa maksimalnim iznosom od 420000 RSD po domaćinstvu. Nakon uspešne realizacije programa, Ministarstvo je najavilo da će narednih šest godina subvencionisati ugradnju solarnih panela kroz programe energetske sanacije domaćinstava. Sredstva se obezbeđuju delom iz budžeta Ministarstva rudarstva i energetike, a delom iz budžeta opština koje učestvuju u programu. Program subvencija sprovode jedinice lokalne samouprave i gradske opštine, koje godišnje raspodeljuju bespovratna sredstva prema utvrđenim kriterijumima. Program se 2022. proširio na 131 opštinu uz zadržavanje istih uslova. Subvencije su nastavljene i tokom 2023. i 2024. godine, uz dodatnu promociju programa radi podsticanja korišćenja solarne energije. U 2024. godini građani su mogli da se prijave za subvencije u 137 opština.

2.2. Troškovi održavanja tokom eksploatacije

Troškovi održavanja solarnog sistema kod kupaca-proizvođača uključuju periodično čišćenje panela, provere i eventualnu zamenu invertora, redovnu inspekciju sistema, kao i manje popravke ili zamenu komponenti. Ukupni godišnji troškovi održavanja u proseku iznose od 1% do 3% od početne investicije.

Periodično čišćenje solarnih panela je potrebno kako bi se uklonila prašina i druge nečistoće koje mogu smanjiti njihovu efikasnost. Ovi troškovi mogu varirati. Prosečni godišnji troškovi čišćenja procenjuju se na 20 do 50 EUR po kW instalisane snage, u zavisnosti od lokacije i učestalosti čišćenja.

Periodične provere i održavanje invertora su neophodne, pri čemu zamena invertora može biti jedan od većih troškova, jer invertori obično imaju vek trajanja između 10 i 15 godina. Cena zamene može iznositi od 1000 do 2000 EUR, dok za sistem od 5 kW iznosi oko 1.000 EUR.

Preporučuje se godišnja ili dvogodišnja inspekcija sistema kako bi se osigurao ispravan rad svih komponenti i otkrili eventualni problemi na vreme. Ovi troškovi su relativno niski i mogu iznositi oko 50 do 100 EUR po poseti. Takođe, vremenom može doći do manjih kvarova ili potrebe za zamenom kablova, konektora i drugih komponenti. Ovi troškovi su uglavnom mali i povremeni, ali se preporučuje da kupci-proizvođači planiraju mali godišnji budžet za nepredviđene popravke.

Solarni paneli zahtevaju minimalno održavanje i imaju životni vek od 25 do 30 godina, sa godišnjom degradacijom efikasnosti od 0,5% do 1%. Takođe, sistemima zasnovanim na solarnim panelima ne treba gorivo, što eliminiše varijabilne troškove karakteristične za fosilna goriva i omogućava dugoročnu stabilnost troškova.

2.3. Neto merenje i neto obračun

Neto merenje je način obračuna neto električne energije, pri kojem višak isporučene električne energije tokom jednog meseca smanjuje količinu neto električne energije u narednom obračunskom periodu. U ovom modelu, utrošena energija predstavlja razliku između preuzete i isporučene energije, uključujući višak iz prethodnih meseci. Na ovaj način, kupci-proizvođači mogu smanjiti svoje buduće račune koristeći prethodno generisani višak energije. Ugovor o potpunom snabdevanju sa neto merenjem može biti zaključen sa domaćinstvima i stambenim zajednicama.

Neto obračun je način obračuna neto električne energije, pri kojem se vrednost viška predate električne energije tokom meseca obračunava i naplaćuje u skladu sa ugovorom između kupca-proizvođača i snabdevača. U ovom slučaju, ako je isporučena električna energija veća od preuzete, višak se prenosi u sledeći obračunski period, unutar perioda poravnanja. Ako višak ostane na kraju perioda poravnanja, predaje se snabdevaču bez naknade [19].

2.4. Račun za električnu energiju kupaca-proizvođača

Za razliku od krajnjih korisnika koji nisu kupci-proizvođači, čija se potrošnja električne energije (EE) obračunava na osnovu utrošene energije, kupcima-proizvođačima iz kategorije domaćinstava obračun se vrši primenom principa neto merenja.

Način obračuna utrošene električne energije u zavisnosti od tipa krajnjeg korisnika.

Krajnji korisnici koji nisu kupci-proizvođači:

$$\text{Utrošena EE} = \text{Preuzeta EE} \tag{2}$$

Krajnji korisnici kupci-proizvođači (neto merenje):

$$\begin{aligned}\text{Utrošena EE} &= \text{Preuzeta EE} - \text{Isporučena EE} \\ &- \text{Višak iz prethodnog perioda}\end{aligned} \tag{3}$$

Tabela 2. Uporedni prikaz troškova računa za električnu energiju potrošača koji nisu kupci-proizvođači i kupca-proizvođača koje snabdeva garantovani snabdevač

Potrošači koji nisu kupci-proizvođači	**Kupci-proizvođači**
Fiksni troškovi koji se plaćaju bez obzira na utrošenu EE	
- Obračunska snaga - Trošak garantovanog snabdevača	- Obračunska snaga - Trošak garantovanog snabdevača
Troškovi povezani sa utrošenom / preuzetom EE	
- Utrošena EE (kWh)* - Naknada za podsticaj povlašćenih proizvođača EE - Naknada za unapređenje energetske efikasnosti	
Troškovi koji se obračunavaju po principu neto-merenja	
	- Utrošena EE (kWh) - Naknada za pristup distributivnom sistemu za razliku preuzete i utrošene EE** - Naknada za unapređenje energetske efikasnosti - Naknada za podsticaj povlašćenih proizvođača EE
Umanjenja računa* **	
- Popust 5% za plaćanje prethodnog računa u roku dospeća - Popust od 50 dinara za elektronsku dostavu računa**** - Umanjenje za energetski ugrožene kupce	
Porezi	
- Akciza - Porez na dodatu vrednost	

* Mrežarina je uključena u iznos cene utrošene električne energije

** Mrežarina je uključena u iznos cene utrošene električne energije, a dodatno se naplaćuje po cenama pristupa distributivnom sistemu i razlika između preuzete i utrošene električne energije

*** Elektroprivreda Srbije AD omogućava kupcima različite popuste – nabrojani su trenutno na snazi ali se relativno često menjaju

**** Elektroprivreda Srbije AD je dala pogodnost za sve kupce na garantovanom snabdevanju – opciju primanja elektronskog računa. Ova digitalna usluga omogućava korisnicima da primaju svoje mesečne račune direktno na email.

U slučaju da je utrošena električna energija negativna, vrednost se tretira kao nula, dok se negativna vrednost dodaje prethodnim viškovima i prenosi u sledeći obračunski period kao višak. Upoređivanjem računa za električnu energiju između potrošača koji nisu kupci-proizvođači i kupaca-proizvođača, mogu se primetiti razlike u načinu obračuna. U Tabeli 2 je dat uporedni prikaz troškova potrošača koji nisu kupci-proizvođači i kupca-proizvođača [20,21].

2.4.1. Naknada za podsticaj povlašćenih proizvođača električne energije

Od 1. juna 2024. godine, naknada za podsticaj povlašćenih proizvođača električne energije obračunava se prema utrošenoj električnoj energiji, u skladu sa novom Uredbom o naknadi za podsticaj povlašćenih proizvođača električne energije [22]. Iznos naknade je 0,801 RSD/kWh.

2.4.2. Naknada za unapređenje energetske efikasnosti

Od 1. januara 2024. godine, naknada za unapređenje energetske efikasnosti obračunava se na osnovu utrošene električne energije, zbog izmena Zakona o naknadama za korišćenje javnih dobara [23]. Iznos naknade iznosi 0,015 RSD/kWh.

2.4.3. Naknada za pristup distributivnom sistemu

Naknada za pristup sistemu obračunava se u skladu sa Metodologijom za određivanje cene pristupa sistemu za distribuciju električne energije Agencije za energetiku Republike Srbije [24]. Ovu naknadu plaćaju svi korisnici distributivnog sistema, bez obzira na njihov status, a obračunava se na ukupno preuzetu električnu energiju. Trenutne cene ove naknade za domaćinstva date su u poslednjoj koloni u Tabeli 3.

Za krajnje korisnike koji nisu kupci-proizvođači, a koje snabdvea garantovani snabdevač, ova naknada je uključena u jedinstvenu cenu za preuzetu električnu energiju. Za kupce-proizvođače, međutim, način obračuna ove naknade je drugačiji. S obzirom na to da su kod neto merenja cene određene prema cenama garantovanog snabdevanja i da ove cene već uključuju trošak za pristup distributivnom sistemu, deo naknade je već obuhvaćen u ceni za utrošenu energiju. Kupac-proizvođač je u obavezi da plati troškove za pristup distributivnom sistemu za ukupnu količinu preuzete energije. Pošto je deo tih troškova već uključen u cenu utrošene energije, kupac-proizvođač plaća razliku. Snabdevač izdaje račun kupcu-proizvođaču, koji je u obavezi da ga plati. Snabdevač prebacuje plaćena sredstva Operatoru distributivnog sistema. Razlika između preuzete i utrošene energije obračunava se kroz stavku „Naknada za obračun pristupa DS za razliku preuzete i utrošene električne energije". Drugim rečima, deo naknade je obračunat kroz cenu za utrošenu energiju, dok se ostatak obračunava kroz stavku koja pokriva naknadu za razliku preuzete i utrošene energije. Ova stavka ulazi u osnovicu za PDV. Ulazni podaci za primer obračuna naknade za pristup distributivnom sistemu dati su u Tabeli 3, gde su sa VT i NT označene viša i niža tarifa, respektivno.

Tabela 3. Ulazni podaci za obračun naknade za pristup distributivnom sistemu

Preuzeta EE [kWh]	Utrošena EE [kWh]	Cena pristupa distributivnom sistemu [RSD] [25]
VT: 403	VT: 0	VT: 3,879
NT: 287	NT: 270	NT: 0,970

Obračun ukupne naknade za pristup distributivnom sistemu na osnovu podataka u Tabeli 3:

$$\left(403-0\right)\cdot 3,879+\left(287-270\right)\cdot 0,970=1579,73\ RSD\ .$$

U slučaju da je korisnik sa jednotarifnim merenjem aktivne energije tada je cena pristupa distributivnom sistemu jednaka 3,394 RSD po kWh [25].

III PRORAČUN SOLARNOG SISTEMA ZA KUPCA-PROIZVOĐAČA IZ KATEGORIJE DOMAĆINSTVO

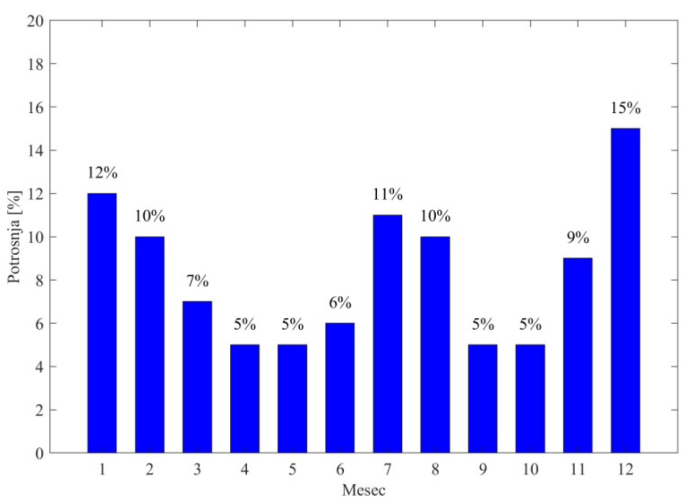
3.1. Prosečna godišnja potrošnja domaćinstva

Na osnovu podataka o potrošnji električne energije u Srbiji za 2021. godinu, izdvojen je uzorak, čiji podaci su iskorišćeni kao ulaz za proračun. Izabrano je šest grupa potrošača definisanih prema godišnjoj potrošnji. U Tabeli 4 su prikazani opsezi godišnje potrošnje za posmatranu grupu u uzorku i prosečna godišnja potrošnja domaćinstava za koja je sproveden proračun. Za svaku grupu analizirana su tri slučaja:

1. domaćinstvo je sa dvotarifnim (DT) obračunom aktivne energije i potrošnjom u %VT koja iznosi 75%;
2. domaćinstvo je sa dvotarifnim obračunom aktivne energije i potrošnjom u %VT koja iznosi 60%;
3. domaćinstvo sa jednotarifnim (JT) obračunom aktivne energije.

Tabela 4. Prosečna godišnja potrošnja analiziranih domaćinstava

Domaćinstvo / grupa	Godišnja potrošnja domaćinstva [kWh/god]	Prosečna god. potrošnja [kWh/po mernom mestu]
1	3501-5000	4220
2	6001-7500	6700
3	9001-10500	9700
4	12001-13500	12685
5	15001-20000	16854
6	>30000	42491



Slika 1. Raspodela potrošnje električne energije domaćinstva po mesecima

Raspodela ukupne godišnje potrošnje domaćinstva po mesecima u godini je prikazana na Slici 1. Prikazana raspodela odgovara potrošaču koji koristi električnu energiju za grejanje tokom zimskog i hlađenje tokom letnjeg perioda.

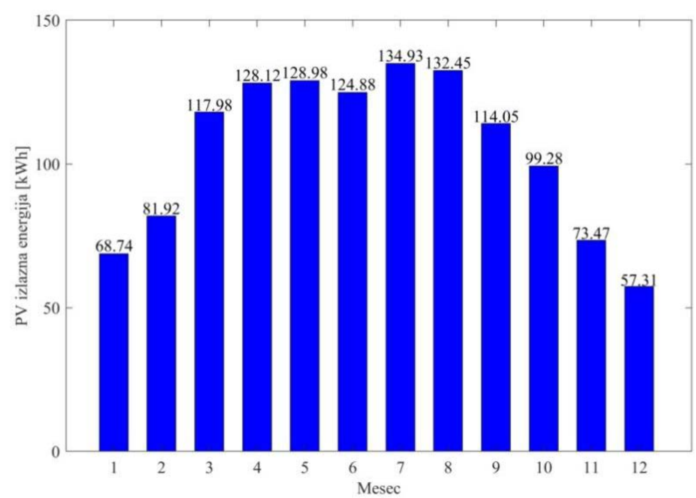
3.2. Izbor snage solarne elektrane

Optimalan izbor snage solarne elektrane u sistemu kupca-proizvođača bio bi onaj kod kojeg na kraju perioda poravnanja ne postoji višak isporučen u elektrodistributivni sistem. Prema važećoj regulativi, 31. marta se vrši poravnanje, kada se višak, ukoliko postoji, vraća na nulto stanje.

Dodatno, viškovi koji su predati u određenoj tarifi samo u toku trajanja te tarife mogu biti iskorišćeni. Iz tog razloga, prilikom procene snage solarne elektrane, treba napraviti razliku između domaćinstava koja koriste jednotarifni i dvotarifni obračun električne energije. U slučaju da se za merenje električne energije koristi dvotarifni obračun, za analizirano domaćinstvo potrebno je odrediti ukupnu potrošnju u VT ostvarenu tokom 12 meseci. U proračunu je pretpostavljeno da je u NT proizvodnja solarne elektrane jednaka 0. Tako da se u slučaju postojanja viškova oni koriste da pokiju potrošnju domaćinstva u VT. Kod domaćinstava kod kojih se koristi jednotarifni obračun određuje se ukupna godišnja potrošnja električne energije.

3.3 Podaci za procenu proizvodnje solarne elektrane

U proračunu su korišćeni podaci proizvodnje PV panela koji su preuzeti sa PVGIS Online Tool [26] za izabranu lokaciju u Beogradu. Optimalni nagibni ugao od 38° je izabrao PVGIS Online Tool, azimutni ugao jednak je 0° i gubici PV sistema 14%. Prema dobijenim podacima, za instaliran 1 kWp PV panela, godišnja proizvodnja inosi 1262,09 kWh. Na Slici 2 je prikazana proizvodnja po mesecima na izabranoj lokaciji.



Slika 2. Proizvodnja za instaliran 1 kWp PV panela

3.4. Procena optimalne instalisane snage solarne elektrane

U Tabeli 5 su prikazane procenjene optimalne instalisane snage solarne elektrane za šest analiziranih grupa potrošača. Za domaćinstva sa većom ukupnom godišnjom potrošnjom (16854 kWh za JT obračun aktivne energije i 42491 kWh za sva tri analizirana slučaja) optimalna snaga solarne elektrane premašila je maksimalno dozvoljenih 10,8 kW. Zbog ovog ograničenja, izabrana je maksimalno dozvoljena instalisana snaga i dalji proračun je izvršen sa snagom od 10,8 kW.

Tabela 5. Procenjene optimalne instalisane snage solarne elektrane

Dom. /grupa	Prosečna god. potrošnja [kWh]	Instalisana snaga solarne elektrane [kW]		
		Dom. DT, 75% VT	Dom. DT, 60% VT	Dom. JT
1	4220	2,5	2	3,3
2	6700	3,9	3,2	5,2
3	9700	5,7	4,6	7,6
4	12685	7,4	6	9,9
5	16854	9,9	7,9	10,8
6	42491	10,8	10,8	10,8

IV Procena isplativosti primene solarnih sistema kod kupca-proizvođača iz kategorije domaćinstvo

U ovom poglavlju izvršena je procena isplativosti primene solarnih sistema. Vrednost potrebnih sredstava za instalaciju solarnog sistema izračunata je prema formuli (1). Kod proračuna uštede u računu za električnu energiju obuhvaćeno je plaćanje:

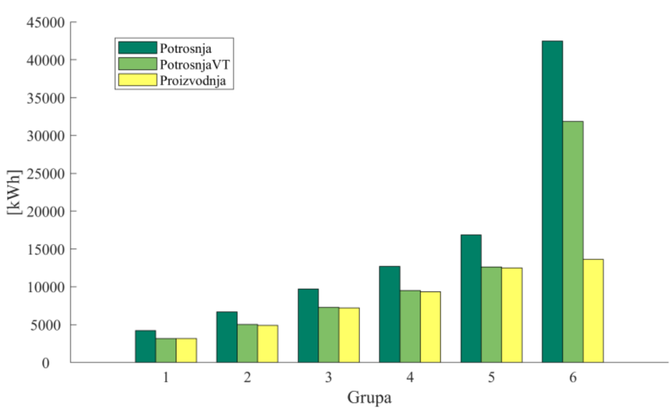
- naknade za utrošenu električnu energiju,
- naknade za podsticaj povlašćenih proizvođača električne energije,
- naknade za unapređenje energetske efikasnosti,
- naknade za pristup DS za razliku preuzete i utrošene električne energije,

uz uračunatu akcizu i PDV.

Vreme povraćaja investicije je procenjeno poređenjem potrebnih sredstva za instalaciju solarne elektrane i uštede na računu za električnu energiju.

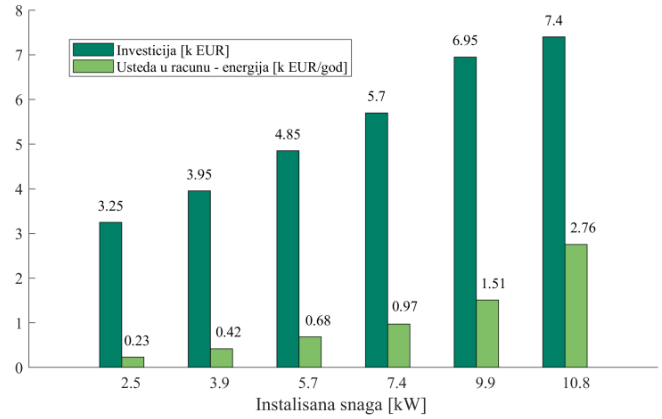
4.1. Domaćinstvo sa dvotarifnim obračunom aktivne energije i potrošnjom koja u VT iznosi 75%

Na Slici 3 prikazana je ukupna godišnja potrošnja električne energije domaćinstva sa dvotarifnim obračunom aktivne energije, pri čemu potrošnja u VT iznosi 75%, kao i potrošnja u VT i procenjena proizvodnja solarne elektrane kupca-proizvođača. Rezultati su prikazani za šest analiziranih grupa.



Slika 3. Godišnja potrošnja EE (ukupna i u VT) i PV proizvodnja KP čija je potrošnja 75% u VT

Na Slici 4, na apscisnoj osi su označene snage solarne elektrane za svaku analiziranu grupu, dok bar dijagram prikazuje potrebna sredstva za instalaciju solarne elektrane i uštedu na računu za električnu energiju na godišnjem nivou. U Tabeli 6 je dodatno prikazano i vreme povraćaja investicije, određeno poređenjem prethodna dva podatka.



Slika 4. Vrednost investicije i ušteda u računu za električnu energiju za KP sa DT obračunom i 75% u VT

Tabela 6. Rezultati za KP sa DT obračunom i 75% u VT

P_{inst} [kW]	C_{invest} [EUR]	Ušteda u računu [EUR]	Vremene povraćaja investicije [god]	Višak EE [kWh]
2,5	3250	233,13	13,94	73,4
3,9	3950	421,73	9,37	108,4
5,7	4850	682,78	7,1	163,3
7,4	5700	971,07	5,87	207,1
9,9	6950	1510,79	4,6	283,2
10,8	7400	2755,4	2,69	0

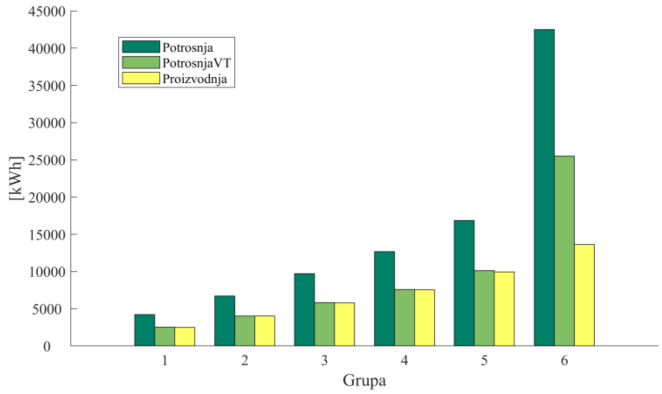
Na Slici 4 i u Tabeli 6 se može uočiti da sa porastom instalisane snage solarne elektrane rastu potrebna sredstva za njenu realizaciju, ali brže rastu i uštede u računima, što dovodi do toga da se sa porastom instalisane snage vreme povrata investicije smanjuje.

U Tabeli 6 su prikazani viškovi električne energije na kraju perioda za poravnanje (31. marta). Za domaćinstva čija je ukupna godišnja potrošnja jednaka 42491kWh, optimalna snaga solarne elektrane bi iznosila 24,8 kW. Međutim, zbog ograničenja koje nameće regulativa, proračun je izvršen tako što je izabrana snaga elektrane 10,8 kW. Kako je ova snaga ispod optimalne, na kraju svakog meseca u godini višak je iznosio 0 kWh.

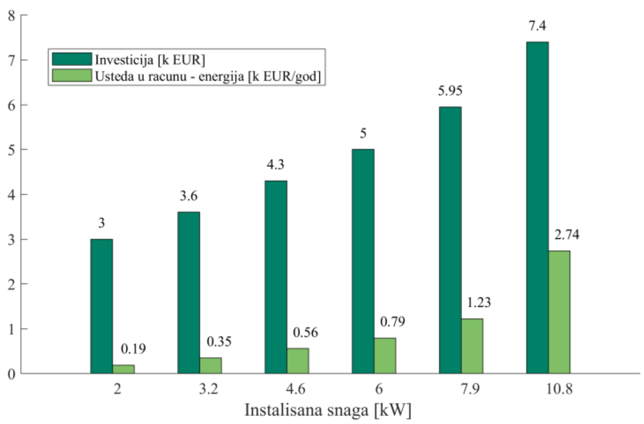
4.2. Domaćinstvo sa dvotarifnim obračunom aktivne energije i potrošnjom koja u VT iznosi 75%

Na Slici 5 je prikazana ukupna godišnja potrošnja električne energije domaćinstva sa dvotarifnim obračunom aktivne energije i potrošnjom koja u VT iznosi 60%, potrošnja u VT i procenjena proizvodnja solarne elektrane kupca-proizvođača. Rezultati su prikazani za šest analiziranih grupa. Na Slici 6 na apscisnoj osi su označene snage solarne elektrane za svaku analiziranu grupu, a bar dijagram prikazuje potrebna sredstva za instalaciju solarne elektrane i uštedu u računu za električnu energiju, dok je u Tabeli 7 prikazano i vreme povraćaja investicije.

Na osnovu dobijenih rezultata se može i u ovom slučaju uočiti da sa porastom instalisane snage solarne elektrane rastu potrebna sredstva za njenu realizaciju, kao i da brže rastu uštede u računima, tako da sa porastom instalisane snage vreme povrata investicije se smanjuje.



Slika 5. Godišnja potrošnja EE (ukupna i u VT) i PV proizvodnja KP čija je potrošnja 60% u VT



Slika 6. Vrednost investicije i ušteda u računu za električnu energiju za KP sa DT obračunom i 60% u VT

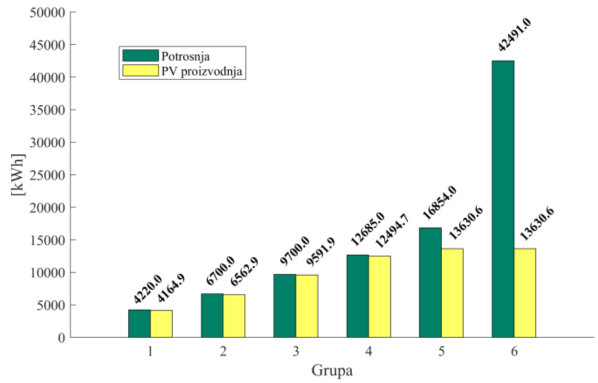
Tabela 7. Rezultati za KP sa DT obračunom i 60% u VT

P_{inst} [kW]	C_{invest} [EUR]	Ušteda u računu [EUR]	Vremene povraćaja investicije [god]	Višak EE [kWh]
2	3000	188,32	15,93	58,7
3,2	3600	349,18	10,31	96,1
4,6	4300	556,45	7,73	135,3
6	5000	793,35	6,3	175,1
7,9	5950	1225	4,86	224,2
10,8	7400	2737	2,7	0

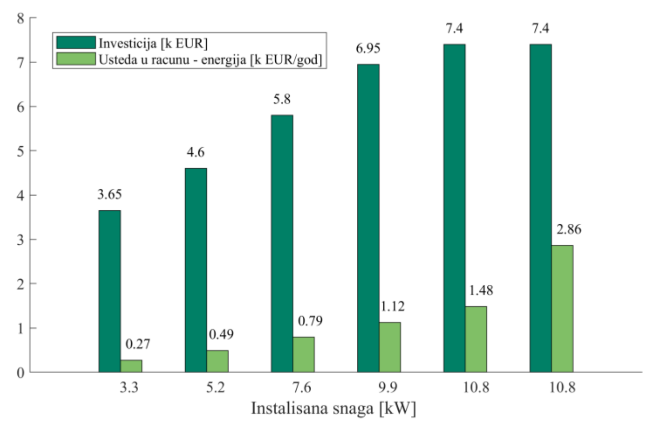
U Tabeli 7 su prikazani viškovi električne energije na kraju perioda za poravnanje (31. marta). Za domaćinstva čija je ukupna godišnja potrošnja jednaka 42491 kWh, optimalna snaga solarne elektrane bi iznosila 19,8 kW. Međutim, zbog ograničenja koje nameće regulativa, proračun je izvršen tako što je odabrana snaga elektrane od 10,8 kW. Kako je ova snaga ispod optimalne, na kraju svakog meseca u toku godine višak je iznosio 0 kWh.

4.3. Domaćinstvo sa jednotarifnim obračunom aktivne energije

Na Slici 7 je prikazana potrošnja električne energije i PV proizvodnja kupca-proizvođača sa JT obračunom aktivne energije. Snage male solarne elektrane po analiziranim grupama su date u Tabeli 8. Na Slici 7 se može uočiti da je za svaku grupu ukupna godišnja potrošnja veća od ukupne godišnje PV proizvodnje, tako da u ovom slučaju nema viškova na kraju perioda poravnanja. Na Slici 8 na x-osi su označene snage solarne elektrane za svaku analiziranu grupu. Bar dijagram prikazuje potrebna sredstva za instalaciju solarne elektrane i uštedu u računu za električnu energiju, dok Tabela 8 prikazuje i vreme povraćaja investicije određeno poređenjem prethodna dva podatka. Kao i u prethodna dva slučaja, može se uočiti da sa porastom instalisane snage solarne elektrane rastu potrebna sredstva za njenu realizaciju, kao i uštede u računima, dok se vreme povrata investicije smanjuje.



Slika 7. Godišnja potrošnja EE i PV proizvodnja KP sa JT obračunom



Slika 8. Vrednost investicije i ušteda u računu za električnu energiju za KP sa JT obračunom

Tabela 8. Rezultati za KP sa JT obračunom

P_{inst} [kW]	C_{invest} [EUR]	Ušteda u računu [EUR]	Vremene povraćaja investicije [god]	Višak EE [kWh]
3,3	3650	271,69	13,43	0
5,2	4600	489,91	9,39	0
7,6	5800	792,26	7,32	0
9,9	6950	1124,64	6,18	0
10,8	7400	1482,53	4,99	0
10,8	7400	2861,05	2,59	0

Za sva tri analizirana slučaja, domaćinstva sa DT obračunom aktivne energije pri 75% i 60% potrošnje u višoj tarifi, kao i JT obračunom, rezultati su pokazali da sa porastom instalisane snage solarne elektrane rastu i potrebna sredstva za njenu realizaciju, što je i očekivano. Istovremeno, povećanje instalisane snage dovodi do većih godišnjih ušteda na računima za električnu energiju, što rezultira kraćim periodom povraćaja investicije za veće instalisane snage.

Takođe, treba imati u vidu da su za potrošače čija je optimalna instalisana snaga manja od dozvoljenih 10,8 kW proračuni izvršeni za solarne elektrane sa instalisanom snagom koja odgovara optimalnoj vrednosti za analizirana domaćinstva. Ukoliko bi se instalirala elektrana sa snagom većom od optimalne, period povrata investicije bi se produžio, što bi moglo dovesti do toga da ulaganje postane neisplativo tokom životnog veka sistema.

Kod potrošača kod kojih je optimalna instalisana snaga veća od dozvoljenih 10,8 kW, primena ograničenja i izbor snage od 10,8 kW, koja je manja od optimalne, dovodi do značajno manje PV proizvodnje u odnosu na potrošnju. Ukoliko bi izbor optimalne snage za ove potrošače bio moguć, investicioni troškovi bi se povećali, ali bi se smanjila potrošnja električne energije u skupljoj zoni, čime bi ušteda u računu bila značajna, pa bi se i održao kraći period otplate.

U slučaju DT obračuna (Tabela 6 i Tabela 7) može se primetiti da višak električne energije na kraju obračunskog perioda nije jednak nuli. Razlog za to leži u činjenici da je izbor optimalne instalisane snage vršen na osnovu ukupne godišnje potrošnje u VT, bez uzimanja u obzir raspodele potrošnje po mesecima u trenutku izbora. Daljom analizom ispitano je da li bi smanjenje instalisane snage, tako da se višak električne energije na kraju obračunskog perioda svede na nulu, dovelo do boljeg ekonomskog efekta za potrošača. Rezultati su pokazali da bi smanjenje instalisane snage umanjilo potrebna investiciona sredstva, ali bi dovelo i do smanjenja ušteda na računima za električnu energiju u meri da bi se period povraćaja investicije produžio, čime bi ukupna isplativost ulaganja bila umanjena.

Prilikom određivanja vremena povraćaja investicije nije razmatran životni vek invertora, koji traje od 10 do 15 godina. To znači da postoji mogućnost da će nakon tog perioda biti potrebna zamena invertora, što bi dovelo do dodatnih troškova u godini kada dođe do zamene. Takođe, nije razmatrana mogućnost dobijanja sredstava iz Programa subvencija koji sprovode 137 jedinica lokalne samouprave i gradske opštine. Ovaj program može pokriti do 50% početnih investicionih troškova, sa maksimalnim iznosom od 420000 RSD po domaćinstvu, za sisteme do 6 kW. Ukoliko bi potrošač dobio subvenciju to bi značajno smanjilo trošak potrošača i doprinelo skraćenju vremena povraćaja investicije.

V ZAKLJUČAK

U radu je analiziran uticaj ugradnje solarnih sistema kao primene novih tehnologija u domaćinstvima. U radu je dat uvid u ključne ekonomske faktore koji utiču na odluku o investiranju, uključujući procenu troškova instalacije, očekivane uštede na računima za električnu energiju i vremenski okvir povraćaja ulaganja. Analiza je obuhvatila primenu solarnih sistema u domaćinstvima kategorije kupaca-proizvođača sa različitim nivoima godišnje potrošnje električne energije i različitim obračunom aktivne energije (DT ili JT), kao i ražličitim odnosima potrošnje u višoj i nižoj tarifi u slučaju DT obračuna. Analiza ukazuje na značaj izbora instalisane snage u zavisnosti od načina obračuna aktivne energije (DT ili JT), kao i procenta potrošnje električne energije u višoj tarifi u slučaju DT obračuna. Neadekvatan izbor bi mogao rezultirati nedovoljnim, ili sa druge strane većim instalisanim snagama, koje bi imale duži period povraćaja investicije ili bi čak bile neisplative.

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Profitability Analysis of Solar System Implementation for Prosumer Households

Abstract – This paper analyses the impact of solar system installation as an application of new technologies in households, focusing on cost assessment, electricity bill savings, and investment payback period. An initial comparison of electricity bill components will be presented between consumers who are not prosumers and those who are. Subsequently, the analysis will cover the application of solar systems in prosumer households with different levels of annual electricity consumption and varying consumption ratios between higher and lower tariff rates. Six consumer groups differing in average annual electricity consumption will be considered, with two consumption ratio scenarios between higher and lower tariff rates analysed for each group. Based on electricity consumption data, the adopted annual consumption distribution by months, and solar system production models obtained using the PVGIS Online Tool, optimal installed solar system capacities for the analysed consumer groups will be determined. The analysis will include the evaluation of required investment funds, expected electricity bill savings, and investment payback periods. Special attention will be given to the impact of the consumption ratio between higher and lower tariff rates on the selection of optimal solar system capacity, as well as the possibilities of utilizing excess generated energy. The expected results should highlight the profitability and justification of the investment depending on the household's annual electricity consumption value.

Index Terms – Prosumer, Solar system, Optimal installed capacity, Economic impact, Households

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